INLAND FISHERIES – PART 2

[Exploratory Study – TEEBAgriFood]

Ecosystem services in freshwater fish production systems and aquatic ecosystems: Recognizing, demonstrating and capturing their value in food production and water management decisions

Food and Agriculture Organization of the United Nations

www.fao.org

The Economics of Ecosystems & Biodiversity

www.teebweb.org

Preparation of this document

This report was prepared under the auspices of a UN Agency to UN Agency Contribution Agreement between the **United Nations Environment Programme** (UNEP) and the **Food and Agriculture Organization of the United Nations** (FAO) and specifically dealt with the project, *The Economics of Ecosystems and Biodiversity (TEEB): Natural Resource Accounting at country-level and across specified industrial sectors.* The report was prepared by Cecile Brugere, David Lymer and Devin M. Bartley at the Marine and Inland Fisheries Branch (FIRF) of FAO. The case studies, which Part 2 is based on, were prepared by:

- **Columbia River** case study, Cedar Morton and Duncan Knowler, Simon Fraser University, Canada
- **Lower Mekong Basin** case study: Rattanawan (Tam) Mungkung, Ratcha Chaichana and Santi Senglertsawai, Kasetsart University, Thailand
- **Lake Victoria** case study: Dismas Mbabazi and Oliva C. Mkumbo, Lake Victoria Fisheries Organisation, Uganda and Cecile Brugere.

The comments received from a number of reviewers (Richard Young, Sustainable Food Trust; Jules Pretty, University of Essex; David Love, John Hopkins Center for a Liveable Future, Harpinder Sandhu, Flinders University) are gratefully acknowledged and have been addressed in the revised version of this report.

Disclaimer

Final technical report for the UNEP´s Initiative "The Economics of Ecosystems and Biodiversity (TEEB): Natural Resource Accounting at country-level and across specified industrial sectors (EP/GLO/617/UEP)

Suggested Citation

Brugere, C., Lymer, D. and Bartley, D.M. (2015) *Ecosystem services in freshwater fish production systems and aquatic ecosystems: Recognizing, demonstrating and capturing their value in food production and water management decisions*. TEEB Agriculture & Food, UNEP, Geneva

PART 2

Case Studies

TABLE OF CONTENTS

PART 2: Case Studies

4. VALUING ECOSYSTEM SERVICES IN INLAND FISHERIES AND FRESHWATER AQUACULTURE IN NORTH AMERICA, ASIA AND AFRICA

4.1 Objectives of the case studies and overview of systems

The goal of the case studies is to assess how, and to what extent, the supply of ecosystem services and benefits associated with inland capture fisheries, freshwater aquaculture and aquatic ecosystem management could be increased and improved in a sustainable manner.

Each case study has two interlinked objectives:

To assess the value of ecosystem services in a set of fish production systems and main water management practices taking into account the impacts, externalities and dependencies between agricultural/economic, environment and social systems, and

To develop a holistic assessment of different production and management scenarios in the inland fisheries/aquaculture sector, taking into account the (hidden) impacts and externalities and dependencies between agricultural/economic, environment and social systems.

The Columbia River in North America, the Lower Mekong Basin in Southeast Asia and Lake Victoria in Africa have been chosen as case studies (see Part 1). Table 1 provides an overview of the fish production systems, water management practices and ecosystem services considered in each of these case studies.

The main ecosystem services considered in each system are: **(I)** food production (animal proteins and nutrients); **(II)** water quality; **(III)** biodiversity; **(IV)** carbon fixation and greenhouse gas emissions; **(V)** nutrient cycling; and **(VI)** income and livelihood support. Other ecosystems services may be considered if important in the context of each case study.

Table 1: Fish production systems, water management practices and ecosystem services considered in each case study area

<table>
<tr><th>Case study area</th><th>Fish production systems</th><th>Main water management objective(s)</th><th>Ecosystem services common to each case study area</th><th>Additional ecosystem services for potential consideration</th></tr>
<tr><td>1. Columbia River, USA</td><td>Recreational/small-scale fisheries (salmon fisheries)</td><td>Water management for irrigation and hydropower generation; fish and habitat conservation</td><td rowspan="6">Food production
Water quality
Biodiversity
Carbon fixation and greenhouse gas emissions
Nutrient cycling
Income and livelihood support</td><td>Sediment regulation
Recreation/tourism (angling)
Spiritual identity, cultural heritage</td></tr>
<tr><td rowspan="3">2. Lower Mekong Basin, South-East Asia</td><td>Rice fields with fish production (artisanal fisheries, including floodplain rice-field fisheries).</td><td>Water retention and management for rice production.</td><td>Water flow regulation
Maintenance of life cycles of migratory species
Indigenous knowledge/cultural heritage
Ground water recharge</td></tr>
<tr><td>Cage aquaculture in reservoirs</td><td>Water management for irrigation and hydropower generation</td><td>Water flow regulation
Education and research
Health impacts</td></tr>
<tr><td>Culture-based fishery (in reservoir or floodplains)
OR
Pond aquaculture</td><td>Water management for irrigation</td><td>Water flow regulation
Ecosystem stability
Education, research, traditional knowledge
Community cohesion (social capital)
Nutrient cycling
Groundwater recharge
Land-based crop production enhancement
Prestige
Education, traditional knowledge</td></tr>
<tr><td rowspan="2">3. Lake Victoria, East Africa</td><td>Industrial fisheries (Nile perch)</td><td>Water for irrigation and drinking</td><td>Ecosystem stability
Income (trade)</td></tr>
<tr><td>Cage aquaculture</td><td>Water for irrigation and drinking</td><td>Education and research</td></tr>
</table>

4.2 Methodological approach to valuation

As was outlined in Part 1, section 2.3, and in line with the overall TEEB approach, the general framework for valuation rests on the concept of marginality (i.e. measuring changes in economic value instead of measuring total economic value). The methodological approach relies essentially on a desk-based analysis of secondary, published literature and available data to describe and analyse the value of ecosystem services under a baseline situation and under one or more alternative development scenarios. The baseline, or business-as-usual scenario, represents the continuation of current management and resource use in each ecosystem.

Valuation of the same ecosystem services under alternative development scenarios is then carried out to compare variations in ecosystem values according to the impacts of prevailing stressors.

The objective of this part of the analysis is to consider the effect on the supply and value of the main ecosystem services of the concerned aquatic ecosystem under the influence of different management and use scenarios. Thus, for the purpose of the analysis, stressors related to increases in water diversions for agriculture, or changes in water management for hydropower generation are preferred over less direct ones such as population growth and climate variability, which are nonetheless recognised as "aggravating factors".

Each case study team was however given the freedom to adapt the valuation approach to suit their case study requirements and data availability. Wherever possible, locally documented values for the concerned ecosystem services are used. If benefit transfer (also called value transfer) is required, it is according to guidelines established by Brander (2013).

Data availability is a challenge. This notwithstanding, the case studies provide interesting methodological advances for the valuation of the concerned ecosystem services. Their results shed light on the importance and vulnerability of the services supplied by inland fisheries and freshwater aquaculture systems when the aquatic ecosystems within which they are embedded are themselves highly sensitive and their ecosystem services under multiple pressures.

The case studies were prepared by:

1. **Columbia River:** Cedar Morton and Duncan Knowler, Simon Fraser University, Canada, over the period May to July 2015.

2. **Lower Mekong Basin:** Rattanawan (Tam) Mungkung, Ratcha Chaichana and Santi Senglertsawai, Kasetsart University, Thailand, over the period May to July 2015.

3. **Lake Victoria:** Dismas Mbabazi and Oliva C. Mkumbo, Lake Victoria Fisheries Organisation, Uganda (with complementary inputs from Cecile Brugere) over the period May to August 2015.

4.3: Case study 1: Columbia River

Case study 1 is an assessment of the value of ecosystem services in a set of fish production systems and water management practices in the Columbia River, North America

EXECUTIVE SUMMARY – COLUMBIA RIVER

To support the project titled: *The economics of ecosystems and biodiversity (TEEB): Natural resource accounting at country-level and across specified industrial sectors (*EP/GLO/617/UEP)*,* the Food and Agriculture Organization of the United Nations (FAO) and the United Nations Environment Programme (UNEP) agreed to develop a holistic assessment of different production and management scenarios in the inland fisheries/aquaculture sector. The assessment takes into account the impacts, externalities, and dependencies between agricultural/ economic, environment and social systems. Broadly, the project's goals are to increase and improve the provision of goods and services in a sustainable manner by supporting informed decision-making in water management regarding trade-offs among ecosystem services.

To understand trade-offs among ecosystem services it is important to examine the full range of services produced, including provisioning, regulating, supporting, and cultural services. This report addresses the Columbia River case study and measures both the capacity of the river to provide a variety of ecosystem services and the actual use of those services in terms of economic value. Our assessment focuses on fish production and the key water management practices that affect this service.

REPORT STRUCTURE

The report is divided into five sections. **Section 1** introduces the Columbia River system and describes services produced by the river. We also present a generic analytical framework that includes discussion of trade-offs among the various ecosystem services and management practices of the basin. **Section 2** develops our integrated assessment and reference case by providing a snapshot of current conditions for a range of services generated by the fish production system, first detailing a range of ecosystem services it directly and indirectly supports, and then describing services that compete with the fish production system, most of which seek to optimize other ecosystem services generated by the Columbia River. Next, **Section 3** provides the rationale for the four ecosystem services we selected for evaluation in this study. In **Section 4** we describe the three alternative development scenarios we created to examine the effects of different river management regimes on the benefits derived from the fish production service. These scenarios include a "business as usual" case (current conditions), and two alternatives that favour hydropower production and fish conservation, respectively. In **Section 5** we outline the biological model we developed to predict changes in fish production under each development scenario.

Section 6 provides results of our economic welfare estimates for the selected ecosystem services, while **Section 7** provides a sensitivity analysis of these results, including an alternative Conservation Priority development scenario and an alternative method for calculating recreational fishing benefits. Finally, **Section 8** contains a summary of our findings and a discussion of the scope and limitations of the report as well as suggestions for further research (e.g. data needs).

MAIN FINDINGS

Below we present our main findings for the four ecosystem services we analyze in detail. A summary table of valuation estimates by ecosystem type is included in Section 8 (**Table 45**), and not reproduced here.

1. Food Production (Commercial Fishing)

The Columbia River provides habitat that supports the production of various fish species. By far the most valuable of these species to US food production are the salmonids, most of which are anadromous.

Summary of key findings for Food Production (Commercial Fishing)

- Columbia River salmon generate about US$26 million/year in direct commercial fleet revenues and about US$50 million/year in economic impact.
- Commercial harvest has declined substantially since development of the river for hydropower and flood control began, and along with increasingly strict fishing regulations.
- Status quo conditions include many improvements for fish conservation since the late 20th century. A return to 1976-1980 levels of development (hydropower prioritization) would result in a deficit in net social benefits of US$961 861 million/year from commercial fishing compared to the status quo.
- A 10 percent greater prioritization of fish conservation from the status quo would shift the annual hydrograph of the Columbia River slightly closer to natural conditions. This would generate an increase in net social benefit of US$1.4 million/year from commercial fishing.
- A return to pristine conditions would permit an increase in net social benefit of US$5.8 million/year from commercial fishing.

2. Recreational Fishing

Many species in the Columbia River are fished recreationally, some native and some introduced. The most preferred of these species include the salmonids as well as sturgeon and bass. Only salmon catch is well documented in the basin and is addressed in the report.

Summary of key findings for Recreational Fishing

- Current direct value data are available for the in-river recreational fishery and indicate a value from trip expenditures of US$32.5 million/year (modelled estimates for Chinook, Coho, Sockeye and Steelhead from Davis (2014))
- Current regional economic impacts of both the in-river and ocean recreational fishery are estimated at US$54.7 million/year (Davis (2014); PFMC (2014))
- Status quo conditions include many improvements for fish conservation. A return to 1976-1980 levels of development (hydropower prioritization) would result in a deficit in net social benefits of US$1.3 million/year from recreational fishing compared to the status quo.
- A 10 percent greater prioritization of fish conservation from the status quo would shift the annual hydrograph of the Columbia River slightly closer to natural conditions. This would generate an increase in net social benefit of US$1.8 million/year from recreational fishing.
- A return to pristine conditions would permit an increase in net social benefit of US$7.3 million/year from recreational fishing.
- An alternative method to calculate recreational fishing benefits (see Section 7) provides somewhat lower value estimates.

3. Cultural/Subsistence Fishing

Native Americans harvest salmon for subsistence use. The associated fishing rights enjoyed by Native American tribes stem from treaties signed with the US federal government in the 1850's. These treaties maintained their right to fish in their traditional fishing grounds but have been a source of conflict in relation to harvest allocations.

Summary of key findings cont'd

- Status quo conditions include many improvements for fish conservation. A return to 1976-1980 levels of development (hydropower prioritization) would result in a deficit in net social benefits of US$332 073 /year from cultural/subsistence fishing compared to the status quo.
- A 10 percent greater prioritization of fish conservation from the status quo would shift the annual hydrograph of the Columbia River slightly closer to natural conditions. This would generate an increase in net social benefit of US$103 598 /year from cultural/subsistence fishing.
- A return to pristine conditions would permit an increase in net social benefit of US$263 561 /year from cultural/subsistence fishing.

4. Nutrient Cycling

The Columbia River acts as a conduit for the cycling of nutrients from ocean to land, particularly via *anadromous salmonids*. Pacific salmon accumulate substantial nutrients in their bodies while maturing at sea – more than 95 percent of their adult body mass is acquired in the ocean. These nutrients are then carried to lakes and streams where they are released when the fish die after spawning.

Summary of key findings cont'd

- Status quo conditions include many improvements for fish conservation over recent decades. As a result, higher fish populations increase nutrient import from the marine to terrestrial realm.
- A return to 1976-1980 levels of development (hydropower prioritization) would result in a deficit in net social benefits of US$5 500 /year from nutrient import compared to the status quo.
- A 10 percent greater prioritization of fish conservation from the status quo would shift the annual hydrograph of the Columbia River slightly closer to natural conditions. The predicted increase in nutrient import would generate an increase in net social benefit of US$1 800 /year.
- These values are quite low because they consider only "net" import of nutrients and not the "gross" amount and the difference in scenarios is not substantive.
- In contrast, a return to pristine conditions would permit an increase in net social benefit of US$17 million/year from nutrient import.

1 INTRODUCTION

1.1 Overview of the Columbia River System

The Columbia River is a large river in the "Pacific Northwest" region of North America that flows 2 000 km from Canadian Rocky Mountains to Pacific Ocean off the coast of Washington State, USA. It is the fourth largest river in the United States by volume and collects runoff from a drainage basin roughly the size of France, spanning portions of seven American states (Washington, Oregon, Idaho, Montana, Wyoming, Utah, Nevada) and one Canadian province (British Columbia). The river's annual cycles are driven by snowpack, which forms on surrounding mountain peaks during cold winter months. About 60 percent of the natural runoff is from this stored precipitation. British Columbia hosts only 15 percent of the Columbia River's catchment area but thanks to the Rocky Mountains generates about 38 percent of its flows. Peak flows occur after the snowpack melts in late spring/early summer (May/June), followed by low flow periods in late summer/early fall. Daily discharge at the river mouth averages 7 504 m^3/s (265 000 cfs[1]).

The basin houses diverse ecosystems including coastal and interior rain forests, grasslands and deserts and is crossed by many major tributaries (e.g. Kootenay, Pend Oreille, Snake and Willamette Rivers), all of which provide essential habitat for aquatic species. The river network is also one of the most developed in the world with over 300 publicly and privately owned dams that provide flood control, irrigation, hydropower production, navigation, and recreation opportunities.

A key location on the river is The Dalles, Oregon, which is the standard reference point for mainstem flow measurements dating as far back as 1878 (see **Figure 1**).

1.2 Important Institutional Arrangements

Several institutional arrangements influence how the Columbia River is managed for various uses. Perhaps the most significant of these is the 1964 Columbia River Treaty, an agreement between Canada and the USA for shared flood control and hydropower benefits. The treaty's content typifies the priority placed on these two uses throughout the basin.

However, in the decades following the treaty other uses gained in importance on both sides of the border, producing new laws and regulations that sometimes compete with flood control and hydropower priorities. For example, the 1973 US Endangered Species Act resulted in the listing of several fish species and subsequent conservation obligations have had a major impact how the river is managed in the US.

---

[1] cubic feet per second

Table 2 lists these and other key institutional arrangements affecting Columbia River ecosystem services.

Figure 1. Columbia River Basin with case study section emphasized in yellow.
Sources: USGS (2014)

Table 2. Key institutional arrangements affecting ecosystem services in the Columbia River

Institutional Arrangement	Relevance
Columbia River Treaty	• Canada/USA power and flood control agreement with shared power benefits. • US is obligated to provide "Canadian Entitlement" of 50 percent additional power produced as a result of the Treaty • Unless otherwise negotiated, in 2024 the US must make "effective use" of its own dams before calling upon Canada for flood control, which will impact its power generating capacity
US Endangered Species Act	• 18 listed fish populations in Columbia River (salmon, steelhead, and bull trout) • Hydropower system must be operated to optimize for both power and endangered fish conservation in accordance with NOAA Biological Opinion
US Pacific Northwest Coordination Agreement	• Coordinates all the region's hydropower utilities so they operate as a single unit. • Permits utilities to take advantage of regional diversity in stream flow and power demand. • Ensures US ability to cover cost of Canadian Entitlement
Pacific Northwest Electric Power Planning and Conservation Act	• Creates the Northwest Power and Conservation Council (NPCC) – an interstate agency whose mandate is to produce management plans for energy production at lowest economic and environmental cost • The NPCC Columbia River Basin Fish and Wildlife Program is one such plan, which among other things, identifies conservation-related financial responsibilities for power producers
Columbia Basin Fish Accords	• Agreement between power producers, states of Idaho and Montana, and Columbia River tribes. The power producers committed to salmon mitigation measures in return for support of the 2008 NOAA Biological Opinion.
Washington Administrative Code	• Establishes minimum required flows in the Columbia River for instream purposes • Establishes procedures for interrupting water rights (ground water and surface water) when forecasted flows are below a minimum level.
Columbia Basin Project Act	• Authorizes the largest irrigation project diverting water directly from the Columbia River mainstem for agricultural use ('The Columbia Basin Project').
Lower Columbia Region Harbour Safety Plan	• Establishes guidelines for adjusting sailing times and allowable draft for incoming and outgoing vessels based on river conditions.
Clean Power Plan	• US-EPA's proposed regulation to reduce GHG emissions from thermal power plants under the Clean Air Act (scheduled enactment - 2015)

1.3 Analytical Framework

The analytical framework presented in
Figure 2 captures the relationships between the Columbia River, the fish production system it supports, the ecosystem services generated by that production system both directly and indirectly via conservation efforts, and the human benefits derived as a result. Other ecosystem services are also generated outside the fish production system. These various uses of the river often compete, which means management decisions typically entail trade-offs that can affect the level of economic welfare generated from fish production. These management decisions are, in-turn, influenced by surrounding institutional, social, cultural, environmental and economic conditions.

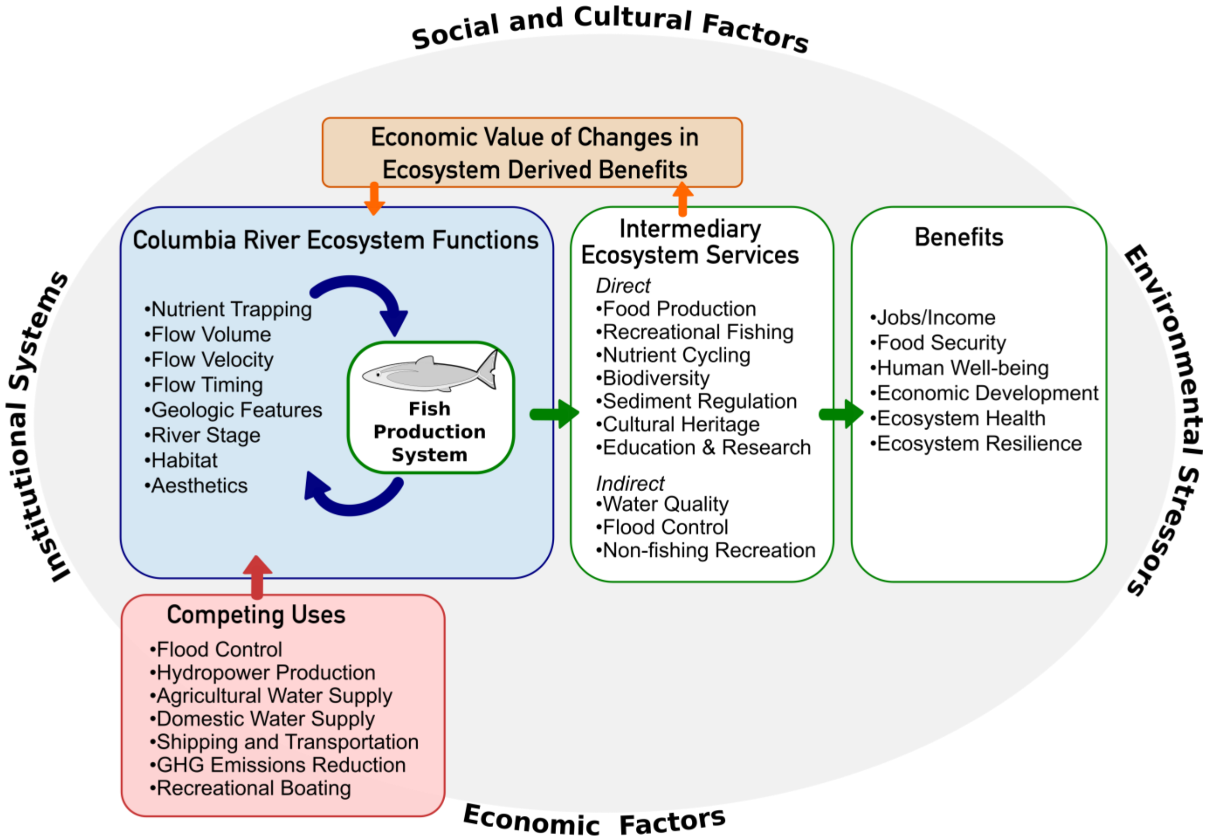


Figure 2. Analytical framework for ecosystem services of the Columbia River fish production system

1.4 Columbia River Ecosystem Functions and Services

The Columbia River performs a number of primary ecosystem functions. The most obvious of these relate to flow regulation. The geologic features of the river (e.g. elevation, channel depth), the volume of precipitation that falls within the basin and forms as snowpack, and the timing of snowmelt all control the volume, velocity, timing and stage (river depth) of the river. Geologic features are also created *by* the river and combine with riparian ecosystems to produce aesthetically attractive landscapes. In addition, the river serves a number of habitat-related functions including trapping and transporting land-based and stream-based nutrients delivered via runoff and the decomposition of aquatic flora and fauna. Numerous aquatic plants, fish, invertebrates, mammals and birds live out all or part of their life cycles in the Columbia River.

Table 3 provides a comprehensive list the ecosystem services produced by the Columbia River along with a description of the processes involved and the types of benefit generated by each service. Colour coding identifies which services are considered part of the fish production system, competing uses, or fundamental river ecosystem functions for the purposes of this study.

Table 3. Ecosystem Services of the Columbia River

Key		
Fish Production System	Competing Uses	River Ecosystem Functions

Services	Processes	Benefits
Provisioning services		
Fish production	Water volume, timing and quality provide habitat for wild and hatchery raised fish (esp. Pacific Salmon)	Jobs, revenue, food supply, non-use value, biodiversity, nutrient cycling
Forest production	Water volume and nutrient cycling provide habitat for riparian forests	Jobs, revenue, non-use value, biodiversity, nutrient cycling
Hydropower production	Geology and water volume/velocity provide hydropower development opportunities	Jobs, revenue, energy supply, GHG reduction
Crop production	Water volume provides irrigation for agriculture	Jobs, revenue, food supply
Shipping and transportation opportunities	Water volume and stage provides shipping and water transport routes	Jobs, revenue, GHG reduction
Domestic water supply	Water volume and quality provide municipal and industrial water supply	Water supply
Regulating Services		
Flood control	Wetlands and deltas absorb flood impacts	Avoided flood damages
Nutrient cycling	Transportation and distribution of elemental nutrients via flows, species migrations and movement (e.g. salmon), and decomposition	Biodiversity, fish production, forest production, crop production
Water quality regulation	Soil infiltration, bank protection by riparian vegetation and in-stream filtration regulate temperature & cleanliness of water	Domestic water supply, fish production, habitat, biodiversity
Climate regulation	Hydropower and water transport reduce GHG emissions compared to alternatives	Avoided climate-related costs, carbon credits
Water flow regulation	Storage as snow, storage in floodplains, infiltration into soil regulates timing, volume, velocity and stage of flow, creates geologic features	Hydropower production, agricultural water supply, domestic water supply, shipping and transport opportunities, sediment regulation

Table 3 cont'd

Services	Processes	Benefits
Supporting services		
Biodiversity	Natural features and processes support biodiverse ecosystems	Genetic diversity, ecosystem resilience
Habitat	Natural features and processes support key life history stages for healthy stocks of wild anadromous and resident fish and other plants and animals, including appropriate water temperatures, water quality, stream geomorphology and productivity, food webs and nutrient cycling	Fish production, forest production, biodiversity, non-use value
Cultural services		
Cultural heritage	Aesthetics, natural beauty, and processes such as food production generate a history of place, cultural identity and foundation for spiritual expression	Human well-being
Recreation and tourism opportunities	Aesthetics, natural features and processes create opportunities for recreation and attract tourists	Jobs, revenue, human well-being
Education and research opportunities	Natural features and processes create opportunities for education and research	Knowledge/learning
Aesthetics and natural features	Natural, clean, and accessible places with aesthetic appeal and unique features provide enjoyment of scenic beauty, boating, fishing and discovery	Recreation and tourism opportunities, non-use value, cultural heritage

Adapted from (Cosens and Fremier 2014; Brugere 2015)

1.5 Trade-offs among Competing Uses

Many of the services in **Table 3** have overlapping processes and benefits, which mean management decisions prioritizing some uses can either negatively or positively impact benefits derived from other uses. **Figure 3** captures the highly interconnected nature of these trade-offs in the Columbia River in a network diagram. The network is a conceptual representation of the general impact each ecosystem service has on other services in the Columbia River as well as the relative importance of relationships among them. Nodes are coloured to represent the fish production system (green), competing uses (red) and river ecosystem functions (blue). Node size represents the service's aggregate impact on all other services. Edge widths represent the relative importance of the relationship. Negative versus positive relationships are not shown.

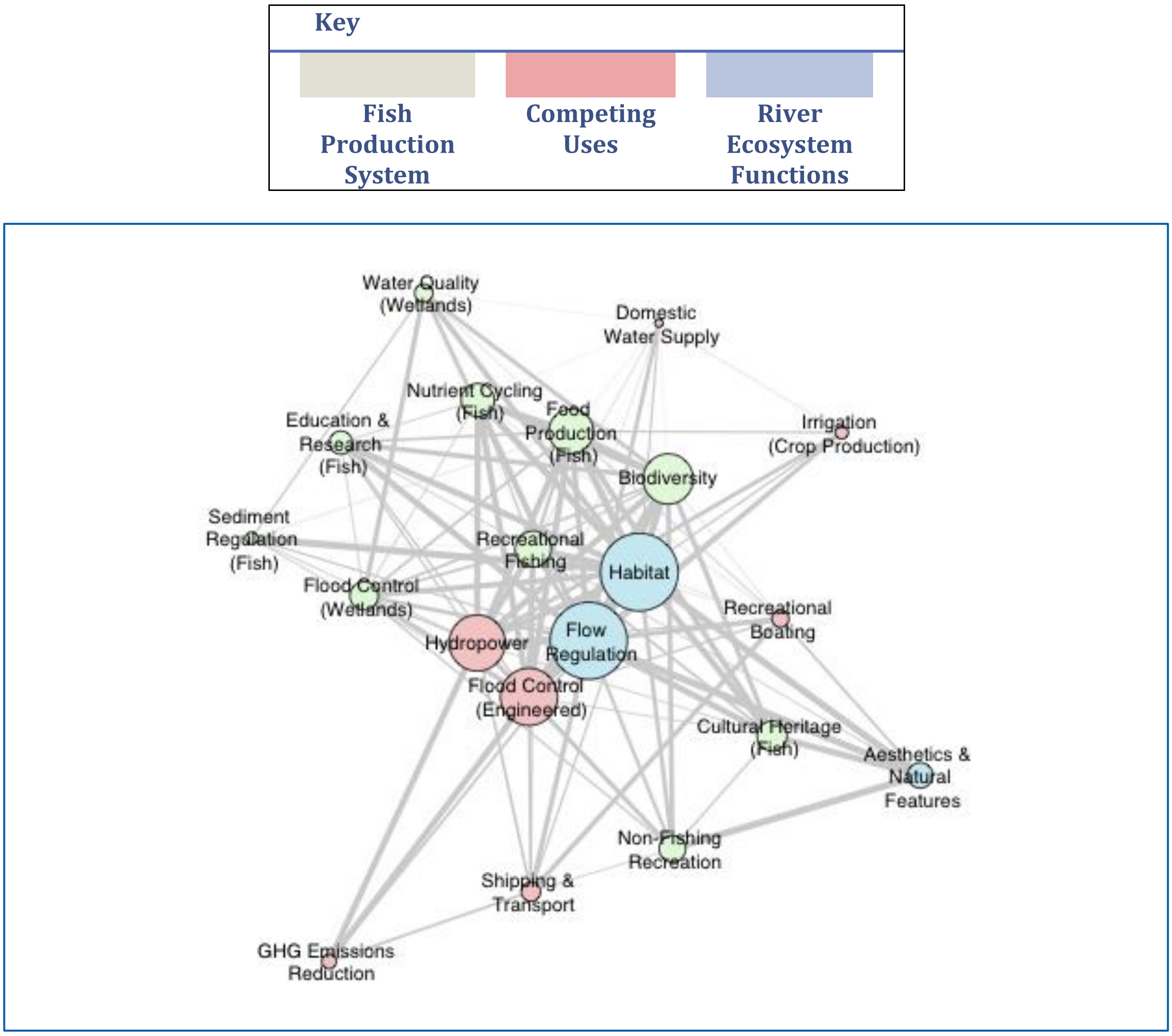


Figure 3. Conceptual representation of relationships among Columbia River ecosystem services

Nodes are coloured to represent the fish production system (green), competing uses (red) and river ecosystem functions (blue).
Node size represents the service's aggregate impact on all other services.
Edge widths represent the relative importance of the relationship.
Negative versus positive relationships are not shown.

Flow regulation and habitat functions, for example are very central in the network because most other ecosystem services rely on these primary functions. Hydropower and engineered flood control also play a central role with many more ties to other nodes than some of the more peripheral services. More than any other use, these two have reshaped the entire Columbia River ecosystem by altering the timing and volume of flows from natural conditions. This impact is most prominent during late spring through to early fall when water supply for irrigation, recreation, and fish production are reduced due to hydropower and flood control priorities. The high priority placed on these two uses partly stems from Canada/USA treaty obligations to share agreed-upon power and flood control benefits. However, in the decades following the Columbia River Treaty, various priorities of the USA shifted in response to public and political pressures. In some cases, domestic legislation was established (e.g. Endangered Species Act), producing competing obligations that challenge the USA's ability to balance between non-power and power/flood-control priorities. Fish conservation became a major focal point of these challenges but other uses such as irrigation, recreation and navigation can also play important roles and sometimes compete with fish production.

The Columbia Basin Project, for example, is a major irrigation project in the semi-arid interior of the basin. Without the Grand Coulee reservoir (Roosevelt Lake), agricultural water supply to this key growing region would be much lower than today. The dam effectively eradicated upstream salmon populations that once migrated into Canada and diversions for irrigation from Roosevelt Lake now compete with downstream fish production during the summer growing season. This competition is tempered by the fact that excess agricultural diversions eventually return to the river, so the overall impact of this use on fish production is much less than from hydropower regulation. Nevertheless, reach-specific impacts are relevant as evidenced by a moratorium placed on new diversions from the river after several fish species were listed as endangered in 1991 (since lifted).

Non-fishing recreation opportunities such as boating and hiking attract many tourists and local residents to the Columbia River and its tributaries. New recreational opportunities were created by the reservoirs and some uses of these engineered features can compete with fish conservation efforts. Recreational users, for example, sometimes attempt to secure preferred water levels behind dams during the summer boating season.

Day-to-day shipping and transportation on the Columbia River affects fish production very little. However, river maintenance for shipping purposes such as dredging may damage fish habitat. One major dredging project completed in 2010 deepened the channel in the lower part of the river to accommodate a deeper draft on large cargo vessels. This project was controversial due to concerns about disturbing salmon habitats.

The competing uses highlighted above can increase risks to salmon from habitat loss, redd dewatering and stranding, poor access of returning adults to spawning areas, and increased downstream migration time for juvenile salmon, which places them at higher risk from predation. Too much flow can also be a problem. High velocity discharge from some dams causes increased fish mortality due to excessive dissolved gas levels. In combination with overfishing, the overall effect is one of decline in fish populations from approximately eleven million salmon in the late 1800s to less than 3 million today **(Huppert et al. 2004; WDFWODFW 2014a)**.

Biodiversity, nutrient cycling, food production and recreational fishing are important services supplied by the fish production system as shown in the network diagram by their relatively high connectivity with other services. When salmon populations decline, these services are all affected. Wild salmon, in particular, are considered critical to the resilience of Columbia River salmon populations via their genetic diversity. Salmon migrations are also an important driver of elemental nutrient cycling from ocean to terrestrial freshwater and riparian ecosystems. Commercial fishing and tribal subsistence harvests provide food supply benefits and recreational fishing generates both revenue and human-wellbeing throughout region. Conservation efforts that preserve salmon habitat also have indirect benefits such as flood control and water filtration via wetlands.

1.6 Study Scope

Relative to other major river basins, the Columbia Basin is highly studied and heavily monitored to produce a wide array of data of various types, each related to different uses of the river. Even so, the system is very complex and significant data gaps remain for specific sections of the basin. Since the timing for this study is compressed, it is necessary to limit our assessment of ecosystem services to manageable portions of the system where data are available and readily utilized. We limit our assessment in four ways: **1)** By considering the river itself as the main driver of production (versus the many tributaries), **2)** By constraining the geographic scope primarily to Washington State, **3)** By selecting specific ecosystem services for evaluation, and **4)** By limiting our focus to Columbia River salmonid species, which are the most economically significant species produced by the system. **Figure 1** highlights the section of the river that is used for this case study.

For many of the ecosystem services derived from the Columbia River, the drivers of their production can be conceived of as either the river itself or as inclusive of all the river's tributaries and the surrounding lands that capture and direct runoff (and nutrients) into the main channel. Our decision to constrain our focus to the river itself is largely due to data availability, but it is also the most relevant natural feature for the fish production system. Limiting our scope in this way means that we focus only on the mainstem's role in producing ecosystem services and exclude contributions from surrounding lands and tributaries. Because we evaluate for the entire salmon population of the basin, this approach necessarily treats non-mainstem effects on that population in aggregate, which is a coarse assumption. However, the intent of the study is to generate management recommendations for the mainstem not tributaries or surrounding lands, the relationships we develop are between salmon survival and mainstem conditions, and, in terms of flow, at least, the mainstem hydrograph is an aggregate reflection of what is occurring in other streams.

One key challenge in studying the Columbia Basin is the lack of publicly available data for certain portions of the basin. For example, hydropower generation data are could not be obtained for all the Canadian dams and studies related to other uses such as recreation and irrigation are rare for that part of the basin. With the exception of Washington State, similar challenges also exist in the US. Where possible and relevant, we consider other states in our analysis, but the primary geographic scope of this study is Washington State. Despite ignoring large areas of the river basin, we feel this restriction still reasonably captures the system because Washington hosts the largest and most productive stretch of the Columbia River.

In addition, since the most economically significant fish species in the basin is anadromous (Pacific Salmon), the fish production system is more complicated in terms of geographic scope. Salmon migrate to the ocean and can travel as far north as Alaska and as far south as California. This behaviour makes it difficult to determine the proportion of the commercial and recreational ocean fishery attributable to the Columbia River. Where possible, we include the ocean fishery in our analysis, but our primary focus is on in-stream commercial and recreational fishing.

Lastly, because sufficient data are unavailable for certain ecosystem services and time does not permit a comprehensive study to collect such data, we are forced to limit our consideration of some ecosystem services generated by the fish production system. Data are available to provide a sense of current conditions for most services and we provide this information where applicable in **Section 2**. However, for comparison across development scenarios (**Section 6**) we identified four ecosystem services with sufficient existing data for evaluation: **1)** food production (commercial fishing), **2)** recreational fishing, **3)** cultural/subsistence fishing, **4)** nutrient cycling. Ecosystem services we are unable to address within the time limitations include, water quality (an indirect benefit of salmon conservation efforts), biodiversity, and carbon fixation/greenhouse gas emissions. Income and livelihood support are captured in the food production valuation.

1.7 Economic Concepts

The perspective that we take in this report regarding economic valuation is quite different from the economic impact perspective that is often taken by stakeholders (e.g. industry groups), or sometimes by governments, although these agents do not always recognize the difference. The economic impact perspective usually concentrates on cursory estimates of jobs created or maintained by current activities. This leads typically, in the fishing industry case, to a position that modest declines in fish landings inevitably lead to processing job losses and a perceived loss of long run economic welfare. This perspective and its general conclusions are not consistent with measuring changes in economic welfare for a variety of reasons and, as a result, it can lead to false conclusions about the true change in social welfare from related environmental changes. For example, if we are concerned with only modest changes in the entire fishing industry's harvest (as we are here), then it is misleading to suggest that employment for the entire processing industry is somehow at stake or even that the processing sector will contract in proportion to the reduction in catch. Economists avoid simplistic assumptions that production changes will lead to equivalent job losses for the economy as a whole. Economies are more resilient than this and contractions in some sectors are usually matched by expansions in others where new workers are needed and given a sufficient time frame.

As an example, post mortem studies were carried out in the US Pacific Northwest, where the Columbia River is located, years after major old growth timber areas were withdrawn from the harvest land base, in part to protect endangered species habitat. Ironically, some analyses have argued that the forest sector was a net welfare gainer during this period, because welfare gains from increases in log prices exceeded losses due to reductions in log quantity **(N Wear and Murray 2004)**. Other studies showed that although there were fewer jobs in the forest industry ex post, the wider economy had expanded enormously, easily swallowing up any losses in the timber industry, in part reflecting longer term structural shifts in the regional economy **(Power 2006)**. These analyses also demonstrate that amongst those forest jobs lost, more resulted from the adoption of labour-saving technology in the industry itself than from timber withdrawals **(Charnley et al. 2006)**. This kind of situation is complex and requires careful modelling using an input-output or general equilibrium approach to account for all the possible linkages and responses in both losing and gaining sectors. Such an analysis was beyond our scope. Instead, we have assumed that economic welfare changes are associated with change in the primary sector only and we have not considered processing or related downstream industry impacts in our analysis.

2 SNAPSHOT OF CURRENT CONDITIONS

This section is divided into two parts. The first part considers ecosystem services directly and indirectly supported by the Columbia River fish production system. The second part considers other ecosystem services generated by the Columbia River, most of which tend to compete with the fish production system.

2.1 Ecosystem Services Directly and Indirectly Supported by the Fish Production System

2.1.1 Food Production (Commercial Fishing)

The Columbia River provides habitat that supports the production of various fish species. By far the most valuable of these species to US food production are the salmonids, most of which are anadromous. In order of abundance these include: Chinook, Coho, Steelhead, Sockeye, Chum and Bull Trout (see Figure **20**). Pacific salmon are the third most valuable commercially fished species in the USA and comprise 7 percent of the total Pacific salmon fishery. Commercial revenues from California, Oregon and Washington ocean catch totalled US$34.1 million in 2013, with total economic impacts estimated at US$79.3 million (direct, induced and indirect effects) (**Pacific Fishery Management Council 2014a**).

Different Columbia River salmon species garner different market prices and these also depend on whether the fish were caught in the ocean or in the river. The average in-river ex-vessel price per commercially caught fish ranges from US$4.32– 116.80 (2013 US$) depending on the species (compiled from various sources) **(Pacific Fishery Management Council 2014a; ODFWWDFW 2002; USACE; NOAA 2014**). Chinook command the highest in-river price since their adult weight is higher than for other species. Adult Chinook caught weight can range from 5–18 kg (11–40 lbs). The average ocean price per fish is US$15.72–52.77 (2013 US$) depending on the species. Ocean prices are lower than in-river prices because ocean fish are typically caught at a younger age and are therefore smaller **(Radtke and Davis 1995; IEAB 2005; Pacific Fishery Management Council 2014a)**.

It is difficult to estimate the total commercial value of salmon landings attributable to the Columbia River because the fish mix in the ocean with salmon from other origins and range from California to Alaska. A rough estimate is US$25.8 million/year (2013 US$) for ocean and in-river commercial catch. This figure is based on 1979-2013 average catches of WA, OR, and CA Chinook and Coho assuming 82 percent of total catch for WA and OR and 40 percent of total catch for CA. About 40 percent of the SE Alaska Chinook fishery is also considered to be of Columbia River origin and is included in the sum. This figure includes both ocean and in-river commercial fishing and tribal fisheries. Davis (2014) estimated direct value from the tribal in-river fishery at US$4.15 million.

Using the same proportions of catch, regional economic impacts (direct, indirect and induced) from commercial fishing of Columbia River stock are estimated at US$50.8 million/yr (2013 US$) (**Pacific Fishery Management Council 2014b)**. US$7.81 million was attributable to the tribal in-river fishery in 2014 **(Davis 2014)**. Note that these estimates are not net values – they do not include costs associated with fishing effort.

Huppert et al. (2004) suggest that net incomes were about 50 percent of gross sales value in the 1990s, but with the exception of the Chinook salmon fishery, this dropped to little or no net value by 2004. This estimate may have changed in more recent years.

The basin's salmon population has been heavily impacted by overfishing and river development. Pre-development salmon abundance (pre-1850) is estimated as at least 11 million salmon/year, compared with the 1977–1981 average of 2.9 million/year **(IEAB 2005)**. Notably, the fish must now navigate a long series of dams during their downstream and upstream migrations. With a small percentage loss due to dam-induced mortality occurring at each dam, this can add up across the entire run.

In addition to inter-dam losses, regulation of the river system for hydropower and flood control results in lower flows during key migration times. These reduced flows slow downstream migration of juveniles, impede access of adults to spawning areas, and can lead to more thermal deaths due to higher river temperatures. High flows can also be a problem at some dams. High velocity spill leading to increased levels of dissolved gas downstream of dams can kill juvenile salmon. Abnormally high flows during peak hydropower generating times may also cause scouring of redds in some reaches. Stranding and dewatering of juveniles and eggs is also an issue when there is too much variability in daily maximum-minimum flows due to the regulation of dams to meet fluctuating hydropower demand. Partly as a result of these challenges, seventeen sub-populations of wild Columbia Basin salmonids are now listed under the US Endangered Species act as threatened or endangered.

Figure 4 shows that commercial catch has declined substantially since development of the river for hydropower and flood control began in 1933. Fishing regulations also played a key role in the pattern shown.

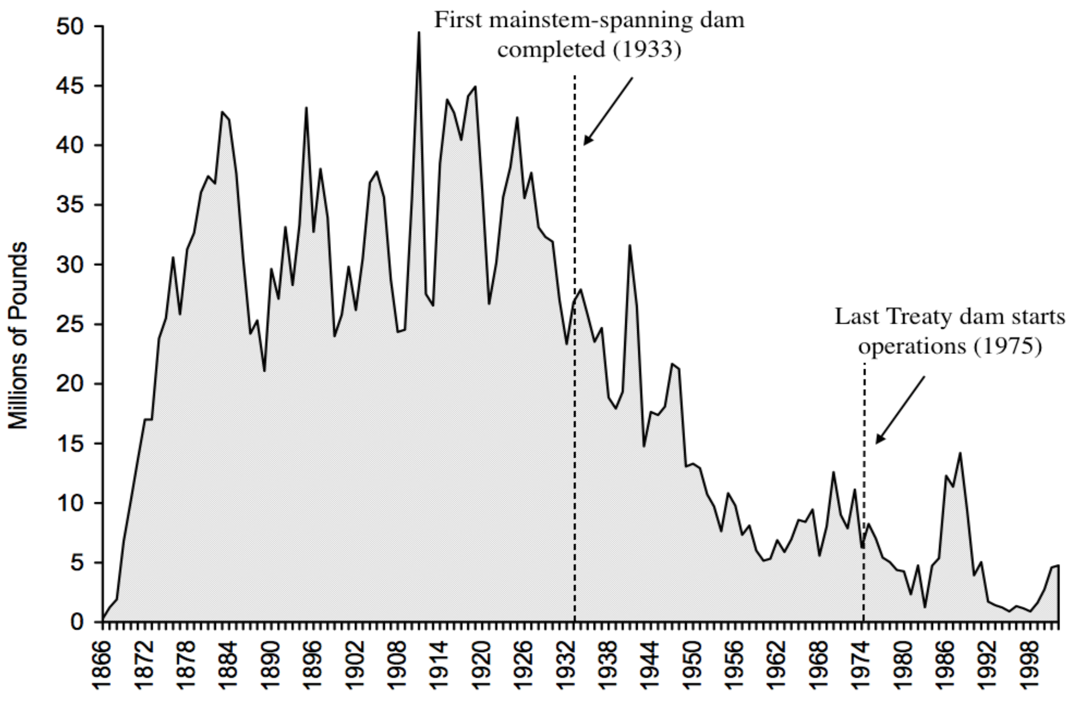


Figure 4. Columbia River Salmon and Steelhead commercial landings (1866-2002). Source: (WDFWODFW 2002)

Tribal fishery

The US government has a treaty obligation with Native American tribes in the Columbia River basin to sustain salmon populations and ensure a 50 percent share of the harvestable fish in-river **(U.S. v. State of Washington 384 F. Supp. 312 (U.S. Dist.) 1974)**. Figure 5 shows how the tribal commercial salmon fishery historically comprised a relatively small portion of the total in-river fishery. The fishery is now managed to ensure an equal share among tribal and non-tribal fishers.

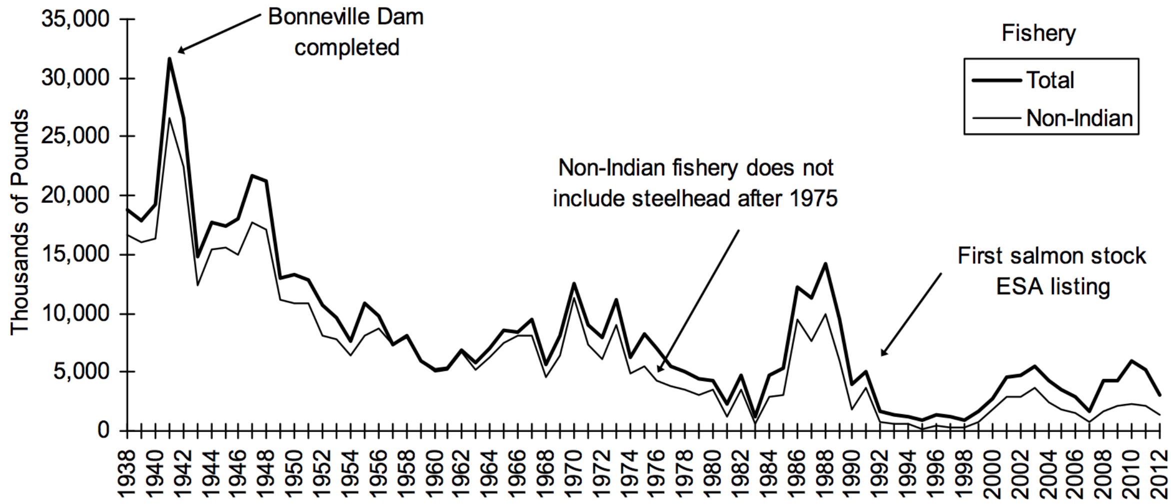


Figure 5. Non-tribal vs. tribal commercial salmon landings in the Columbia River (1938-2012). Source: (Davis 2014)

The US government's responsibility to the Columbia Basin tribes can confer significant influence to the tribes in terms of decision-making about how tradeoffs are managed between hydropower and fish conservation. For example, under the Columbia Basin Fish Accords, the basin's federal power production agencies (Bonneville Power Administration, US Army Corps of Engineers, US Bureau of Reclamation) agreed to commit US$933 million over ten years to salmon mitigation measures in return for tribal and state support of the 2008 NOAA Biological Opinion (Montana and Idaho were also part of the agreement). Example salmon mitigation measures include the manipulation of flow timing and volume using dams and reservoirs, hatcheries, and habitat improvements.

2.1.2 Recreational Fishing Opportunities

In addition to food production value, fish species provide opportunities for recreational fishing. Many species in the Columbia River are fished recreationally, some native and some introduced. The most preferred of these species include the Salmonids as well as sturgeon and bass. Only salmon catch is well documented in the basin and is addressed below.

Trends in recreational fishing value are driven by catch-per-trip expectations of anglers, which are in turn influenced by fish abundance **(Huppert et al. 2004)**. Direct and indirect values for recreational fishing are determined based on trip expenditures and often rely on trip frequency data supplied by fisheries agencies. The same difficulties exist for recreational fishing as for commercial fishing in terms of isolating the contribution of Columbia River stock to ocean recreational fishing. No existing reports or data are available that readily permit a direct value estimate of this fishery. However, data are available for the in-river fishery and indicate an annual direct value of US$32.5 million in trip expenditures for 2013 **(Davis 2014)**. Regional economic impacts from both in-river and ocean recreational fishing were estimated at US$54.7 million **(Pacific Fishery Management Council 2014b; Davis 2014)**.

The value of the recreational fishery can also be considered in terms of consumer surplus. Seven existing valuation studies use contingent valuation methods or travel cost methods to estimate recreational users' willingness to pay per-fish in twelve different regions of the Pacific Northwest, including the Columbia River (Helvoigt and Charlton 2009). General values for salmon range from US$61–332 per fish. Species-specific values range from US$62–337 per fish for Chinook and US$37–997 per fish for Steelhead (Helvoigt and Charlton 2009). The overall average across all studies is US$219 per fish (2013 US$).

2.1.3 Fishing for Cultural/Subsistence Use

In addition to the commercial fishery, Native Americans harvest salmon for subsistence use. The associated fishing rights enjoyed by the Columbia Basin tribes stem from treaties signed with the US federal government in the 1850's. These treaties maintained Native Americans' right to fish in traditional fishing grounds but the tribes have had to fight continuously to have this right respected. **The 1974 Boldt Decision** upheld this fishing right and specified that the tribes were entitled to a 50 percent share of the salmon harvest in traditional fishing areas.

From 2003-2012 tribal subsistence and ceremonial salmon harvests in the Columbia River ranged from 8 068–21 350 salmon (Davis 2014). Although the Native American salmon harvest for cultural/subsistence use represents only small proportion of the total harvest, the tribes have worked for the last several decades to preserve these harvests by protecting and restoring salmon habitat. Given their unique perspective and association with the salmon runs, the tribes are uniquely able to restore habitat at a landscape scale. Restoring opportunities for fish passage throughout the state is an example of how treaties can support salmon recovery significantly (J. J. Brown and Footen 2010).

2.1.4 Nutrient Cycling

The Columbia River acts as a conduit for the cycling of nutrients from ocean to land, particularly via anadromous Salmonids, which mature at sea and return upstream to spawn and die. Pacific Salmon accumulate substantial nutrients in their bodies while maturing at sea – more than 95 percent of their adult body mass is acquired in the ocean. These nutrients are then carried to lakes and streams where they are released after spawning (Naiman et al. 2002).

Assimilation of nutrients occurs not only in the aquatic environment, but also the terrestrial environment because bears and other carnivores consume salmon and drag carcasses into surrounding lands (Willson and Halupka 1995; Hilderbrand and Farley 1996). In this way, salmon help sustain their own productivity as well as that of other salmon-dependent species (Cederholm et al. 1999).

On the central coast of British Columbia, salmon are known to import as much as 266 g/m^2 of nitrogen to streams during mass migrations (Harding and Reynolds 2014), but the digging of nests during spawning also suspends sediment and results in the export equivalent of 55 percent of this imported nutrient (Moore et al. 2007). In addition, juvenile migrations are estimated to export an average of 22 percent of the nitrogen and 30 percent of the phosphorous imported by their parents in the Columbia Basin (Kohler et al. 2013). With the caveat that these figures are specific to different regions, they suggest a net import for nitrogen at roughly 23 percent of total nitrogen contained in the biomass of returning adult salmon.

Despite this relatively low net effect, research suggests a wide range of benefits from salmon-based nutrient import. These benefits include the enhancement of river productivity, maintenance of rearing habitat productivity for future generations of salmon, and support of trophic food webs (Kohler et al. 2012). Because the biomass of returning adult salmon has declined so dramatically since the onset of development, it is also possible that nutrient transport ratios are quite altered relative to historic levels. This situation creates a feedback loop in which salmon population sizes are maintained at well below historic levels due to reduced carrying capacity in nutrient deficient streams (Kohler et al. 2012).

2.1.5 Sediment Regulation By Fish

Fish species in the Columbia River also create and maintain their own habitat via bioturbation, or the disturbance of sedimentary deposits. Spawning Pacific salmon disturb sediments while constructing redds (nests). Mass spawning events can temporarily alter streambeds, producing a more favourable environment for incubating eggs by surrounding them with sediment that is less mobile and therefore less susceptible to scouring from higher river flows. The reduction in fine sediments may also maintain interstitial flows of oxygen and water necessary for egg incubation (Groot and Margolis 1991).

Repeated spawning over time can modify the entire contour of river bottoms, sometimes building up bedforms and dunes over a meter high (DeVries 1997). These more permanent features provide refuge areas for juveniles and added protection to nests (Holmlund and Hammer 1999). Sediment regulation is also connected with nutrient cycling. Spawning activities are thought to displace invertebrates and algae from stream bottoms, making them more available to aquatic predators (Bilby, Fransen, and Bisson 1998). However, as discussed in the previous section, this bioavailability is short-lived because a portion of nutrients is swept downstream. Sediment suspension of this type typically results in a large export of nutrients from local ecosystems during salmon spawning events.

However, while this depletion is true immediately after the event, the displacement of fine sediments may increase river productivity overall by providing algae with greater access to sunlight (Moore, Schindler, and Scheuerell 2004). Combined, these ecosystem services support the fish production system and operate in a positive feedback loop. Decreased spawning activity decreases the engineering of optimal habitat which increases embryo mortality, ultimately decreasing the number of returning spawners (Montgomery and Buffington 1996). Decreases in the salmon population, in turn, decrease productivity benefits generated by mass spawning events that affect the bioavailability of nutrients to other species.

2.1.6 Biodiversity

Natural features and processes of the Columbia River support a multitude of fish species. These genetic resources collectively contribute to overall ecosystem resilience. **Table 4** lists all established native and introduced fish species in the US portion of the Columbia River.

Table 4. Fishes of the Columbia River

Family	Species (I)=introduced	
Catfish (Ictaluridae)	Channel catfish (I) Brown bullhead (I) Yellow bullhead (I)	Black bullhead (I) Tadpole madtom (I)
Cod (Gadidae)	Eelpout	
Herring (Clupeidae)	American shad (I)	
Killfish (Cyprinodontidae)	Banded killfish (I)	
Lamprey (Petromyzontidae)	Pacific lamprey Western brook lamprey	
Live-bearer (Poeciliidae)	Western mosquitofish (I)	
Minnow (Cyprinidae)	Chiselmouth Northern pikeminnow Redside shiner Peamouth Longnose dace	Speckled dace Carp (I) Goldfish (I) Tench (I)
Perch (Percidae)	Yellow perch (I) Walleye (I)	
Pike (Esocidae)	Northern pike (I) Grass pickerel (I)	
Salmonids (Salmonidae)	Mountain whitefish Bull trout Cutthroat trout Steelhead Rainbow trout Chinook salmon	Coho salmon Sockeye salmon Lake whitefish (I) Brown trout (I) Brook trout (I) Lake trout (I)
Sculpin (Cottidae)	Prickly sculpin Torrent sculpin Paiute sculpin	Margined sculpin Mottled sculpin
Stickleback (Gasterosteidae)	Three-spine stickleback	
Sturgeon (Acipenseridae)	White sturgeon	
Sucker (Catostomidae)	Largemouth sucker Bridgelip sucker	Longnose sucker Mountain sucker
Sunfish (Centrarchidae)	Smallmouth bass (I) Largemouth bass (I) Bluegill (I)	Pumpkinseed (I) Black crappie (I) White crappie (I)
Trout-perch (Percopsidae)	**Sand roller**	

Source: (PNNL 2015)

Several of these species or their sub-populations are listed under the US Endangered Species Act (ESA). There are 64 unique animals species and 24 unique plant species listed as either threatened or endangered in Washington, Oregon and Idaho combined (comprises the majority of the US portion of the basin) (USFWS 2014). Table 5 shows ESA–listed fish species for the Columbia River. Most at-risk species are Salmonids (White sturgeon are the one exception). River development drastically changed the location and genetic composition of salmon in the Columbia River. Prior to 1850 28 percent of all salmon originated in the lower portions of the river and 72 percent originated in the upstream portions. Now about 58 percent originate in the lower river, the majority of which are hatchery raised (IEAB 2005). Total smolt production in all Columbia basin hatcheries was about 140 million individuals in the 2000s, or about half of all hatchery and wild production combined (Davis 2014). While hatchery raised fish boosted salmon production, there are concerns about these fish weakening the gene pool and undermining the overall resilience of salmon populations. The US has gone to considerable lengths to preserve the wild fish population. By the early 2000's about three-quarters of harvest was of hatchery raised fish due to mark selective fisheries, avoidance, and other techniques to reduce impacts on wild populations (Davis 2014).

Table 5. Columbia River Fish Species Listed under the US Endangered Species Act

Population	ESA Status
Bull Trout	Threatened (1998)
Chinook (Lower Columbia)	Threatened (1999)
Chinook (Upper Columbia, Spring run)	Threatened (1999)
Chinook (Snake River)	Threatened (1992)
Chinook (Upper Willamette)	Threatened (1999)
Chum	Threatened (1999)
Coho (Lower Columbia)	Threatened (2005)
Steelhead (Lower Columbia)	Threatened (1998)
Steelhead (Upper Columbia)	Threatened (1998)
Steelhead (Snake River)	Threatened (1998)
Steelhead (Upper Willamette)	Threatened (1999)
Sockeye (Snake River)	Endangered (1992)
White Sturgeon	Endangered (1994)

Source: (USFWS 2014)

Bonneville Power Administration's (BPA) cumulative fish and wildlife conservation costs from 1978–2013 reflect a large portion of federal expenditures on ESA-listed species in the Columbia Basin. These costs totalled US$13.75 billion (2013 US$) (NPCC 2014). Additional federal and state level expenditures are reported by the US Fish & Wildlife Service (USFWS 2012).

2.1.7 Cultural Heritage

Natural features and processes of the Columbia River system help create culture and contribute to human well-being. The river is a source of inspiration and deep cultural and spiritual values for Native Americans and non-indigenous people. The surrounding region includes a number of historic sites, Native American archaeological sites and

traditional cultural properties (BPA, USACE, USBOR 1995). The fish production system plays a particularly important role in generating cultural benefits.
Native Americans view their "entire heritage, including beliefs, traditions, customs, and spiritual relationship to the earth and natural resources, as sacred cultural resources" (BPA, USACE, USBOR 1995) (p. 2–21). These resources are tied to a long history of association with natural cycles facilitated by the Columbia River and the river's role as a transportation corridor and economic hub (Barber 2005). Much of this role was shaped by annual salmon migrations long before European contact (R. White 1995). After colonization, the cultural link was significantly altered by new regulations imposed on Columbia River tribes. For example, while the original tribal fishery extended up and down the length of the Columbia River, under current regulations tribal commercial fishers are only permitted to fish in the lowest reaches below Bonneville dam (and Willamette River if quotas are not achieved).

Non-indigenous residents also derive a sense of heritage from the fish production system since it facilitated settlement and played an important role in the history of American development. As in other areas in the Pacific Northwest, abundant fish resources were a key part of that early development as evidenced by the salmon canneries that once proliferated up and down the coast. The river continues to provide opportunities to connect with nature and engage in activities such as fishing that are culturally important to North Americans.

Much of this intrinsic or "non-use" value is captured in studies using contingent valuation methods (CVM) to estimate consumer surplus. Annual per household willingness-to-pay (WTP) for improvements in salmon populations in and around the Columbia Basin ranges from US$34–2 428 (2013 US$) and varies depending on the assumed starting population of fish, the associated increase in populations being evaluated, as well as the type of management project proposed (e.g. dam removal, water diversions, water sharing agreements, fish habitat improvements) (Olsen, Richards, and Scott 1991; Hanemann, Loomis, and Kanninen 1991; Loomis and White 1996; Douglas and Taylor 1999; Layton, Brown, and Plummer 1999; Bell, Huppert, and Johnson 2003; Mansfield et al. 2012; Loomis 1999b). Generally, the smaller the starting population, the higher the value households place on the existence of salmon, suggesting that endangered fish are of higher value to Americans. One additional study estimates the total annual WTP of all Pacific Northwest households for an increase in endangered salmon along the Snake River at 88.6–1 172 million/yr (all households WA, OR, MT, ID, 2013 US$) (Loomis 1999a).

2.1.8 Research Opportunities

The Columbia River fish production system provides opportunities for education and research. A large volume of research is conducted in the Columbia River Basin, much of which is environmental research facilitated by the river and its surrounding lands. Loomis & Richardson (2000) state that there are two types of benefit stemming new discoveries and knowledge about natural environments: 1) avoidance or reduction of expensive resource management mistakes, endangered species recovery efforts, and environmental restoration activities, and 2) spillover benefits to the rest of the economy that result in economic growth. One way to estimate this value is by attributing value to the number of academic journal articles related to a case study or topic.

Using search terms “Columbia River” and “fish” in the topic fields of Thompson-Reuters Web of Science database-search, we identified 904 articles containing research about fish in the Columbia River. Figure 6 shows how the annual frequency of these publications has increased exponentially since 1948.

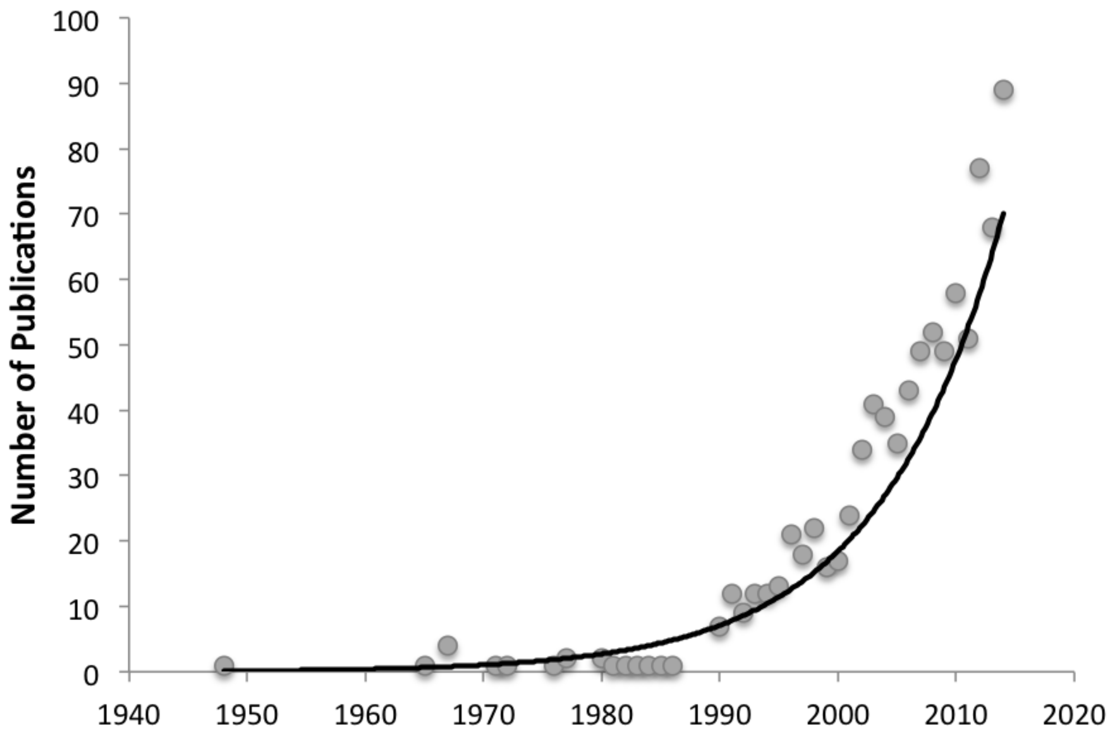


Figure 6. Research about Columbia River Fish Species 1948-2014 (n=904).
Source: (Thompson-Reuters 2015)

Loomis and Richardson (2000) relied on Black (1996) to estimate the annual economic value to society of producing a research article at US$12 000 per article (national income benefits) (Loomis and Richardson 2000). The Wilderness Society (2008) also applied this value to publications generated per year by national forests in Alaska (The Wilderness Society 2008). Following these methods, the total annual value of all publications related to Columbia River fish species is over US$10.8 million (2000 US$).

However, this result assumes equal value held by each publication regardless of when it was published. A more refined estimate would account for changes in value of each publication over time.

2.1.9 Water Quality Regulation

In addition to directly supporting ecosystem services, the fish production system in the Columbia River indirectly supports other services through conservation efforts designed to preserve fish habitat. Bonneville Power Administration (BPA), the main power broker in the basin, is the primary participant in the NPCC’s Columbia River Basin Fish and Wildlife Conservation program, which mainly focuses on salmon conservation. Costs associated with this program provide some indication of how much the USA values conservation of fish habitat. BPA's cumulative fish and wildlife conservation costs from 1978–2013 totalled US$13.75 billion (NPCC 2014). The annual cost for 2013 was US$291.1 million, 84 percent of which was from anadromous and resident fish conservation (2013 US$). About 40 percent of the annual cost was dedicated directly to habitat restoration and protection (US$118.3 million).

Many habitat restoration projects in the Columbia Basin target wetlands, marshes, floodplains and estuaries. These ecosystems constitute important fish habitat by providing refuges for juvenile salmon and playing a key role as nurseries for the rearing of these young fish (Teel et al. 2009; Bottom et al. 2005). Much of the wetland habitat that supports fish production also plays a role in regulating water quality (EPA 2010). Therefore, fish conservation efforts that focus on preserving this habitat also generate water quality benefits.

One study for the City of Portland (lower Columbia River) estimated a US$549 per year per acre (US$135,661 per year per km^2) value for water filtration services from 140 acres (0.57 km^2) of wetland artificially created in the Lents sub-area (US$35 million cost) (David Evans & AssociatesECONorthwest 2004). Table 6 shows results from another Washington State study that used benefit transfer methods to determine water quality benefits in US$/ km^2/year from a variety of land types, including wetlands. The low end of these values aligns quite closely with the Portland study.

Table 6. Water quality benefits from different land types in Washington State.

Land Type	Low (US$/$km^2$/year)	High (US$/$km^2$/year)
Forests	1 360 808	1 360 808
Grasslands	1 968 934	1 968 934
Agricultural	1 236	1 236
Urban Greenspace	118 610	118 610
Wetland	130 966	130 966

Source: (Earth Economics 2015)

2.1.10 Natural Flood Control

Various wetlands and marshes located along the Columbia River also regulate river inundation during high flow years. These natural buffers work in tandem with engineered flood control by intercepting precipitation and storing water, thereby mitigating damages during flood events.

Change in the flood control value provided by wetlands is driven by changes in their areal extent. Such changes are typically driven by land use changes where wetlands are infilled and developed or converted to engineered flood control alternatives. For example, damming of the Columbia River for hydropower and flood control would have flooded some wetlands (reservoirs), depleted others (below dams), and/or created new wetlands along new shorelines created by the reservoirs.

Based on the creation of 140 acres (0.57 km^2) of new wetland,

Table 7 shows the estimated value of avoided flood damage along the Columbia River from a study conducted for the City of Portland (scaled to a 1 in 10 year flood event).

Table 7. Avoided flood costs from creation of 140 acres (0.57 km^2) of wetland

	Avoided cost (2002 US$)	
Sector	per 10-yr flood event	Total over 100yrs
Residential	66 700	5 437 451
Business	457 065	4 163 416
Utilities	10 500	208 171
Emergency services	5 000	45 255
Total	539 265	9 854 293

Source: (David Evans & AssociatesECONorthwest 2004)

These values indicate a range of about US$3 800 (10 years flood) to US$70 400 (100 years flood) in avoided costs per acre from wetland restoration (2002 US$). Another study of two Washington cities found the range of marginal value from wetland-based flood protection was about US$7 800–51 000 per acre (US$1 927 420 – US$12 602 363 per km^2) (based on two specific storm events at one site and a 100 year storm event at the other, 1997 US$) **(WDE 1997)**.

2.1.11 Non-fishing Recreation and Tourism

Conservation of salmon habitat can enhance the aesthetics, natural features and processes in the Columbia River that create opportunities for recreation and attract tourists. In addition to recreational fishing, a variety of other tourism and recreation opportunities are supported by the river. These include boating, rafting, swimming, kayaking, sightseeing, shoreline recreation, pick-nicking, hiking, camping and bird hunting.

The 1995 Columbia River System Operation Review used survey-based travel cost methods to develop demand curves based on different hypothetical water levels at each reservoir along the mainstem. Consumer surplus was estimated for each scenario using visitation frequencies from May-August (an underestimate as some recreational uses occur year-round) **(BPA, USACE, USBOR 1995)**. **Table 8** and

Table 9 show results from this study for two reservoirs in Washington (as reported by Huppert et al. (2004)).

Table 8. Estimated annual recreation days by activity for Columbia River in WA (1995)

Activity	Lake Roosevelt	John Day
Boating	436 222	675 900
Fishing	308 629	580 073
Camping	362 906	512 355
Picknicking	403 155	510 056
Swimming	159 325	277 004

Source: (Huppert et al. 2004)

Table 9. Average annual consumer surplus for Columbia River recreation in WA (1995)

Reservoir	Consumer surplus (US$)
Lake Roosevelt	121 730 000
John Day	38 160 00

Source: (Huppert et al. 2004)

More recent studies estimate the value of recreational benefits based on the volume of instream flow. These studies rely on the assumption of a shift in recreational use due to changes in flow. For example from swimming, flat-water boating and sailing to more high value uses (e.g. white-water rafting, kayaking and jet-boating). Duffield et al (2007) estimated values of US$0–25 (US$0–6,178 /km^2) (2006 US$) per acre-foot in Montana (range depends on high or low starting flows) (US$0–6 178/km^2). 7 percent -53 percent of this value was attributable to non-fishing recreation depending on the site (Duffield, Neher, and Brown 2007). Another study on the Snake River estimates per-trip benefits for non-fishing recreation at US$46 (McKean, Johnson, and Taylor 2012). This is a status quo value that assumes no dam breaching. If dams are breached (i.e. the river is returned to natural flow conditions), the value rises to US$401 per trip (Loomis 2002), indicating a non-fishing recreation benefit of US$355 per person per trip with dam breaching.

Recreation is estimated to support nearly 200 000 jobs in Washington State, 62 percent of which derive from expenditures associated with outdoor recreation on public lands (Earth Economics 2015). Annual expenditures on all outdoor recreation total US$21.6 billion dollars (includes fishing), US$11.3 billion of which are attributable to direct sales for non-fishing activities (2014 US$).

Table 10. Non-fishing participant days and expenditures by land type for Washington State (in-state visitors)

Land Type	Participant Days ('000s)	Expenditures ('000s, 2014 US$)	Per-person Per-Day Expenditures (2014 US$)
Federal Lands	32 853	1 323 545	40
State Lands	49 095	1 347 192	27
Private Lands	27 946	1 933 961	69
Public Waters (non- fishing)	82 207	3 825 698	47
Local Parks	189 915	1 439 096	8
Events	44 516	1 439 096	45
Total	426 532	11 308 588	26

Source: Adapted from (Earth Economics 2015)

Total consumer surplus for non-fishing recreation is estimated at US$18.3 billion dollars (2014 US$; WTP studies) (**Table 11**). Averaged across all land types this suggests an additional (hidden) value of US$52 per person per day above the US$26 actually paid (see **Table 10 and Table 11**). This result is roughly consistent with the US$46 per-trip estimate from McKean, Johnson and Taylor (2012).

Table 11. Non-fishing consumer surplus by land type for Washington State (in-state visitors, private lands and events not available)

Land Type	Participant Days ('000s)	Annual Consumer Surplus ('000s, 2014 US$)	Consumer Surplus Per-Person Per Day (2014 US$)
Federal Lands	32 853	1 809 691	55
State Lands	49 095	1 872 298	38
Public Waters (non-fishing)	82 207	2 587 541	31
Local Parks	189 915	12 010 768	63
Total	354 070	18 280 298	52

Source: Adapted from (Earth Economics 2015)

2.2 Other Ecosystem Services of the Columbia River

The Columbia River is dramatically engineered from its natural state. While the river's engineered condition benefits the USA in terms of flood management and other uses, the fish production system it hosts has been altered as a result. In addition to engineered flood protection, the river itself supplies a number of ecosystem services external to the fish production system that can create conflicting priorities (as described in **Sections 1.4** and **1.5)**. Management practices designed to optimize the value of these services contend with fish production to varying degrees. Many have little to no detectable effect, but the cumulative effects of all these uses are significant. In order from most to least impact, these practices include engineered flood control, hydropower production, GHG emissions reduction, agricultural water supply, recreational boating, shipping and transportation, and domestic water supply.

By far the most important of these practices, hydropower and flood control regulation result in a smoothing of the natural hydrograph, shifting flows from spring flood season to winter when energy needs are highest (Error! Reference source not found.).

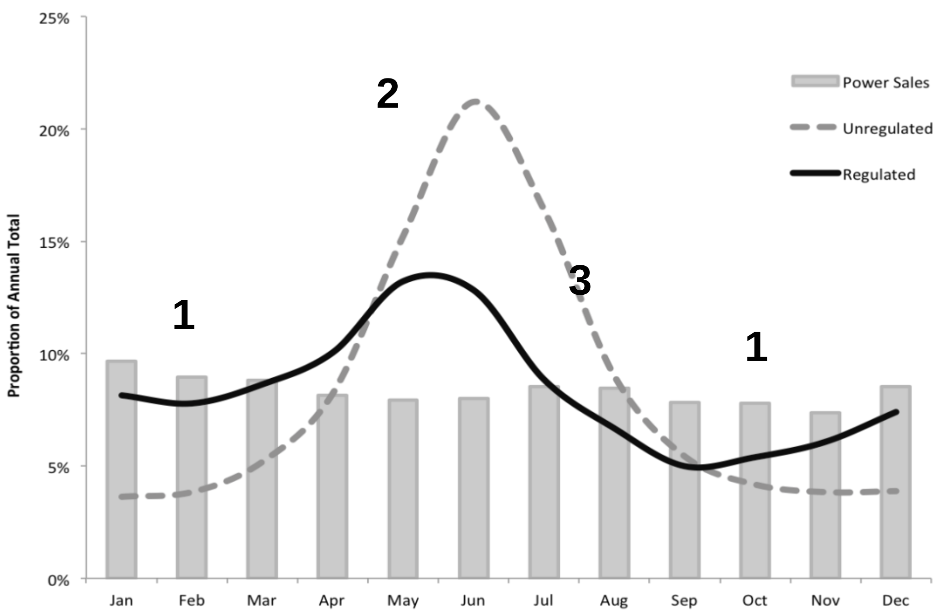


Figure 7. Columbia River flow regulation and monthly electricity demand

The two hydrographs in **Figure 7** represent average monthly discharge at The Dalles for regulated (1984–2013) and unregulated (1879–1908) flows (USGS 2014). Power sales are the 2004–2014 average of MWh sold per day by all municipal/private utilities in Washington, Oregon, and Idaho (does not include federal sales) (USEIA 2015a). From late-fall to early-spring (**1**) reservoirs are drafted, producing higher than natural flows, which increases hydropower capacity in response to peak energy demand. In late spring and early summer (**2**) reservoirs refill during spring snowmelt causing lower than natural flows and protecting from floods. Energy demand is lower and thus easily met. During summer and early fall (**3**) the reservoirs are maintained at or near capacity in preparation for winter energy demand. This results in flows that are lower than natural.

The following sections describe other ecosystem services generated by the Columbia River and the economic benefits they generate.

2.2.1 Hydropower production

High volume and high velocity flows are services of the Columbia River harnessed using dams and reservoirs for the purposes of hydropower production. Total revenue from non-firm energy generated by the Columbia River was estimated at US$417.9 billion in 2001 (Hamlet, Huppert, and Lettenmaier 2002). About 44 percent of hydroelectricity generated in the USA and 50 percent of that generated in British Columbia originates from this single basin (USEIA 2014; CBT 2012). Much of the American power is consumed by California. There are 11 power-producing dams on the US portion of the mainstem. Many other hydropower dams are situated throughout the basin, including 3 major dams on the Canadian side of the border.

Power generation on the Columbia River is closely related to discharge levels. Error! Reference source not found. shows that the Columbia River Treaty is a significant factor in this relationship. Rising generation values (black line) observable from 1964–1975 represent the four treaty dams becoming operational and the effects of improved system coordination.

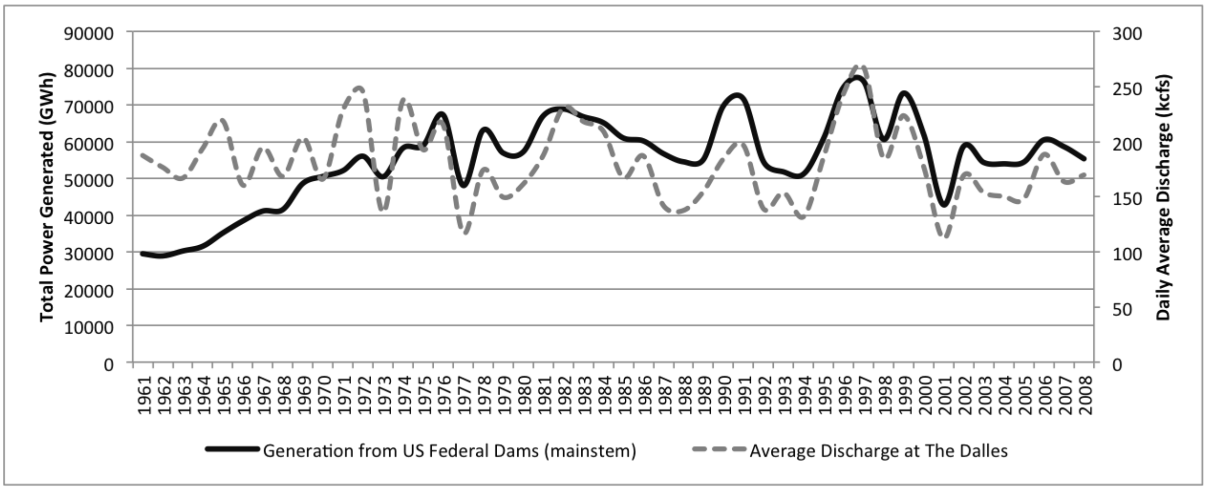


Figure 8. Columbia River power generation and average discharge (1961-2008).

Power generation figures are for six federal dams on the US portion of the Columbia River mainstem (USACE 2015a). Five privately operated dams are also located on the mainstem for which public data may not be available. Discharge is the annual average of daily average discharge observations at The Dalles, Oregon (USGS 2014).

Error! Reference source not found. also shows the positive relationship between discharge at The Dalles and power generation from six federal dams post-Columbia River Treaty.

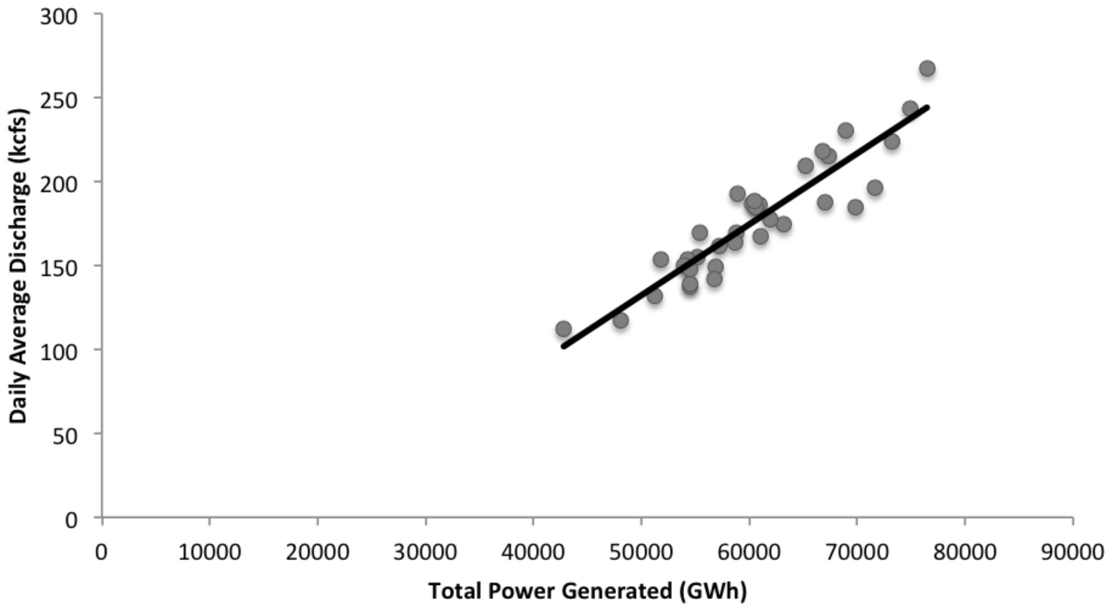


Figure 9. Columbia River power generation vs. discharge 1975-2008 (n=37)

Most generating capacity in the basin is federally owned (70 percent), the rest is municipal (19 percent) and private (12 percent) (USEIA 2014). No potential for further dam development exists along the mainstem but additional power generation is still possible via different management practices, infrastructure and technologies. For example, a return to pre-ESA river regulation, while unlikely, would provide gains to hydropower production approximately equivalent to the difference between total power generated in the 1970s (when hydropower was most prioritized) and current conditions. Less hydropower generation is also a possibility as competing priorities continue to shift and new energy options such as wind power increasingly cause excess supply events (NPCC 2011). Each opportunity to reduce hydropower generation and relax flood control practices would shift the river closer to natural flow conditions.

Electricity is the only commodity that cannot be stored economically, is a critical input to everyday life, is expected to be available on immediate, unscheduled demand and can lead to sudden large socio-economic impacts due to system instability if demand is not met (e.g. blackouts). These characteristics cause wholesale market prices of electricity fluctuate dramatically and on an hourly basis in relation to the supply-demand balance. During a typical day, prices rise with demand during waking hours and fall at night. They also rise and fall in relation to seasonal patterns. Hydropower pricing in the Columbia River system is based on “mid-C” prices. Mid-C stands for middle-Columbia and refers to the trading hub of power utilities located in the middle reaches of the river. Error! Reference source not found. shows the monthly trend in prices based on 2002–2013 operating years.

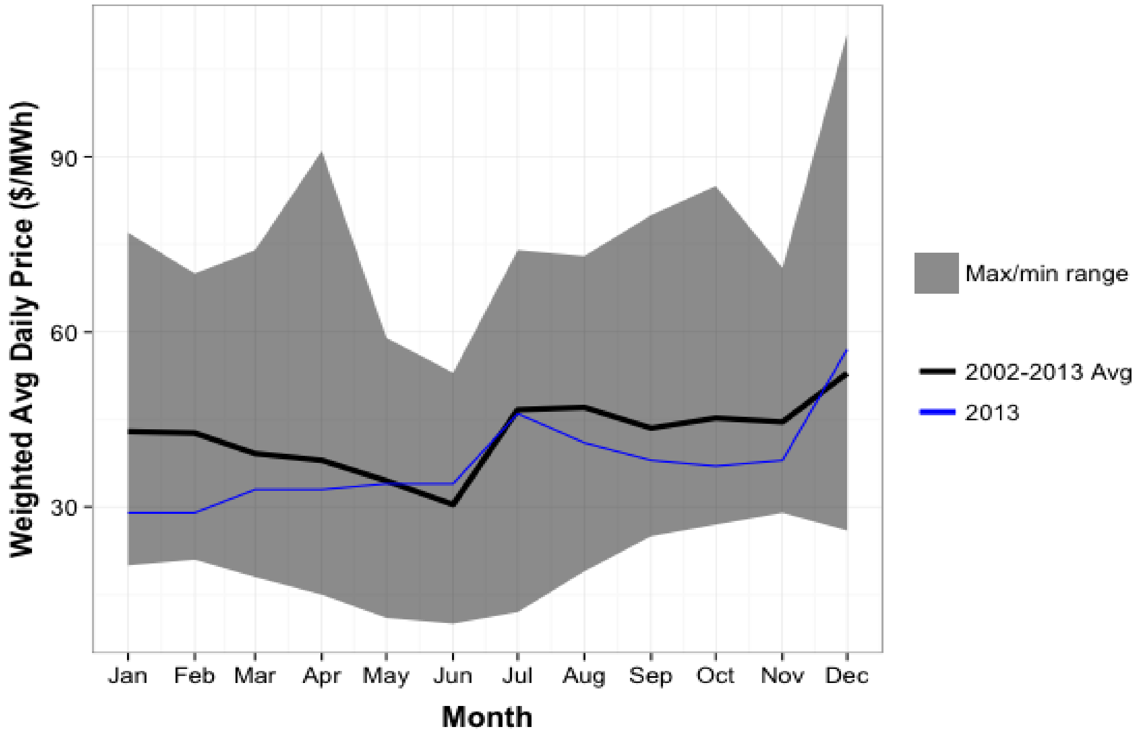


Figure 10. Mid-C wholesale energy prices (2002-2013) (2015 US$). Source: (USEIA 2015b)

In addition to the value of total power generated, "firm energy" has unique value. Firm energy is the energy capacity of a system that can be relied on with a high degree of certainty, for example during a low flow year. Utilities must demonstrate firm energy capacity to ensure they can meet customer load. In the Columbia River system this capacity is calculated using the critically low flow conditions of the 1937 water year (October 1936–September 1937). Hamlet et al. (2002) estimated the value of this capacity at US$1.42 billion per year (56.9 million MWh x US$25 /MWh) (2001 US$) of additional value from hydropower production.

2.2.2 GHG emissions reduction (via Hydropower and Shipping)

The same ecosystem functions of the Columbia River that permit the production of hydropower and opportunities for shipping indirectly generate climate regulation benefits in the form of greenhouse gas (GHG) emissions reductions. The energy mix in the Northwest Power Grid includes hydropower, coal, gas, wind, nuclear, biomass, geothermal, oil and solar (ordered from greatest to least) (USEPA 2014). Hydropower production is considered a clean source of energy in the USA so zero emissions are assumed in carbon emissions calculations. As such, hydropower displaces more carbon-intensive modes power generation, particularly coal burning thermal plants. Similarly, shipping and transport using waterways is more fuel-efficient and displaces other modes of transportation (**Table 12**).

Table 12. GHG emissions by transport alternative

	GHG emissions **(grams per ton-mile)**
Truck	0.136
Rail	0.064

Barge	0.046

Source: (Texas Transport Institute 2007)

Table 13 shows that hydropower (43.6 percent) and coal (31.3 percent) are the top two energy types in the Northwest Power Grid (USEPA 2014). Therefore, if hydropower were reduced to 0 percent, coal could be expected to increase to 0.313/(1-0.436) = 0.555, or 55.5 percent.

The Northwest Power Grid has an emissions factor of 846.97 $lbCO_2e/MWh$. Since hydropower is considered to have zero emissions, the increase in emissions factor due to a redistribution from hydropower to coal can be calculated as 846.97/(1-0.436)=1500.40. So the GHG emissions that are avoided for each MWh of hydropower produced equals the difference between these emissions factors (1 500.40-846.97=653.43 $lbCO_2e$). This value is equivalent to 297 tCO_2e/GWh, which can then be multiplied by California ($11.50 US$/tCO_2e) or British Columbia ($22.50 US$/tCO_2e) carbon prices to arrive at US$3 416–6 683 per MWh in carbon savings provided by hydropower production.

Table 13. Energy mix for the Northwest power grid with and without hydropower

Energy Source	Current Mix	Mix without Hydropower
Hydro	43.55%	0.00%
Coal	31.30%	55.45%
Gas	14.34%	25.40%
Wind	4.84%	8.57%
Nuclear	3.45%	6.11%
Biomass	1.24%	2.19%
Geo-thermal	0.70%	1.24%
Oil	0.33%	0.58%
Other fossil	0.14%	0.25%
Unknown	0.12%	0.21%
Solar	0.00%	0.00%

Source: (USEPA 2014)

2.2.3 Agricultural Water Supply

Flows generated by the Columbia River are utilized for agricultural irrigation, particularly during the summer growing season. Approximately 6 percent of the basin's annual runoff is diverted to irrigate about 20 639 km^2 (5.1 million acres) of land, primarily in arid regions of eastern Washington, north-eastern Oregon, and southern Idaho (FWEE 2015; NPCC 2008). Specific irrigated crops include: hay (alfalfa), orchard crops (apples, pears, sweet cherries, wine grapes), vegetable crops (asparagus, carrots, sweet corn, onions, peas), hops, dry beans, corn for grain and silage, peppermint, spearmint, potatoes and wheat, all of which generate significant revenue (**Table 14**). Washington State alone saw US$5.5 billion in irrigated crop sales according to the 2012 Census (USDA 2015). 3 696 km^2 (913 380 acres) of agricultural land in Washington are irrigated directly by surface water from the Columbia River (Huppert et al. 2004).

Table 14. Area (km²) by agricultural commodity in the Columbia River Basin (irrigated and non-irrigated)

Commodity	2007 Census (km²)	2012 Census (km²)
Corn	2 188.63	2 526.72
Crops, Other	17 355.89	16 905.44
Horticulture	317.94	358.09
Orchards	1 568.59	1 656.54
Small Grains	19 831.23	20 607.13
Soybeans	2.41	-
Vegetables	3 283.30	3 258.26
Total	**44 548.00**	**45 312.18**

Source: (USDA 2015)

One major irrigation project is the Columbia Basin Project (CBP), which services about 2 614 km² (646 000 acres) in the basin's semi-arid interior. This area comprises about half of all land irrigated by the Columbia River in Washington, making it the largest irrigation project diverting water directly from the mainstem. The region produces about 16 percent of Washington's agricultural output and has the potential for expansion to about 4 047 km² (1 million acres) (FWEE 2015). Other lands along or near the Columbia River are also used for agricultural purposes, accounting for about 31 percent of total diverted surface water from the river (WDE 2015).

The CBP diverts 3 947 million m³ (3.2 Maf) of water each year. Not all the diverted water is utilized for crop production. System-wide conveyance efficiency (water retained after transport) for the CBP is estimated at 99 percent for irrigated areas downstream of the CBP and 85 percent for irrigated areas upstream of the CBP (82 percent average) (Huppert et al. 2004). Also, any water that is not consumed by evapotranspiration eventually flows back to the river, which means this use has much less impact on mainstem flows than flood control and hydropower.

However, water consumption is not the only way cropland affects the Columbia River. Agricultural land use also impacts aquatic habitat and water quality in streams throughout the region (Riseng et al. 2011). For example the US Environmental Protection Agency reports that DDT pesticides still persist at harmful levels in the Columbia River despite a ban on the chemical in the 1970s (EPA 2009). Other legacy and emerging agricultural contaminants continue to enter the river primarily via soil erosion and runoff (Alvarez et al. 2014; Nilsen et al. 2014; Nilsen and Morace 2014). Once in the river, these chemicals bio-accumulate up the food chain to a variety of fish species including salmon.

Agricultural Diversion Rights

5 674 million m³ (4.6 Maf) of surface water is divertible from the Columbia River every year (2012 figures) (WDE 2015). A number of pending applications for new water rights also exist (WDE 2015). In Washington State, 91 percent of the rights for these water diversions go to irrigated agriculture (Huppert et al. 2004). There is no established market where water rights along the Columbia River are traded openly.

Rights are based on prior appropriation, which means seniority dictates interruptibility of rights during times of low flow. Some users even have uninterruptible rights if they were established before the Washington Administrative Code Ch. 173-563 (WAC) (Washington State Legislature 2015).

To date, the only instance of interruption under the WAC occurred in 2001. For 11 weeks, the Washington Department of Environment reduced flows to interruptible license holders by 20 percent. The US government paid US$1million to BPA to ensure continued supply to water rights holders and to maintain instream flows for fish production. This amount is the equivalent of US$12 987 per day for "un-regulating" flows to maintain a minimum water supply for agriculture during such events (US$1 million/77 days).

Table 15. Columbia River annual diversion rights, pending applications, and square kilometers irrigated (2012)

Pool	Surface Water Rights (m^3)	Surface Water Applications (m^3)	km^2 Irrigated (existing rights)
Bonneville	9 869 088	3 126 877	5.03
The Dalles	5 077 011	3 917 538	1.29
John Day	478 998 009	4 919 126	349.06
McNary	876 808 242	187 479 374	467.30
Priest Rapids	37 444 809	2 151 192	31.00
Wannapum	39 628 072	3 853 397	32.42
Rock Island	93 188 321	139 377 282	52.50
Rocky Reach	81 264 252	20 726 196	46.75
Wells	82 565 575	4 325 821	61.65
Chief Joseph	47 172 047	1 293 922	33.11
Grand Coulee	3 913 062 067	5 793 664	2616.21
Total	5 665 077 491	376 964 390	3696.32

Source: (WDE 2015)

2.2.4 Shipping and transportation

River elevation (stage) and velocity are ecosystem services produced by the Columbia River that are utilized for the purposes of transporting people and goods. The Columbia and Snake Rivers provide approximately 465 miles of navigable water from the mouth of the Columbia to Lewiston, Idaho – referred to as the 'Inland-Marine Transportation System' (IMTS) (Huppert et al. 2004).

The navigable sections of the river can be considered in two segments: 1) the downstream portion is deep and wide and permits access for deep-draft ocean freighters to Portland, OR and Vancouver, WA, 2) the upstream portion is shallower and narrower and can only accommodate barges. Shipping and transport are enabled by eight locks on the mainstem and lower Snake dams. There are 34 port facilities on the Columbia River and 20 on the lower Snake River. These are connected to land routes by two rail lines and the interstate highway system (CEDER 2005).

Idaho, Montana, Oregon and Washington all depend heavily on the Columbia River to transport goods to market, but the system also services 39 other states.

The IMTS is the USA's top wheat, barley and wood export gateway, number two soybean export gateway, and the third largest grain export gateway in the world (CEDER 2005; PNWA 2014; PNWA 2013). Most of the grain exports go to Asia (Port of Portland 2010). Error! Reference source not found. shows Columbia Basin shipping by commodity type for 2012.

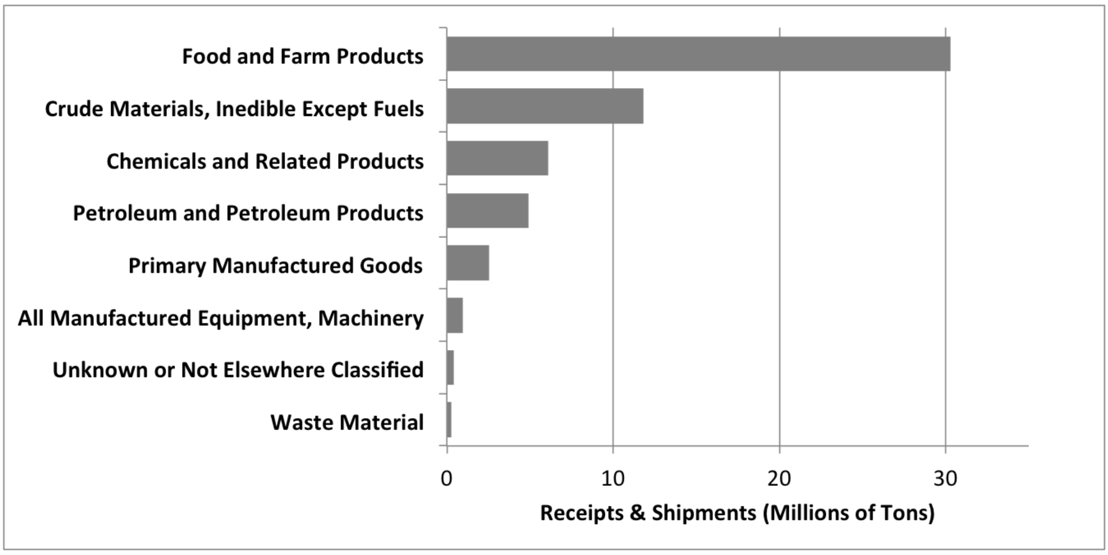


Figure 11. Columbia Basin shipping by commodity type (2012).
Source: Cargo by waterways, sheet 5 (USACE 2015b)

55.7 million tons of freight was transported on the Columbia-Snake system in 2013, 83 percent of which originated from the USA (local and outbound shipping) (USACE 2015c) (see Error! Reference source not found.).

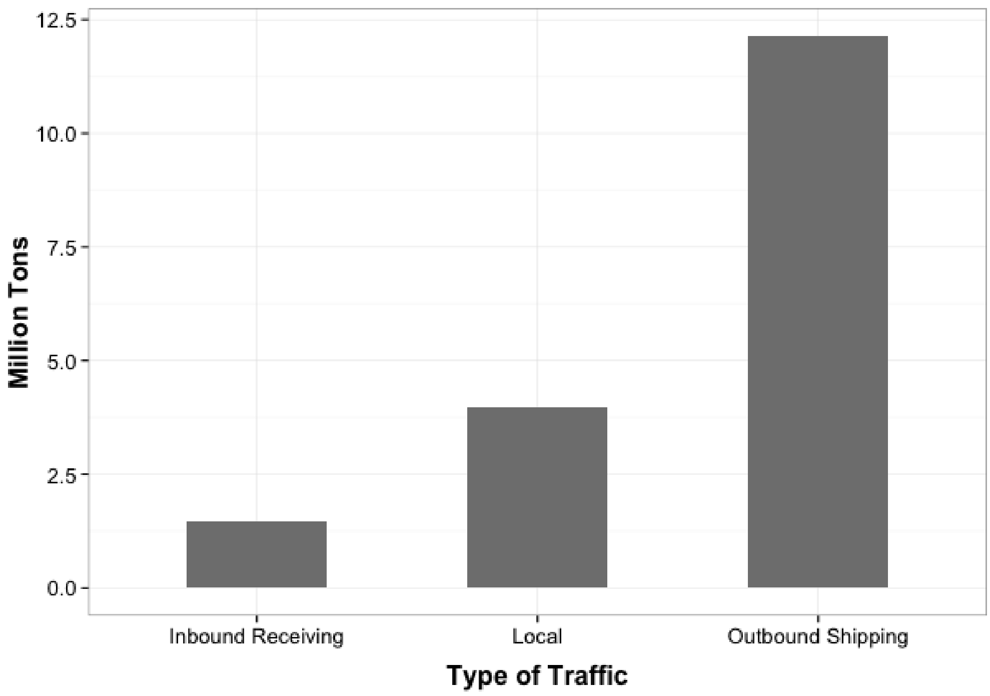


Figure 12. Columbia-Snake River shipping traffic type (2013). Source: Total Waterborne Commerce, Columbia River Basin, OR, WA, ID (reference code 8902) (USACE 2015c)

The value of all freight shipped was approximately US$15–20 billion US$ on the downstream section alone (CEDER 2005; PNWA 2013). **Table 16** shows how this activity generates significant employment and income benefits for the region.

Table 16. Regional Economic Impact of Columbia Basin Shipping Activity (2000)

Shipping Activity	Direct	Total*
	Number of jobs	
Downstream (deep-draft)	15 632	40 098
Upstream	1 134	2 640
Total	**16 766**	**42 738**
Income (millions 2000 US$)		
Downstream (deep-draft)	576	1 809
Upstream	39	80
Total	**615**	**1 889**

***Sum of direct, indirect and induced effects. Source: (CEDER 2005)**

Transporting cargo via inland waterways also has significant cost benefits compared to alternative forms of transport. A single 60 000 ton shipping vessel can carry the equivalent of 600 rail cars or 2 400 semi trucks. A single barge can carry the equivalent of 35 rail cars (PNWA 2013). **Table 17** shows the difference in freight revenue in cents per ton-mile across barge, rail and truck. These figures represent the cost to producers of transporting one ton of freight one mile.

Table 17. Freight Revenue Per Ton-mile by Transport Alternative (1990-2010 average)

Transport Alternative	Revenue **(cents/mile)**
Truck	13.84
Rail	2.69
Barge	1.57

Source: (USDT-BTS 2015)

The Columbia River navigation system requires considerable maintenance paid for via a mix of federal and private funders. For example, operations and maintenance costs are 100 percent privately paid (through user fees) for the downstream section and 100 percent federally paid for the upstream section. A mix of federal and private sources pay port costs, except for tug, barge and steamship facilities, which are 100 percent private.

Costs can be significant, particularly for large projects like the dredging project completed in 2010. The downstream portion of the river was deepened from 40 feet to 43 feet (12.2 m to13.1 m) at a cost of US$183 million (paid by OR, WA, and federal governments), an estimated annual maintenance cost of US$50–200 million, and an estimated benefit of US$400 million in new private investments (Port of Vancouver (USA) 2013). The project permitted ships that could previously only load 60,000 tons to increase their loads by 10 000 tons. However, concerns were raised by conservation interests throughout the project about its effect on salmon habitat.

Economic losses are also incurred under less than optimal operating conditions.

Huppert et al (2004) describe optimal navigation conditions as “allowing for use of channels, locks and facilities at or in excess of their present use without increased maintenance costs or compromised safety”. For example, the minimum optimal condition in the upstream portion of the Columbia-Snake River navigation system is “one that allows a vessel with a 14-foot draft to move unimpeded through the locks of the dams…” (p.89).

Different development scenarios that shift the annual hydrograph of the Columbia River toward more or less regulation for hydropower and flood control are likely to affect navigation conditions in three key ways, by increasing or decreasing: 1) the frequency of groundings and collisions, 2) the frequency and duration of delays, and/or 3) the available draft. More frequent high flow events could increase delays and collisions, while more frequent low flow events could increase groundings and the available draft. High flows may also lead to more frequent groundings via shoaling. Figure **13** and **Figure 14** illustrate there is no support for these intuitive relationships in the available time series data (2005–2008). However, Huppert et al (2004) suggest that navigation disruptions from low flows begin to occur at 70 kcfs[2] (1 982 m^3/s) daily average discharge levels from Bonneville dam, at which point vessels can carry less freight.

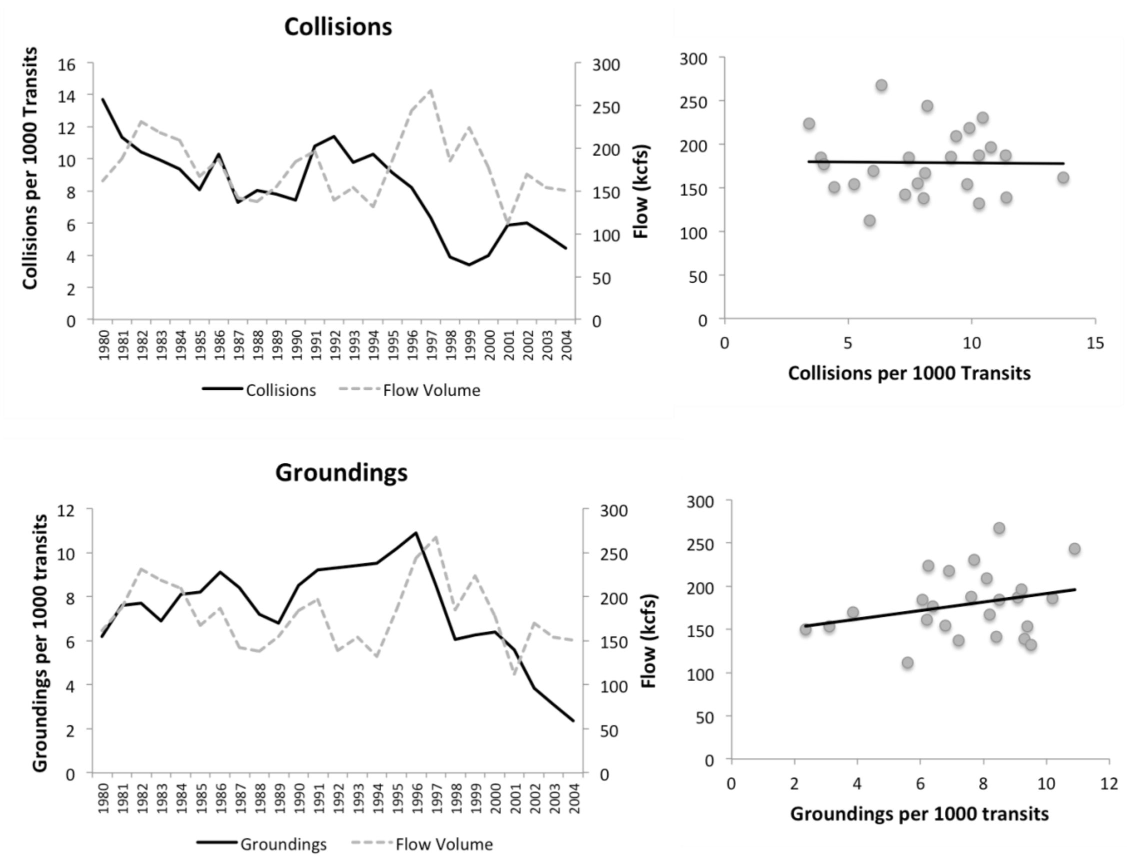


Figure 13. Grounding and Collision Rates for Commercial Vessels on the Columbia River and Annual Average Discharge at The Dalles (2005-2008). Source: (Port of Portland 2010)

[2] Thousands of Cubic Feet Per Second

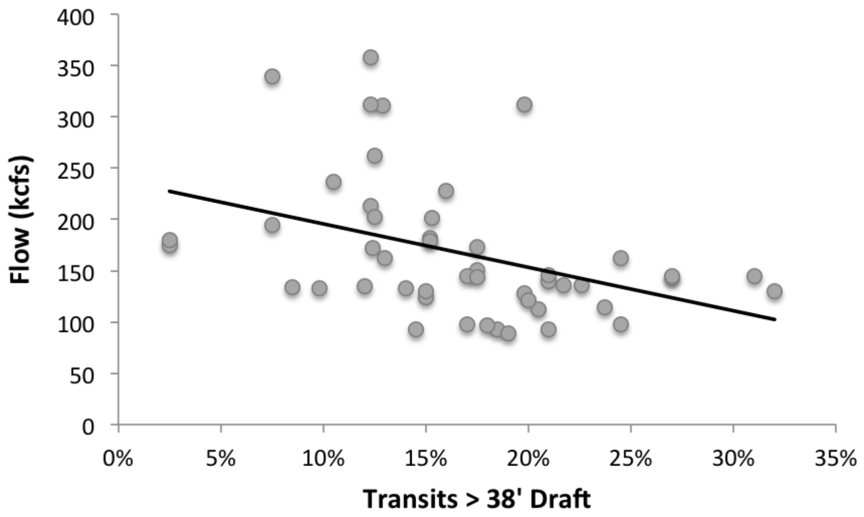


Figure 14. Observed Draft vs. Flow at The Dalles (2005-2008). Source: (Port of Portland 2010)

One study by the Port of Portland estimates the average economic loss associated with grounding at US$0.5 million per incident (dry cargo vessels) (Port of Portland 2010). Also, in one 1995 collision a tug pulling 4 barges crashed into a dam and resulted in an estimated US$10 million in property losses. Environmental clean-up costs are also a risk in the event of a spill (US Coast Guard 2015).

The Port of Portland's study also estimated a cost of US$2 000 /hr in-port for delayed deep-draft vessels. The USACE's guide to deep-draft vessel operating costs is more conservative, suggesting US$359–456 per hour in-port (2004 US$) depending on the boat's tonnage (35 000–80 000) (USACE-IWR 2012). Note that these are direct costs in terms of labour, operations and maintenance and do not incorporate economic impacts from delays down the supply chain.

In terms of draft, the USACE suggests a benefit in added freight of US$6.3 million per year (2003 US$) for each additional foot of draft available in the river (based on estimated benefits resulting from the 2010 dredging project) (USACE 2003). As mentioned, high flows can cause sediment build-up (shoaling), decreasing available draft. No data are available for the relationship between flows and shoaling but in 2011 significant shoaling occurred when peak flows at The Dalles reached 15 744 m3/s or 556 kcfs (600 kcfs is considered critical in terms of potential for major flood damages).

2.2.5 Domestic water supply

The Columbia River produces clean and voluminous flows that are utilized for domestic water supply (defined here as municipal and industrial supply). Only 9 percent of the water diversion rights from the Columbia River go to municipal and industrial users in Washington State (includes groundwater rights within 1 mile of the river) (Huppert et al. 2004). 2 percent of this supply is for municipal use and 5.3 percent is for industrial use. These diversions are so small that they are often ignored by management agencies as a consumptive use of water.

Also, diversions for domestic use have a higher return flow to the river than diversions for agricultural use so they have less impact on fish production. However, domestic water does have a higher marginal value than agricultural diversions (see

Table 18), which could incentivize agricultural users to stockpile surpluses for sale to domestic users during drought years.

As with agricultural supply, municipal and industrial water rights are based on prior appropriation. However, they also have priority over all other water rights and are thus highly secure and unlikely to decrease under alternative development scenarios – they will increase due to population growth, which rose at a rate of 2.2 percent annually from 1990-2014 in the Washington State counties that border the Columbia River (**Figure 15**).

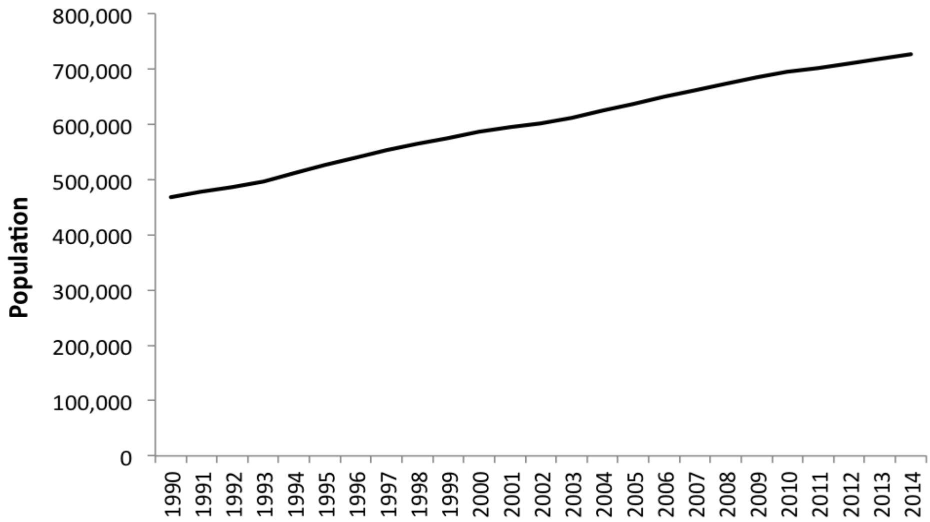


Figure 15. Population Trend for Washington State Counties Bordering the Columbia River. Source: (State of Washington 2015)

While there is no established market where domestic water rights along the Columbia River are traded openly, the few trades that do exist are recorded in the Bren School's US Water Transfers database. The price differs depending on the direction of trade between sectors. The average trading price for all recorded Agricultural-to-Urban water transfers in WA, OR, and ID averages US$13.48 per acre-foot (37 transactions) (US$0.011 m^3) while for Urban-to-Agricultural transfers the price is US$2.73 per acre-foot (4 transactions) (US$0.002 m^3). This suggests a higher value for domestic water compared with agricultural water (Bren School 2015).
Table 18 also supports this conclusion, with an average price more than 4 times higher for all municipal/industrial water transactions.

Table 18. Range of Transaction Prices for Water 1990-2009 (WA, OR, ID)*

	Municipal/industrial (US$) **(n=33)**	Agricultural (US$) **(n=79)**
Maximum	323.41 ($0.26)	108.60 ($0.09)
Average	45.43 ($0.04)	10.48 ($0.01)
Minimum	0.83 ($0.0007)	0.29 ($0.0002)

*Prices are in US dollars per committed acre-foot with US dollars per cubic meter in brackets (Bren School 2015)

Figure 16 below shows a possible negative relationship between flows at The Dalles and price, which would align with expectations (i.e. lower flow years at The Dalles should correlate with drier years for the region and higher prices due to scarcity and demand).

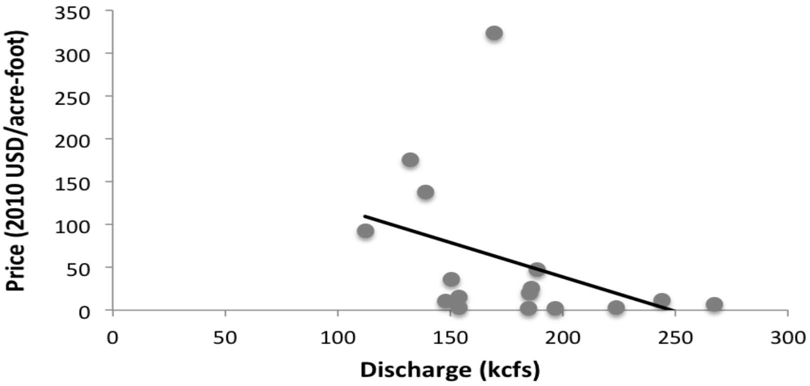


Figure 16. Avg. Annual Transaction Price for Municipal and Industrial Water vs. Average Annual Discharge at The Dalles (WA, OR, ID) n=16. Source: (Bren School 2015)

Huppert et al. (2004) provide the following table displaying municipal and industrial diversion rights within 1-mile of the Columbia River (**Figure 17**).

County	Certificates & Permits (AF)	Applications (AF)
Benton	223,081	65,085
Chelan	33,878	0
Douglas	101	0
Ferry	4	0
Franklin	7,774	5,203
Grant	2,539	0
Kittitas	62	0
Klickitat	25,416	5
Lincoln	676	0
Okanogan	2,467	0
Stevens	2,737	0
Walla Walla	38,303	6,504
Total	337,039	76,798

Figure 17. Municipal and Industrial Diversion Rights within 1 Mile the Columbia River Mainstem from Huppert et al. (2004)

While the diversion rights in the table above are out-dated, multiplying the volumetric total by the average water transaction price shown in

Table 18 suggests an average annual value of US$15.3 million for Columbia River water rights (2010 US$).

3 SELECTION OF ECOSYSTEM SERVICES FOR EVALUATION

Given time constraints and data availability, we selected indicator ecosystem services of the fish production system and evaluated only changes in these services. However, in anticipation of that more refined analysis the following section assesses data gaps and challenges for evaluating all of the fish production system's services outlined in Section 2 and identifies which services we assessed in this study.

We developed four criteria to select ecosystem services for quantitative evaluation. These are described in **Table 19** and include: **1)** Materiality, **2)** Data availability, **3)** Feasibility, and **4)** Fish Production System.

Table 19. Selection Criteria for Ecosystem Services Included in this Study

Materiality	Changes in the service are likely to impact the value of the fish production system in a measurable way
Data availability	Data and/or existing studies are available with which to estimate quantitative changes in the provision of ecosystem service under each scenario and consequent changes in welfare
Feasibility	The analysis can be conducted within the given time at minimum possible complexity (e.g. modelling of environmental changes)
Fish Production System	The service is generated by the fish production system

Table 20. Selection Results

	Materiality	Data Availability	Feasibility	Fish Production System
Food Production (Commercial Fishing)	✓	✓	✓	✓
Recreational Fishing	✓	✓	✓	✓
Ceremonial/Subsistence Fishing	✓	✓	✓	✓
Nutrient Cycling	✓	✓	✓	✓
Sediment Regulation	✓	✗	✗	✓
Biodiversity	✓	?	✗	✓
Cultural Heritage	✓	✗	✗	✓
Research Opportunities	✗	✓	✗	✓
Water Quality (Wetlands)	✓	✓	✗	✓
Natural Flood Control (Wetlands)	✓	✓	✗	✓
Non-fishing Recreation & Tourism	✓	✓	✗	✓
Hydropower production	✓	✓	✓	✗
GHG Emissions Reduction	✓	✓	✓	✗
Agricultural Water Supply	?	✓	?	✗
Shipping and Transportation Opportunities	✗	✓	✗	✗
Domestic Water Supply	✗	✓	?	✗

Key: ✓ criterion met, ✗ criterion unmet, ? criterion somewhat met or uncertain

Results shown in **Table 20** indicate that four ecosystem services meet our selection criteria for this study. These include: **1)** Food Production (Commercial Fishing), **2)** Recreational Fishing, **3)** Ceremonial/subsistence Fishing, and **4)** Nutrient Cycling.

Other ecosystem services of the fish production system either have no precedent in terms of research or data availability for valuation purposes or it is difficult to evaluate changes in these services under our proposed development scenarios. For example, evaluating changes in the water quality and flood control benefits from wetlands would entail complex modelling and inundation mapping beyond the scope of this study. To our knowledge, the habitat engineering service provided by salmon via sediment regulation has not been established quantitatively – either in terms of the impact of this service on fish productivity or in terms of economic value. It is not possible to assign value to cultural heritage (unrelated to ceremonial/subsistence fish consumption), and while data are available to assess the current value of research opportunities, relationships between flow regime changes and these opportunities are tenuous. Changes in the annual hydrograph on the scale we are considering in our proposed scenarios would likely be immaterial to this service. Where relevant, we discuss opportunities for future analysis in the appendix.

Competing ecosystem services such as hydropower production and GHG emissions reduction could be evaluated but are not included in this analysis because they are not part of the fish production system. Future analysis could model trade-offs between fish production and these services and are also discussed in the appendix. Indeed assessing such trade-offs would be essential to correctly evaluating the full social costs of any alternative management strategies.

Agricultural water supply is not material to fish production relative to other competing uses such as hydropower and flood control, but it would be affected by our proposed scenarios and so should be incorporated in any future assessment of trade-offs. This service is more complex to analyse than other services due to the need to model changes in irrigated land area and subsequent shifts in crop type. Shipping and transportation opportunities are also immaterial to fish production unless additional dredging is conducted to improve this service – an unlikely possibility in the near term considering that a major dredging project was just finalized in 2010. Our development scenarios would affect shipping and transportation but it is unclear to what extent.

The net effect may be zero since higher and lower flows are associated with both benefits and costs, thereby creating offsetting effects. Adequately capturing this value is complex since it involves modelling changes in groundings and collisions resulting from different flow regimes (for which there are insufficient data), changes in available draft, and effects of delays throughout the transportation chain, which extends across 39 US states. Domestic water supply is immaterial to fish production and also would not be greatly affected by our development scenarios so this service can be omitted from future study.

4 DEVELOPMENT SCENARIOS

We identify the following three factors driving development related to the Columbia River:

1. Level of prioritization for hydropower and flood control
2. Land area used for irrigated agriculture
3. Regional population growth (domestic water demand)

For example, changes in hydropower and flood control are likely to drive changes in other uses that can compete with the fish production system such as recreational boating, and shipping and transportation. Changes in GHG emissions will also be driven by shifts in hydropower production. Demand for agricultural water supply will change if more or less land area is brought into production for irrigated crop-types. Population growth will change demand for domestic water supply and could have a variety of indirect effects on economic activity and water use in the basin. Since population in the region has grown at a relatively consistent rate for several decades, it is reasonable to assume population will continue to grow and not decline within our study timeframe.

Since our focus is on impacts on the fish production system and the preceding sections establish that domestic and agricultural water supply has relatively little effect on fish production, we recommend focusing on hydropower/flood control as the primary source of development affecting the Columbia River fish production system. This permits us to isolate three development scenarios (including status quo) shown in **Table 21**, which we recommend for this study:

Table 21. Proposed Development Scenarios

Scenario 1 – Status quo	Current conditions	Benefits from fish production system and other ecosystem services remain unchanged.
Scenario 2 – Hydropower Priority	Increased prioritization of hydropower and flood control	Benefits of fish production ecosystem services decrease. Hydropower, flood control, GHG reduction and recreational boating benefits increase. Irrigation benefits decrease, shipping and transportation benefits both increase and decrease (possibly no net effect).
Scenario 3 – Conservation Priority	Decreased prioritization of hydropower and flood control	Benefits of fish production ecosystem services increase. Hydropower, flood control, GHG reduction and recreational boating benefits decrease. Irrigation benefits increase, shipping and transportation benefits both increase and decrease (possibly no net effect).

4.1 Approach to Valuation

In this report we adapt an approach to valuation from Knowler et al (2003). The approach is consistent with welfare measurement where habitat quality is an input into production and is based on long-run stock estimates for a fishery managed for constant adult spawner exploitation and escapement.

The primary objective of our evaluation is to assess how net social benefits from the Columbia River salmon change when habitat quality is altered to accommodate different flow management regimes. To accomplish this, we develop a biological model linking changes in habitat quality to changes in fish productivity. By varying the level of environmental quality in the model according to our development scenarios we solve for salmon abundance and total harvest. Each ecosystem service we evaluate is valued separately for each development scenario using distinctive valuation methods. For example, for commercial salmon fishing we feed the abundance and harvest share results into a production function to derive changes in welfare using estimates for cost of fishing effort, catchability and price per fish. Results for different habitat quality scenarios are then compared to results for the status quo scenario, which represents average "current" conditions based on available empirical data (1970–2000). The difference between the results for alternative and status quo habitat quality conditions is a measure of the net social gain or loss associated with changes in habitat quality.

Our derivation of the habitat quality scenarios is described below, followed by an explanation of the biological model.

4.2 Habitat Quality Scenarios

We assume natural or "unregulated" river conditions are optimal for fish and develop a habitat quality index based on differences in the annual hydrograph from these conditions as measured at The Dalles, which is the gauge location most commonly used as an indicator of river conditions. To illustrate, Figure 18 compares the hydrographs of our three development scenarios with an average unregulated hydrograph from the pre-development era. The closer the hydrograph gets to natural conditions, the more optimal conditions are for the fish production system.

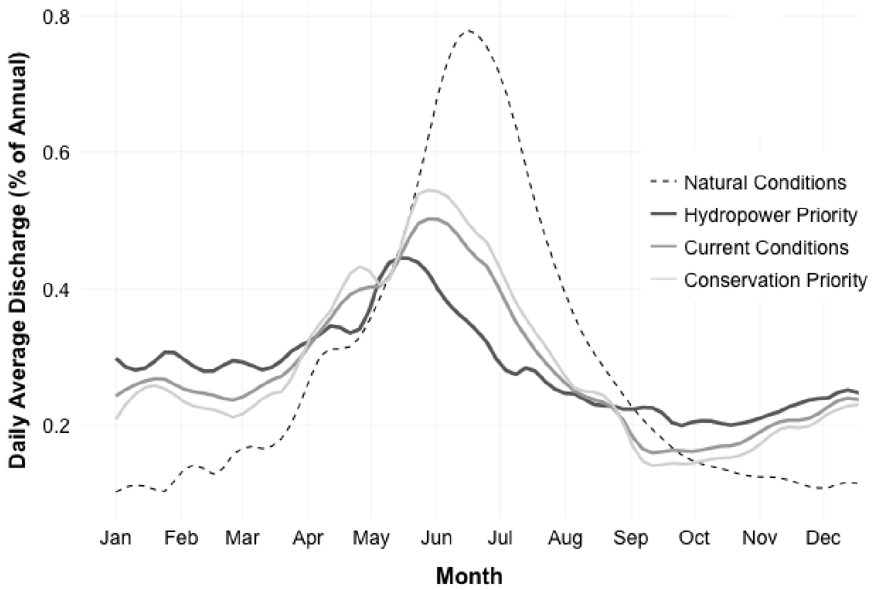


Figure 18. Annual Hydrographs at The Dalles for Proposed Development Scenarios

In
Figure **18**, the grey dotted line represents a pre-development hydrograph based on 1878-1888 average flows at The Dalles. Current conditions (middle gradient of grey) are based on 2000–2014 average discharges at The Dalles and represent **Scenario 1 – Status Quo**. The darkest solid line represents **Scenario 2 - Hydropower Priority** and is based on observed discharge immediately following the completion of the last Columbia River Treaty dam (1976–1980 average), which preceded most river management for salmon conservation. The lightest solid line assumes a 10 percent improvement in regulation for conservation from current conditions and represents **Scenario 3 – Conservation Priority**. Later we consider a second river management scenario with our sensitivity analysis consisting of a 20 percent improvement in regulation for conservation.

Table 22 and **Table 23** show the results from Figure **18** in tabular form for monthly discharge in kcfs and proportion of annual discharge respectively.

Table 22. Discharge at The Dalles for Proposed Scenarios in m3/s (kcfs)

Month	Natural Conditions **1878–1888 average**	Status Quo **2000–2014 average**	Hydropower Priority **1976–1980 average**	Conservation Priority **+10% from Current**
Jan	2 464 (87)	4 446 (157)	4 814 (170)	3 993 (141)
Feb	3 313 (117)	4 163 (147)	4 729 (167)	3 766 (133)
Mar	4 163 (147)	4 587 (162)	4 842 (171)	4 276 (151)
Apr	6 966 (246)	6 258 (221)	5 550 (196)	6 909 (244)
May	11 072 (391)	7 730 (273)	7 108 (251)	8 495 (300)
Jun	17 018 (601)	7 929 (280)	5 777 (204)	8 722 (308)
Jul	12 459 (440)	5 522 (195)	4 417 (156)	6 060 (214)
Aug	6 909 (244)	4 021 (142)	3 908 (138)	4 417 (156)
Sep	4 248 (150)	2 803 (99)	3 483 (123)	3 087 (109)
Oct	3 087 (109)	2 917 (103)	3 370 (119)	3 030 (107)
Nov	2 718 (96)	3 511 (124)	3 738 (132)	3 171 (112)

Dec	2 520 (89)	3 993 (141)	3 993 (141)	3 596 (127)

Source: (USGS 2014)

Table 23. Monthly Proportion of Annual Discharge at The Dalles for Proposed Scenarios

Month	Natural Conditions **1878–1888 average**	Status Quo **2000–2014 average**	Hydropower Priority **1976–1980 average**	Conservation Priority **+10% from Current**
Jan	3.2%	7.7%	8.7%	6.7%
Feb	4.3%	7.2%	8.5%	6.3%
Mar	5.4%	7.9%	8.7%	7.2%
Apr	9.1%	10.8%	10.0%	11.6%
May	14.4%	13.4%	12.8%	14.3%
Jun	22.1%	13.7%	10.4%	14.6%
Jul	16.2%	9.5%	7.9%	10.2%
Aug	9.0%	6.9%	7.0%	7.4%
Sep	5.5%	4.8%	6.2%	5.2%
Oct	4.0%	5.1%	6.0%	5.1%
Nov	3.5%	6.1%	6.7%	5.3%
Dec	3.3%	6.9%	7.2%	6.1%

Source: (USGS 2014)

To compare our three development scenarios with natural conditions, we used Bonneville Power Administration's (BPA) 2010 Level Modified Streamflows database (available at: http://www.bpa.gov/power/streamflow/default.aspx). The database includes natural flow scenarios that estimate daily discharge values at The Dalles from 1970–2000 in the absence of hydropower regulation and diversions for agriculture. We used the annual averages of the daily percent change between discharge from natural conditions and regulated flows to produce an index of habitat quality where 1 is equivalent to pristine habitat conditions (i.e. no difference from natural flows) and zero is a hypothetical fully degraded state (no flow). **Table 24** shows index results for the 31-year period of the dataset.

Table 24. Egg-to-spawner Survival Rates and Habitat Quality Index
Measured from 0 to 1 (based on deviations in average daily flow from pristine conditions)

Year	**Survival Rate**	**Index Value**	**Year**	**Survival Rate**	**Index Value**
1970	0.0006	0.63	1986	0.0011	0.63
1971	0.0008	0.68	1987	0.0007	0.31
1972	0.0006	0.63	1988	0.0008	0.31
1973	0.0005	0.57	1989	0.0005	0.47
1974	0.0005	0.54	1990	0.0005	0.53
1975	0.0005	0.55	1991	0.0006	0.44
1976	0.0005	0.47	1992	0.0013	0.50
1977	0.0009	0.41	1993	0.0007	0.46
1978	0.0006	0.49	1994	0.0005	0.46
1979	0.0006	0.33	1995	0.0004	0.71
1980	0.0004	0.55	1996	0.0005	0.56
1981	0.0008	0.62	1997	0.0011	0.64
1982	0.0012	0.57	1998	0.0007	0.59
1983	0.0007	0.62	1999	0.0006	0.57

1984	0.0012	0.64	1999	0.0010	0.47
1985	0.0009	0.33	2000	0.0011	0.63
Pristine	0.0013	1			
Degraded	0.0000	0			

We used the "observed" data in Table 22, comprising average survival estimates across all species from 1970–2000 and the index values, to fit a linear function between habitat quality index values and egg-to-spawner survival (**Figure 19**). We then used the fitted line to adjust the egg-to-spawner survival rate based on different levels of habitat quality.

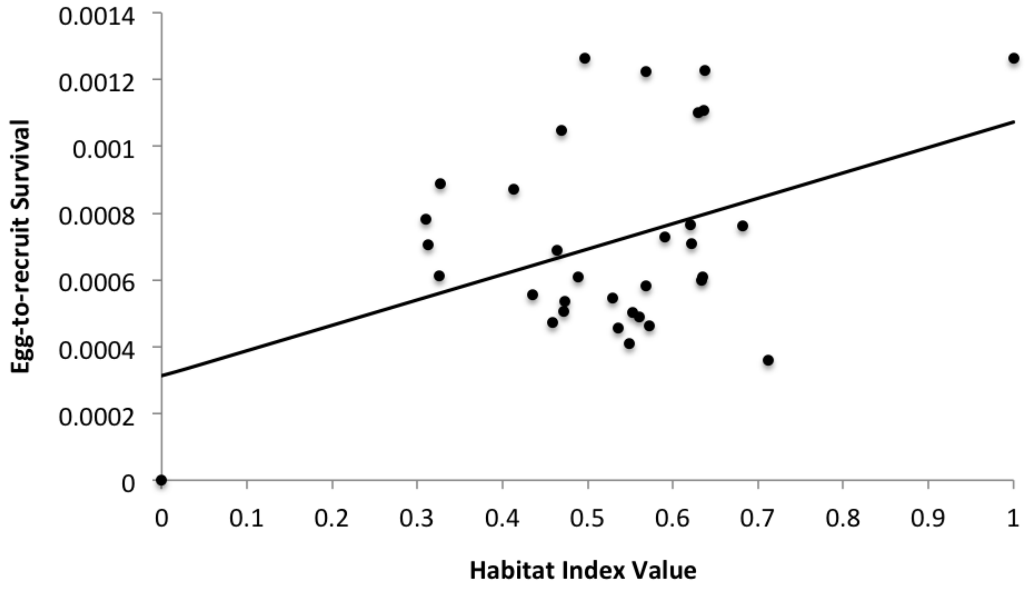


Figure 19. Salmon Survival vs. Habitat Quality Index

The fitted linear equation we estimated is:

$$S = 0.00076096hq + 0.0003118 \quad (1)$$

where S is egg-to-recruit survival at hq, the habitat quality index value from Table 24. Using values of S, we generated a "habitat factor", which is an adjustment to average survival rates determined by subtracting S under pristine conditions from S under each of the development scenarios. Table 25 shows survival rates and habitat factors for habitat quality indices corresponding to each of the development scenarios evaluated in this study.

Table 25. Habitat Quality Indices, Predicted Survival, and Habitat Factors for Development Scenarios

	Index Value	Predicted Survival	Habitat Factor*
Scenario 1 **Status Quo**	0.63	0.00079	-0.00028
Scenario 2 **Hydropower Priority**	0.57	0.00075	-0.00033
Scenario 3 **Conservation Priority**	0.72	0.00086	-0.00021

Pristine Conditions	1	0.001	0.00000

*** Determined as predicted survival for given scenario minus Pristine survival (0.00092)**

One limitation of the approach outlined above is that it does not consider possible differential effects from high versus low flow periods and, instead, assumes deviations either way have similar impacts. However, we tested the separate effects of these flow periods by obtaining unique index values for each type of flow period. Using regression analysis, we found no statistically significant relationship between the separate index values and survival rates. We would also suggest that our fitted line becomes less realistic towards the extreme points but we believe it produces satisfactory estimates between these values.

5 BIOLOGICAL MODEL

5.1 Data

Spawners

To examine the effects of habitat quality on salmon populations, we rely primarily on aggregate harvest and escapement data for Chinook, Coho, Sockeye, Chum and Steelhead compiled from the Pacific Fishery Management Council (PFMC) and the Oregon and Washington Departments of Fish and Wildlife (DFW). We estimate the total number of salmon of all species surviving to spawn for each return year (1967-2000) using data on adult returns at the Columbia River mouth and the relationship

$$SP_{t,i} = AR_{t,i} * (1 - downr_{t,i}) * (1 - upr_{t,i}) * int_{t,i} \qquad (2)$$

where AR is the estimated adult returns at the river mouth below Bonneville Dam for species *i* in year *t*, *downr* is the downriver exploitation rate, *upr* is the upriver exploitation rate, and *int* is the inter-dam survival rate for adult passage past dams from river mouth to spawning locations[3]. Results of this exercise are shown in Table 26.

Table 26. Estimated Number of Salmon Surviving to Spawn in the Columbia River System (all species)

Return Year	Number of fish	Return Year	Number of fish
1967	1 881 500	**1984**	1 706 700
1968	1 478 200	**1985**	1 876 900
1969	1 670 500	**1986**	3 181 900
1970	2 324 900	**1987**	2 229 400
1971	2 063 000	**1988**	2 409 300
1972	1 628 200	**1989**	2 055 100
1973	1 730 900	**1990**	1 262 100
1974	1 440 800	**1991**	1 965 300
1975	1 410 500	**1992**	1 236 500
1976	1 403 800	**1993**	947 600

[3] We used an inter-dam survival rate for Hanford Reach Fall Chinook salmon from Harnish et al (2012). This rate only captures inter-dam survival from the river mouth to past Priest Rapids Dam. However, only four run of river dams exist upstream of Priest Rapids Dam on the mainstem before salmon passage is entirely cut-off by Chief Joseph and Grand Coulee. Also, the bulk of the salmon population spawns downstream of these dams so we assume their effects are minimal.

1977	1 380 500	**1994**	854 300
1978	1 315 600	**1995**	749 500
1979	1 160 900	**1996**	906 000
1980	1 191 600	**1997**	1 057 500
1981	1 091 000	**1998**	858 300
1982	1 486 500	**1999**	1 063 100
1983	1 034 900	**2000**	1 715 700

Source: this study

Figure 20 shows the average proportion of spawners by salmon species and indicates that Chinook, Coho and Steelhead are the dominant populations in the Columbia River.

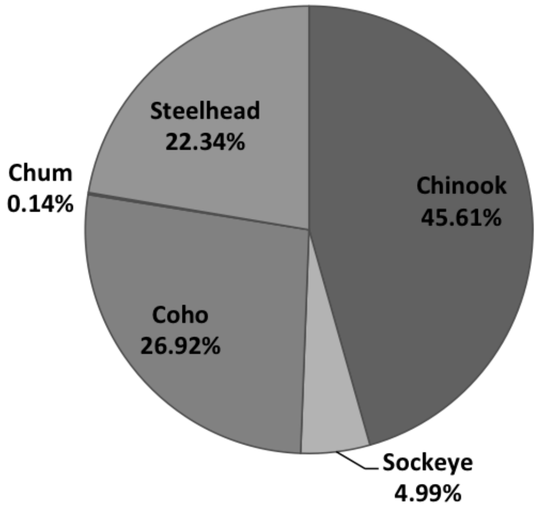


Figure 20. Average Proportion of Adults Returning to Columbia River Mouth by Species
Source: (WDFWODFW 2002)

Exploitation

For salmon harvest, we compiled the total number of fish harvested in each return year (1967–2000) using commercial, recreational and cultural/subsistence harvest data for ocean and in-river fisheries. For ocean recreational fishing (Chinook and Coho) only aggregate data were available for Washington and Oregon. We assume 80 percent of the recreational ocean catch in these two states is attributable to salmon of Columbia River origin. This figure is consistent with commercial catch proportions applied by the Pacific Salmon Commission Joint Technical Committee (PSC-CTC 2014). Table 27 shows results for total harvest of salmon from the Columbia River. Figure 21 shows the average proportion of harvest by fishing type.

Table 27. Estimated Number of Columbia River Fish Harvested
(all salmon species, ocean and in-river, all fishing types)

Return Year	No. Fish Harvested	Return Year	No. Fish Harvested
1967	3 134 849	**1984**	1 770 609
1968	2 807 249	**1985**	3 057 530
1969	3 006 849	**1986**	2 440 230
1970	3 381 049	**1987**	2 716 630
1971	3 169 049	**1988**	2 387 730
1972	3 035 849	**1989**	1 843 430

1973	3 145 749	**1990**	1 428 870
1974	2 890 649	**1991**	869 470
1975	2 886 949	**1992**	792 070
1976	2 865 149	**1993**	743 370
1977	2 743 749	**1994**	713 170
1978	2 748 449	**1995**	491 763
1979	2 703 249	**1996**	509 763
1980	2 852 849	**1997**	463 563
1981	1 391 209	**1998**	548 863
1982	1 612 909	**1999**	669 863
1983	1 309 909	**2000**	630 200

Source: (Pacific Fishery Management Council 2014a; WDFWODFW 2014b; WDFWODFW 2014a)

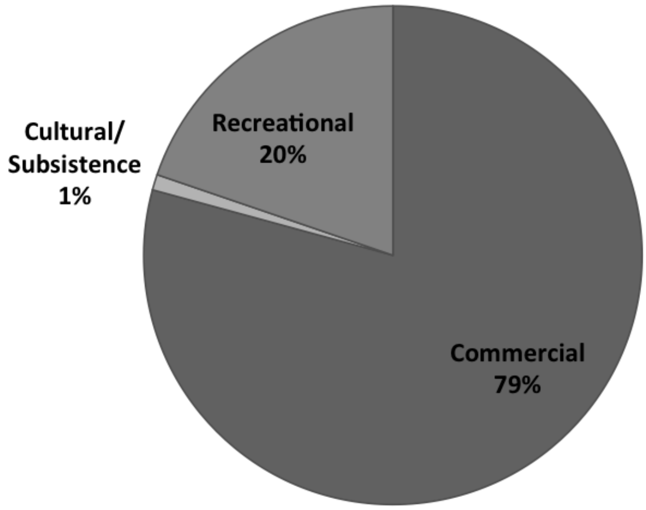


Figure 21. Average Proportion of Harvest by Fishing Type (all species, ocean and river). Source: (Pacific Fishery Management Council 2014a; WDFWODFW 2014b; WDFWODFW 2014a)

We developed annual exploitation rates for each salmon species in ocean, downriver and upriver areas by dividing harvest totals in each area by the number of exploitable fish. For the ocean fishery, we calculated exploitable stock by adding marine harvest and natural marine mortality to adult returns at the river mouth. Exploitable stock for the downriver fishery is simply adult return estimates below Bonneville dam (these incorporate downriver harvest totals), and for the upriver fishery exploitable stock is adult return estimates less downriver harvest. We did not consider inter-dam losses as exploitable stock.

We then averaged these on a weighted basis, by numbers of fish to get a single estimate for exploitation rate incorporating all species.

Eggs & Survival Rates

We estimated the number of eggs corresponding to the brood year for returning adult salmon by assuming a 1:1 ratio of females to males and average female fecundity for each salmon species. We assigned brood years based on predominant adult return ages for each species (note that this is not an age-structured approach, which would be more accurate but was not feasible for this study).

Table 28. Average Female Fecundity and Average Adult Return Ages by Species

Species	Fecundity (# eggs/female)	Return Age (year)
Chinook	3 188	3
Sockeye	3 500	4
Chum	3 300	4
Coho	3 478	3
Steelhead	3 500	4

Sources: (Harnish et al. 2014; Manzer and Miki 1985; Beacham 1982; Brannon, POWELL, and QUINN 2004)

The equation for calculating number of eggs is shown below:

$$Eggs_{t-n} = \left(\frac{SP_{t-n}}{2}\right) * fecundity \qquad (3)$$

where SP is the number of spawners in the corresponding brood year t-n; and n is the average adult return age minus 1.

We estimated egg-to-spawner survival rates for each species by dividing the number of adult returns less harvest and inter-dam mortality by the number of eggs. Due to lack of available data for other species, we relied on the inter-dam survival rate reported by Harnish et al. (2012) for Fall Chinook salmon (0.759) (Harnish et al. 2012). We did not apply this rate to Chum salmon, which primarily spawn in the lower sections of the river.

5.2 Stock-Recruit Model

Following Knowler et al (2003), we model salmon recruitment to the exploitable stock as a modified Beverton-Holt stock-recruitment function making use of the habitat quality factor derived earlier. We adjust the number of recruits for harvest rates, ocean mortality and inter-dam loss to arrive at total exploitable stock numbers. The equation is as follows:

$$R(X_{t-n} - h_{t-n};\ \bar{Q}) = \frac{a(s+\bar{Q})\ (X_{t-n}-h_{t-n})}{\left(1+\frac{a}{b}(X_{t-n}-h_{t-n})\right)(int \cdot oc \cdot (1-h1)\cdot(1-h2)\cdot(1-h3))} \qquad (4)$$

where $R(X_{t-n} - h_{t-n})$ is recruitment to the exploitable stock, a is the productivity parameter defined as the weighted average number of eggs produced per spawner across all species (see Table 29 for weighting proportions); s is the average egg-to-recruit survival rate for all salmon species 1970--2000; $\bar{Q}$ is an adjustment to the average egg-to-recruit survival rate for all salmon species derived from the habitat quality index (Table 25); b is the weighted capacity parameter, or the weighted maximum number of eggs that are produced in the Columbia River; int is the inter-dam survival rate; oc is the natural marine survival rate; $h1, h2, h3$ are ocean, average downriver and upriver harvest rates respectively; X is the total exploitable stock of all species; and h is the total harvest of all salmon species from the exploitable stock.

Table 29. Average Annual Proportion of Total Eggs Produced 1970-2000 used for Weighted Averaging of Beverton-Holt ‘a’ and ‘b’ Parameters

Species	Weighting proportion (%)
Chinook	42.90
Sockeye	4.08
Coho	14.72
Chum	0.11
Steelhead	22.10

5.3 Biological Parameters

The Beverton-Holt *a* parameter, or productivity parameter, is set at 3 336, which is the weighted average of all the average female fecundities shown in **Table 27**. The Beverton-Holt *b* parameter, or capacity, is 2 087 340 236 eggs, which is the maximum number of eggs estimated using the historic weighted adult return data for all species (see Eqn 3). Egg-to-recruit survival is the average survival across all years 1970–2000 and equals 0.000715347. The habitat quality parameter *Q* is varied dependent on the development scenario and equals the corresponding estimated habitat factor values listed in table **Table 25**. Inter-dam survival (*int*) is 0.759 based on estimated rates in Harnish et al. (2014) for Fall Chinook. Natural ocean survival is 0.8 based on personal communications with staff at the Pacific Northwest National Laboratory for Fall Chinook. The ocean, downriver and upriver harvest rates are 0.1640, 0.2165, and 0.0689 respectively and represent average exploitation rates across all species 1970–2000 inclusive of commercial, recreational and cultural/subsistence fisheries (note that only Chinook and Coho have a regulated ocean fishery). All biological parameter assumptions are shown in
Table 30.

Table 30. Parameters Used in the Aggregate Biological Model for all Species

Parameter	Units	Value	Source
Habitat factor, *Q*, by development scenario	n.a.	Hydro = -0.00033, Base = -0.00028, Conserv= -0.00021	this study
Density independent recruitment parameter, *a*	n.a.	3336	this study
Density dependent recruitment parameter, *b*	n.a.	2 087 340 236	this study
Average egg-to-recruit survival, *s*	n.a.	0.00071535	this study
Inter-dam survival, *int*	n.a.	0.759	(Harnish et al. 2012) (Fall Chinook)
Natural ocean survival, *oc*	n.a.	0.8	personal communications with staff at PNNL (Fall Chinook)
Ocean harvest , *h1*	n.a.	0.1640	this study
Downriver harvest, *h2*	n.a.	0.2165	this study
Upriver harvest, *h3*	n.a.	0.0689	this study

5.4 Aggregate Biological Model Results for all Species

To estimate total exploitable stock and harvest under each development scenario, we assumed a fishery managed at a constant level of escapement. Total harvest was estimated from total exploitable stock, accounting for natural marine mortality and inter-dam loss then applying weighted average harvest rates for river and ocean fisheries, different fishery types and different species. **Table 31** details proportions of total exploitable stock used for weighting purposes throughout this study.

Table 31. Allocation of Total Harvest across Species and End Users for Columbia River Salmon, Average 1970 to 2000

	Ocean harvest			River harvest				Grand Total
	Commercial	Recreational	Total	Commercial	Recreational	Cultural	Total	
Chinook	30.00%	3.00%	33.00%	11.5%	1.25%	0.50%	13.25%	**46.25%**
Coho	30.00%	12.00%	42.00%	9.5%	1.00%	n/a	10.50%	**52.50%**
Sockeye	n/a	n/a	n/a	n/a	n/a	0.20%	0.20%	**0.20%**
Steelhead	n/a	n/a	n/a	n/a	0.75%	0.30%	1.05	**1.05%**
Chum	n/a	n/a	n/a	neg.	neg.	neg.	neg.	**neg.**
All Species	60.00%	15.00%	75.00%	21.00%	3.00%	1.00%	25.00%	**100%**

Table 32 shows the base case results assuming the 1967–2000 average escapement for all species (780 036 spawners) as the constant escapement. Commercial, recreational and cultural/subsistence harvests were determined using the proportions identified in **Table 31**.

Table 32. Total Exploitable Stock and Harvest Results by Fishing Type (number of fish)*

		HARVEST			
	EXPLOITABLE STOCK	**Commercial (Chinook + Coho only)**	**Recreational**	**Cultural/ Subsistence**	**Total**
Scenario 1 **Status Quo**	2 474 708	562 819	154 408	8 707	788 632
Scenario 2 **Hydropower Priority**	2 331 901	527 662	144 763	8 042	725 934
Scenario 3 **Conservation Priority**	2 688 919	611 537	167 774	9 321	680 467

Pristine Conditions	3 355 352	759 249	208 299	11 572	979 120

***Constant escapement is assumed to be the 1967-2000 average escapement (780 036 spawners)**

6 ECONOMIC WELFARE ESTIMATION

6.1 Food Production (Commercial Fishing)

For this part of the study, we make the assumption that the Columbia River commercial fishery is managed as a both a troll ocean fishery and a gillnet river fishery, selling salmon into an international market where its price is exogenously determined. The expression we use to determine net social benefits is:

$$W = ph - cE(X,h) \quad (4)$$

Where W is the net social benefit from the salmon stock in period; ph is the gross benefits from salmon catch (price p x harvest h); and cE is the cost incurred by the commercial fishery (unit cost c x effort E). We further assume that effort E is a function of the exploitable stock X of Chinook and Coho and harvest h.

We used the 2013 fishing year for our baseline assumptions about the commercial fishing price and cost parameters. To determine a price per-fish, we relied on the weighted average price per kilogram for ocean and in-river caught Chinook and Coho multiplied by a weighted average caught weight per fish. Price data for 2013 were available from the Pacific Fishery Management Council (2014) and we accounted for differences in value for ocean and in-river caught fish. All other data sources are described in the footnote below[4]. All values were adjusted to 2013 prices using the US Gross Domestic Product Implicit Price Deflator. To estimate the caught weight we used an average of retailers' advertised weights per whole salmon for each species. We then determined a single adult caught weight for Chinook and Coho using a weighted average with the proportions reported in **Table 31**. Next, we obtained a cost per boat-day via personal e-mail communications with the US National Marine Fisheries Service (NMFS). The NMFS data included 2013 cost estimates for both ocean troll and river gillnet salmon fisheries. We assumed the seasonal average number of days at sea for gillnet salmon boats at 33.34 and for trollers at 43.9 per the NMFS data. Again, using the proportions in **Table 31**, we weighted these costs to arrive at a single cost per boat-day[5]. Both fixed and variable costs were included. Our assumptions for salmon price, fishing cost per day and catchability are summarized in **Table** 33.

Table 33. Parameter Values for Commercial Fishing Welfare Estimation

Parameter	Units	Value	Source
Price, *p*	$per salmon; 2013 US$	29.03	PFMC (2014); see also footnote 2
Cost, *c*	$per boat-day; 2013 US$	$766.11	NOAA-NMFS (2015); see also footnote 3
Catchability coefficient, *q*	n.a	0.00003	Argue et al (1983)
Fishing effort, *E*	#boat-days/season	Hydro=12,464	this study

[4] We determined a single commercial price for a combined Chinook/Coho salmon by first calculating a weighted average caught weight per fish using harvest proportions from Table 31 and average whole fish caught weights from the Seattle Fish Company (www.seattlefish.com), Wild Salmon Seafood Market (http://wildsalmonseafood.com), and the Pure Food Fish Market (www.freshseafood.com) (All accessed July, 2015). Average Chinook caught weights were 6.6 kg/fish (14.5 lbs/fish) in-river and 2.5 kg/fish (5.5 lbs/fish) in ocean. Average Coho caught weights were 3.1 kg/fish (6.75 lbs/fish) in-river and 2.3 kg/fish (5 lbs) in ocean. The weighted average combined caught weight was 3.54 kg (7.81 lbs). We then relied on ex-vessel price data for California, Oregon and Washington in-river and ocean fisheries from the Pacific Fishery Management Council (2014) and the harvest proportions in Table 31 to calculate a weighted average price per kg (US$1.69 /kg or US$3.72 /lb), which we then multiplied by the weighted average caught weight per fish to arrive at US$29.03/fish.

[5] Per-day cost of fishing effort for gillnet in 2013 was US$930 and US$711 for trolling. Using the total proportions in Table 31 for in-river (25%) and ocean (75%) fisheries, this works out to a weighted average cost of US$766.11.

	Base=12,541 Conserv=12,541

To determine the fishing effort in total number of boat-days, we used a production (catch) function model from Knowler et al. (2003) but the expression for catch was inverted to isolate fishing effort as the unknown on the left side. We required an estimate of the catchability coefficient and used a value developed initially by Argue et al (1983) and used again in Knowler et al. (2003) for the Strait of Georgia Chinook and Coho fishery of q = 0.00003. The expression we used for this procedure was:

$$E = \frac{1}{q}(LN(X) - LN(X - h)) \qquad (5)$$

where q is the catchability coefficient, E is fishing effort in boat-days, X is the total exploitable stock of Chinook and Coho and h is the commercial fishing harvest for these two species. Inserting the relevant variable values for exploitable stock, long run harvest and catchability into the above expression yielded a long run effort level of 12 541 boat-days per year for all scenarios except Scenario 2 – Hydropower Priority, which yielded a lower effort of 12 464 boat-days per year.

Table 34 shows total commercial harvest results assuming management for a constant average escapement of 780 036 salmon (the 1967–2000 average). Results for net social benefit from commercial fishing are also reported.

Table 34. Total Exploitable Stock and Harvest Results for Commercial Fishery (Chinook & Coho Ocean and River Fisheries Only) (number of fish)

	Exploitable stock **(#)**	Total commercial harvest **(#)**	Net social benefit per year **(US$)**	Difference from Status Quo per year **(US$)**	Difference from Status Quo as NPV* **(US$)**
***Scenario 1* Status Quo**	1 794 964	562 819	6 732 487	-	-
***Scenario 2* Hydropower Priority**	1 691 382	527 662	5 770 626	(961 861)	(9 618 609)
***Scenario 3* Conservation Priority**	1 950 336	611 537	8 146 900	1 414 413	14 144 133
Pristine Conditions	2 433 716	759 249	12 494 249	5 761 762	57 617 621

***NPV = net present value over an infinite time period using a 10 percent discount rate**

6.2 Recreational Fishing

For the recreational fishery, several approaches to valuation are possible. We report one approach here and then consider a second possibility in our sensitivity analysis below. Here, we follow Huppert et al (2004) and assume that trends in angler trips are driven by trends in catch/trip, which are in turn influenced by fish abundance. The authors estimate an average catch/trip of 1.13 fish for recreational fishing on the Columbia River and 1.14 fish/trip for recreational ocean fishing in Washington. Like Huppert et al, we assume that allowable catch increases with run size and that the number of angler trips increases in proportion, so for each increase in 1 fish caught, the in-river recreational fishery would increase by 1/1.13=0.89 trips and the ocean recreational fishery would increase by 1/1.14=0.88 trips. Taking net values per fishing trip, measured as willingness-to-pay (WTP), from Olsen et al (1991) and adjusting for inflation, we obtain updated estimates of net value per trip in 2013 US$ as US$184.76/trip for in-river recreational fishing and US$148.30/trip for ocean recreational fishing. Therefore, the net value per additional fish is US$184.76 x 0.89 = US$164.43 in the river and US$148.30 x 0.88 = US$130.09 in the ocean. Then we multiply these per-fish net values by harvest totals for each of our scenarios and report these totals in **Table 35**.

Table 35. Scenario Results for Recreational Fishing using Huppert et al 2004 Method (US$ 2013)

	Total recreational harvest	Net social benefit per year* (US$)	Difference from Status Quo per year (US$)	Difference from Status Quo as NPV* (US$)
Scenario 1 **Status Quo**	154 408	20 958 061	-	-
Scenario 2 **Hydropower Priority**	144 763	19 648 901	(1 309 160)	(13 091 602)
Scenario 3 **Conservation Priority**	167 774	22 772 193	1 814 131	18 141 312
Pristine Conditions	208 299	28 272 642	7 314 581	73 145 807

***NPV = net present value over an infinite time period using a 10 percent discount rate**

6.3 Cultural/Subsistence Fishing

The tribal cultural/subsistence share of annual catch in the Columbia River is about 1 percent (see **Figure 21**). We assume that these fish are used primarily for household consumption. In reference to non-timber tropical forest products, Godoy et al (1993) state that goods for the market and goods for the home should be valued differently. Specifically, "products consumed at home or exchanged with kin should be valued at their traditional retail purchasing price" (p.225). Following this approach we collected several whole fish retail prices for each species by spot-checking different online fish markets that sell Washington and/or Columbia River salmon and steelhead[6].

[6] Chinook price is from the Wild Salmon Seafood Market (http://wildsalmonseafood.com) based on an average weight per whole fish of 6.80 kg (14.99 lbs) and an advertised price of US$6.58 /kg (US$14.50 /lb), Sockeye price is the average between the Seattle Fish Company (http://www.seattlefish.com) (average 2.5 kg (5.5 lbs) at US$31.74 (US$69.98 /lb)) and the Wild Salmon Seafood Market (average 2.95 kg (6.5 lbs) at US$5.89 /kg (US$12.99 /lb)). Steelhead price is from Fitt's Seafood (http://www.fitts.net) (average 4.54 kg (10 lbs) at US$6.80 /kg US$(14.99 /lb)). All prices were accessed July, 2015.

Table 36 below shows our assumptions for price, cost, catchability, fishing effort, and proportion of harvest by species. **Table 37** shows the predicted cultural/subsistence harvest by species – note that these values are somewhat lower than those reported in Section 2.1.3 by Davis (2014) due to the different time series data applied (Davis reports catch values for 2003–2012, while our values are based on the assumption of a constant escapement equivalent to the average escapement from 1967–2000). Therefore, our results should be considered as a lower bound conservative estimate. **Table 38** reports the results of our net social benefit calculations for cultural/subsistence fishing.

Table 36. Parameter Values for Cultural/Subsistence Fishing Estimation

Parameter	Units	Value	Source
Price, *p*	$per salmon; 2013 US$	Chinook=$217.36; Sockeye=$77.21; Steelhead=$149.90	Seattle Fish Company (2015), Wild Salmon Seafood Market (2015), Fitt's Seafood (2015)
Cost, *c*	$per boat-day; 2013 US$	$930	NOAA-NMFS (2015)
Catchability coefficient, *q*	n.a	0.00003	Argue et al (1983)
Fishing effort, *E*	#boat-days/season	Hydro=236 Base=240 Conserv=236	this study
Proportions of harvest by species	%	Chinook=45% Sockeye=16% Steelhead=40%	PFMC (2014)

Table 37. Predicted Cultural/Subsistence Harvest by Species (number of fish)

	Total	Chinook	Sockeye	Steelhead
Scenario 1 **Status Quo**	8 707	3 895	1 357	3 454
Scenario 2 **Hydropower Priority**	8 042	3 598	1 254	3 191
Scenario 3 **Conservation Priority**	9 321	4 170	1 453	3 698
Pristine Conditions	11 572	5 177	1 804	4 591

Table 38. Net Social Benefits from Cultural/Subsistence Salmon Fishing

	Net social benefit per year **(US$)**	Difference from Status Quo per year **(US$)**	Difference from Status Quo as NPV **(US$)**
Scenario 1 **Status Quo**	1 245 999	-	-
Scenario 2 **Hydropower Priority**	1 137 183	(108 815)	(1 088 152)
Scenario 3 **Conservation Priority**	1 352 906	106 908	1 069 076
Pristine Conditions	1 732 817	486 819	4 868 186

***NPV = net present value over an infinite time period using a 10 percent discount rate.**

6.4 Nutrient Cycling

Nutrient cycling between marine and terrestrial aquatic ecosystems is an ecosystem service provided by Columbia River salmon. Here we follow Knowler et al. (2001) and use a 'replacement cost' approach to determine the total benefit of salmon-based nutrient cycling (Knowler et al. 2001). This approach estimates the value of an asset by calculating the cost of replacing its services, often with a human-produced substitute (Knowler and Lovett 1996). In this case we use fertilizer pellets that are applied during forest restoration efforts as the substitute. We use prices for pellets used in a restoration project on the Keogh River in British Columbia. These prices indicate a replacement cost of about US$0.01 /kg (US$0.02 /lb) of salmon (adjusted from 2001 CDN to 2013 US$). We rely on these numbers for this preliminary study but more up to date values that are specific to the Columbia River Basin may be available to future researchers.

To calculate total biomass we assume only fish that die in the river contribute to total nutrient import, so we increase the predicted number of recruits to the spawning population by the interdam loss rate and multiply by an average in-river weight per salmon of 4.7 kg (10.37 lbs) (weighted average across all species migrating upriver). We then reduce the result to 23 percent of total biomass as discussed in Section 2.1.4 to arrive at net import of nutrients (**Table 39**). Finally we multiply the net biomass values by the per pound replacement cost indicated above.

Table 40 below shows these results for each development scenario.

Table 39. Biomass Results for Adult Salmon Returns at Columbia River Mouth.

	Number of adult fish returns at river mouth	Total biomass[1]	Net import of biomass[2]
Scenario 1 **Status Quo**	1 213 574	12 581 120	2 893 658
Scenario 2 **Hydropower Priority**	1 137 767	11 795 231	2 712 903
Scenario 3 **Conservation Priority**	1 318 621	13 670 143	3 144 133
Pristine Conditions	1 637 124	16 972 061	3 903 574

[1] Total biomass calculated using an average weight per fish of 10.37 lbs (rounded from 10.36699997).
[2] Net import of biomass calculated as 23 percent of the total biomass.
Discrepancies in figures are due to rounding errors.

Table 40. Scenario Results for Benefits of Nutrient Transport

	Net social benefit[1] (US$)	Difference from Status Quo (US$)	NPV (10% Discount Rate) (US$)
Scenario 1 **Status Quo**	47 659	-	-
Scenario 2 **Hydropower Priority**	44 682	(2 977)	(29 770)
Scenario 3 **Conservation Priority**	51 784	4 125	41 253
Pristine Conditions	64 292	16 633	166 334

[1] Net social benefit calculated using US$0.02 /lb (rounded from 0.01647 as the value after conversion from 2001 CDN to 2013 US$ accounting for exchange rate and inflation).
Discrepancies in figures are due to rounding errors.

7 SENSITIVITY ANALYSIS

Since there is considerable uncertainty in undertaking a valuation exercise with limited resources, we carried out a selective sensitivity analysis. We first consider several key parameters from our salmon population modelling and flow management assumptions, since these parameters affect all scenarios, although not necessarily in exactly the same way. Next we consider a specific case in which we alter the underlying assumption governing the Conservation Priority Scenario that involved a 10 percent change in regulation of the river system for conservation (to 20 percent). Finally, we recalculate the values associated with the recreational fishery using a different methodology from a Canadian research study that would be expected to produce lower values (as it does) but which perhaps aligns more closely with economic theory.

7.1 Variation in Key Biological & Management Parameters

Because there are so many parameters to consider in the models we present above, we were unable to perform the large number of calculations needed to do a full sensitivity analysis for this study. Instead we focus on three key underlying biological and management assumptions that we predict could have significant impact on our results. First we change by +/-20 percent the Beverton-Holt 'a' and 'b' parameters. These parameters govern the non-density dependent and density dependent features of the Beverton-Holt model.

Variability in these parameters is highly likely. For example, our value for the 'a' parameter is based on weighted averages for each species, which could change year-to-year depending on brood stock characteristics. In addition, the Beverton-Holt 'b' parameter could fluctuate widely depending on the time-series data used to develop this figure and observed fecundity values (in our case we relied on 1970–2000 estimates of eggs and average fecundity values).

Table 41 next page shows the results of our sensitivity analysis for these biological parameters.

Considering only the status quo scenario, a 20 percent increase in the ‘a’ parameter would increase our results by US$850 959, while a 20 percent decrease would decrease our results by US$1 332 090. Likewise, a 20 percent increase or decrease in the ‘b’ parameter would have a slightly larger but similar effect.

Table 41. Sensitivity Analysis of Key Biological Parameters (US$ 2013)

	Net social benefit per year (US$)	Difference from Base Case per year (US$)	Difference from Base Case as NPV (US$)
Parameter: Beverton-Holt 'a' +20%			
Scenario 1 **Status Quo**	30 058 422	850 959	8 509 588
Scenario 2 **Hydropower Priority**	29 515 506	2 914 115	29 141 147
Scenario 3 **Conservation Priority**	33 394 690	850 959	8 509 588
Pristine Conditions	46 757 095	4 193 096	41 930 956
Parameter: Beverton-Holt 'a' -20%			
Scenario 1 **Status Quo**	27 875 373	(1 332 090)	(13 320 901)
Scenario 2 **Hydropower Priority**	22 959 686	(3 641 706)	(36 417 060)
Scenario 3 **Conservation Priority**	31 211 641	(1 332 090)	(13 320 901)
Pristine Conditions	37 323 979	(5 240 021)	(52 400 207)
Parameter: Beverton-Holt 'b' +20%			
Scenario 1 **Status Quo**	30 264 136	1 056 673	10 566 735
Scenario 2 **Hydropower Priority**	30 307 965	3 706 573	37 065 731
Scenario 3 **Conservation Priority**	33 600 404	1 056 673	10 566 735
Pristine Conditions	47 897 357	5 333 358	53 333 576
Parameter: Beverton-Holt 'b' -20%			
Scenario 1 **Status Quo**	27 535 655	(1 671 808)	(16 718 079)
Scenario 2 **Hydropower Priority**	22 170 450	(4 430 942)	(44 309 421)
Scenario 3 **Conservation Priority**	30 871 923	(1 671 808)	(16 718 079)
Pristine Conditions	36 188 354	(6 375 646)	(63 756 461)

In addition to the biological parameters, our model assumes a constant escapement management target. We based this target on average escapements from 1967–2000 (780 036 spawners). In reality, annual escapements can vary widely and, in particular, could be altered by major shifts in management toward hydropower or conservation priorities. Under any of these shifts, our constant escapement targets may be unrealistic. A full sensitivity analysis should consider multiple scenarios, but for the purposes of this study we selected one alternative time-series (1991–2000) to derive a new constant escapement target of 683 580 fish. **Table 42** below shows the results of this sensitivity analysis.

Table 42. Sensitivity Analysis of Key Management Parameters (Constant Escapement Target) (US$ 2013)

	Net social benefit/year (US$)	Difference from Base Case/year (US$)	Difference from Base Case as NPV (US$)
Parameter: Constant escapement target 1991-2000 average (683,580 fish)			
Scenario 1 **Status Quo**	26 788 206	(2 419 257)	(24 192 565)
Scenario 2 **Hydropower Priority**	25 584 425	(1 016 967)	(10 169 670)
Scenario 3 **Conservation Priority**	29 911 475	(2 632 256)	(26 322 557)
Pristine Conditions	39 471 571	(3 092 429)	(30 924 289)

Considering only the status quo scenario, a reduced management target from an escapement of 780 036 to 683 580 fish would reduce the welfare generated by the Columbia River fish production system by about US$2.4 million per year.

7.2 Alternative Conservation Priority Scenario

For the **Conservation Priority Scenario** we assumed only a modest 10 percent increase in regulation for conservation, which may seem quite low. We selected this value in recognition of the fact that the Columbia River system is already managed with a substantial emphasis on protecting salmon runs. Therefore, it might be suspected that there are only limited opportunities to enhance this management emphasis. Nonetheless, there is debate about the extent to which the Columbia River hydropower system currently accommodates conservation needs (e.g. see (Hamlet 2010). Further, the base case value for the Conservation Scenario is somewhat lower than our assumption for the increase in regulation for power generation assumed in the Hydropower Development Scenario (see Figure 18 for a visual comparison).

As a result, we carry out an additional sensitivity analysis where we increase the regulation for conservation by 20 percent instead of 10 percent, in line with the variations considered in the previous section under our sensitivity analysis of individual parameter assumptions.
Table 43 presents the results of this alternative Conservation Priority scenario for each ecosystem service in isolation and for the total across all services. It is useful to compare these values with the values in **Table 34**, **Table 35**, **Table 38**, and

Table 40.

Table 43. Results for Alternative Conservation Priority Scenario Based on a 20 percent Improvement in Regulation for Conservation (US$ 2013)

	Net social benefit per year (US$)	Difference from Status Quo per year (US$)	Difference from Status Quo as NPV (US$)
Commercial Fishery	8 932 685	2 200 199	22 001 985
Recreational Fishery	23 780 043	2 821 982	28 219 818
Cultural/Subsistence	1 642 466	173 210	1 732 095
Nutrient Cycling	54 076	6 417	64 172
Sub-total	34 409 270	5 201 807	52 018 071

7.3 Alternative Method for Recreational Fishery Valuation

For our sensitivity analysis of the recreational fishery results, we use an alternative valuation method that follows Gislason et al. (1996), who studied commercial and recreational salmon fisheries in the Canadian Fraser River system (Gislason et al. 1996). Their method assumes that increases in fish availability do not increase fishery values proportionally, since the dimensions of the recreational fishing experience unaffected by fish availability (e.g. being outdoors, social aspects) do not change. Thus, we would expect to see the value of an incremental fish caught to be somewhat lower than the value of an average fish caught. Instead, the approach assumes that increases in fish availability translate into increased numbers of fishing days (as catching a fish now has a higher probability) and an increase in the willingness-to-pay per fishing day demand for fishing days and the elasticity of WTP to the probability of catching a fish (given the better prospects of catching a fish on a given day). How substantial these responses are to increased fish availability depends on the appropriate "elasticity". Gislason et al. (1996) report these elasticities as the percentage change in fishing days or WTP per trip in response to a 10 percent change in catch success. Their estimates range from 1.0 to 4.5 percent and 1.0 to 2.0 percent, respectively, with the range for each elasticity measure reflecting the different types of fishing experiences (lodge-based, independent, etc.).[7] Since we did not have information on the distribution of the recreational salmon catch by type of experience we take the mid values for each range of elasticity values, i.e. 2.75 percent for fishing days and 1.5 percent for WTP.

Using the fish/trip estimates reported above from Huppert et al. (2004), the status quo recreational catch of 125 600 fish from **Table 35**, and the allocation between ocean and river-based catches shown in **Table 31** (85 percent and 15 percent, respectively), we determined the number of days involved in the recreational catch. This value was adjusted by first dividing the new annual recreational catch under each scenario by the initial number of recreational fishing days to obtain a new estimate of catch success. Dividing this latter value by the initial catch success (1.14 or 1.13 fish per day), we then obtained the proportional increase in catch success. Subsequently, we multiplied this proportional change in catch success by the elasticity values expressed above (expressed per 10 percent change in catch success) and by the initial number of recreational fishing days to yield the new estimate of fishing days. We used a similar procedure to adjust the WTP value per fishing day, assuming that the average fishing

[7] Gislason et al. (1996) derived their range of elasticity values from a literature review including 14 different studies, reported in their study as Exhibit 5.3 (p5-4).

trip was one day. Final net social benefit values are reported in **Table 44**. Using this method, the estimated changes in net social benefits are over half the size of the values estimated using the Huppert et al. (2004) method, providing a lower bound to our value estimates.

Table 44. Sensitivity Analysis of the Scenario Results for Recreational Fishing Based upon the Gislason et al (1996) Valuation Method (US$ 2013)

	Net social benefit per year* (US$)	Difference from Status Quo year (US$)	Difference from Status Quo as NPV** (US$)
Scenario 1 Status Quo	20 860 622	-	-
Scenario 2 Hydropower Priority	20 310 173	(550 449)	(5 504 486)
Scenario 3 Conservation Priority	21 634 490	773 869	7 738 686
Pristine Conditions	24 059 681	3 199 060	31 990 597

*Values reported are estimates using Gislason et al. (1996) method in place of the Huppert et al. (2004) method

**NPV = net present value over an infinite time period using a 10 percent discount rate

8 SUMMARY AND CONCLUSIONS

In this section we summarize our valuation results for fish-related ecosystem services supported by the Columbia River by type of ecosystem service and by development scenario. For reasons of data availability, we limited our consideration of ecosystem services generated by the fish production system for comparison across development scenarios. We identified four ecosystem services with sufficient existing data for evaluation: **a)** food production (commercial fishing); **b)** recreational fishing; **c)** cultural/subsistence fishing; and **d)** nutrient cycling. Ecosystem services we were unable to address within the time limitations included water quality (an indirect benefit of salmon conservation efforts), biodiversity, and carbon fixation/ greenhouse gas emissions. Income and livelihood support are captured in the food production valuation. However, data were available to provide a sense of current conditions for most of the ecosystem services we did not analyse in detail (we provided this information in **Section 2**).

As illustrated in **Table 45** next page, the most important ecosystem service was recreational fishing. Under some scenarios this sector generated twice the value of the next largest sector (commercial fishing). This result is not surprising since most economic assessments of the value of a "marginal" fish indicate they are more highly valued when allocated to the recreational fishery. Under most scenarios the value of the subsistence/cultural catch is only a small proportion of the combined commercial and recreational catch. Even though we have used an accepted methodology that values these highly (at retail prices), the catch is relatively small by comparison at only a few percent of the total harvest of Columbia River salmon. Finally, our calculation for the value of nutrient cycling indicates this value is almost negligible because the true "net" import of nutrients from sea to land via salmon spawning is much smaller than often recognized (versus the "gross" import of nutrients per spawning fish carcass). Chiefly accounting for the lower net import is the export of nutrients via juvenile migration to the sea and the stirring up of sediments during construction of redds.

Also evident in **Table 45** is the welfare change associated with shifting from one development scenario to another. Comparing a shift from the status quo to the

Hydropower Priority to a similar shift to the Conservation Priority is of particular interest. In the former case, there is a net welfare *loss* of US$2.6 million per year, whereas in the latter case there is a US$3.3 million *gain* in welfare. This result is instructive from a management point of view: although management of the Columbia River system has emphasized fisheries in recent decades it appears the opportunities for welfare gain from such emphasis have not been fully exploited. Considering our Conservation Priority scenario only minimally alters the flow regime by comparison to the Hydropower Priority scenario (see Figure 18), only strengthens this argument. However, care is needed in such interpretations because the welfare gains stemming from increased hydropower production under the Hydropower Priority scenario are not considered here and might well outweigh the difference between the two scenarios of nearly US$6 million per year (US$2 606 071 plus US$3 336 278). Confirming whether this is the case, unfortunately, was beyond the scope of our report. Nonetheless, our results could be helpful in future assessments that take this wider perspective.

Table 45. Summary of Estimated Changes in the Value of Ecosystem Services for Four Ecosystem Services Associated with the Columbia River Fish Production System under Two Alternative Development Scenarios and Pristine Conditions (US$ 2013)

	Net social benefit per year (US$)	Difference from Status Quo per year (US$)	Difference from Status Quo as NPV (US$)
***Scenario 1* - Status Quo**			
Commercial Fishery	6 732 487	-	-
Recreational Fishery	20 958 061	-	-
Cultural/Subsistence	1 469 256	-	-
Nutrient Cycling	47 659	-	-
Sub-total	29 207 463	-	-
***Scenario 2* - Hydropower Priority**			
Commercial Fishery	5 770 626	(961 861)	(9 618 609)
Recreational Fishery	19 648 901	(1 309 160)	(13 091 602)
Cultural/Subsistence	1 137 183	(332 073)	(3 320 730)
Nutrient Cycling	44 682	(2 977)	(29 770)
Sub-total	26 601 392	(2 606 071)	(26 060 711)
***Scenario 3a* - Conservation Priority (+10% regulation)**			
Commercial Fishery	8 146 900	1 414 413	14 144 133
Recreational Fishery	22 772 193	1 814 131	18 141 312
Cultural/Subsistence	1 572 854	103 598	1 035 982
Nutrient Cycling	51 784	4 125	41 253

Sub-total	32 543 731	3 336 268	33 362 681
Scenario 3b **- Conservation Priority (+20% regulation)**			
Commercial Fishery	8 932 685	2 200 199	22 001 985
Recreational Fishery	23 780 043	2 821 982	28 219 818
Cultural/Subsistence	1 642 466	173 210	1 732 095
Nutrient Cycling	54 076	6 417	64 172
Sub-total	34 409 270	5 201 807	52 018 071

Table 45 cont'd

	Net social benefit per year (US$)	Difference from Status Quo per year (US$)	Difference from Status Quo as NPV (US$)
Pristine Conditions			
Commercial Fishery	12 494 249	5 761 762	57 617 621
Recreational Fishery	28 272 642	7 314 581	73 145 807
Cultural/Subsistence	1 732 817	263 561	2 635 609
Nutrient Cycling	64 292	16 633	166 334
Sub-total	**42 564 000**	**13 356 537**	**133 565 370**

In contrast, our assessment of Pristine Conditions suggests that society today is worse off by US$13 million per year in fish production system terms, compared to the status quo. However, again we are disregarding the non-fishery benefits associated with Columbia River development over the past century or so. Obviously, these benefits have been substantial.

Although the Columbia Basin is highly studied and produces a wide array of data, the system is very complex and significant data gaps remain for specific sections of the basin. Since the timing for this study was compressed, we limited our assessment of ecosystem services to manageable portions of the system where data were readily available. We limited our assessment in four ways: a) By considering the river itself as the main driver of production (versus the many tributaries); b) By constraining the geographic scope primarily to Washington State; c) By selecting specific ecosystem services for evaluation; and d) By limiting our focus to Columbia River salmonid species, which are the most economically significant species produced by the system. Where possible, we included the ocean fishery in our analysis, but our primary focus was on in-stream commercial and recreational fishing. Nonetheless, it was difficult to determine the proportion of the commercial and recreational ocean fishery attributable to the Columbia River.

One key challenge in studying the Columbia Basin is the lack of publicly available data for certain portions of the basin. For example, hydropower generation data could not be obtained for all the Canadian dams and studies related to other uses, such as recreation and irrigation are rare for that part of the basin. With the exception of Washington State, similar challenges also exist in the US. Despite ignoring large areas of the river basin, we feel this restriction still reasonably captures the system because Washington hosts the largest and most productive stretch of the Columbia River.

Several recommendations can be noted for improving the value estimates presented here in terms of both breadth and depth. As a result, we have prepared a detailed assessment of data needs and possible methodologies for estimating the economic value of ecosystem services generated by the Columbia River fish production system that did not meet our selection criteria but still have potential for future evaluation (see Appendix A). We also consider options for estimating the value of other ecosystem services generated by the Columbia River that are not part of the fish production system but would be affected by the development scenarios we propose in this study.

REFERENCES

Alvarez, David, Stephanie Perkins, Elena Nilsen, and Jennifer Morace. 2014. "*Science of the Total Environment*." Science of the Total Environment, the 484 (C). Elsevier B.V.: 322–30. doi:10.1016/j.scitotenv.2013.07.128.

Barber, K. 2005. *Death of Celilo Falls.* Seattle, USA: University of Washington Press.

Beacham, T D. 1982. "Fecundity of Coho Salmon (Oncorhynchus Kisutch) and Chum Salmon (O. Keta) in the Northeast Pacific Ocean." *Canadian Journal of Zoology*.

Bell, Kathleen P., Daniel Huppert, and Rebecca L. Johnson. 2003. "Willingness to Pay for Local Coho Salmon Enhancement in Coastal Communities." *Marine Resource Economics* 18 (1). Marine Resources Foundation.

Bilby, R E, B R Fransen, and P A Bisson. 1998. "Response of Juvenile Coho Salmon (Oncorhynchus Kisutch) and Steelhead (Oncorhynchus Mykiss) to the Addition of Salmon Carcasses to Two Streams in Southwestern Washington, USA" *Can. J. Fish. Aquat. Sci*. 55: 1909–1918

Bottom, Daniel L, Charles A Simenstad, Jennifer Burke, Antonio M Baptista, and David A Jay. 2005. *Salmon at River's End: the Role of the Estuary in the Decline and Recovery of Columbia River Salmon*. Portland State University.

BPA. 2011. 2010 *Level Modified Streamflow 1928-2008*: Main Report. Bonneville Power Administration.

BPA. 2014. "Streamflow." Bpa.Gov. Accessed November. www.bpa.gov/power/streamflow/default.aspx

BPA, USACE, USBOR. 1995. *Columbia River System Operation Review: Final Environmental Impact Statement - Main Report*. Bonneville Power Administration, US Army Corps of Engineers, US Bureau of Reclamation.

Brannon, E L, M S POWELL, and T P QUINN. 2004. "*Population Structure of Columbia River Basin Chinook Salmon and Steelhead Trout*." Reviews in Fisheries …. doi:10.1080/10641260490280313.

Bren School. 2015. "Bren School Water Transfer Database." Bren.Ucsb.Edu. Accessed April. www.bren.ucsb.edu/news/water_transfers.htm

Brown, Jovana J, and Brian Footen. 2010. "*Pacific Northwest Salmon Habitat: the Culvert Case and the Power of Treaties*." The Evergreen State College, 1–26.

Brugere, Cecile. 2015. *Increasing the Visibility of Fisheries and Aquaculture's Services: Laying a Basis for Recognizing, Demonstrating and Capturing Their Value in Decision-Making.* Unpublished report. United Nations Food and Agriculture Organization.

CBT. 2012. *Columbia River Basin: Dams and Hydroelectricity*. Columbia Basin Trust. www.cbt.org

CEDER. 2005. *Columbia/Snake River System and Oregon Coastal Cargo Ports: Marine Transportation System (MTS) Study.* Center for Economic Development Education and Research.

Cederholm, C Jeff, Matt D Kunze, Takeshi Murota, and Atuhiro Sibatani. 1999. "Pacific Salmon Carcasses: Essential Contributions of Nutrients and Energy for Aquatic and *Terrestrial Ecosystems." Fisheries* 24 (10): 6–15. doi:10.1577/1548-8446(1999)024<0006:PSC>2.0.CO;2.

Charnley, Susan, Ellen M Donoghue, Claudia Stuart, Canadace Dillingham, Lita P Buttolph, William Kay, Rebecca J McLain, Cassandra Moseley, Richard H Phillips, and Lisa Tobe. 2006. *Northwest Forest Plan: the First 10 Years (1994-2003)*. General Technical Report PNW-GTR-649 Vol.1. US Department of Agriculture, US Forest Service, Pacific Northwest Research Station.

Cosens, Barbara, and Alexander Fremier. 2014. "Assessing System Resilience and Ecosystem Services in Large River Basins: a Case Study of the Columbia River Basin." *Idaho Law Review* 51: 92–125.

David Evans & Associates, ECONorthwest. 2004. *Final Submittal: Comparative Valuation of Ecosystem Services: Lents Project Case Study*. City of Portland Watershed Management Program.

Davis, Shannon. 2014. *Economic Effects and Social Implications Section: Double Crested Cormorant Management Plan to Reduce Predation of Juvenile Salmonids in the Columbia River Estuary Version 2.1*. Corvallis, USA: The Research Group, LLC.

DeVries, P. 1997. "Riverine Salmonid Egg Burial Depths: Review of Published Data and Implications for Scour Studies." *Canadian Journal of Fisheries and Aquatic ...*.

Douglas, Aaron J, and Jonathan G Taylor. 1999. "The Economic Value of Trinity River Water." *International Journal of Water Resources Development* 15 (3): 309–22.

Duffield, J.W., C.J. Neher, and T.C. Brown. 2007. "Recreation Benefits of Instream Flow: Application to Montana's Big Hole and Bitterroot Rivers." *Water Resources Research* 28 (9). American Geophysical Union: 2169–81.

Earth Economics. 2015. *Economic Analysis of Outdoor Recreation in Washington State*. Olympia, USA: Washington State Recreation and Conservation Office.

EPA. 2009. *Columbia River Basin: State of the River Report for Toxics*. United States Environmental Protection Agency.

EPA. 2010. *Columbia River BasinToxics Reduction Action Plan*. United States Environmental Protection Agency.

FWEE. 2015. "Irrigation: Foundation for Water and Energy Education." *Fwee.org*. Accessed April. http://fwee.org/environment/what-makes-the-columbia-river-basin-unique-and-how-we-benefit/irrigation/.

Gislason, Gordon, Edna Lam, Julie Paul, Ellen Battle, The ARA Consulting Group Inc. 1996. *The Economic Value of Salmon: Chinook and Coho in British Columbia*. Vancouver, Canada: Government of Canada and Government of the Province of British Columbia.

Groot, C, and L Margolis. 1991. "Life History of Chinook Salmon." In *Pacific Salmon Life Histories*, 1–86. Vancouver: UBC Press.

Hamlet, Alan F. 2010. "Assessing Water Resources Adaptive Capacity to Climate Change Impacts in the Pacific Northwest Region of North America." *Water Resources* 7: 4437–71.

Hamlet, Alan F, D Huppert, and D P Lettenmaier. 2002. "Economic Value of Long-Lead Streamflow Forecasts for Columbia River Hydropower." *Journal of Water Resources* .

Hanemann, M., John B Loomis, and B. Kanninen. 1991. "Statistical Efficiency of Double-Bounded Dichotomous Choice Contingent Valuation." *American Journal of Agricultural Economics* 73 (4). Oxford University Press: 1255–63.

Harding, Jennifer N, and John D Reynolds. 2014. "Opposing Forces: Evaluating Multiple Ecological Roles of Pacific Salmon in Coastal Stream Ecosystems." *Ecosphere* 5 (12): art157. doi:10.1890/ES14-00207.1.

Harnish, Ryan A, Rishi Sharma, Geoffrey A. McMichael, Russell B Langshaw, Todd N Pearsons, and D A Bernard. 2012. *Effect of Priest Rapids Dam Operations on Hanford Reach Fall Chinook Salmon Productivity and Estimation of Maximum Sustainable Yield, 1975-2004*. Final Report. Richland, USA: Battelle Pacific Northwest Division.

Harnish, Ryan A, Rishi Sharma, Geoffrey A. McMichael, Russell B Langshaw, Todd N Pearsons, and Ray Hilborn. 2014. "Effect of Hydroelectric Dam Operations on the Freshwater Productivity of a Columbia River Fall Chinook Salmon Population." *Canadian Journal of Fisheries and Aquatic Sciences*, February, 1–14. doi:10.1139/cjfas-2013-0276.

Helvoigt, Ted L, and Diane Charlton. 2009. *The Economic Value of Rogue River Salmon*. Eugene, OR: ECONorthwest.

Hilderbrand, G V, and S D Farley. 1996. "Use of Stable Isotopes to Determine Diets of Living and Extinct Bears." *… Journal of Zoology*.

Holmlund, CM, and M Hammer. 1999. "Ecosystem Services Generated by Fish Populations." *Ecological Economics* 29 (2): 253–68.

Huppert, Daniel, Gareth Green, William Beyers, Andrew Subkoviak, and Andrew Wenzl. 2004. *Economics of Columbia River Initiative*. CRI Economics Advisory Committee.

IEAB. 2005. "Economic Effects From Columbia River Basin Anadromous Salmonid Fish Production," December, 1–166.

Knowler, D, and J Lovett. 1996. *Training Manual for Environmental Assessment in Forestry*.

Knowler, DJ, Brice MacGregor, Michael Bradford, and Randall M Peterman. 2001. *Valuing the Quality of Freshwater Salmon Habitat - a Pilot Project*. Unpublished manuscript. Simon Fraser University, School of Resource and Environmental Management.

Knowler, DJ, BW MacGregor, MJ Bradford, and RM Peterman. 2003. "Valuing Freshwater Salmon Habitat on the West Coast of Canada." *Journal of Environmental Management* 69 (3): 261–73. doi:10.1016/j.jenvman.2003.09.001.

Kohler, Andre E, Paul C Kusnierz, Timothy Copeland, David A Venditti, Lytle Denny, Josh Gable, Bert A Lewis, et al. 2013. "Salmon-Mediated Nutrient Flux in Selected Streams of the Columbia River Basin, USA." *Canadian Journal of Fisheries and Aquatic Sciences* 70 (3): 502–12. doi:10.1139/cjfas-2012-0347.

Kohler, Andre E, Todd N Pearsons, Joseph S Zendt, Matthew G Mesa, Christopher L Johnson, and Patrick J Connolly. 2012. "Nutrient Enrichment with Salmon Carcass Analogs in the Columbia River Basin, USA: a Stream Food Web Analysis." *Transactions of the American Fisheries Society* 141 (3): 802–24. doi:10.1080/00028487.2012.676380.

Layton, D., G. Brown, and M. Plummer. 1999. "Valuing Multiple Programs to Improve Fish Populations." *Washington Department of Ecology. Olympia, WA*.

Loomis, John B. 1999a. "Recreation and Passive Use Values From Removing the Dams on the Lower Snake River to Increase Salmon." *Report From AEI to US Army Corps of Engineers*.

Loomis, John B. 1999b. *Passive Use Values of Wild Salmon and Free-Flowing Rivers*. USACE.

Loomis, John B. 2002. "Quantifying Recreation Use Values From Removing Dams and Restoring Free-Flowing Rivers: a Contingent Behavior Travel Cost Demand Model for the Lower Snake River." *Water Resources Research* 38 (6): 2–1–2–8. doi:10.1029/2000WR000136.

Loomis, John B, and DS White. 1996. "Economic Values of Increasingly Rare and Endangered Fish." *Fisheries* 21 (11): 6–10.

Loomis, John B, and Robert Richardson. 2000. *Economic Values of Protecting Roadless Areas in the United States*. Fort Collins, USA: The Wilderness Society and Heritage Forests Campaign.

Mansfield, C., G. Van Houtven, A. Hendershott, P. Chen, J. Porter, V. Nourani, and V. Kilambi. 2012. *Klamath River Basin Restoration Nonuse Value Survey*. RTI International.

Manzer, J I, and I Miki. 1985. "Fecundity and Egg Retention of Some Sockeye Salmon (Oncorhynchus Nerka) Stocks in British Columbia." *Canadian Journal of Fisheries and Aquatic Sciences* 43: 1643–55.

McKean, John R, Donn Johnson, and R G Taylor. 2012. "Journal of Environmental Management." *Journal of Environmental Management* 112 (C). Elsevier Ltd: 321–29. doi:10.1016/j.jenvman.2012.08.017.

Montgomery, D R, and J M Buffington. 1996. "Stream-Bed Scour, Egg Burial Depths, and the Influence of Salmonid Spawning on Bed Surface Mobility and Embryo Survival." *... Journal of Fisheries ...*.

Moore, Jonathan W, Daniel E Schindler, and Mark D Scheuerell. 2004. "Disturbance of Freshwater Habitats by Anadromous Salmon in Alaska." *Oecologia* 139 (2): 298–308. doi:10.1007/s00442-004-1509-3.

Moore, Jonathan W, Daniel E Schindler, Jackie L Carter, Justin Fox, Jennifer Griffiths, and Gordon W Holtgrieve. 2007. "Biotic Control of Stream Fluxes: Spawning Salmon Drive Nutrient and Matter Export." *Ecology* 88 (5): 1278–91.

N Wear, David, and Brian C Murray. 2004. "Federal Timber Restrictions, Interregional Spillovers, and the Impact on US Softwood Markets." *Journal of Environmental Economics and Management* 47 (2): 307–30. doi:10.1016/S0095-0696(03)00081-0.

Naiman, Robert J, Robert E Bilby, Daniel E Schindler, and James M Helfield. 2002. "Pacific Salmon, Nutrients, and the Dynamics of Freshwater and Riparian Ecosystems." *Ecosystems* 5 (4): 399–417. doi:10.1007/s10021-001-0083-3.

Nilsen, Elena, and Jennifer Morace. 2014. "Science of the Total Environment." *Science of the Total Environment, the* 484 (C). Elsevier B.V.: 319–21. doi:10.1016/j.scitotenv.2013.07.127.

Nilsen, Elena, Steven Zaugg, David Alvarez, Jennifer Morace, Ian Waite, Timothy Counihan, Jill Hardiman, et al. 2014. "Science of the Total Environment." *Science of the Total Environment, the* 484 (C). Elsevier B.V.: 344–52. doi:10.1016/j.scitotenv.2013.04.012.

NOAA. 2014. "Marine and Anadromous Fish - Office of Protected Resources - NOAA Fisheries." *Nmfs.Noaa.Gov*. National Oceanic and Atmospheric Administration (NOAA) National Marine Fisheries Service (NMFS). Accessed November. www.nmfs.noaa.gov/pr/species/fish/

NPCC. 2008. “Irrigation.” *Nwcouncil.org*. www.nwcouncil.org/history/irrigation

NPCC. 2011. *The Effects of an Increasing Surplus of Energy Generating Capability in the Pacific Northwest*. Northwest Power Planning Council.

NPCC. 2014. *2013 Columbia River Basin Fish and Wildlife Program Costs Report*. Northwest Power and Conservation Council.

ODFW, WDFW. 2002. *Status Report: Columbia River Fish Runs and Fisheries 1938-2002 TABLES ONLY*. Oregon Department of Fish & Wildlife and Washington Department of Fish & Wildlife.

Olsen, D, J Richards, and RD Scott. 1991. “Existence and Sport Values for Doubling the Size of Columbia River Basin Salmon and Steelhead Runs..” *Rivers* 2 (1): 44–56.

Pacific Fishery Management Council. 2014a. *Review of 2013 Ocean Salmon Fisheries*. Portland, USA: Pacific Fishery Management Council.

Pacific Fishery Management Council. 2014b. *Preseason Report III: Council Adopted Management Measures and Environmental Assessment for 2014 Ocean Salmon Fishery Regulations*. Pacific Fishery Management Council.

Pant, Raghav, Kash Barker, and Thomas L Landers. 2014. “Dynamic Impacts of Commodity Flow Disruptions in Inland Waterway Networks.” *Computers & Industrial Engineering*, December. Elsevier Ltd, 1–13. doi:10.1016/j.cie.2014.11.016.

PNNL. 2015. “Fishes of the Columbia River.” *Pacific Northwest National Laboratory*. Accessed May. http://ecology.pnnl.gov/Fishes_Columbia_River.asp.

PNWA. 2013. *Columbia Snake River System Facts*. Pacific Northwest Waterways Association.

PNWA. 2014. *PNWA Member Lower Columbia River Ports*. Pacific Northwest Waterways Association.

Port of Portland. 2010. *Estimating Economic Benefits From NOAA PORTS Information: a Case Study of the Columbia River*. Port of Portland.

Port of Vancouver (USA). 2013. *Port of Vancouver USA - Letter to BPA and USACE February 12, 2013*.

Power, T M. 2006. “Public Timber Supply, Market Adjustments, and Local Economies: Economic Assumptions of the Northwest Forest Plan.” *Conservation Biology*. doi:10.1111/j.1523-1739.2006.00383.x.

PSC-CTC. 2014. *2013 Exploitation Rate Analysis and Model Calibration*. Vol. 2. Pacific Salmon Commission Joint Chinook Technical Committee.

Radtke, Hans, and Shannon Davis. 1995. *An Estimate of the Asset Value for Historic Columbia River Salmon Runs*. Eugene, USA: The Institute for Fisheries Resources.

Riseng, C M, M J Wiley, R W Black, and M D Munn. 2011. "Impacts of Agricultural Land Use on Biological Integrity: a Causal Analysis." *Ecological Applications* 21 (8): 3128–46.

State of Washington. 2015. "WAOFM - April 1 - Population by State, County and City, 1990 to Present." *State of Washington*. Accessed April. https://data.wa.gov/Demographics/WAOFM-April-1-Population-by-State-County-and-City-/tecv-qzfm.

Teel, David J, Cyndi Baker, David R Kuligowski, Thomas A Friesen, and Barbara Shields. 2009. "Genetic Stock Composition of Subyearling Chinook Salmon in Seasonal Floodplain Wetlands of the Lower Willamette River, Oregon." *Transactions of the American Fisheries Society* 138 (1): 211–17. doi:10.1577/T08-084.1.

Texas Transport Institute. 2007. *A Modal Comparison of Domestic Freight Transportation Effects on the General Public*. Texas Transport Institute.

The Wilderness Society. 2008. *Greater Than Zero: Toward the Total Economic Value of Alaska's National Forest Wildlands*. The Wilderness Society.

Thompson-Reuters. 2015. "Web of Science [v.5.17] - Web of Science Core Collection Home." *Thompson Reuters*. Accessed April. http://apps.webofknowledge.com.

US Coast Guard. 2015. "USCG CGMIX Incident Investigation Reports Home Page." *Cgmix.Uscg.Mil*. Accessed April. https://cgmix.uscg.mil/iir/Default.aspx.

US Entity. 2013. *U.S. Entity Regional Recommendation for the Future of the Columbia River Treaty After 2024*. US Entity to the Columbia River Treaty.

USACE. 2003. *Columbia River Channel Improvement Project: Final Supplemental Integrated Feasibility Report and Environmental Impact Statement*. United States Army Corps of Engineers (USACE), Portland District.

USACE. *Fish Identification Booklet*. Portland, USA: US Army Corps of Engineers.

USACE. 2015a. "USACE Power Summary Reports: Columbia River." *Nwd-Wc.Usace.Army.Mil*. Accessed April. www.nwd-wc.usace.army.mil/ftppub/power/

USACE. 2015b. "2012 Waterborne Commerce of the United States (WCUS)." *Navigationdatacenter.Us*. Accessed April. www.navigationdatacenter.us/wcsc/webpub12/webpubpart-4.htm.

USACE. 2015c. "NDC - U.S. Waterway Data - Waterborne Commerce of the United States (WCUS)." *Navigationdatacenter.Us*. Accessed April. www.navigationdatacenter.us/data/datawcus.htm.

USACE-IWR. 2012. *Appendix H: Guide to Deep-Draft Vessel Operating Costs*. United States Army Corps of Engineers (USACE), Institute for Water Resources.

USBOR. 2003. *Economic Analysis of Dam Decommissioning*. Technical Memorandum Number EC-2003-01. U.S. Department of the Interior Bureau of Reclamation.

USDA. 2015. "USDA/NASS QuickStats Ad-Hoc Query Tool." *Quickstats.Nass.Usda.Gov*. Accessed April. http://quickstats.nass.usda.gov.

USDT-BTS. 2015. "Table 3-21: Average Freight Revenue Per Ton-Mile (Current ¢) | Bureau of Transportation Statistics." *Rita.Dot.Gov*. Accessed April. www.rita.dot.gov/bts/sites/rita.dot.gov.bts/files/publications/national_transportation_statistics/html/table_03_21.html.

USEIA. 2014. "The Columbia River Basin Provides More Than 40% of Total U.S. Hydroelectric Generation." *United States Energy Information Administration (USEIA)*. www.eia.gov/todayinenergy/detail.cfm?id=16891.

USEIA. 2015a. "U.S. Energy Information Administration (EIA) - Data." *United States Energy Information Administration (USEIA)*. Accessed January. www.eia.gov/electricity/data.cfm#sales.

USEIA. 2015b. "Wholesale Electricity and Natural Gas Market Data." *United States Energy Information Administration (USEIA)*. Accessed April. www.eia.gov/electricity/wholesale/.

USEIA. 2015c. "Annual Electric Utility Data - Form EIA-906 Database." *United States Energy Information Administration (USEIA)*. Accessed May. www.eia.gov/electricity/data/eia923/eia906u.html.

USEPA. 2014. *eGRID 9th Edition Version 1.0 Year 2010 Summary Tables*. USEPA - Clean Air Markets Division.

USFWS. 2012. *Federal and State Endangered and Threatened Species Expenditures: Fiscal Year 2011*. United States Fish and Wildlife Service.

USFWS. 2014. "US Fish & Wildlife Service: Endangered Species | Home Page." *Fws.Gov*. Accessed October 2015. www.fws.gov/endangered/.

USGS. 2014. "USGS Surface Water Data for USA: USGS Surface-Water Daily Statistics." *United States Geological Survey*. United States Geological Survey. http://nwis.waterdata.usgs.gov/nwis/dvstat/?search_site_no=14105700&agency_cd=USGS&referred_module=sw&format=sites_selection_links

Walsh, Richard G, John B Loomis, and Richard A Gillman. 1984. "Valuing Option, Existence, and Bequest Demands for Wilderness." *Land Economics*. JSTOR, 14–29.

Washington State Legislature. 2015. "Chapter 173-563 WAC: INSTREAM RESOURCES PROTECTION PROGRAM for the MAIN STEM COLUMBIA RIVER in WASHINGTON STATE." *Washington State Legislature*. Accessed April. http://app.leg.wa.gov/WAC/default.aspx?cite=173-563.

WDE. 1997. *The Economic Value of Wetlands*. Ecology Publication No. 97-100. Washington Department of Ecology.

WDE. 2015. "Office of Columbia River Water Budget." *Ecy.Wa.Gov*. Accessed April. www.ecy.wa.gov/programs/wr/cwp/cr_wtrbud.html.

WDFW, ODFW. 2002. *Status Report: Columbia River Fish Runs and Fisheries 1938-2000*. Washington Department of Fish & Wildlife/Oregon Department of Fish & Wildlife.

WDFW, ODFW. 2014a. *2014 Joint Staff Report: Stock Status and Fisheries for Spring Chinook, Summer Chinook, Sockeye, Steelhead, and Other Species, and Miscellaneous Regulations*. Washington Department of Fish & Wildlife/Oregon Department of Fish & Wildlife.

WDFW, ODFW. 2014b. *2014 Joint Staff Report: Stock Status and Fisheries for Fall Chinook Salmon, Coho Salmon, Chum Salmon, Summer Steelhead, and White Sturgeon*. Washington Department of Fish & Wildlife/Oregon Department of Fish & Wildlife.

White, Richard. 1995. *The Organic Machine: the Remaking of the Columbia River*. New York, USA: Hill and Wang.

Willson, M F, and K C Halupka. 1995. "Anadromous Fish as Keystone Species in Vertebrate Communities." *Conservation Biology*.

1974. *U.S. v. State of Washington 384 F. Supp. 312 (U.S. Dist.)* ccrh.org.

Appendix 1: Options to Assess Other Ecosystem Services with Additional Time and Data

This section details options for estimating the economic value of ecosystem services generated by the Columbia River fish production system that did not meet our selection criteria but still have potential for future evaluation. In addition, we consider options for estimating the value of other ecosystem services generated by the Columbia River that are not part of the fish production system but would be affected by the development scenarios we propose in this study.

Fish Production System

Biodiversity

Methods for this ecosystem service still require discussion/development. Change in benefits from biodiversity in the Columbia River basin can be driven by changes in river management as well as land use changes. One way to gauge biodiversity status is the number of threatened or endangered species and costs associated with protecting these species. Other approaches frame habitat improvements targeted at specific species as an indirect proxy for biodiversity benefits (see (David Evans & AssociatesECONorthwest 2004)). Yet another approach is to evaluate changes in the value of protected lands (habitat) as a proxy for changes in biodiversity benefits (see (Knowler et al. 2003; Walsh, Loomis, and Gillman 1984)). The latter two options are not feasible for this study because they risk double counting with other fish production services or they are unrelated to changes in flow regime. The first option is likely most feasible.

Section 2.1.6 provides a list of fish that are threatened or endangered under the US Endangered Species Act and reports BPA's Fish & Wildlife Conservation costs (US$13.75 billion (2013 US$)), which represent the bulk of expenditures on ESA-listed species in the Columbia River. Protection of salmon's biodiversity value in the Columbia River can be considered in terms of hydropower benefits that are foregone as a result of these efforts. Foregone hydropower benefits can be calculated from BPA's costs. Cumulative foregone hydropower benefits are US$3.02 billion from 1978–2013 for an annual average of around US$86 million (NPCC 2014). Alternatively, 2013 foregone benefits were estimated at US$135.5 million (NPCC 2014). If we consider these foregone benefits to be US$0 under pre-development conditions, we can assume a linear curve through the two data points. Note that this would be a very rough assumption and would also imply that the value of foregone hydropower benefits for endangered species conservation adequately reflects the welfare provided by those species. Relying on our development scenarios would also suggest that changes in hydropower/flood control priorities are sufficient to restore these species and reduce the cost of foregone hydropower benefits.

Research Opportunities

Change in benefits from research opportunities depend on the availability of fish to study as well as funding. Since species at highest risk tend to attract the most funding, research opportunities may well increase with development to address the increased threat to species. Therefore, benefits from this ecosystem service could, perversely, continue to rise up to the point at which all fish species are extinct. Section 2.1.8 indicates a value to society of US$12 000 per published research article and a total current value of US$10.8 million (2000 US$). If we assume research benefits close to US$0 under natural conditions, and a sudden drop to US$0 again beyond a certain threshold of hydropower/flood control development to represent extinction, we could develop an exponential curve using existing data that roughly represents changes in research benefits under our three development scenarios.

Water Quality & Natural Flood Control (Wetlands)

Changes in water quality benefits from wetlands in the Columbia River basin are primarily driven by land use changes and river development that increase or decrease the area of available wetlands. This service is difficult to evaluate for our development scenarios because there are no available data linking hydropower and flood control development to changes in the areal extent of wetlands along the Columbia River. As such, evaluating this ecosystem service would entail GIS modeling of inundation under pre-development conditions and assumptions about what elevation of water constitutes "wetland".

Non-fishing Recreation Opportunities

The value of this ecosystem service can change based on available surface water or based on flow conditions, which in turn impact the number of visitor days. Opportunities for recreation decrease if available surface area decreases and recreational uses can shift to higher or lesser value uses depending on flow conditions. Flows that are closer to natural conditions are considered to attract higher value recreational uses (McKean, Johnson, and Taylor 2012). Relying on consumer surplus figures provided in Section 2.1.11, we recommend using the range of US$46 per-trip for current conditions and US$401 per-trip for natural conditions (i.e. the dam breaching scenario reported by McKean et al). Visitor days by county can be compiled from the 1995 System Operating Review and we can run sensitivity analysis across a range of changes in visitor days to account for the older data.

Other Services

Hydropower Production

Since there is no more capacity for additional dams in the Columbia River system, the main way the value of this ecosystem service might change is if dams are operated to accommodate different priorities or if dams are removed. Dam removal has been explored on the Snake River but is an unlikely outcome along the mainstem in the near future. Throughout this section I refer to operational changes at dams as shifts towards more or less "regulated" management regimes. "Pre-regulation" and "post-regulation" refer to the periods before and after the onset of major river development for hydropower in the basin (approx. pre- and post- 1888).

Rough estimates of annual hydropower sales revenue can be achieved by multiplying monthly average electricity prices by net power generation, then by summing the monthly totals. Changes in this value can be calculated by estimating predicted changes in power sales under different development scenarios. In Figure 22 we used observed data to develop a logarithmic growth curve predicting changes in net generation from natural conditions (0 kcfs difference) to increasingly developed conditions (1000 kcfs difference or 28.3 m^3/s).

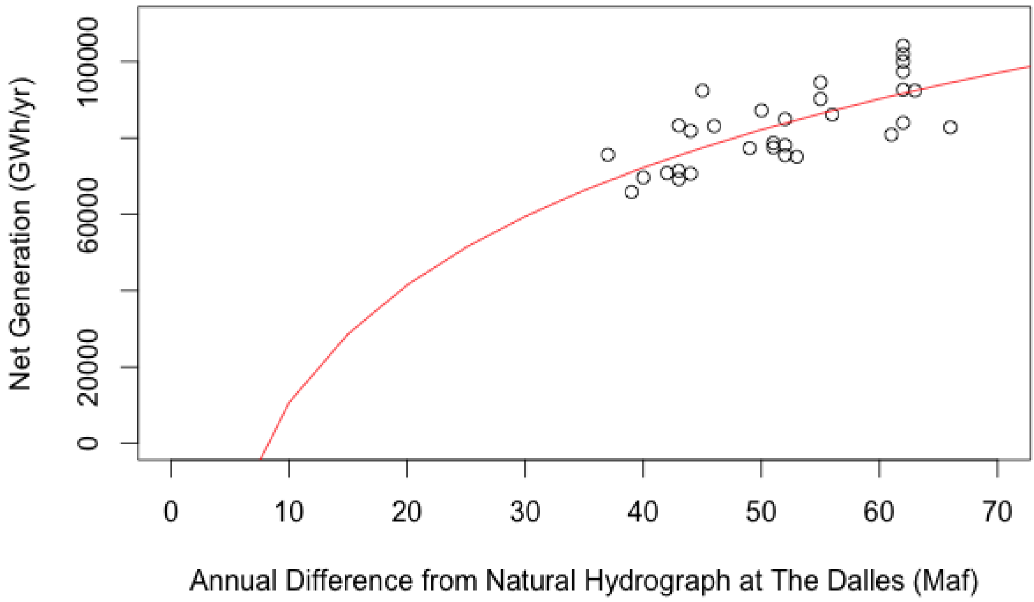


Figure 22. Change in Columbia River net power generation with hydropower/flood control development

For the figure above, we compiled net generation over 31 years (1970–2000) using USACE data for federal dams and USEIA data for private utilities (USEIA 2015c; USACE 2015a). These data represent total net power generation along the US portion of the Columbia River mainstem. To obtain annual differences from the natural hydrograph at The Dalles, we summed the absolute value of the daily difference in average flow volume between observed discharge and modelled unregulated flows from BPA's 2010 Level Modified Streamflow assessment (BPA 2011).

If this method is used, we may want to structure our hydropower pricing to address both high and low demand hours (e.g. 16hrs of the day are high demand, 8hrs of the day are low demand, each with different average prices).

Note that Huppert et al (2004) use a similar approach in their assessment of the impact of increased irrigation diversions on hydropower benefits, but slightly simpler. The authors first determined a "power factor", or the power produced per unit of flow, and then multiplied this factor by the change in flow under different scenarios. The model we present above is an improvement to this approach.

An alternative to calculating changes in direct sales revenue is to apply a substitute cost method with levelized cost adjustments. Reductions in MWh of power sales under the Conservation Priority scenario could be valued in terms of the cost of the most likely replacement facility, which would be a Simple Cycle Combustion Turbine (SCCT) plant. Capital, fixed, and variable costs as well as transmission investments are available for SCCTs in dollars per MWh from USEIA ("Energy Outlook 2014" – new release was scheduled for March 2015). Note that renewable energy is also a possible substitute, so if we consider this approach we may want to look at a combination of renewable and thermal generation. The same method could be used to evaluate the value of firm energy.

GHG Emissions Reduction

Changes in GHG emissions reduction benefits will occur if hydropower production is reduced or increased. Benefits from current conditions can be estimated by multiplying the emissions factor calculated in Section 2.2.2 by MWh of annual power sales. As for hydropower, the value of this benefit would be zero under unregulated conditions and would follow the same curve as that shown in Figure 22.

Agricultural Water Supply

The main way that the value of this ecosystem service can change is if utilized agricultural area is reduced due to changes in available irrigation water. Available irrigation water can be affected by regulation of flows for hydropower and flood control. Generally, a higher hydropower and flood control priority would correspond with less irrigation water available during the summer growing season.

Based on the low flow event in 2001 (see Section 2.2.3), it is reasonable to assume that the likelihood of water rights interruptions is higher the more flows are regulated (for hydropower) and that the cost of "un-regulating" flows to maintain a minimum water supply for agriculture is at least US$12 987 per day during such events. One way to assess marginal changes in value from irrigation is to estimate the frequency and cost of interruptions during low flow events under more regulated versus less regulated (for hydropower) conditions. This method would require identifying the number of days under "natural" flow conditions that fall below the interruption threshold (specified based on flows at The Dalles), then comparing these to our three development scenarios. The additional cost to agricultural producers from interruptions could also be estimated using the estimated volume of flow curtailment that would occur according to the Washington Administrative Code regulations (WAC Ch. 173-563-050). These volumes could be multiplied by average agricultural water trade prices from the Bren School's Water Transfers Database (see
Table 18). However, this is only a rough method that does not account for potential industry shifts in production resulting from perceived higher or lower interruption risk.

Another very simple approach is to use BPA's modified streamflow models to obtain an estimate of irrigation diversion volumes under our three different development scenarios. BPA's models estimate unregulated flows at each dam along the Columbia River mainstem based on historic inflows then modify these flows to account for irrigation diversions. The difference between the two datasets provides an estimate of daily diversion volumes for each historic flow year in the dataset. Figure 23 shows irrigation diversions estimated using this approach for our three development scenarios. Note that these are only for cumulative upstream diversions at The Dalles. A better representation of all diversions would occur at Bonneville Dam (the most downstream dam on the mainstem). Annual diversion volumes can then be multiplied by average agricultural water trade prices from Bren School's Water Transfers Database (see

Table 18).

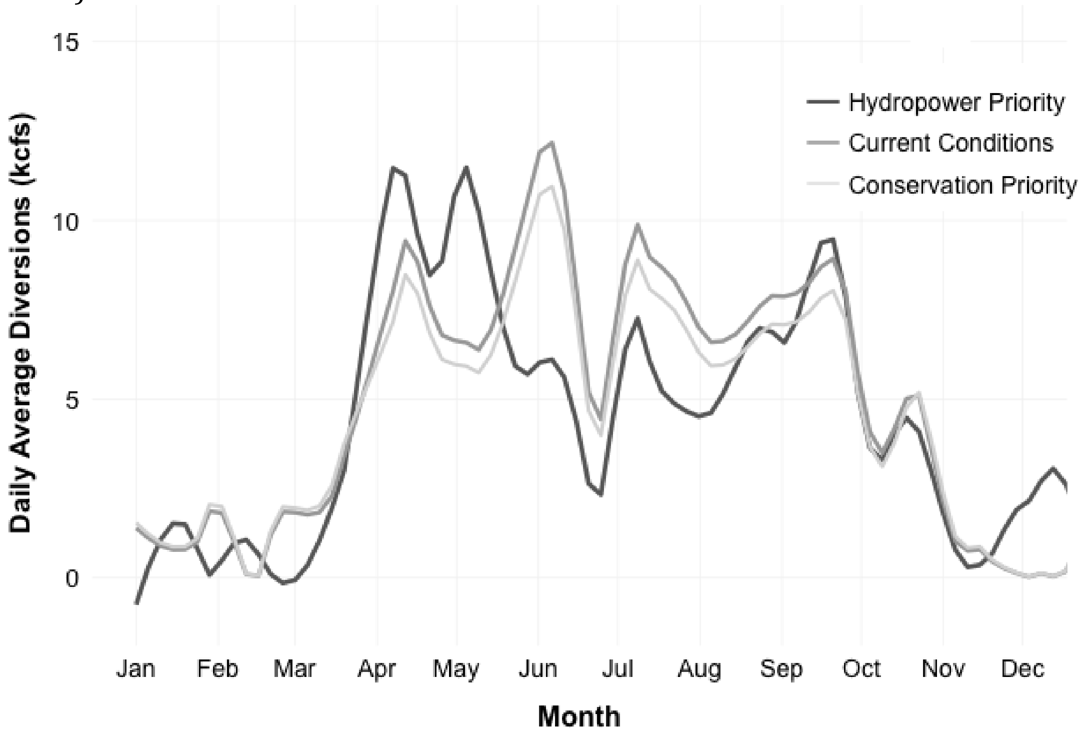


Figure 23. Diversions for agricultural, municipal and industrial use under different development scenarios

Curves are the difference between modelled unregulated flows and the same flows modified to reflect diversions from the Columbia River according to year-2010 level diversions. Hydropower Priority scenario is based on 1976-1980 average discharge, Current Conditions scenario is 2000-2007, and Conservation Priority is a 10 percent increase from current conditions in flow regulation for salmon conservation. Source: (BPA 2014; USGS 2014).

Huppert et al. (2004) present an alternative method for valuing changes in crop value based on different management scenarios that involve a range of increases in Columbia River water diversion rights. This method is more suited to estimating welfare since it accounts for the cost of production.

The method works by: **1)** determining the total water diversion rights for each county that borders the Columbia River and assuming these rights are fully utilized each year, **2)** determining irrigated crop area per county, **3)** isolating the appropriate crop mix that relies on Columbia River water, **4)** calculating actual "applied water" per square kilometre per county by adjusting diversion rights volumes for conveyance efficiency, irrigation efficiency and crop consumptive use (measures available in report), **5)** determining hypothetical increases or decreases in water diversion rights and resulting change in availability of applied water, **6)** calculating the change in area irrigated based on applied water availability (simple %-change), **7)** multiplying the new area by the crop mix proportions to get change in area per crop type, **8)** multiplying the areas by per square kilometre crop revenues and subtracting variable and fixed costs of production for each crop type (via enterprise budgets, which are economic budgets that incorporate opportunity costs, unlike accounting budgets).

Note that this is not an optimization model and so does not account for feedbacks between supply and demand. We could adapt Huppert et al's approach using BPA's modified streamflows instead of water diversion rights –this would provide a more accurate evaluation since not all water diversion rights are used each year.

Shipping and Transport

Changes in the value of this provisioning service can occur if transport becomes less efficient, infrastructure is damaged, or if safety is compromised (US Entity 2013). In the context of hydropower regulation, this change is not straightforward to detect since more or less regulated flows each have anecdotal consequences for shipping and transport, but these consequences are not observable in the available time series data. We recommend excluding shipping and transport from the analysis.

However, if we do incorporate this ecosystem service, losses in navigation are typically evaluated in terms of the added cost from the least expensive alternative transportation option (USBOR 2003). Since most freight moved through the Columbia River system is outbound shipping, it would be possible to focus on transport by rail to a coastal port as the next best alternative to the status quo (see Table 17). Note that in addition to the new cost per ton-mile, any alternate scenario would need to consider capital expenditures to establish the appropriate infrastructure.

Also note that commodity flow disruptions originating from reduced navigation capacity on the Columbia River system would have economic impacts along the full transportation and commodity production network. This extends across 39 states. Few studies model such disruptions for inland waterways in the USA but one recent example presents a dynamic multi-regional, multi-industry impact model for a network of inland ports on the Mississippi system (based on an input-output model) (Pant, Barker, and Landers 2014). However, the data inputs to this model are complex and would be difficult to acquire within the given timeframe.

Huppert et al. (2004) take a conceptually simpler approach by focusing only on low flow effects to navigation on the Columbia River mainstem (this would correspond to the more regulated for hydropower scenario). The authors estimate the impact of irrigation diversions on navigation downstream by calculating the percentage-change in flows. Results indicate only very modest changes in flow and consequently no economic effect of irrigation diversions was estimated.

4.4: Case study 2: Mekong River Basin

Case study 2 is an assessment of the value of ecosystem services in a set of fisheries production systems and main water management practices in the lower Mekong basin.

EXECUTIVE SUMMARY

The Mekong River is a trans-boundary river that flows through 6 countries including China, Myanmar, Lao PDR, Thailand, Cambodia and Viet Nam. The Mekong River is ranked the world's 12th longest river (4,350 km) and has the world's 8th largest average annual discharge (457 km^3/year). It can be divided into two basins (the Upper Mekong Basin (UMB) and the Lower Mekong Basin). The Lower Mekong Basin encompasses Myanmar, Lao PDR, Thailand, Cambodia and Viet Nam (76 percent of basin area). A variety of natural resources support local people in terms of food sources, shelters and medicine. The LMB is among the biologically most diverse places on Earth, second to the Amazon. There are 60 million people living in the LMB. Their livelihoods rely on goods and services provided by the LMB ecosystem.

This report gives an overview on the value of ecosystem services in the Lower Mekong River basin in the current situation (Business as usual: BAU) and assesses the impacts of planned hydropower development projects on ecosystem service values based on the review of published literature. The services provided by ecosystems are categorized into four categories (MA 2005):

1. Provisioning services: The products obtained from ecosystems such as food, water, timber, genetic resources.
2. Regulating services: The benefits obtained from the regulation of ecosystem process such as regulation of climate, floods, water quality.
3. Cultural services: The nonmaterial benefits people obtain from ecosystems such as spiritual fulfillment, aesthetic enjoyment and recreation.
4. Supporting services: The services that are necessary for the production of all other ecosystem services such as soil formation, nutrient cycling and pollination.

Within these four categories this report considers six ecosystem services including; food production (in terms of fishery production); water quality; biodiversity; carbon sequestration; nutrient cycling; and income and livelihood support.

In term of inland fishery, the estimated fish production in the Mekong basin is 2.1 million tonnes per year. While the Mekong delta marine fishery is poorly understood, it produces more than 0.5 million tonnes of fish per year. Based on the literature, the values of fisheries provided by wetland, forest, coastal ecosystems range from 24 – 658 US$/ha/year. The values of water quality regulation are higher, ranging from 718 – 1 436 US$/ha/year. For biodiversity, the economic benefits that people gain from local use of non-forest timber products and wetland products are approximately 26 and 198 US$/ha/year, respectively. The estimated carbon storage values range from 100-2 085 US$/ha/year. The LMB also exports 26 400 tonnes/year of nutrients that sustain the Mekong floodplains and delta. At the price of fertilizer about US$400 per ton, the estimated value of nutrient cycling is about 10 560 000 US$/year.

In this study, future scenarios were used to estimate the potential changes of ecosystem's goods and services that are likely to be affected by development projects within the LMB. Particularly interest was paid to the hydropower development policy that most countries along the Mekong River have proposed and which includes construction of a number of hydropower dams in the main stream and tributaries of the

Mekong River by 2030. Based on the literature, agricultural production would be reduced due to changes in land use and water flow patterns. A minimum of 9 000 hectares of suitable agricultural land would be inundated. The value lost due to losses of agricultural land and river bank gardens would be around US$ 5.4million/year and US$ 20.7 million/year, respectively. The expected losses of inland fishery production would also be substantial. The value lost in inland fisheries production directly due to the construction of LMB mainstream dams would reach US$476 million/year. Water quality conditions in the Mekong River are likely to be poorer during construction and operational phases of the dams. The constructed barriers and resulting reduction of sediment loading could have adverse and cumulative effects on nutrient cycling and biodiversity, especially of fish. In 2030, under the LMB mainstream dam development scenario, it is estimated that sediment load will be reduced by 75 percent or approximately 6 600 tonnes/year. The effects of this are likely to be significant as large areas of land and suitable habitats for plants and animals will also be lost due to the proposed tributary projects.

Although there is no scientific data regarding carbon fixation specific to the LMB, several studies show that reduction in sediment load will lead to a decrease in associated nutrient replenishment for phytoplankton, thus reducing potential of carbon fixation. Hydropower projects and reservoirs are also considered as a source of greenhouse gasses from the decomposing of plants in reservoirs, which can contribute to global warming. Due to losses of agricultural land, biodiversity and other services, hydropower projects are likely to affect the Mekong riverine communities in term of quality of life, income and health. For example, loss of river bank gardens in the reservoir areas would affect 450 000 households, with significant impacts through the loss of an important rural food source. Impacts on transport could also be negative if dams make trips along the Mekong more difficult, due to the hindrance of dam walls or due to unpredictable water flows. Health issues such as transmission of schistosomiasis related to hydropower dams in LMB are also likely to increase significantly.

Effective management of the transboundary Mekong River should include integration of science and technology, society and policy. International cooperation among countries as well as expanding civil society engagement in the development of LMB can play a key role for maintaining a healthy and sustainable LMB. However, there are still research gaps and limited information on a range of ecosystem services in the LMB (nutrient cycling, carbon fixation, GHG emissions). It is therefore recommended that more extensive research be carried out to help bridge the knowledge gap and fill in missing data. Lastly, if development projects such as hydropower dams cannot be avoided, environmental impact assessment (EIA) and strategic environmental assessment (SEA) are required together with innovative technology and good governance approaches to alt the deterioration of natural resources and ecosystem services and avoid conflicts among stakeholders.

Project description

FAO and **UNEP** have agreed to develop a holistic assessment of different production and management scenarios in the inland fisheries/aquaculture sector, taking into account the (hidden) impacts, and externalities and dependencies between agricultural/ economic, environment and social systems. Applying the ecosystem services (provisioning, regulating, habitat and cultural) concept is a way of providing guidance to water management and make informed trade-offs and decisions of all the ecosystem services and their associated benefits and values for these systems. To make these trade-offs it will be important to examine the full range of ecosystem services, including the non-provisioning services such as cultural, recreational, regulating and supporting services and to consider trade-offs.

Overall the project will aim at measure both the capacity of an ecosystem to provide a service (e.g., cultural value of a wetland, how much fish can a lake provide on a sustainable basis, how much water could sustainably be diverted for irrigated agriculture), and also measure the actual use of that service (e.g. fish harvesting for food and how much water is actually diverted for irrigated agriculture)

The contribution of this report, with the focus on the lower Mekong basin, is:

To increase and improve provision of goods and services from inland fisheries and aquaculture in a sustainable manner *through the development of a holistic assessment of different production and management scenarios in the inland fisheries/aquaculture sector, taking into account the (hidden) impacts and externalities and dependencies between agricultural/economic, environment and social systems.*

1. Ecosystem services in the lower Mekong basin

1.1 Overview of the river systems

Originating in the Tibetan plateau, the Mekong River is a transboundary river that flows through 6 countries including China8, Myanmar9, Lao PDR10, Thailand11, Cambodia12 and Viet Nam13. The River is ranked the world's 12th longest river (4 350 km) and has the world's 8th largest average annual discharge (457 km^3/year). The total drainage area of the Mekong River is approximately 795 000 km2, which can be divided into two basins: the Upper Mekong Basin (UMB) and the Lower Mekong Basin (LMB). The Upper Mekong River Basin covers an area in Tibet and China (24 percent) whereas the Lower Mekong River Basin encompasses Myanmar, Laos PDR, Thailand, Cambodia and Viet Nam (76 percent) (**Table 1**). The estimated population living in the Lower Mekong Basin is 60 million people.

Table 1 Country share of Mekong Basin territory and water flows
(Source : Mekong River Commission)

	China	Myanmar	Lao PDR	Thailand	Cambodia	Viet Nam	Total
River basin area **(km^2)**	165 000	24 000	202 000	184 000	155 000	65 000	795 000
Catchment as percent of MRB	21	3	25	23	20	8	100
Flow as percent of MRB	16	2	35	18	18	11	100

1.1.1 Water resources

The water resources can be characterized as (Kamoto and Juntopas. 2011, quoted in MRC 2003):

- ***Abundant:*** Annual runoff averages around 475 km^3/year. Per capita resources currently is at 8 500 m^3/person/year — compared with 2 200 m^3/person/year for the Nile River; 1 400 m^3/person/year for the Rhine River; 2 265 m^3/person/year for the Yangtze River and 1 700–4 000 m^3/person/year for the Ganges River.

- ***A low level of exploitation for extractive uses:*** Average annual withdrawals are estimated at 12 percent of total annual flows (or 60 km^3), current volume regulated or stored for hydropower and irrigation is under 5 percent of annual flow (20 km^3); volume of water stored in the Lower Mekong Basin is estimated at 230 m^3 per person, which is about nine times less than that of China.

- ***Highly dependent on on-stream and in-stream uses (particularly by the poor):*** The Mekong fishery is the largest inland fishery in the world, worth at least US$ 2 000 million annually (see 1.2.2). These fisheries resources make up a major source of protein and nutrients for the basin's rural poor, estimated at nearly 40 million people (MRC 2010). Inland navigation is also an important mode of transport for many areas where road access is limited.

[8] the People's Republic of China
[9] the Republic of the Union of Myanmar
[10] Lao People's Democratic Republic
[11] the Kingdom of Thailand
[12] the Kingdom of Cambodia
[13] the Socialist Republic of Viet Nam

- ***Extremely seasonal*:** In most parts of the basin, flows in the driest three months are less than 10 percent of total annual flows, while flows in the wettest three months make up over 50 percent of total annual flows. Flows are also uneven between riparian countries (Table 1). The contribution from the upstream countries is higher in the dry season, when snow melt contributes a significant component of flow

- ***With a flood pulse of great importance for the ecology of the floodplain and the Mekong fishery*:** During the wet season, 1 to 4 million hectares of floodplain is submerged, including the Tonle Sap Great Lake.

- ***Dry season water shortages*:** Dry season shortages occur as a result of the rainfall seasonality, concentration of extractions in the driest period and drought events during the onset of the wet season.

- ***Generally good water quality*:** Water quality in the mainstream is generally good, and is rarely a constraint to water use. The exception is saline intrusion, acid sulfate drainage and pollution in intensively used areas of the Mekong Delta.

- ***Groundwater*:** Groundwater resources are very widely used as a source for domestic and industrial supply. Use for irrigation is limited, but expanding. Groundwater systems in the flood plain are closely coupled to the river.

1.1.2 Water management

Water retention and management for rice production

The most important crop in terms of production in the Lower Mekong River is rice. There are different rice cultivation practices used and rain-fed rice cropping occupies the largest area (**Table 2**) because of high amount of rainfall during the rainy season together with extensive flooding areas and water logging of riparian and floodplain soils (Mekong River Commission 2009).

Table 2 Rice cultivation types in Lao PDR and Cambodia
(Source: Mekong River Commission 2010)

Type	Cambodia (%)	Lao PDR (%)
Irrigated rice	11	12
Rain fed lowland rice	84	67
Deep water rice	3	0

The climate of the Lower Basin is dominated by the southwest monsoon as well as tropical storms and cyclones coming from the eastern parts of the basin. The hydrological regimes of the Mekong River and its tributaries result in high water discharge up to 40 000 cubic metre per second in the rainy season, and low water discharge in the dry season (**Figure 1**). The rainy and hence cultivation season starts from mid-June and lasts until early November. August and September are usually the months with the highest rainfall during the year. The dry season occurs from January until May when water shortages become acute especially in the north-eastern parts of Thailand and Lao PDR. As a result, farmers use irrigation water from constructed ponds and/or reservoirs for their rice fields during this time of limited water availability. Therefore the area of rice cultivation during the dry season is much smaller than during the wet season, with the exception of the Delta in Viet Nam where farmers can cultivate rice up to seven crops every two years (Mekong River Commission 2009).

Viet Nam is the country that produces and exports the most rice from the Mekong Delta worldwide. The FAO estimates that 97 percent of the 7.4 million ha of land sown with rice in Viet Nam is irrigated. In 2010, total rice production in Viet Nam was 40 million tonnes with an average yield of 5.34 ton/ha. Farmers in Viet Nam, especially in the Mekong Delta cultivate 3 crops of rice each year, divided into winter, spring, and autumn seasonal periods with the spring crop being the largest followed by the autumn and the winter crop. In 2015, the FAO predicts that Viet Nam is expected to export about 6.9 million tonnes rice which is an increase of about 7 percent from last year (worth US$2 800 million). In term of values of rice production, the price of rice is around US$413 per tonne (Oryza, 2015). For Thailand, rice cultivation covers around 12.64 million ha and it is estimated that out of these about 2.2 million ha (22 percent) is irrigated. About half of the rice lands (~ 6 million ha) are located in the northeastern region (part of The Lower Mekong Basin), but only 12 percent of the area is irrigated. Rice yield is higher in irrigated areas, around 3.3 tonnes/ha compare to 2.2 tonnes/ha in rainfed areas (Office of Agricultural Economics, 2014; Royal Irrigation Department, 2010).

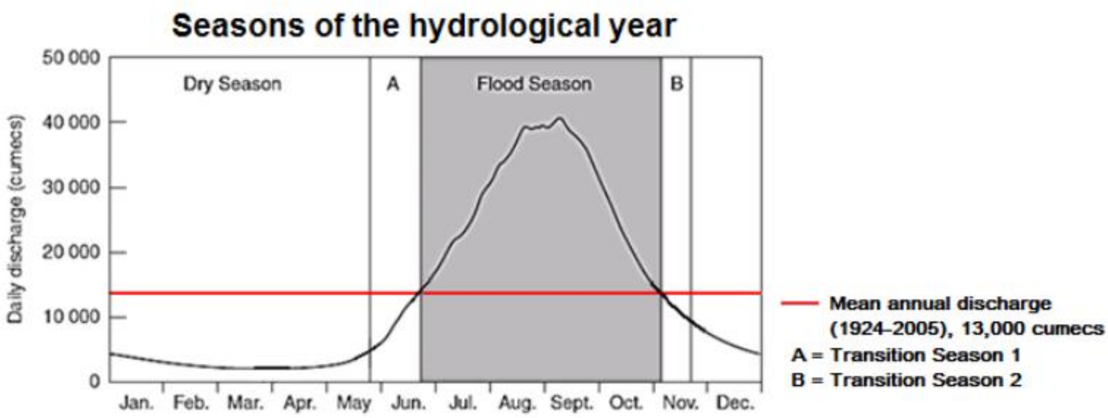


Figure 1 Seasonal variation of water discharge in the Mekong River Basin (Source: Freden 2011).

The rice yields in the Mekong River Basin vary between countries. Yields of rice in Lao PDR and the central highlands of Viet Nam were about 3 tonnes/ha, which are much higher than rice yields in Cambodia and Thailand that are only 1.5–2 tonnes/ha (Fisher and Cook 2012). The lower rice production in Cambodia and Thailand could be the results of infertile soil, late rainfall and long dry periods.

The overall water resource availability and withdrawal in the Mekong Basin for various purposes is showed in Table 3. Availability of water resources varies widely by country. Water availability in Lao PDR, Cambodia and Thailand depends almost entirely on the Mekong (Ringler 2001). Only Myanmar is relatively independent of Mekong waters. Changes in water availability and withdrawal due to development projects such as constructing of cascading dams will inevitably and adversely affect rice production of the region.

Table 3 Water availability and withdrawal in the Mekong Basin (Source Ringler 2001)

Country	Availability (km3/yr)		Withdrawal		Withdrawal share of availability
	(km3/yr)	(m3/cap/yr)	(km3/yr)	(m3/cap/yr)	(%)
Cambodia	88	8 585	1	98	1
China	2 812	2 292	500	407	18
Lao PDR	270	55 305	1	205	<1
Myanmar	606	13 024	4	86	<1
Thailand	210	2 559	33	559	16
Viet Nam	318	4 479	65	915	20

Water management for irrigation and hydropower generation

The potential of hydropower in the Mekong River Basin is about 53 000 MW consisting of 23 000 MW in the Upper Mekong Basin (China) and 30 000 MW in Lower Mekong Basin (Lao PDR, Thailand, Cambodia and Viet Nam) (Mekong River Commission, 2010). A total of 8 dams are included in the Chinese hydropower plans of which three are already operational and are situated on the main stream in the upper part of the Lanchang Jiang basin (Freden 2011) (Figure 2).

In the Lower Mekong Basin, many smaller hydropower and irrigation dams have been completed on the Mekong tributaries in Lao PDR and Viet Nam (Freden 2011). Large-scale hydropower expansion is also planned in the tributary basins of the 3Ss (Sekong, Sesan, and Sre Pok) that cover parts of Lao PDR, Cambodia and Viet Nam (Xue et al. 2011).

Figure 2 Locations of existing, under construction and planned dams across the Mekong River Basin. Source: Freden (2011)

Water management for irrigation

Irrigated agriculture, especially rice cropping, is important in the Lower Mekong Basin. The total area equipped for irrigation in the Mekong River Basin is estimated to be around 4.3 million ha, of which Viet Nam accounts for 42 percent, Thailand 30 percent, China 12 percent, Cambodia 8 percent, Lao People´s Democratic Republic 7 percent and Myanmar 2 percent (Freden 2011). The area irrigated by surface water accounts for 98 percent while groundwater accounts for 2 percent. Most of the intensive agricultural farming occurs in northeast Thailand and the Viet Nam delta (Mekong River Commission 2009). Currently irrigation development is increasing because of rapid expansion of agricultural areas.

1.2. Ecosystem values in the lower Mekong basin

1.2.1 Overview of fish production system dominating the LMB landscape

The following fisheries and aquaculture production systems are widely practiced the lower Mekong basin:

I. Rice fields with fish production
II. Cage aquaculture in reservoirs
III. Culture-based fisheries

However, it is recognized that pond culture is also widespread and that riverine fisheries are also important.

Rice fields with fish production

This includes artisanal fisheries and floodplain rice-field fisheries and is practiced in all of the four lower Mekong basin countries.

Viet Nam

The combination of rice and fish cultivation is encouraged by the state and local governments, as it increases the income and reduces the economic risk of rice monoculture system and price fluctuations. Moreover, it is considered as ecologically desirable as it utilizes the existing farm ecology in a more efficient way. Rice-fish cultivation in the floodplains is mainly located in Co Do District (3 024 ha). About 85 percent of the total area is rice paddy fields. The farmland size range from 0.7–6.0 ha and the rice can be cultivated as either two (spring and summer) or three crops (winter, spring and summer).

When three crops are cultivated, common carp fingerlings (150–200 fish/kg) are released at a density of 4 kg of fish per ha of paddy rice into the channel after harvest of the winter rice. After the field is filled with water and the preparation of spring rice is completed, the fingerlings will enter the paddy field and feed on existing foods (i.e. no additional feeds). Before the winter rice preparation, 150 kg of common carp (5–6 fish/kg) can be harvested including an additional 20 kg of climbing fish, snakehead and silver carb that are naturally introduced from existing fish populations in the canal water.

In the floodplain area, 50–96 percent of households' income is dependent on rice cultivation and sale and fish is the second most important source of income. Depending on availability and season, the prices of fish are: common carp (9 000–13 000 VND/kg), snakehead (12 000–18 000 VND/kg), silver barb (6 000–8 000 VND/kg) and silver carp (3 000–6 000 VND/kg). Rearing multiple fish is advantageous, as they occupy different niches, which allows a more effective utilization of the small farms and motivates farmers to sustain the biodiversity of the farms (Ikeguchi et al 2008).

Thailand

In Thailand, rice–fish culture has been widely credited with improving the income status, household nutrition, public health and general social well-being of communities. The rice–fish system provides an example of the symbiotic relationships that can exist in wetlands between different provisioning services / livelihoods and can be beneficial for other ecosystem services. The main provisioning service is rice, with a variety of by-products especially fish. It has been observed that the rice-fish system provides a vital habitat to more than 50 Mekong fish species (some World Conservation Union [IUCN] Red List species) for feeding and completing their life cycles. An additional ecosystem service of rice–fish culture systems is that the fish may help reduce the relative abundance of populations of disease vectors such as mosquitoes and certain species of snails. This also encourages farmers to adopt IPM practices (reducing the use of chemical pesticides in the process) with direct benefits to environment and public health.

Lao PDR

In Lao PDR, fish are both cultured and captured as a by-product of rice cultivation, along with a wide variety of other aquatic organisms that contribute to local diets (FAO, 2003). More than 20 species of fish have been found in rice field systems. Apart from fish, there are other aquatic organisms (OAA) that are commonly harvested from rice fields for sale and local consumption, such as: crabs, shrimp, bivalve mollusks, frogs and tadpoles, insects, water snakes, turtles and edible aquatic plants. Rice fields continue to yield valuable food items that are important in local people’s diets long into the dry season after the rice harvest has been completed, hence increasing food security. Some aquatic species, such as crabs and insects, burrow into soil and are dug out by villagers in the dry season (David J.H. Blake, NA).

Cambodia

In Cambodia, rice fields occupy about 23 000 km^2, and include rainfed wet-season lowland rice (83 percent of the area), dryseason irrigated rice (11 percent of the area), and small areas of rainfed upland rice and deepwater floating rice (McKenney and Prom, 2003 quoted in Horte et al., 2004). Rice field fisheries are a major source of fish for people in many provinces in Cambodia and the contribution to the protein requirement for rural households is significant, 65-75 percent. Fish and many OAAs (including crabs, shrimps, clams, snails and insects) harvested from rice fields make a major contribution to people's nutrition, with a typical estimated yield of 50–100 kg/ha/year of animal protein worth up to about 40 percent of the value of the rice produced (Guttman, 1999 quoted in Horte et al., 2004). Systems for rice-fish culture have been developed and rainfed lowland and irrigated rice ecosystems offer potential for further improvements in yield (Gregory, 1997 quoted in Horte et al., 2004). More than 700 families have adopted the practices which yielded at 20–30 tons of fish per season (Guttman, 1999). The total fish production from rice- field fisheries are between 75 000 and 120 000 tonnes per year (Table 4), in addition to (unquantified) quantities of OAA harvested in these systems.

Cage aquaculture in reservoirs

Viet Nam

In Viet Nam, the major cultured species in freshwater cages is catfishes (*Pangasius bocouri, P. hypophthalmus and P. mioronemus*). It is estimated that *Pangasius* has become a significant source of export earnings as a result, worth almost US$1 billion in 2007, and reportedly supports the livelihoods (directly and indirectly) of 105 535 individuals and provides an additional 116 000 jobs in the processing sector (Belton et al., 2011). The production of *Pangasius* has sharply increased during 1997–2008 (**Figure 3**).

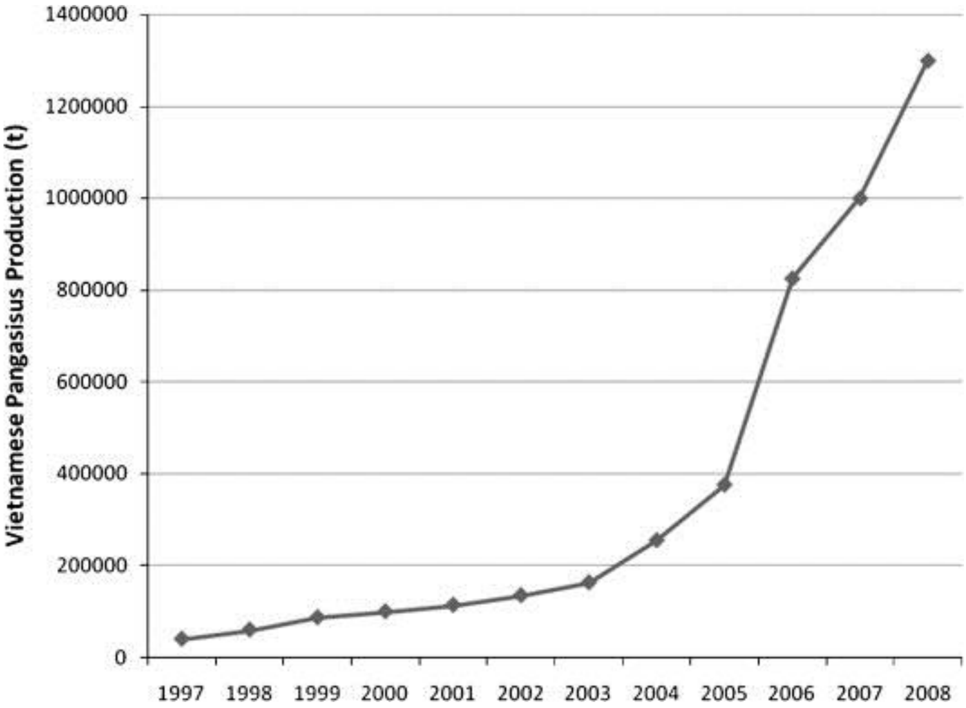


Figure 3 Production of *Pangasius* during 1997-2008. Source : Belton et al. 2011.

Thailand

In Thailand, fish farmers in the Mekong Basin cultivate their fish in earthen ponds and in cages. For cage culture, the most popular fishes are male Nile tilapia and red tilapia. Eight cm sized fingerlings are usually used for stocking and they grow to 300–500 g (marketable size) in three to four months, making two crops a year possible. Cage culture has been actively promoted by pellet-feed manufacturers, who provide technical assistance and supply fish seed and feed. The promoters also promise to buy the farmer's produce (Oopatham Pawaputanon Na Mahasarakarm, 2007). Clarias catfish, mostly grown in ponds, is among many other species being farmed in Thailand. In fact, the production of walking catfish is second only to tilapias among fresh-water fish species. Grow-out ponds for walking catfish are typically small, from 400 m^2 to 1 ha, with greatly varying productivity. A typical farm stocking 32, 10-g fish/m^2 and feeding chicken processing wastes can grow fish to 200–500 g in three or four months. Yields range 50–60 tonnes/ha/crop, with three to four annual crops common (Yuan et al, 2006).

Lao PDR

In Lao PDR, fish cage aquaculture is spreading throughout the country, with an estimated number of nearly 2 000 cages in 7 provinces. Several fish species are reported to be cultured in cages including *Pangasius larnaudii*, *Channa striata*, *Pangasius sutchi* and tilapia and several carp species: silver barb, common carp, big head carp and silver carp. There are three major cage farming systems: mono-sex tilapia; bighead and silver carp system (without feed) and snakehead cage culture. Tilapia is the most common fish cultured in cages, and the number of cages is increasing. The culture of fish in cages is seen as a means of diversifying production and generating income. With the additional benefit of having lower cost compared to constructing a pond, and it is also easier to harvest and feed the stocked fish. However, it is recognized that cage culture relies on feed supply and that this supplementary feed is relatively expensive. Cage culture is also sensitive to environmental changes, especially water pollution (LARReC and NACA, 2001).

Cambodia

In Cambodia, the fish production of inland aquaculture increased from 1 610 tonnes in 1984 to 20 760 tonnes in 2004. As much as 60-90 percent of the inland aquaculture production comes from cage cultures and depends on both seed and feed made of wild fish. The most commonly cultured species are river catfishes and snakeheads . A more recent culture system that has increased rapidly is pond culture and the most popular species being cultivated in ponds are e.g. Trey pra (*Pangasianodon hypophthalmus*) and Trey andaing (hybrid between *Clarias batrachus* and *Clarias gariepinis*) (Nam et al. 2005 quoted in Camber, NA).

Culture-based fisheries: practiced in both in reservoir and floodplains

Viet Nam

In Viet Nam, most reservoirs were impounded after 1954 for different purposes such as irrigation, hydro-electricity, flood control and water supply for domestic consumption and industry. There are about 4 000 community reservoirs (Hoi 1999) of which 460 are medium or large in size, with a water volume of more than a million m^3. Fisheries resources in any reservoir are dependent on geographical location, level of exploitation and protection. The size and population structure of the fish species, including stocked species, have decreased in most reservoirs. There is great variability in yield from reservoirs: the lowest yield (11.1 kg/ha) is found in the large-size reservoir; middle yield (Nui Coc, Cam Son, Suoi Hai and Dong Mo 34.8–48.1 kg/ha) is from the medium-size reservoirs (about 2 000 ha and 1 000 ha) and the highest yield (83.0 kg/ha) is from small-size reservoirs (Sy Van, N. and Thanh Luu, 2000).

Thailand

In Thailand, freshwater bodies, including rivers, canals, swamps and reservoirs, make up an aggregated inland water area of 566 400 ha (Office of Agriculture and Economics, 1992). For irrigation purposes, the Royal Irrigation Department has classified these water bodies into 25 river basins; these have a combined annual water flow of 213 423 million m^3 and extend over a total area of 51 136 100 ha. Fisheries are an important factor in the economy of the Thai Mekong Basin, the annual inland fish production of 795 000 tonnes is worth around 23 850 million baht (approximately US$700 million) (Oopatham, 2007). Thirty seven percent of the land area (18 793 200 ha) lies within the lower Mekong basin and here inland fisheries resources are vital as a source of protein and nutrients for the population. On average, the drainage from this part of basin contributes 2 560 m^3/s (cubic metre per second) to the flow of the Mekong.

Culture-based fisheries are widely practiced in small waterbodies throughout the Northeast of Thailand. Fish yields in 16 villages ranged from 26– 2 881 (median 652) kg/ha/year (Garaway and Lorenzen, 2001). These yields were strongly related to the trophic status of the waterbody and to stocking density (with an optimum at 9 800 fish/ha/year of 2-3 cm seed fish). Catches are dominated by tilapia in the most eutrophic water bodies and by carp species in all others.

Lao PDR

In Lao PDR, the fisheries yield in Lao PDR was estimated by Hortle (2007) to be 208 503 tonnes of which 167 922 tonnes were fish and 40 581 tonnes were other aquatic organisms. These estimates were based on consumption studies and expressed as Fresh Whole Animal

Equivalent Weights (FWAEs) in tonnes/year as a surrogate of fisheries yield. Based on this yield and the average first hand sale price of US$0.68/kg (MRC, 2003), an estimate of 208 500 tonnes of fish in Lao PDR is worth about US$142 million per year. In large hydropower reservoirs such as Nam Ngum and Nam Theun 2, commercial fishers are dominant.

Cambodia

In Cambodia, about 86 percent of the land area is within the Mekong catchment, and about 20 percent of the Mekong River's catchment is within Cambodia. The inland fisheries of Cambodia are among the largest and most significant in the world and are based on utilizing hundreds of different species which are caught using at least 150 kinds of gear. The fish catch is conservatively estimated at over 400 000 tonnes per year (Table 4), worth around US$300 million, and the catch of other aquatic animals (OAAs) such as shrimps, crabs, snails, frogs, insects, snakes and turtles is at least 60 000 tonnes per year (value unknown). Fish and OAAs are crucial for nutrition and food security in Cambodia because they provide 80 percent of the total animal protein.

Table 4 Estimated annual fish production by different types of fisheries in Cambodia (2001-2010) - Source : Nam and Song, (2011)

Type of fisheries	**Annual catch range** (tonnes)		**%**
	Min.	**Max.**	
1. Freshwater capture fisheries	314 000	450 000	75.6
- Large-scale fisheries	*39 000*	*105 000*	*23.3*
- ***fishing lots***	*25 000*	*75 000*	
- ***stationary bag-net (Dai) fishery***	*14 000*	*30,000*	
- Medium-scale fishery	*85 000*	*100 000*	*22.2*
- Small of family-scale fishery	*115 000*	*120 000*	*26.7*
- Rice field fishery	*75 000*	*125 000*	*27.8*
2. Marine fisheries	42 000	85 000	14.3
3. Aquaculture production	14,000	60 000	10.1
Grand total	370 000	595 000	100.0

1.2.2 Food production (in terms of rice and animal proteins and nutrients)

In freshwater wetlands and seasonal flooded forests around the Mekong River, local people make use of natural resources with an average annual values of US$4.12 per ha for non-timber products and US$3.55 per ha for fisheries, for example in the Lower Songkhram river in Thailand (Khonchantet, 2007). The estimated economic value of direct resource harvests of wetlands in Udon Thani province is worth US$24 per ha (Pagdee at al., 2007), which is higher than in the Lower Songkhram river. In Cambodia, the average value of wetlands in Stoeng Treng Ramsar Site is US$658 per ha (Chong, 2005).

Around 3 000 Cambodian households regularly use wetland resources such as fish, aquatic animals and plants, water birds and building materials for their daily lives. Estimated river capture fisheries of the 5 countries in the Lower Mekong Basin shows that Thailand produces the largest river fisheries catch in the Lower Mekong Basin (**Table 5**).

Table 5 Estimated production from river capture fisheries in the Lower Mekong Basin in 2000 (**Source :** Van Zalinge et al., 2004).

Country	**Production** (tonnes)
Cambodia	682 150
Lao PDR	182 700
Thailand	932 300
Viet Nam	844 850
Total	**2 642 000**

The Mekong River produces about 2.6 million tonnes of fish per year in the lower Mekong river basin. Per unit area, Cambodia is the most productive inland fishery in the world, where 1 ha of water yields up to 230 kg of fish per year. Fish consumption of people in the Lower Mekong Basin is between 24–34 kg/person/year (Hortle, 2007). The bulk of the fish and aquatic products are from the mainstream Mekong River and tributaries, accounting for 75.4 percent of total fish production in the lower Mekong basin (**Table 6**). The total value of Mekong fish catches is higher than US$2 000 million/year.

Table 6 Fish and other aquatic organisms production and value in the LMB (**Source** : Barlow 2002)

Fish and aquatic product source	**Quantity** (tonnes)	**Prices** (US$/kg)	**Value** (million US$)
Riverine capture fisheries	1 533 000	0.68	1 042
Aquaculture	260 000	1.05	273
Reservoirs	240 000	0.68	163
Total	**2 033 000**		**1 478**

The Lower Mekong Basin is particularly rich in natural resources such as forests, minerals, agriculture and fisheries. A wide variety of natural resources support local people in term of food sources, shelters and medicine as well as it provides an important source of income for millions of people living along the Mekong River. The Lower Mekong River Basin also serves as home for thousands of different species of animals and plants. For instance, the Mekong has a very high species richness of fish, between 768–1 200 species (FishBase REF). Goods and services provided by the Mekong ecosystem thus make the region one of the biologically richest places on earth only after the Amazon.

Ecosystem services generated by fish populations (adapted from C.M. Holmlund, M. Hammer, 1999) include (**Figure 4**):

- **I.** Provisional service, which are (a) fish as food.
- **II.** Regulating services, which are (a) top-down effects regulating population dynamics and nutrient availability, (b) bioturbation in or near sediments, and (c) carbon exchange. Linking services include active transport of nutrients, carbon and energy between the pelagic and (d) hard and soft bottoms, (e) the littoral, (k) for purifying water, (m) for mitigating the spread of diseases.
- **III.** Supporting services which are: passive transport of nutrients between ecosystems when fish eggs, fry, juveniles, adults, and carcasses are preyed on by (f) birds, and (g) mammals, including fish as indicators of (h) ecosystem health, recovery and resilience, (i) environmental recorders, and (n) for aquaculture.
- **IV.** Cultural services include fish (l) for recreation,.

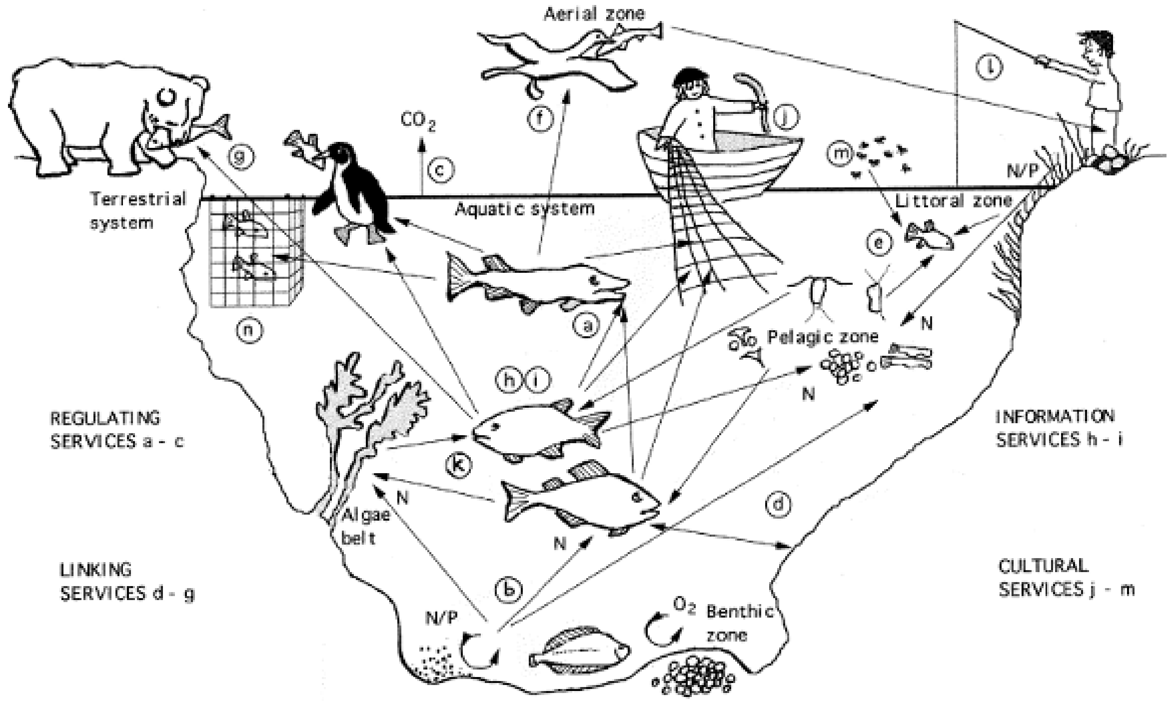


Figure 4 Ecosystem services generated by fish population
(Source: Holmlund and Hammer 1999)

1.2.3 Water quality

The Mekong River Commission (MRC) established the Water Quality Monitoring Network (WQMN) in 1985 to ensure that water quality of the Mekong River is in good conditions and can maintain the environmental health of the Mekong River and its tributaries (MRC, 2008). An intensive water quality monitoring programme was conducted by WQMN in 2005 covering 90 stations of the mainstream Mekong River, its tributaries and the Mekong delta and the results showed that water quality of the LMB and tributaries for aquatic life is generally good. Signs of significant human impact on water quality are observed at stations in the uppermost part of the LMB and downstream of Phnom Penh. The lower index values for water quality at the downstream stations reflect higher population densities, particularly in the highly populated and intensively farmed delta (Mekong River Commission, 2008).

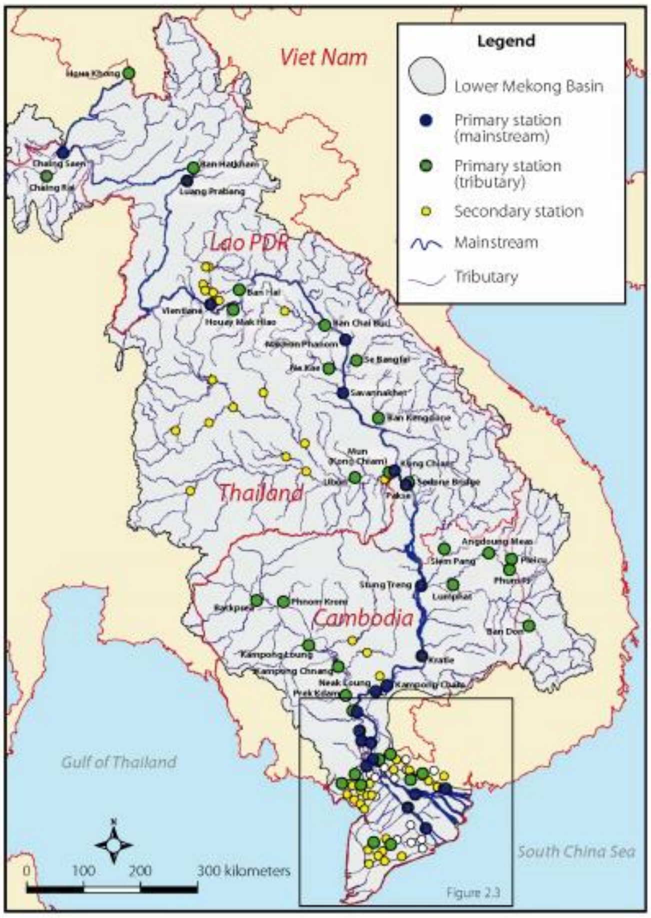


Figure 5 Water monitoring stations across LMB conducted since 2005
Source : Mekong River Commission (2008)

The water quality in the Mun river (Fougeirol 2007), one of the Mekong tributaries, is similar to the mainstream Mekong and no transboundary pollution has been identified within the LMB (**Table 7**).

Table 7 Water quality of the Lower Mekong River Basin and its tributaries
Sources: [a] Mekong River Commission (2008) and [b]Fougeirol (2007)

Parameters	2000[a]	2007[b]
Dissolved oxygen (DO) (mg/l)	6.37	7.48
pH	7.06	7.45
Conductivity (µS/cm)	2 810	2 620
COD (mg/l)	3.26	2.95
NH_4 (mg/l)	0.061	0.07
Total phosphorus (mg/l)	0.081	0.047

Good water quality can sustain not only ecological processes that support a variety of aquatic plants and animals, but can also influence the way in which communities use the water for other uses such as drinking water, recreation and irrigation. The estimated value of water quality and additional flow services from fresh water wetlands of the Lower Mekong River is around 1 436 US$/ha/year (World Wildlife Fund, 2013).

1.2.4 Biodiversity

The Mekong River Basin supports significant biodiversity because the region has a large variety of geographic landscapes (such as swamp, forests, floodplains, lakes, rivers and deltas) and climatic zones. An estimated 20 000 plant species, 1 200 birds, 850 fish species, 800 reptiles and 430 species of mammals exist within the basin. Indigenous and rare species of animals found only in this region include Mekong giant catfish (*Pangasianodon gigas*) and Irrawaddy dolphins (*Orcaella brevirostris*). In particular, the Mekong is a fish biodiversity hotspot and with 781 known species scientifically it is home to the second highest fish biodiversity in the world after the Amazon River. The Mekong is also characterized by very intensive fish migrations, at least a third of Mekong fish species need to migrate between downstream floodplains where they feed and upstream tributaries where they breed (ICEM, 2010).

During the last decade, scientists and researchers have discovered more than 1 000 new species and in 2014, 139 new species were discovered in the Mekong region and these new species are 90 flora species, 23 reptile species, 16 amphibian species, nine fish species, and one mammal species (WWF, 2015). *Ampulex dementor, Phryganistria Tamdaoensis, Hypsugo dolichodon* and *Cyrtodactylus vilaphongi* are among several species that were discovered in 2014.

Goods and services provided by the Lower Mekong Basin can help generate income for local people. A study of World Wildlife Fund (2013) revealed that the economic benefits that people gain from local use of non-forest timber products and wetland products are approximately 26 and 198 US$/ha/year, respectively.

1.2.5 Carbon fixation and greenhouse gas emissions

Carbon fixation

The nutrients carried by the plumes can contribute to enhancing primary production in the Mekong River and coastal areas of Viet Nam, which ultimately leads to carbon sequestration by phytoplankton. A recent study shows that nitrogen-fixing cyanobacteria play a crucial role in enhancing the productivity of large tropical river plumes. The result could have implications for carbon sinks associated with river plumes, making it important for regional carbon budgets. This is also consistent with nutrient cycling in this report that the Mekong plume seems to support various nitrogen fixers - even as far offshore as the upwelling zone that can contribute to C fixation (Dumé, 2008).

Carbon sequestration in the Lower Mekong by forests was estimated around US$968 ha/year and by mangrove around US$100 ha/year (WWF, 2013).

Greenhouse gas emissions

Hydropower is often believed to be in an inherently "climate-friendly" technology. But contrary to popular belief, scientific studies have indicated that the decomposing of organic matter in reservoirs and hydropower dams produces significant amounts of greenhouse gases, such as carbon dioxide, methane and nitrous oxide, with important warming impact, in particular in the tropics (Barros et al. 2011, Chen et al. 2009, Duchemin et al. 2002). The Mekong region is rapidly developing and energy to support economic growth is in high demand. Current instability of oil and gas prices, concerns about the future of fossil fuel energy, and the availability of private financing are making hydropower more attractive and accelerates its development in the Mekong River Basin.

The potential of hydropower in the Mekong River Basin is about 53 000 MW, 23 000 MW in the Upper Mekong Basin (China) and 30 000 MW in Lower Mekong Basin (Lao PDR, Thailand, Cambodia and Viet Nam). The locations and current stage of hydropower projects, of which 26 projects are located in the mainstream and the remaining 126 projects are in the tributaries (Figure 6). There are four operating hydropower facilities in the mainstream of Mekong River in Yunnan Province of China with install capacity of 8 850 MW. Another three projects are under construction and two of these, Xiaowan and Nuozhadu, have large storage reservoirs (> 27 km^3), which could cause significant changes in flow regimes, water quality and sediment transport.

Except for Cambodia, electricity prices in Lower Mekong countries fall within in a similar range around 0.1 US$/kw. Cambodia has the highest prices in the region, with a flat tariff for all uses of between 0.18 and 0.40 US$/kw (GiZ, 2014). The tributaries in the LMB are currently producing 3 225 MW or 3.225 million KW (10 percent of its potential) and a further 3 209 MW (US$188 000) are under construction equivalent to US$322 500 and US$320 900 respectively. Thailand and Viet Nam have developed most of their potential tributaries sites. Lao PDR has the largest remaining potential for hydropower and is currently striving to accelerate development.

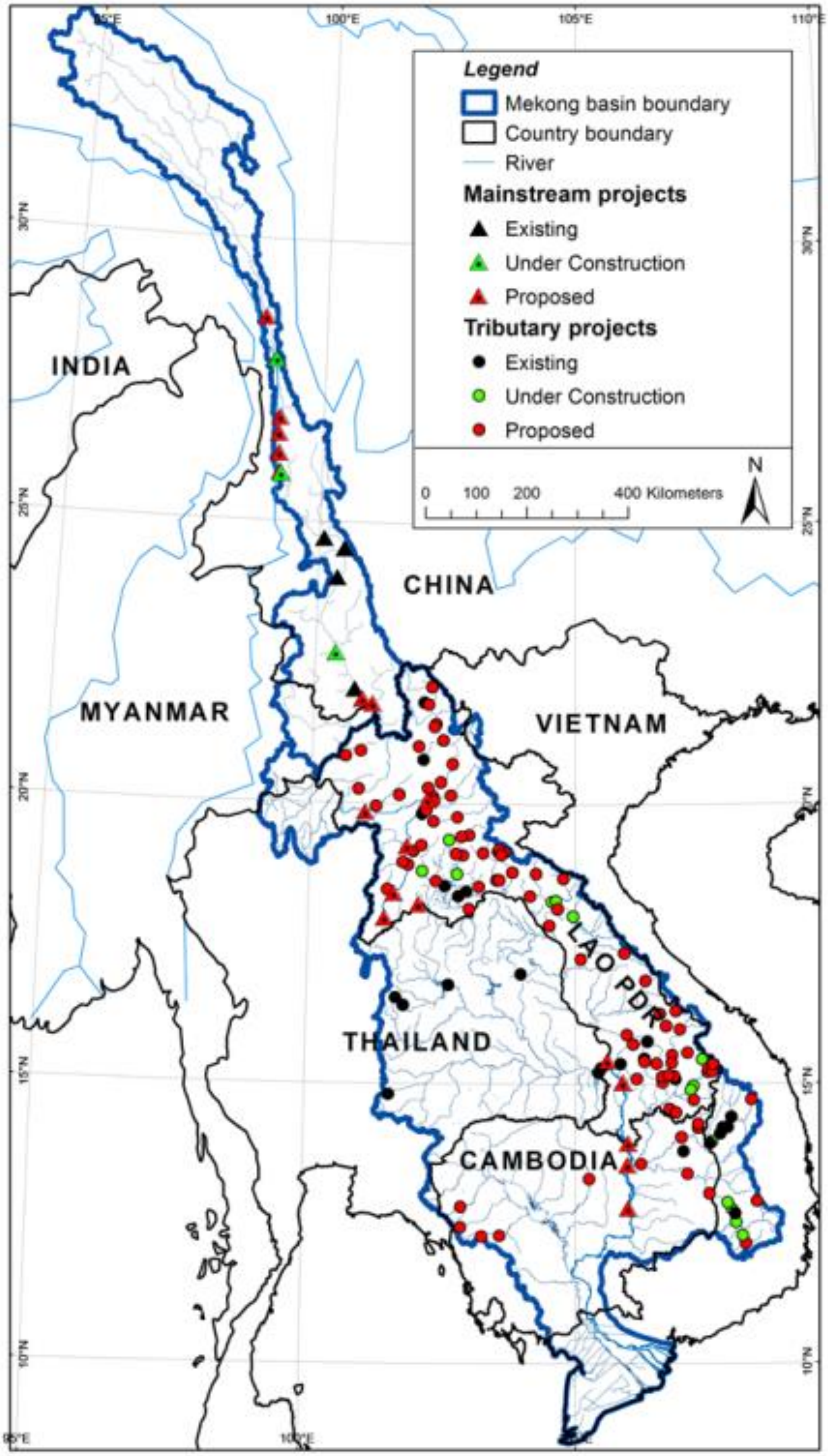


Figure 6 Hydropower projects in the Mekong River.
Source: http://mekongriver.info/hydropower

In terms of GHG emissions associated with fisheries and aquaculture systems, there are a few studies. Phong, et al. (2011) evaluated the environmental impact of integrated agriculture–aquaculture farming systems in the Mekong Delta that differ in types of aquaculture intensification: 3 farms in a rice-based and high input fish system(R-HF); 4 farms in a rice-based and medium input fish system(R-MF); and 4 farms in an orchard-based and low input fish system (O-LF). The inventory data and GWP values were reported (**Tables 8** and **9**).

Table 8 Mean land use, animal numbers, inputs and outputs of the study farms in the three systems (standard error between parentheses) **Source:** Phong et al. (2008)

Parameter	Unit	R-HF[1]	R-MF	O-LF	All farms
Farms	n	3	4	4	11
Land use					
Orchard	ha	0.33 (0.03)	0.40 (0.05)	0.44 (0.10)	0.39 (0.04)
Rice field	ha	2.05[a] (0.78)	0.48[b] (0.78)	0.08[b] (0.05)	0.76 (0.27)
Vegetable field	ha	0.02 (0.01)	0.04 (0.01)	-	0.02 (0.01)
Fish pond	ha	0.48[a] (0.08)	0.15[b] (0.01)	0.11[b] (0.02)	0.23 (0.04)
Whole farm	ha	2.90[a] (0.86)	1.16[b] (0.12)	0.64[b] (0.09)	1.45 (0.30)
Purchased materials					
Inorganic fertilizers	$kg\ ha^{-1*}\ y^{-1}$	364 (49)	336 (58)	741 (229)	491 (93)
Diesel	$kg\ ha^{-1}\ y^{-1}$	29 (11)	7 (2)	21 (8)	18 (5)
Pesticides	$kg\ ha^{-1}\ y^{-1}$	5 (1)	3 (1)	8 (3)	5 (1)
Concentrates	$kg\ y^{-1}$	1695 (1188)	1093 (217)	251 (64)	951 (337)
Rice co-products[2]	$kg\ y^{-1}$	7053 (5617)	3718 (560)	2423 (589)	4156 (1514)
Other feed[3]	$kg\ y^{-1}$	3636 (1690)	1179 (529)	832 (290)	1723 (544)
Crop production					
Rice	$kg\ ha^{-1}\ y^{-1}$	4113[a] (1349)	4014[a] (721)	674[b] (506)	2827 (582)
Fruits[4]	$kg\ ha^{-1}\ y^{-1}$	1295[b] (494)	1147[b] (182)	5263[a] (1142)	2684 (599)
Vegetable[5]	$kg\ ha^{-1}\ y^{-1}$	23 (23)	1431 (231)	3002 (2084)	1618 (775)
Animal production					
Pigs	n	10 (8)	16 (3)	7 (2)	11 (3)
Poultry	n	196[a] (43)	145[ab] (23)	56[b] (13)	126 (19)
Pigs	$kg\ y^{-1}$	2210 (2020)	1118 (168)	602 (196)	1228 (541)
Poultry	$kg\ y^{-1}$	286 (75)	297 (83)	109 (37)	226 (42)
Fish[6]	$kg\ ha^{-1}\ y^{-1}$	830[a] (302)	480[ab] (98)	200[b] (45)	474 (101)

-: Not applicable. Different superscripts ([ab]) denote significant differences between means within rows ($P<0.05$): *: ha farm area.

[1] R-HF: rice-based and high input fish system; R-MF: rice-based and medium input fish system; O-LF: orchard-based and low input fish system.

[2] Rice grain, milled rice, broken rice, and bran.

[3] Crab, snail, weeds/grasses, banana stem kitchen leftover and alcoholic draft.

[4] In the O-LF system: longan, rose apple citrus,and banana; in the R-MF system: longan, citrus, coconut, cherry, rose apple, mango and banana; and in the R-HF system: mango, sapodilla, cherry, and banana.

[5] In the O-LF system: water melon; in the R-MF system: hot pepper, onion, water spinach, cucumber, bitter melon, cabbage, and mushroom; and in the R-HF system: hot pepper, mung bean, and cabbage.

[6] Tilapia, kissing gourami, giant gourami, silver barb, common carp, silver carp, and striped catfish

Table 9: Total farm calories produced, and impact categories per kcal of farm product in the three systems (standard error between parentheses) **Source :** Phong, et al. (2011)

Impact	R-HF	R-MF	O-LF	All farms
Number of farms	3	4	4	11
Total calories per farm (Mcal)	7044[a] (2819)	2180b (386.5)	573b (79.95)	2922 (927.7)
Land use (m^2 $kcal^{-1}$)				
On-farm	0.009 (0.003)	0.007 (0.002)	0.013 (0.002)	0.010 (0.002)
Off-farm	0.007 (0.002)	0.010 (0.001)	0.008 (0.001)	0.007 (0.002)
Total	0.016 (0.006)	0.015 (0.004)	0.023 (0.002)	0.018 (0.002)
Energy use (kJ $kcal^{-1}$)				
On-farm	1.248 (0.581)	0.349 (0.148)	1.404 (0.661)	0.978 (0.297)
Off-farm	16.167 (6.242)	13.897 (2.442)	25.664 (3.658)	18.795 (2.489)
Total	11.256 (3.379)	10.096 (1.837)	27.662 (8.324)	16.801 (3.574)
GWP ($gCo_2eq.kcal^{-1}$)				
On-farm	8.574 (2.348)	7.438 (1.469)	23.781 (8.047)	13.691 (3.354)
Off-farm	2.582 (1.068)	2.658 (0.431)	3.881 (0.497)	3.110 (0.378)
Total	11.256 (3.379)	10.096 (1.837)	27.662 (8.324)	16.801 (3.574)
EP ($gNO^-_3eq.kcal^{-1}$)				
On-farm	0.128[b] (0.070)	0.081[b] (0.027)	0.413[a] (0.128)	0.214 (0.059)
Off-farm	0.177 (0.078)	0.191 (0.034)	0.159 (0.026)	0.176 (0.025)
Total	0.305 (0.125)	0.272 (0.051)	0.572 (0.127)	0.390 (0.065)
AP (gSO_2eq $kcal^{-1}$)				
On-farm	0.044 (0.011)	0.035 (0.008)	0.121 (0.41)	0.069 (0.017)
Off-farm	0.020 (0.009)	0.021 (0.004)	0.031 (0.004)	0.025 (0.003)
Total	0.64[b] (0.019)	0.056[b] (0.008)	0.152[a] (0.042)	0.094 (0.018)

R-HF: rive-based and high input fish system; R-MF: rice-based and medium input fish system; O-LF: orchard-based and low input fish system.

Different superscripts (a,b,c) denote significant differences between means within rowa (P<0.05).

Huysveld et al. (2013) evaluated the resource use (from cradle to farm gate, starting from production of juveniles in hatcheries to the harvest of Pangasius fish at farm level), expressed as the Cumulative Exergy Extraction from the Natural Environment (CEENE), as shown in Figure 7. The total CEENE over the cradle to farm gate life cycle amounts to 305 GJ (equivalent to 7.3 tonnes of fossil oil) per tonne Pangasius. The share of the input flows to the hatchery and the farm in the total CEENE input was showed in the graph below.

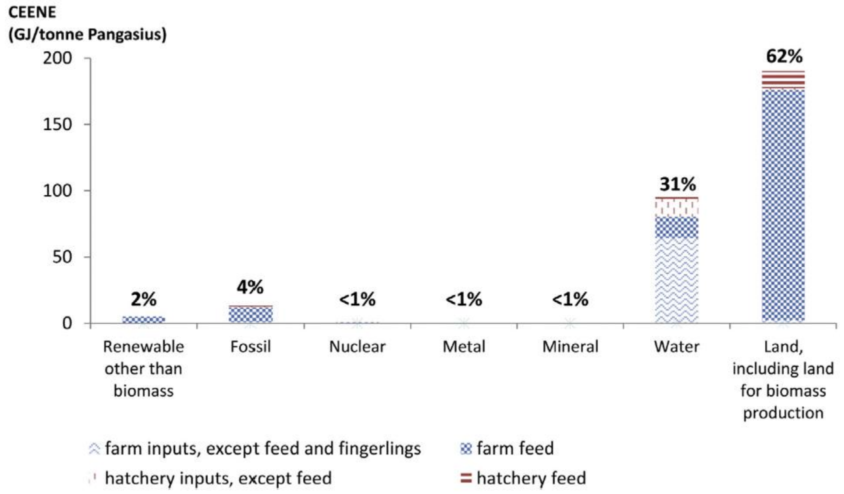


Fig. 3. Nature of inputs, in terms of the CEENE resource footprint (GJ/tonne *Pangasius*) of the complete *Pangasius* farming life cycle.

Figure 7 Nature of inputs in terms of the CEENE resource footprint
Source : Huysveld et al. (2013)

Bosma et al. (2011) evaluated the potential environmental impacts of intensive striped catfish farming in the Mekong Delta (Tables 10 to 13). The global warming potential was approximately 9 tonnes CO_2 per tonnes fish, while total water use for the production of striped catfish was estimated at 6 150 m^3/tonne fish.

Table 10 Survey results for 28 catfish farms (mean ± standard deviation)

Item	**Unit**	**All farms**
Pond area	ha	3.4±3.0
Fish production	Tonnes ha^{-1} $year^{-1}$	427±273
Feed consumed	100 t ha^{-1} $year^{-1}$	0.81±0.53
FCR	kg/kg	1.86±0.28
Electricity use	kWh t^{-1} fish	41±40
Diesel use	1 t^{-1} fish	5±9
Lime use	kg t^{-1} fish	5.2±5.9
Chemical use	kg t^{-1} fish	0.12±0.17

Table 11 Sediment for 28 catfish farms

Dependent variables	**Predictive equations**	**kg ha^{-1} $year^{-1}$**	**Sediment kg/ton fish**
Total sediment (TS)	TS = 206 + 50*Excreta	1 248 000	4 161
N (N_{ACC})	N_{ACC} = 304 + 129*Excreta	3 220	10.7
P (P_{ACC})	P_{ACC} = 89 + 58*Excreta	1 448	4.8

Table 12 Characteristics of inlet and discharge water, water of various pond types, waste water, sludge and pond sediment for aquaculture systems in SE Asia and the Mekong Delta

	P/M	Unit	BOD	COD	TAN	NO_x	N-tot	P-tot
Inlet water (Dang 2007)	10/12	mg/l					3.5	0.26
Shallow pond water (Dang 2007)	10/12	mg/l		13.6		0.08	7.1	1
Outlet water (Vu et al. 2008)	9/3	mg/l	4.6	9.5	2.2	3.3	14.8	3.2
Refreshment water (Pham et al. 2010)	4/5	mg/l	22	27	2.2	-	4	1.7
Waste water containing sludge (Pham et al. 2010)	4/5	mg/l		1 769			45.6	22.7

P/M **number of ponds/measurements,** ***TAN*** **total ammonia nitrogen, Nox =** $NO_2 + NO_3^-$

Table 13 LCIA results for striped catfish production in the Mekong Delta (LCA-panga-MD) compared with results for four other farm-exit aquaculture LCIAs for main impact categories (all impacts per ton crop produced)

LCIA (source)	Impact category Unit	GW ton CO_2	EU kg PO_4- eq	AC kgSO_2.eq	HT Kg DB eq	MAET t DB eq	Energy GJ
***Pangasius*, MD**		8.93	65a	48.1	4 280	2 512	13.2
Salmon, flow-though (Ayer and Tyedmers 2009)		5.04	31	33.3	2 570	3 840	132
Trout flow-through (Aubin et al. 2009)		2.75	66	19.2	-	-	78
Rainbow trout, flow-through (Papatryphon et al. 2004)		1.3	44	6.7	-	-	21

Henriksson et al. (2014) evaluated the life cycle impacts of three different scales of Pangasius farming and results showed relatively similar GHG emissions (Figure 8), even between the two allocation scenarios (mass and economic scenarios).

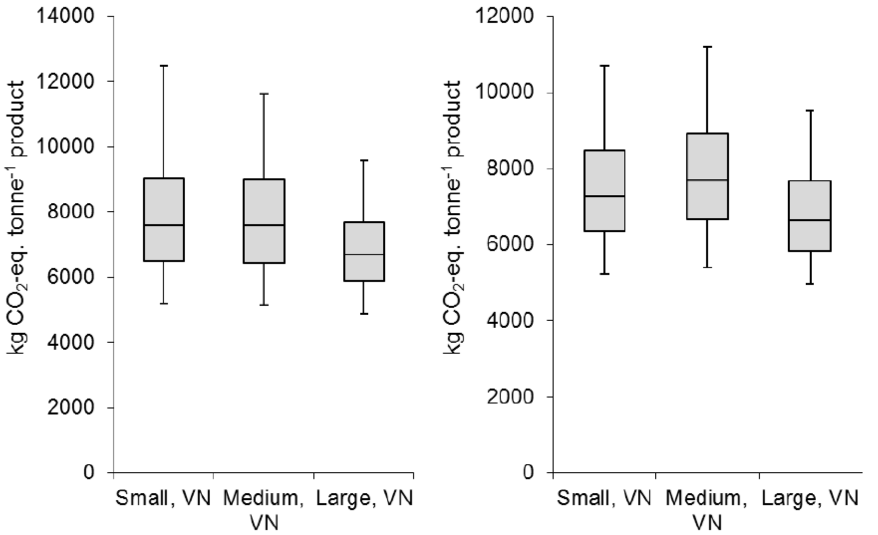


Figure 15: Global warming, mass allocation, per tonne Pangasius fillets from small (alternative 5), medium (alternative 6) and large (alternative 7) scale farms in Vietnam.

Figure 15: Global warming, economic allocation, per tonne Pangasius fillets from small (alternative 5), medium (alternative 6) and large (alternative 7) scale farms in Vietnam.

Figure 8 GWP of Pangasius fillets in Viet Nam. Source : Henriksson et al. (2014)

1.2.6 Nutrient cycling

Nutrient cycling is an important factor maintaining the balance of an ecosystem. A cycle of nutrient such as nitrogen and phosphorus is a repeated pathway of the movement of inorganic matter into the living organisms and then are recycled back to the environment. A study of nutrient cycling in Mekong estuary of Viet Nam was conducted by Voss et al. (2009). The result revealed that upwelling nitrate fluxes of 17±2 mmol N m^{-2} day^{-1} (millimoles Nitrogen per square meter per day) in July 2004 were consistent with N-demands of primary productivity. Nitrogen fixation was a significant N-source for higher trophic levels in the area (up to 375 mmol N m^{-2} day^{-1} in offshore waters) - equal to 2 percent - 25 percent of diffusive nitrate fluxes. It was also found that the plume extension depends on the monsoon season and rainfall and nutrient concentrations are not high in the Mekong, except for silica. The Mekong plume seems to support various nitrogen fixers - even as far offshore as the upwelling zone.

The load of suspended sediment also plays a crucial in nutrient cycling. Currently, some 26 400 tonnes/year of nutrients are supplied to the Mekong floodplains and delta by the fine-sized suspended sediment load (ICEM, 2010). Production of marine plankton is linked to sediment and associated nutrient loading from Mekong River. It is estimated that according to the model, for example, the load at Kompong Cham, LMB, in 2020s is 6.3×10^4 tN a^{-1} (+ 13.0 percent compared to 1990s) and 4.3×10^3 tP a^{-1} (+ 24.7 percent). The estimated load appeared to satisfactorily describe the seasonal cycle and spatial distribution of the Mekong's hydrology, which indicated that the simulated surface flow has sufficient precision for calculating nutrient transport in this basin (Yoshimura et al., 2009).

1.2.7 Income and livelihood support

The four Lower Mekong countries have a population of 165 million in total. However, only 56.6 million live in the Mekong basin part of these countries. Nearly all of Lao PDR and Cambodia's population reside in the Mekong basin, but together they comprise only 19 million or one-third of the basin's population. However, most of the LMB resources lie in the two smaller countries surrounded by larger riparian countries, Thailand and Viet Nam, whose whole population together stands over 140 million, and who are experiencing increasingly scarce resources. About 21 million, or 33 percent population of Thailand, and 17 million of Viet Nam's people (20 percent of the country's population) live in the Mekong Basin part of their country (MRC, 2005).

It is estimated that two thirds of the basin's population of 56.6 million live in rural areas. These rural dwellers are mostly subsistence farmers who supplement rice and farm crops with fish from capture fisheries and also other aquatic animals and plants for food. Many other basic needs are also covered by "direct harvest" from forests and wetlands including building materials, materials for basic household tools and medicinal plants. Nearly 40 percent of the people in Cambodia and Lao PDR live under the poverty line. The Mekong Basin part of Thailand is home to 62 percent of all the poor in Thailand. The number of the poor is also high in the Viet Nam Delta, although the depth of poverty is highest in Lao PDR and Cambodia (Kamoto and Juntopas 2011).

The average household size in Cambodia and Lao PDR is 5–6 persons, reflecting a common feature in rural, subsistence households in the LMB. In Thailand, the average household size has dropped from 6 to 4 persons due to declining fertility rates and a similar transition is occurring in Viet Nam. Over half of the population in Cambodia and Lao PDR are children and youth below the age of 15 years and this translates into a high dependency ratio, meaning that each working adult must support other household members who are non-working and of non-earning age. Overall, women head about one-quarter of the households in the LMB. In rural areas, female household heads tend to be widows who lost their husbands in war, or married women whose husbands are away working as migrant labourers. In rural areas of northern Lao PDR, among older household heads, as many as 60–70 percent are women.

Using an average farm-gate price of US$1.05 per kg for cultured fish and an average initial sale price of US$0.68 per kg for captured fish, the monetary value of the 2 million tonnes of fish caught and produced from the Lower Mekong Basin is estimated at US$1 400 million[14] (MRC, 2002).

Household incomes vary widely across the basin. In Thailand and Viet Nam, there is a significant and widening gap between the incomes of the basin part and those regions outside. This is also true among LMB countries themselves. Incomes in Thailand are three times higher than those in Viet Nam and more than four times greater than those in Cambodia and Lao PDR. There are also significant differences within the countries, between regions and in urban and rural areas.

Since the financial crisis in 1997, the north and northeast regions of Thailand have experienced significant unemployment and the return of workers who have lost their jobs in urban areas. Urban incomes in Viet Nam are nearly four times higher than rural incomes. In Cambodia and Lao PDR, urban incomes are approximately twice the national average. Incomes in the Mekong Delta and the Central Highlands (in Viet Nam) are, respectively, 20 and 40 percent below the national average (Table 14). Income levels remain low in Viet Nam, despite strong economic growth during the 1990s. This is also due to very high population densities. In addition, as a consequence of the overall high population density, there is less arable land per capita compared with other LMB countries. Also, benefits from foreign investment and exchange earning need to be spread over a much larger population.

In general, women in the LMB tend to work at low-paying and more menial jobs. Their overall income levels are 60 to 75 percent of the men's incomes. Data available for Cambodia and Lao PDR suggest that non-agricultural wage levels for women are about 80 percent of those of men. In Thailand, women working in the public sector have income levels nearly equal to men, but they earn only about 75 percent of men's wages in private sector, non-agricultural jobs. In Viet Nam, women's wages are 72 percent of men's, but only 62 percent of men's in the agriculture sector.

Table 14 Socio-economic trends during the life of the Mekong River Commission
Source: Kamoto and Juntopas (2011)

	GDP (US$ billions)		**Per Capita GDP** (US$)		**Poverty rate** (nation line)	
	1995	2004	1995	2004	1993	2003
China	700.2	1 649.4	578.1	1 268.7	6.7	3
Myanmar	5.5	9.1	122.6	167.1	35	25
Lao PDR	1.8	2.4	382.1	415.7	45	33
Thailand	168	163.5	2 825.7	2 512.2	13.1	<2
Cambodia	3.4	4.4	321.1	314.1	39	36
Viet Nam	20.7	43.9	288	534.8	50.9	29

[14] This figure excludes the value of 500 000 tonnes of OAA.

Table 15 Estimated freshwater fish and aquatic product consumption in the Lower Mekong Basin. Source: Sjorslev (2001)

Country	Population in LMB 1999 /2000	Assessed consumption per capita per year of all fisheries products. Average (range), kg	Assessed total consumption of freshwater fish, fish products and aquatic animals (tonnes) 1999/2000
Cambodia total	10 775 000	47 (10-89)	508 000
Lao PDR total	5 087 000	26 (17-36)	133 000
N-E Thailand	22 439 000	35 (20-41)	795 000
Viet Nam - Mekong delta	17 958 000	33 (15-60)	597 000
TOTAL	56 259 000	36	2 033 000

Table 16 shows the production and value of fish, fish products and other aquatic animal in the LMB. Aquaculture plays an important role in terms of socio-economic but the bulk of inland fisheries production comes from capture fisheries.

Table 16 Production and value of fish, fish products and other aquatic animal in the LMB Prices of capture and aquaculture fish. Source: MRC (2002)

Fish, fish products and aquatic animal source	Quantity (tonnes)	Price ($ per kg)	Value ($ millions)
Riverine capture fishers	1 533 000	0.68	1 042
Aquaculture	260 000	1.05	273
Reservoirs	240 000	0.63	163
TOTAL	**2 033 000**		**1 478**

1.2.8 Other ecosystem services (such as tourism)

The Irrawaddy dolphin (*Orcaella brevirostris*) population inhabiting the Mekong River is classified by the IUCN as Critically Endangered. Dolphin-watching tourism began in two areas along the dolphin's habitat in the Mekong River: 1) Chiteal Pool on the Lao PDR /Cambodian border; and 2) Kampi Pool in Kratie Province, Cambodia.

1.3. Policy contexts

In this section, we mainly focus on water resource management, fisheries and hydropower development policy since these policies appear to have strong effects on ecosystem services and livelihoods of people in the LMB. We also apply these policies to create possible scenarios in the next section.

1.3.1 Viet Nam

Aquaculture Planning and Management Tools (APMTs) are applied in in Viet Nam (Table 17). The Vietnamese aquaculture sector is managed by: Directorate of Fisheries (D-FISH), through its associated departments including the Department of Aquaculture and the Center for Aquaculture Input Testing, Inspecting and Verifying; Department of Animal Health (DAH) and its provincial departments; The National Agro-Forestry – Fisheries Quality Assurance Department (NAFIQAD) and its provincial departments; and Provincial Department of Agriculture and Rural Development (DARD) through its Sub-Department of Aquaculture. The three agencies of D-FISH, DAH and NAFIQAD operate under the Ministry of Agriculture and

Rural Development (MARD), whilst DARD belongs to the Provincial Peoples Committee (PPC). In order to manage the aquaculture sector sustainably, a number of policies have been promulgated to cover the use of various tools for aquaculture development, management and planning.

In term of hydropower policy, hydropower has increased rapidly in Viet Nam over the past decade and now generates more than a third of the country's electricity. In 2013 the National Assembly reported that 268 hydropower projects were up and running, with a further 205 projects expected to be generating by 2017. The hydropower projects are helping to meet the national demand for energy that is forecasted to triple between 2010 and 2020 (The Economist, 2015).

Table 17 Summary of APMTs Application in Viet Nam.
Source: Weimin et al. (2013)

Tools		Level of awareness[1]	Level of capacity[1]	Extent of use[1]	Supporting legal instruments[1]
I. Planning tools					
1	Aquaculture development: spatial planing/zoning (e.g. based on carrying capacity)	c	b	b	Yes
2	Environment impact assessment (EIA) of aquaculture operations	c	c	c, d, e	Yes
3	Ecological risk analysis (genetics and biodiversity)	a	a	c, d	Yes
4	Social impact assessment	c	b	B	No
5	Import risk analysis (IRA) for introducing	c	c	c, d	Yes
6	GHG emissions/carbon footprint studies	b	a	B	Yes
II. Management tools					
1	Health certification	d	d	c, d, e	Yes
2	Quarantine	d	d	c, d, e	Yes
3	Disease surveillance & early warning system	d	d	c	Yes
4	Residue inspection and monitoring	d	d	c, d, e	Yes
5	Record keeping and traceability	d	c		Yes
6	Input quality assessment and monitoring	c	c	d	Yes
7	Production process (e.f.public and private certification)	d	c	e	Yes
8	Farm management tools (e.g. BMP/GAP)	d	c	b	Yes

[1] Levels of awareness/capacity: *a* - policy makers and scientists at the national level; *b* - policy makers, scientists, at the provincial level; *c* - all stakeholders at local level except farmers; *d* - all

[2] Extent of use: *a* - never used; *b* - used in some projects: *c* - used at national level; *d* - uesd at provincial level; *e* - used at local level

[3] Supporting legal instruments: Yes; no; under development

1.3.2 Thailand

The institutional framework for implementation of APMTs in Thailand (Figure 9) builds on that the Department of Fisheries is the core institute responsible for establishing regulatory frameworks and implementation for sustainable aquaculture development. The Ministry of Natural Resources and Environment is responsible for planning in environmental control, zoning and the national plan of action related to climate change. Universities play a role in research into Life Cycle Assessment (LCA) and environmental footprint studies. The National Bureau of Agricultural Commodity and Food Standards (ACFS) is responsible for standard-setting in aquaculture production systems and food safety, accreditation of certification bodies, food standard control and promotion of standard compliance for farms and food establishments. The Thai Food and Drug Administration (Thai FDA) is responsible for implementation of food and drug laws.

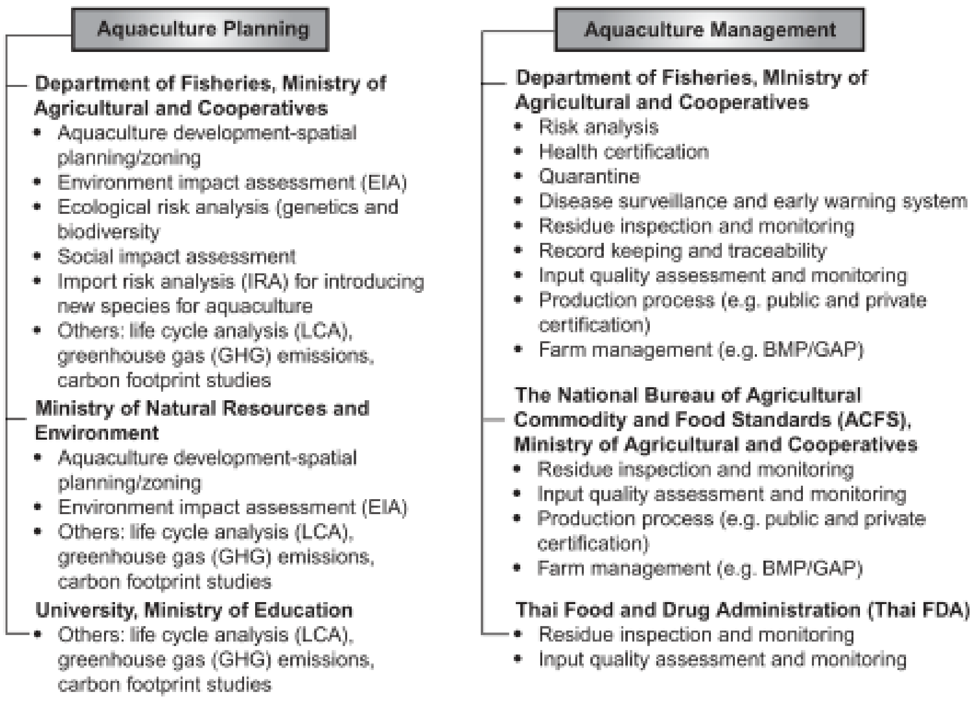


Figure 13 Institutional framework for implementation of APMTs in Thailand

Figure 9. Institutional framework for implementation of APMTs in Thailand.
Source : Weimin et al. (2013)

Thailand has committed to increase its production of renewable energy to 25 percent of output by 2021 using a variety of sources, including hydropower development. The Electricity Generating Authority of Thailand (EGAT) will purchase over 90 percent of the power from Xayaburi dam and may purchase power from Don Sahong as it looks to reduce Thailand's dependency on fossil fuels in the face off Thailand's fast-growing demand for energy.

1.3.3 Lao PDR

In Lao PDR, inland fisheries and aquaculture activities are administered by the ministry responsible for agriculture. The Fisheries Section is lodged in the Technical Division of the Department of Livestock and Fisheries (DLF) of the Ministry of Agriculture and Forestry (MAF). One of the main responsibilities of the local administration is to manage and protect natural resources and the environment within their area of jurisdiction. Provincial governors, district heads, municipality heads and village heads are vested with regulatory powers to take measures aiming at implementing state laws and regulations. Local regulations may also be enacted to regulate the use and protection of natural resources, including fisheries, at the local level (Cacaud and Latdavong, 2009)

As it strives to become the "battery of Southeast Asia," hydropower development is increasing rapidly in Lao PDR. Increasing power demand from neighbouring Thailand and Viet Nam and new investors from Thailand, China, Russia, Viet Nam and Malaysia are driving this expansion. Six large dams are officially under construction in Lao PDR and at least 12 more are at advanced planning stages. Lao PDR is also proposing six dams for the mainstream Mekong River (International Rivers, 2008).

1.3.4 Cambodia

The Ministry of Agriculture, Forestry and Fisheries is the government ministry of Cambodia that is responsible for governing activities of agriculture, forestry and the fishery industry in Cambodia. The Department of Fisheries plays the roles both as policy maker and as implementer. The provincial fisheries offices take the responsibility for managing the fisheries resources in the provincial territories (Sour and Viseth, NA). The current fisheries management in Cambodia is based on the Fisheries Law management and administration that consists of general rules on the exploitation of freshwater capture fisheries and marine fisheries, aquaculture and processing of fresh water and marine fisheries products, competent authorities involved in the resolution of law violations, and the penalties. Aquaculture is a new sub-sector in fisheries, and the legal framework for aquaculture comes from the Fiat Law on Fisheries (Vuthy et al., NA).

The report by the Ministry for Industry, Mines and Energy (MIME) and the Cambodian National Mekong Committee (CNMC) in 2003 identified 60 possible sites for hydropower development in Cambodia and estimated the country's total generation potential at 10 000 MW, of which 50 percent is on the mainstream Mekong, 40 percent on its tributaries and 10 percent in the southwest outside the Mekong basin[4].

All large-scale projects currently under development are under build-operate-transfer (BOT) agreements of 25 years and upwards. Smaller dam projects that have been constructed include:

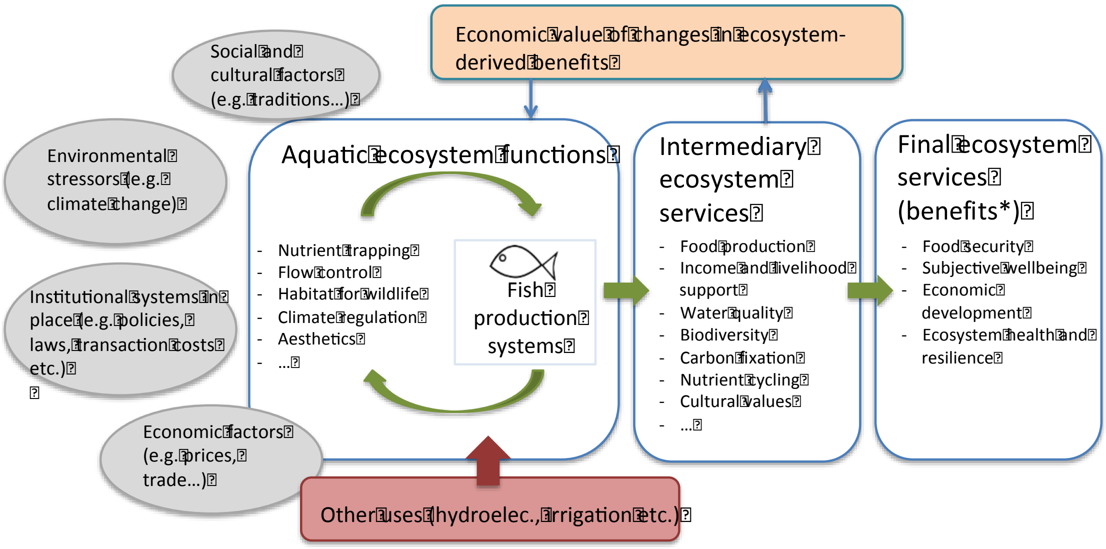
- Kirirom I (12 MW) in Kampong Speu
- Kamchay (193 MW) in Kampot, which started operating in 2011
- Kirirom III (18 MW), which started operating in 2013
- Lower Russei Chrum (338 MW) in Koh Kong, which started testing operations in early 2014.

Stung Tatay (246 MW), and Stung Atay (120 MW), also in Koh Kong, are under construction. The first of 3 generators at Stung Tatay began operating in August 2014. (Open Development Cambodia, 2015)

It can clearly be seen that due to rapid economic growth and electricity demand, every countries in the LMB has proposed the same main policy about hydropower generation and construction in the mainstream and tributaries. Every country believes that hydropower could generate great benefits for the development of the Mekong Basin as well as for livelihoods of local people living along the river. On the other hand, hydropower projects and the series of dams may have catastrophic effects on the ecosystems, production of natural resources (e.g. fish) and low income people in rural riparian areas that rely on these resources. Therefore in the next section the analysis of ecosystem services that could be affected by hydropower projects is challenging and important since the main proposed policy of hydropower development in the LMB region may turn out to be a serious threat to the people and environment of the LMB basin. The analysis also provides us better understanding of the potential risks and losses and gains from hydropower projects. Based on good governance, policy makers and governments of LMB should therefore consider and take all possible affected aspects including economy, society and environment into account before starting development of dams.

2. ANALYTICAL FRAMEWORK FOR VALUING ECOSYSTEM SERVICES

The analytical framework for valuing ecosystem services in the Lower Mekong River Basin used (**Figure 10**), represent the relationships between aquatic ecosystem services, external drivers of change and human wellbeing (benefits for people e.g. fish production, water supply, recreation, etc.).



- Benefits may differ according to social and economic groups: fishers/aquaculturists, rural communities, future generations etc.
- Red arrow: threat to the functioning of aquatic ecosystem services and the supply of ecosystem services from aquatic ecosystems AND fish production systems.
- Green arrows mean 'influence the supply of'.
- Grey ovals represent driving influences on the supply of aquatic ecosystem services. They also drive other uses of aquatic ecosystem. Grey ovals can also directly influence how the benefits of aquatic ecosystem services and fish production systems are distributed among social and cultural groups, and vice-versa (grey arrows).

Figure 10 Generic framework representing the relationships between aquatic ecosystem services, fish production, human wellbeing and external drivers of change

2.1. Approach to economic valuation of ecosystem services

Benefits (direct and indirect) provided by ecosystems are categorized into four main categories (MA, 2005; UNEP, 2010; Brugere, 2015):

Provisioning services - The products obtained from ecosystems such as food, water, timber, genetic resources.
Regulating services - The benefits obtained from the regulation of ecosystem process such as regulation of climate, floods, water quality.
Cultural services - The nonmaterial benefits people obtain from ecosystems such as spiritual fulfillment, aesthetic enjoyment and recreation.
Supporting services - Ecosystem services that are necessary for the production of all other ecosystem services such as soil formation, nutrient cycling and pollination.

Since ecosystem services often have no prices in the market, therefore the values (benefits) of ecosystem are always not fully taking into consideration when making policy decision. Economic valuations are the methods to place monetary value on these ecosystem services to facilitate policy maker in making decision over the use and management of ecosystem services.

There are two main branches of primary valuation methods for estimating the value of ecosystem services: Revealed Preference (RP) Methods and Stated Preference (SP) Methods. RP methods are based on the observation of the use of ecosystem services to elicit values while SP methods simulate a demand for ecosystem services using the surveys on hypothetical changes in the provision of ecosystem services. There are varieties of economic valuation techniques which are suitable for different types of ecosystem services. It is very important understand the strengths and limitations of valuation techniques in order to select the appropriate one.

Since the primary valuation method is very expensive and time consuming and policy makers often requires information quickly at low cost. There are methods transferring the value estimates from primary studies to the policy interest area: Benefit Transfer Methods. There are three main types of Benefit Transfer Methods: Unit value transfer, Value function transfer and Meta-analytic function transfer (UNEP, 2004).

- **Unit value transfer** - uses values of ecosystem services from primary studies (may be unit value from a single study or the average unit value from multiple studies) combined with information on the quantity of units at the policy interest area to estimate ecosystem service values.
- **Value function transfer** - uses a value function estimated in single primary study in conjunction with information on the characteristics of the policy interest area to estimate ecosystem service values.
- **Meta-analytic function transfer** - uses a value function estimated from multiple primary studies in conjunction with information on the characteristics of the policy interest area to estimate ecosystem service values.

2.2. Economic analysis of ecosystem services in the LMB

In this section, the ecosystem services generated by the LMB and directly and indirectly supported by its fish production system are considered jointly. In term of ecosystem services generated by the fish production systems, there is no existing literature on the ecosystem services provided by the fish production systems found in the LMB landscape (i.e. rice-fish, cage aquaculture in reservoirs, culture-based fisheries). All available studies estimate ecosystem service values by ecosystem type (e.g. wetland, forest, coastal, etc.). Due to this limitation, the ecosystem services generated exclusively by the fish production systems dominating the LMB landscape in the last part of the section were estimated based on secondary data from Thailand.

This study focuses on six ecosystem services including 1) Food production (in terms of fishery production), 2) Water quality, 3) Biodiversity, 4) Carbon fixation and greenhouse gas emission, 5) Nutrient cycling, and 6) Income and livelihood support. The economic value of each ecosystem service is described hereafter.

2.2.1 Fishery

The most reliable estimate of fish production in the Mekong basin is 2.1 million tonnes per year, with estimates varying from 0.75 to 2.6 million tonnes per year. By FAO records, this represents 22 percent of the world's freshwater fisheries. This catch of fish is supplemented by about half a million tonnes of other aquatic animals (freshwater shrimps, snails, crabs, frogs, etc.) complementing the catch and the diet of riparian people (ICEM, 2010).

For freshwater wetlands, Chong (2005) presents estimates of the local livelihood value of fish, aquatic animals, water birds and building materials to the 3 000 or so households living in the Stoeng Treng Ramsar site. With an average value per household of US$3 200 a year, the total annual value of the 14 600 ha wetland area is calculated at some US$9 600 000, or US$658 /ha.

Data on forest and coastal ecosystem values is provided in Emerton et al. (2002a) for Preah Sihanouk (Ream) National Park, Cambodia. The net annual value of fisheries within the park is just over US$515 000 or US$286 /ha. Bann (1997b), looking at the 63 700 ha of mangroves in Koh Kong province, meanwhile estimates that local fishing benefits are worth some US$84 /ha, firewood is valued at US$3.50 /ha, and sustainable charcoal production US$413 /ha (WWF, 2013).

There are 945 000 ha of rivers, water bodies and other natural and constructed wetlands in Lao PDR, which provide fish and other aquatic animals worth US$101.01 million a year for household subsistence, income and small-scale trade, an average of US$106 /ha (WWF, 2013).

Pagdee et al. (2007) addresses the economic value of freshwater wetlands in Udon Thani province. Direct resource harvests are estimated to be worth approximately US$270 per household per year, to a total gross value of US$108 000 or US$24 /ha. Seenprachawong (2002) estimates the value for fisheries and other direct uses at Phang Nga Bay in Phang Nga and Krabi provinces Thailand (not in Lower Mekong Basin, but may be used as a proxy value), he finds a total annual value of US$996 335, or US$16.5 /ha to adjacent dwellers.

2.2.2 Water quality

Whilst the river is relatively clean and in good ecosystem health at present, there are increasing point sources of pollution, e.g. urban areas, and dispersed sources, e.g. agricultural run-off, which are currently mitigated by the large dilution effect of the river flow. The result of this is that poor water quality is often rather localized, and quickly diluted, with rapid improvement in water quality e.g. after high polluting loads from urban areas.

There are signs of decreasing water quality – a trend which is expected to increase in the future with an increasing population. These trends are strongest for downstream areas of the LMB and also near growing population centers.

ADB (2010), looking at the proposed biodiversity conservation corridor linking seven protected areas in Mondulkiri and Koh Kong provinces, Cambodia, estimates the value of water quality regulation at US$1 018 ha/year. For the proposed biodiversity conservation corridor linking four protected areas in Attapeu, Champasak and Xekong provinces, Lao PDR, ADB (2010) estimates water quality regulation at US$718 ha/year. ADB (2010), also looking at the proposed biodiversity conservation corridor linking seven protected areas in Quang Nam, Thua Thien Hue and Quang Tri provinces Viet Nam, estimates water quality regulation at US$1 131 ha/year.

Gerrard (2004) describes the ways in which the 2 000 ha that Luang marsh in Vientiane Lao PDR serves to generate economically valuable regulating services that are critical to the functioning of the city, and to the basic standard of living of its human population. She calculates flood protection and wastewater treatment services to be worth some US$2.87 million a year or US$1 436 per ha to the 38 000 people living around the marsh.

2.2.3 Biodiversity

Almost 50 percent of the Mekong riparian corridor is considered as key biodiversity areas (KBAs) of global significance but poor management and lack of protected area zoning will led to a continued degradation of the corridor over the next 20 years. More than 1 005 km of 2 040 km of the Lower Mekong (Chiang Saen to the sea) are identified as KBAs, but only about 100 km of the river actually lies within a nationally protected area.

The Mekong is a fish biodiversity hotspot and with 781 scientifically known species, it is home to the second highest fish biodiversity in the world after the Amazon River. The Mekong is also characterized by very intensive fish migrations where at least a third of Mekong fish species need to migrate between downstream floodplains where they feed and upstream tributaries where they breed. Dams are a major obstacle to these migrations and could hence affect biodiversity

The aquatic ecosystems of the Mekong are relatively pristine at the moment, with high diversity of aquatic habitats – rapids, deep pools, sandbars etc. that all contribute to the very high biodiversity in the river. There have been some changes in recent years, e.g. the development of two upstream dams in China, and on some of the tributaries in the LMB, that have begun to alter the hydrology and patterns of sediment discharge, so that the river morphology is beginning to change. As these developments increase in size and numbers, this process of change will continue in the absence of the mainstream dams.

Pressures from human activities are increasingly putting river dependent fauna at risk, with a minimum of 28 species listed as endangered or vulnerable. This includes many of the charismatic Mekong species.

Based on TEEB database, Chong (2005) estimates biodiversity protection service values of Stoeng Treng Ramsar Site, Cambodia at US$31 ha/year. The estimated biodiversity protection service values based on meta-analysis using the TEEB database for tropical forest and inland wetland are US$272 ha/year and US$ 246 ha/year respectively.

2.2.4 Carbon fixation and greenhouse gas emission

Carbon storage values have been estimated at US$1 743 ha/year, in the proposed biodiversity conservation corridor linking seven protected areas in Mondulkiri and Koh Kong provinces, Cambodia (ADB, 2010). For the proposed biodiversity conservation corridor linking four protected areas in Attapeu, Champasak and Xekong provinces, Lao PDR, ADB (2010) estimates carbon storage values at US$1 846 ha/year. ADB (2010), also looking at the proposed biodiversity conservation corridor linking seven protected areas in Quang Nam, Thua Thien Hue and Quang Tri provinces Viet Nam, estimates carbon storage values at US$2 085 ha/year.

The amount of carbon emission and fixation depend on the activities and forest areas in the Basin. The carbon price traded in the market is about US$8.30 /tCO2e (Carbon Emission Futures prices on 27 June 2015).

2.2.5 Nutrient cycling

Currently, some 26 400 tonnes/year of nutrients are supplied to the Mekong floodplains and delta by the fine-sized suspended sediment load. At the price of fertilizer about US$400 per ton (The Office of Agricultural Economics, Thailand), the estimate value of nutrient cycling about US$10 560 000.

2.2.6 Income and livelihood support

A study of Smajgl and Ward, (2013) shows that in the **Mekong Delta**, rice and remittances are the primary sources of income in the LMB, contributing income to 50 percent and 30 percent of the households, respectively.

The sale of fish, irrigated/seasonal and full-time employment, each contributes to the income of 25 percent of the total households. In the Tonle Sap Lake area of Cambodia and the Siphandone area of Lao PDR, fish sales generate income for approximately 40 percent of households.

In **Cambodia**, a large proportion of people depend on forestry and fishers as their sources of income. Approximately 16 percent of the poor derive more than 50 percent of their income from forestry and fisheries. Figure 11 shows different aquatic food sources of the LMB region.

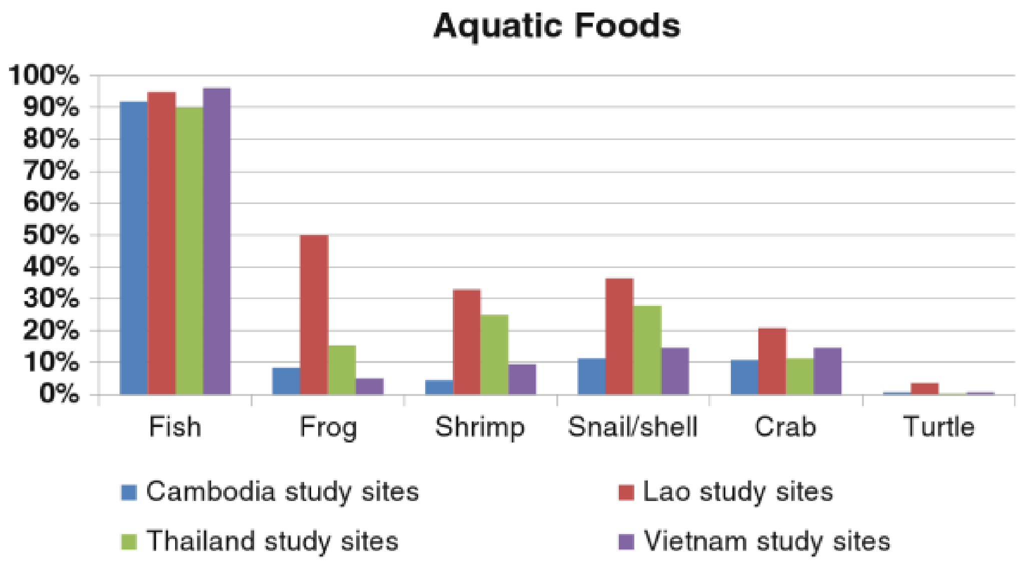


Figure 11 Aquatic food source
Source: Hall and Bouapoa (2010) cited in Smahgl and Ward (2013)

Similar to the sources of income, households in the Tonle Sap area rely heavily on fish as a primary source. Fishing households around the Tonle Sap derived over two thirds of their household income from fishing, far more than those in other areas.

Studies of small-scale inland fisheries in Cambodia revealed that the average net profits of family fishing was US$12 and US$4.6 per trip during the open (October to May) and close (June to September) seasons, respectively; but real profit—deducting the cost for family labour from net profit—was only US$4.5 and US$1.6 during the open and close seasons, respectively (Navy and Bhattarai, 2009).

In **Lao PDR**, most household food consumption in rural area in the Mekong corridor is natural or self-produced, whereas most food consumed by rural people in Thailand and other countries' Mekong corridors is purchased (Smajgl and Ward, 2013).

2.7 Summary of values

Table 18 summarise of ecosystem services values in the Lower Mekong Basin.

Table 18 Summary of ecosystem services values in the Lower Mekong Basin.

Type of services	Type of Ecosystem	Value	Country	Year of study	2014 US$ value
Fish production	Riverine capture fisheries	US$1.042 million/year 1 533 000 tonnes/year	LMB	2002	US$2.483 million/year
	Reservoir capture fisheries	US$163 000 /year 260 000 tonnes/year	LMB	2002	US$388 423 /year
	Aquaculture	US$1.478 million/year 2 033 000 tonnes/year	LMB	2002	US$3.522 million/year
	Total	US$2.683 million/year	LMB		US$6.393 million/year
Water quality (value of wetland's regulation service e.g. purification)	Protected areas	US$1 018 /year/ha	Cambodia	2010	US$1 106 /year/ha
	Protected areas	US$1 131 /year/ha	Viet Nam	2010	US$1 652 /year/ha
	Protected areas	US$ 718 /year/ha	Lao PDR	2010	US$843 /year/ha
	Wetland	US$1 436 /year/ha	Lao PDR	2004	US$2 535 /year/ha
Biodiversity	Wetland	US$31 /year/ha	Cambodia	2005	US$45 /year/ha
	Tropical Forest	US$272 /year/ha	LMB	2014	US$272 /year/ha
	Wetland	US$46 /year/ha	LMB	2014	US$46 /year/ha
Carbon fixation and greenhouse gas emissions	Protected areas	US$1 743 /year/ha	Cambodia	2010	US$1 893 /year/ha
	Protected areas	US$1 846 /year/ha	Lao PDR	2010	US$2 167 /year/ha
	Protected areas	US$2 085 /year/ha	Viet Nam	2010	US$3 046 /year/ha
Nutrient cycling	Sediment loading	26 400 tonnes/year = US$10 560 000 /year	LMB	2010	26 400 tonnes/year = US$10 560 000 /year
Income and livelihood support	wetland values, i.e. fish, aquatic animals, water birds, building materials	US$658 /year/ha	Cambodia and Lao PDR	2005	US$945 /year/ha
	fish and aquatic animals for household subsistence	US$ 106/year/ha	Lao PDR	2013	US$106 /year/ha
	direct resource harvest	US$ 24/year/ha	Thailand	2007	US$29 /year/ha
Other ecosystem services (such as tourism)	Boat trip/tourism	US$ 1 million/year	LMB	2005	US$1.948 million/year

2.8 Economic value of the services generated by fish production systems in the Lower Mekong Basin

Here the focus is on the ecosystem services supported directly and indirectly by the fish production systems that make up a large part of the LMB landscape.

Table 19 Values (US dollar/year/area) for the assessed fish production systems per ecosystem service (based on calculation of secondary data from Thailand only)

Types	Rice fields with fish production	Cage aquaculture in reservoirs	Culture-based fishery (in reservoir or floodplains)
Food production			
Fish	245 US$/ha/yr Based on 125 kg/ha/yr	5 896 US$/$m^3$/yr Based on 88 kg/$m^3$/yr	106 593 US$/ha/yr Based on 3 125 kg/ha/yr
Rice	1 802 US$/ha/yr Based on 3 500 kg/ha/yr	-	-
Water quality	-	-	-
Biodiversity	-	-	-
Carbon fixation and greenhouse gas emissions	-	-	-
Nutrient cycling	6 334 US$/ha/yr Based on N fixers e.g. blue green algae that increase rice production around 20-24%	-	-
Income and livelihood support	2 047 US$/ha/yr	5 896 US$/$m^3$/yr	106 593 US$/ha/yr
Other ecosystem services (such as tourism)	-	-	-

Sources : rice production : Thai rice exporters association www.thairiceexporters.or.th/production.htm
www.eto.ku.ac.th/neweto/e-book/fish/planakow.pdf
http://guru.sanook.com/814/
http://gms.oae.go.th/Z_Show.asp?ArticleID=198

3. EVALUATION OF VARIATIONS IN THE GENERATION AND VALUES OF ECOSYSTEM SERVICES UNDER DIFFERENT POLICY SCENARIOS

3.1. Management/development of possible scenarios

We identify the most possible development scenarios based on current policies of countries in the Lower Mekong Basin as follows (Table 20):

- Scenario I - Business as usual (BAU)
- Scenario II - Hydropower development (represents existing and proposed hydropower development projects in the main Mekong River and tributaries in the next 15 years or by 2030.

Scenario II is chosen because power demands of current development trends in the Mekong River Basin are expected to rise 7 percent per year between 2010 and 2030. Although sustainable hydropower could potentially boost economies, raise standard of living and provide energy security, the development of the Mekong River Basin is highly controversial and concerns have intensified over the potential cumulative impacts of the proposed dams on the environment, fisheries, and people's livelihoods (ICEM, 2010).

Table 20 Possible scenarios. Source : ICEM (2010)

Type of Development	BAU	20Y with LMB mainstream hydropower
Hydropower Development	6 dams in China 11 LMB mainstream dams 40 LMB tributary dams	6 dams in China 11 LMB mainstream dams 71 LMB tributary dams
Irrigation Development	$4*10^6$ ha	$6*10^6$ ha
Water supply	$2\,938*10^6$ ha	$4\,581*10^6$ ha

3.1.1 Business-as-usual (current management practices)

BAU scenario represents all the certain hydropower developments that exist, are under construction or have secured firm agreement for development. Current projects include 6 Chinese dams and 40 LMB tributary dams.

3.1.2 Policy option (recommended policy options)

Orr, et al. (2012) proposed the scenarios to evaluate the potential impacts of dam construction in the Lower Mekong Basin that could considerably reduce fish catch (Table 21) and place heightened demands on the resources necessary to replace lost protein and calories (Table 22). Additional land and water required to replace lost fish protein with livestock products were modeled using land and water footprint methods. Scenario 1: Replacement of 340 000 tonnes (16 percent reduction) of lost fish protein directly attributable to the proposed 11 main stream dams; and Scenario 2: Replacement of the net loss in fish protein due to the impact of all 88 proposed dam developments by 2030 (Table 23).

Table 21 Volume and portion of changes in fish resources in the Mekong Basin.
Source : Orr, et al. (2012)

Changes in fish catch forecast for 2030	Change in wild freshwater fish catch (tonnes)	Change in fish resources (%)
▪ Scenario 1 : Losses due to the 11 main stream dams planned for the Mekong	-340 000	-16
▪ Losses due to the net impact of 77 proposed tributary dam development by 2030	-210 000	-10 to -26
▪ Sum of losses in capture fisheries from 88 dams	-550 000 to -880 000	-26 to -42
▪ Minus the highest estimate of gains (10% of capture fishery losses) in fish production from reservoir fisheries	+55 000 to +88 000	+2.6 to +4.2
▪ Scenario 2 : Resulting net losses in fish resources from all 88 dams planned for the Mekong	-495 000 to -792 000	-23.4 to -37.8

Table 22 Production export, import and consumption*of the main non-fish, meat and milk products and their share of calorie and protein in Cambodia, Lao PDR, Thailand and Viet Nam (tonnes/y) during **2005-2007**
Source: Orr, et al. (2012)

	Products	Quantity 000 tonnes/y				Equivalent calorie value		Equivalent value	Protein
		Production	Import	Export	Consumed as food	10 Kcal/yr	Calorie share	Protein tonnes/y	Protein share
Cambodia	Beef and buffalo meat	70	0.2	0	70	53 643	12%	7 872	23%
	Eggs primary	17	0	0	16	22 240	5%	1 712	5%
	Milk	23	59.5	0	81	49 613	11%	2 684	8%
	Pig meat	131	0.1	0	132	290 400	63%	17 688	51%
	Poultry meat	26	0	0	26	48 100	10%	4 446	13%
	Sheep and goat meat	0	0	0	0	0	0%	0	0%
	Total	266	59.9	0	325	463 997	100%	34 402	100%
Lao PDR	Beef and buffalo meat	41	0	0	41	31 827	16%	4 671	29%
	Eggs primary	14	0	0	11	15 753	8%	1 213	8%
	Milk	7	27.7	0	27	16 673	8%	902	6%
	Pig meat	43	0	0	43	93 867	47%	5 717	35%
	Poultry meat	20	0	0	20	37 617	19%	3 477	22%
	Sheep and goat meat	1	0	0	1	2 630	1%	135	1%
	Total	125	27.7	0	144	198 367	100%	16 115	100%
Thailand	Beef and buffalo meat	299	2.3	3.5	296	228 177	4%	33 486	9%
	Eggs primary	817	0.1	11.7	621	863 190	17%	66 447	17%
	Milk	846	1 147.6	285.7	1 598	974 983	19%	52 745	14%
	Pig meat	805	0.5	10.2	793	1 743 867	34%	106 217	28%
	Poultry meat	1052	0.6	453.6	731	1 352 350	26%	125 001	33%
	Sheep and goat meat	1	0.7	0	2	5 260	0%	270	0%
	Total	3820	1151.9	764.5	4041	5 167 827	100%	384 166	100%

Viet Nam	Beef and buffalo meat	275	1.3	0.5	275	212 007	3%	31 113	6%
	Eggs primary	207	0	1.4	189	262 710	4%	20 223	4%
	Milk	247	823.6	2	908	590 683	8%	31 955	6%
	Pig meat	2449	5.7	14.5	2443	5 373 867	73%	327 317	66%
	Poultry meat	428	66.3	0	494	913 900	12%	84 474	17%
	Sheep and goat meat	10	0.6	0	11	28 930	0%	1 485	0%
	Total	3 616	897.5	18.4	4 380	7 382 097	100%	496 567	100%
	Lower Mekong nation total	7 827	2 137	782.9	8 891	13 212 287		931 250	

Note: Major portions of Thailand and Viet Nam are outside the Basin.
The consumption figures here do not fully tally with production plus imports minus exports due to wastages and reporting discrepancies.

Table 23 The equivalent losses in calories and protein value related to estimated loss in fish supply for domestic consumption as a result of dam construction. Elaborated from FAO (2001) and ICEM (2010a,b). Source : Orr et al. (2012)

		Cambodia	**Lao PDR**	**Thailand**	**Viet Nam**	**Mekong Basin**
National portion of Mekong Basin fish catch (%) (ICEM, 2010a)	Min	23	4	27	18	
	Max	51	8	35	34	
Scenario 1 (S1-11)						
Resulting losses in capture fish resources in 2030 basses on -340 000 tonnes per year (tonnes/y)	Min	78 200	13 600	91 800	61 200	340 000
	Max	173 400	27 200	119 000	115 600	340 000
Fish energy losses at 69 Kcal/100 g (kcal x 10^6/yr)	Min	53 958	9 384	63 342	42 228	234 600
	Max	119 645	18 768	82 110	79 764	234 600
Resulting energy lost as a portion of the non-fish meat and milk diet development (%)	Min	14	6	2	1	2
	Max	30	12	2	2	2
Fish protein losses at 11 g/100 g (tonnes/y)	Min	8 602	1 496	10 098	6 732	37 400
	Max	19 074	2 992	13 090	12 716	37 400
Resulting protein lost as a portion of the non-fish meat and milk (%)	Min	29	12	3	2	5
	Max	63	24	4	4	5
Scenario 2 (S2-88)						
Resulting net loss in fish resources in 2030 based on 495 000 to 792 000 tonnes per year (tonnes/y)	Min	113 850	19 800	133 650	89 100	49 500
	Max	403 920	63 360	277 200	269 280	792 000
Fish energy losses at 69 Kcal/100 g-net(Kcal x 10^6/yr)	Min	78 557	13 662	92 219	61 479	341 550
	Max	278 705	43 718	191 268	185 803	545 480
Resulting energy lost as a portion of the non-fish meat and milk diet (%)	Min	17	7	2	1	3
	Max	60	22	4	3	4
Fish protein losses at 11 g/100 g-net (tonnes/y)	Min	12 524	2 178	14 702	9 801	54 450
	Max	44 431	6 970	30 492	29 621	87 120
Resulting protein lost as a portion of the non-fish meat and milk diet (%)	Min	36	14	4	2	6
	Max	12	43	8	6	9

An increase in WF for the LMB countries may be a minimum increase of 4–7 percent under scenario 1, but would be considerably higher for two specific countries: Cambodia (29–64 percent) and Lao PDR (12–24 percent). Under scenario 2, the water increases are on average

6–17 percent, and rise considerably within Cambodia (42–150 percent) and Lao PDR (18–56 percent). Cambodia and Lao PDR are more vulnerable to change as a larger portion of their countries are dependent on fish protein; thus more resources are required to replace protein in these countries. The results suggest that basic food security is potentially at a high risk of disruption and therefore basin stakeholders should be fully engaged in strategies to offset these impacts.

3.1.3 Approach to quantify changes in the economic value of ecosystem services

The methodology of ICEM to quantify changes in the economic value of ecosystem services starts by establishing a baseline which differentiates between impacts of existing and definite development and impacts of planned development well into the future without mainstream projects. That approach allows the analysis to describe the incremental opportunities and risks of the LMB mainstream projects against two levels of basin development, the more distant coinciding with commencement of the mainstream projects operations if approved. The projected quantified changes were also based on secondary data, research data and consultation with local experts in the LMB.

3.2. Assessment of changing ecosystem services

This section assesses the economic value losses/gain due to change in ecosystem service from Business-as-usual to recommended policy options. Assessment of changing ecosystem services is based on ICEM (2010). Summary of estimated loss and gain of ecosystem services is showed in Tables 24 and 25.

Table 24 Estimated loss and gain of ecosystem services due to hydropower construction (in the year 2030 with 12 hydropower projects). Source: ICEM (2010).

Ecosystem services	Indicators	Gain/loss	Annual net loss/gain
Fisheries	Fish production	Loss (capture fisheries)	-340 000 tonnes/yr -US$476 million/yr
		Gain (reservoir fisheries)	-10 000 tonnes/yr -US$14 million/yr
	Ancillary and up-stream Industries (boat manufacture)	Loss (knock-on effect of fisheries loss)	-Loss of 2 million boats without engines, worth US$1 000-2 000 each - US$2-4 billion – likely to decline in proportion to the fisheries
Nutrient cycling	Nutrients	Loss of nutrients to the sediment plume	Loss of 4 535 tonnes of phosphates to marine area/year
		Loss (value of nutrients (Phosphates) to agriculture)	-Loss of 3 400 tonnes of phosphates to flood plains/year -Replacement value of fertiliser around US$ 24 million/year
Agriculture and forestry	Paddy production	Loss (inundated paddy and transmission lines)	-Loss of 7 962 ha of paddy -Loss of 22 475 tonnes of rice/year -Loss of US$4.1 million/year
		Gain (increased irrigation)	-Gain of 17 866 ha of paddy -Gain of 77 701 tonnes of rice/year -Gain of US$15.54 million/year
Tourism	Tourism revenues	Loss (degradation of natural resource base)	N/A
		Gain (HP project viewing)	N/A
Wetlands	Clean water supply,	Loss (due to reservoir	Loss of between US$4 million

	plants for food and medicines, fuel wood, water purification wildlife habitats groundwater recharge, flood control, carbon sequestration, storm protection etc.	creation)	and US$13.8 million per year

Table 25 Change due to Hydropower development for ecosystem services selected for the study

	Impacts	**Negative effects**	**Positive effects**
Food production	Losses in fish production	~400 000 tonnes/year ~ US$476 million/year	
	Gain in reservoir fisheries		~10 000 tonnes/year ~ US$14 million/year
Water quality			
- **Construction phase**	Increased sediment load	Increased fish mortality and reduced fish growth rates	
	Higher tubidity	Primary producer become less abundant	
	Increased organic matter	Increased solid and wastewater loading and spill to downstream areas	
	Flood large land area	Decomposition of vegetative matter	
- **Operational phase**		Reduced organic matter transport	
		By 2030, phosphorous and nitrogen levels would increase by 100 percent and 85 percent respectively.	
		Waste water discharge would increase by 35 percent	
		Increased risk of major pollutant events	
Biodiversity	Raised dry season water levels and decreasing sediment coming down the river	Reduce the diversity of the Lower Mekong Basin	
		Irrawaddy dolphin and giant Mekong catfish are likely to be threat to the extinction	
		Mollusks and amphibians (turtles, Siamese crocodiles) are threatened due to loss in habitat and loss of sand-bars and seasonal breeding grounds	
		At least 41 mainstream species out of 262 species in the ecological zone upstream of Vientiane are threatened by severe alteration of their habitat	
Carbon fixation and greenhouse gas emissions		Reduction in sediment load and flooding lead to reducing potential of Carbon fixation	
			Emission from the electricity sector would be reduced up to 50 million tonnes of CO_2/year

Table 25 continued

	Impacts	Negative effects	Positive effects
Nutrient cycling		Sediment load will be reduced by 75 percent (~6 600 tonnes/year) = US$2.64 million/year	
Income and livelihood support		Changes in farming, fishing, and transportation practices as well as recreational activities. People living in the dam area may also have relocated to new areas. The impacts are estimated to put the livelihoods at risk of some 4 360 000 people within the LMB (Lao PDR - 907 000; Thailand - 516 000; Cambodia – 1 212 000; Viet Nam – 1 725 000)	
			increase the navigability of the river
			increase the navigability of the river
Other ecosystem services (such as tourism)		Trip along Mekong more difficult.	
			large hydro-electricity projects also attract tourism

3.2.1 Food Production

Agriculture

Hydropower development in LMB can adversely affect agricultural productions due to changes in land use (inundated land) and changes in water flow patterns. It is estimated that a minimum of 9 000 hectares of suitable agricultural land will be inundated by the proposed Lower Basin mainstream dams (ICEM, 2010; William and Pearse-Smith, 2012). Severe flooding can also influence crops and livestock. In addition, reduction of river flow due to upstream hydropower development can result in salt-water intrusion, especially in the Mekong delta. Increases the salinity of agricultural land affect the fertility of the soil and production of rice and in severe cases, high content of salinity can render the land unsuitable for agricultural purposes. In Viet Nam, it is reported (Nhan et al., 2012) that annually, around 1.8 million ha is subject to dry season salinity, of which around 1.3 million ha is affected by saline water above 5 g/l and especially during low river flow periods between March and April, saline water intrudes up 40–50 km inland from estuaries through main river systems. The Vietnamese Ministry of Agriculture and Rural Development reported that, out of 650 000 ha of high-yielding rice grown in the lower delta, annually about 100 000 ha of rice is highly risky to dry-season salinity intrusion.

The net balance of agricultural opportunities and losses (including river bank gardens) would likely be negative. Increasing in agricultural activity planned in the irrigation schemes of the mainstream dams amount to US$15 million/year, while losses associated with agricultural land (US$5.4 million/year) and river bank gardens (US$20.7 million/year) would more than offset any potential gains (ICEM, 2010).

Consequently, the LMB mainstream projects would worsen the distribution of agricultural benefits among riverine communities with agricultural losses incurred along its entire length affecting in the order of 20 percent of the 11.9 million people dependent on the Mekong river, while the benefits would be localized at irrigation schemes near individual dam sites (ICEM 2010).

Fisheries

Hydropower development creates a number of environmental problems especially on fish stock and distribution. The major impact of dam construction is that dams create a physical barrier for fish migration and destroy fish habitats. For example, a study in Pak Mun Dam Thailand shows that after completion of Pak Mun dam, at least 50 fish species dependent on rapids have disappeared, and many other species declined significantly. Migratory and rapid dependent species were affected seriously as their migration route is blocked in the beginning of the rainy season together with the head pond that has inundated their spawning ground and the fish pass is not performing (Amornsakchai et al., 2010). In addition, reduced productivity of downstream and upstream aquaculture is likely to happen due to reduced feed (arising from reduced fish fecundity) (Knowles, 2014).

It is clear that damming the Mekong tributaries have altered fish community structure by restricting migratory species (Phomikong et al., 2014). Poor performance of existing fish ladders is a typically result from unsuitable designs for the height of a given migration barrier and ignorance of the behavior and swimming ability of local/native fish species. Fish migrations underpinned by hydrological and ecological connectivity are of paramount importance to the exceptionally high fish productivity and diversity of the Mekong river, but the existing mitigation measures obviously do not meet the requirements for sustaining this connectivity, putting the world's largest inland fisheries at risk.

A recent study of Kummu and Sarkkula (2008) concluded that dam developments will lead to flow alterations in the Mekong River. These flow alterations will threaten Tonle Sap Lake by changing the flood-pulse system of the lake. Relatively small rises in the dry-season lake water level would permanently inundate disproportionately large areas of floodplain, rendering it inaccessible to floodplain vegetation and eroding the productivity basis of the ecosystem. A study of Lamberts (2001) also stated that the impacts of dam constructions would be lower flood levels, less flooded area and higher dry-season flow rates. The timing of the flood cycle would likely be altered, which might result in the loss of the synchronization between the reproductive behaviour of (migratory) fish species and the hydrological events. This could have serious impact on fish migrations and the distribution of eggs and fry (van Zalinge et al., 1999) and a reduction of the flooded area also reduced access for fishers to the stocks.

The losses in fisheries directly due to LMB mainstream dams, if all were to proceed are expected to be worth US$476 million/year, excluding effects on the coastal and delta fisheries which are likely to be significant but have not been studied. Gains in reservoir fisheries are expected to be worth US$14 million/year (ICEM, 2010).

The LMB mainstream projects enter the basin at a time when tributary hydropower already threatens the diversity and size of the Mekong fishery. Fish yield in the Mekong is comprised to at least 35 percent of long-distance migrant species whose migrations would be barred by the proposed dams. The mainstream projects would fundamentally undermine the abundance, productivity and diversity of the Mekong fish resources, affecting the millions of rural people who rely on it for nutrition and livelihoods.

If 11 mainstream dams were in place, the total loss in fish resources would be ~400 000 tonnes compared to the situation in 2015 – ~340 000 tonnes of that estimate directly due to mainstream dams. The amount of protein at risk of being lost annually if 11 mainstream dams were built by 2030 represents 110 percent of the current total annual livestock production of Cambodia and Lao PDR (ICEM, 2010).

By 2030, reservoir fish production in all the tributary and UMB or LMB dams is likely to reach 53 000 tonnes/year (range of 15 000–240 000). Reservoir fisheries cannot compensate for the loss in capture fisheries and at best would produce one tenth of the lost capture fisheries production. In the long term, the reduction in sediment and nutrient outflow predicted for 2030 of from 50 percent to 75 percent of the current average annual load would have a major impact on coastal fish production, and subsequently on the Vietnamese fishing sector and fish trade – a sector which has shown strong growth in the last 10 years and produces some 500 000 tonnes of fish annually (ICEM, 2010).

LMB mainstream reservoirs are predicted to collectively produce 10 000 tonnes of fish per year, the best case scenario being in the order of 30 000 tonnes per year. Reservoir productivity is influenced by i) surface area; ii) storage volumes in the superficial layers of dam; iii) connectivity to upstream tributaries. In this context, aquaculture development needs to be given special consideration as an alternative mitigating the decline in capture fisheries.

Mekong marine fisheries are a productive component of the Mekong system and are dependent on the nutrient and sediment dynamics of the river. The Mekong marine fishery is a significant component of the Vietnamese delta economy, with a production in the order of 500 000–726 000 tonnes per year and utilizing almost 6 000 fishing boats. The Chinese mainstream and LMB tributary dams will induce a 50 percent reduction in the arrival of sediments and nutrients to the coastal zone by 2030. Therefore, sediment retention by dams is expected to have a major impact on coastal fish production, and subsequently on the Vietnamese fishing sector and fish trade. This would also impact the delta aquaculture sector, which is dependent on protein from marine 'trash-fish' to feed the aquaculture fish for feedstock.

3.2.2 Water quality

The impacts on water quality differ during construction and operational phases. Depending on the phasing of mainstream projects, the construction period impacts could be drawn out well beyond a single project construction phase of some 5 to 8 years (ICEM, 2010).

Construction: the adverse water quality impacts during construction are likely to be worst during the dry season.

- Increased sediment loads: rock blasting and earth moving activities are likely to increase sediment loads which could have significant localized implications smothering gravel beds and riffles downstream and have impacts on fish spawning. Sediment loading can clog gills of fish and invertebrates (food of fish) leading to increased mortality and reduced growth rates of fish.
- Primary producers become less abundant in the impacted area because of the higher turbidity and siltation from the earth works.
- There is likely to be diversion of flows during the construction phase and without an effective fish pass in place this will impede upstream and downstream migration

- Increased organic matter: increased solid and wastewater loading with localized implications
- Increased oxygen demand and nutrients: the Cambodian projects would flood large land areas causing the decomposition of vegetative matter.
- Spillages: localized implications from fuels, oils, toxic compounds, concrete & other construction materials' into the downstream areas.

Operational phase: the long-term implications of the LMB mainstream projects to the water quality of the Mekong river would be less severe than during construction:

- Reduced turbidity: the sediment load would drop by 75 percent (one third of which is directly related to the mainstream dams) this would in the long term reduce the turbidity of the water column.
- Reduced organic matter transport: The Mekong river transports a significant amount of vegetative and woody debris along its length which play an important role in the recycling of nutrients back into the Mekong system. The mainstream dams would cause the concentration of this matter within the reservoirs severing one of the important longitudinal bio-chemical connections between the headwaters and floodplains of the Mekong system.
- Cumulative effects: predictions suggest that by 2030; phosphorous and nitrogen levels would increase by 100 percent and 85 percent respectively, while waste water discharges would increase by 35 percent which may lead to seasonal localized reductions in water quality in some of the mainstream reservoirs.
- Increased risk of major pollution events: nutrients and products used during operations, for example transformer oil, have the potential to cause catastrophic impacts on water quality through spillages, leaks and component failure. For example, the ammonia nitrogen content in the pre-dam period was lower than in the post-construction period and increased sharply eight years after Manwan Dam was completed, due to the cumulative impacts of inundated plant decomposition, release from soil and sewage discharge, and decreased self-flushing and purification capacity in the reservoir. The total phosphorous content showed a similar trend (International Rivers, nd).

3.2.3 Biodiversity

Changing hydrology and sediment flows due to the development of upstream dams will alter the river morphology and the productivity of different parts of the river channel in the mainstream. Raised dry season water levels and decreasing sediment coming down the river will tend to reduce the diversity and productivity of the Mekong mainstream (ICEM, 2010).

The loss of habitats would encourage the proliferation of generalist species that can breed within the body of the reservoir and do not require specialized habitats or hydrological triggers to induce spawning. The fragmentation of the river system by the 11 mainstream dams would isolate aquatic populations into pockets leading to a loss of species.

The most significant biodiversity losses for fish species would be due to the barriers created by the dams that will disrupt upstream spawning migration, including also economically and biologically important species (ICEM, 2010; Dugan et al., 2010). In addition, the downstream drift of fish eggs and larval stages that sustain fisheries recruitment will be compromised, mainly because juvenile life stages will be trapped in the impoundments. Dams in the middle and lower reaches of the lower Mekong basin, including in the major tributaries, will stop the longest migrations and disrupt recruitment to the lower reaches of the river. A report shows that of the eight cascade dams, Mengsong Dam attracted the most concern regarding the impact on fisheries, as it was likely to block the passage of migratory fish from the Lower Mekong to the Buyuan River (International Rivers, nd). For Irrawaddy dolphin and giant Mekong catfish this is likely to be the final threat that will leadto them becoming extinct.

Liu et al., (2011) conducted fish surveys in 2009 and 2010 and found that the number of fish species reduced from 139 to 80, compared to historic data collected along the Lancang River in Yunnan. Dam construction has caused the loss of habitats for demersal fishes which are more adapted to fast flowing conditions, such as *Labeoninae* and *Cobitidae*, and the fish species that live in the middle and bottom layers of flowing water, such as *Siluridae*, *Sisoridae* and *Barbinae*, because the dams cause the loss of living habitat, reproduction areas and food.

Mollusks and amphibians (turtles, Siamese crocodiles) are also vulnerable to hydropower projects due to the loss in habitat and loss of sand-bars and seasonal breeding grounds. River dependent birds that rely on exposed sand bars and riverbanks for breeding and nesting would also suffer from lost habitats (birds to be affected such as various storks (painted and woolly necked), greater and lesser Adjutants, and ibises such as the Great Ibis, Black-shouldered Ibis, endangered River Terns and the endemic Mekong wagtails) (ICEM, 2010).

It is also expected that 25 000 ha of forest land would be inundated, together with the 8 000 ha of cultivated land due to 10 of the LMB mainstream projects. Much of the forests adjacent to the Mekong are already rather degraded, although some mature river bank vegetation would be lost. Flooded forests and shrub lands in the river channel, especially in the reservoirs of Pak Chom, Ban Koum and the two Cambodian dams would be lost. The two Cambodian dams differ in that they would flood larger areas, including forest and cultivated land - Sambor alone would flood more than 16 000 ha of terrestrial lands (almost 50 percent of the total).

The reservoirs would change the landscape of the Mekong river valley, permanently maintaining the water levels above the current high flow levels with little seasonal change. In some reaches of the river (5-10 percent) immediately up stream of the dam walls water levels would be above any in recorded history and above the levels associated with the 1 in 1 000 year flood event. 1 370 km^2 of riverine terrestrial lands would be permanently inundated by the elevated water levels of the 11 LMB mainstream reservoirs.

The projects would have an impact on terrestrial and aquatic biodiversity which is of international significance – about half the length of the Lower Mekong has been recognized as Key Biodiversity Areas.

- 80 percent of the Key Biodiversity Areas (KBA) along the Mekong River would be affected by the dams with loss of landscape value, habitat diversity and breeding and feeding areas for characteristic species, especially birds.
- The globally important Siphandone wetlands would be directly affected with reduced seasonal variability and loss of wetland habitats
- An internationally Ramsar site above Stung Treng would be directly affected. Notification to the Ramsar Convention Secretariat that the Stung Treng site should be placed on the Montreux Record of threatened wetlands with designation being likely if the Stung Treng dam is built.

At least 250 000 ha of floodplains will be lost by 2030 due to the proposed tributary projects. This will reduce the available habitat putting increased pressures on the fishery: In 2000, 20.6 percent of the Lower Mekong Basin was already barred by 16 dams and was inaccessible to fish species having to migrate to the upstream parts of the river network.

- In 2015, this area will have increased by 14 percent (from 164 000 to 188 000 km^2);
- By 2030, the presence of 77 tributary dams in the basin by 2030 will result in obstruction of 37 percent of fish migration routes.

If all LMB mainstream dams proceed, 55 percent of the Mekong River between Chiang Saen and Kratie would be converted into reservoir, shifting the environment from riverine to lacustrine. This would have major impacts on species composition and productivity:

- The reservoirs resulting from dam construction would flood critical riverine wetland habitats along the Mekong channel, resulting in the loss of 76 percent of all rapids; 48 percent of all deep pools; and 16 percent of all sand bars in the section between the Chinese border and Sambor.

- Reservoirs would not be able to support the same fish species diversity as the more diversified natural riverine system, and would result in a loss of the number of Mekong fish species. An additional 58 000 hectares of floodplain habitat would be lost due to dam development and subsequent changes in flooding.

At least 41 mainstream species out of 262 species in the ecological zone upstream of Vientiane are threatened by a severe alteration of their habitat. There is no information as to whether any of these species threatened can complete their life cycle in reservoirs. The family most exposed would be *Balitoridae* (river loaches), with about 10 percent of its 93 Mekong species at risk. The iconic, endemic and critically endangered Mekong Giant catfish would become extinct in the wild since its main breeding area is located in this area, near Chiang Saen. However, beyond these 41 mainstream species, it is not possible to separate the impacts of the 6 proposed mainstream dams from the 17 proposed tributary dams.

Impacts of the middle and lower clusters of dams on biodiversity are unclear. Fish biodiversity in these zones is high (386 and 669 species respectively) and would decrease, but the specific impact of mainstream dams compared to that of other drivers such as land use changes, habitat fragmentation or agricultural intensification could not be quantified.

Fifty-eight species are highly vulnerable to mainstream dam development and a further 26 species are at medium risk of impact. Those 86 species only represent species at risk because of their migratory behavior; the figure does not include the many species at risk because of environmental changes brought about by dams (e.g. another 41 species found only in the mainstream upstream of Vientiane are at risk if a cluster of 6 dams turns 90 percent of this river section into a reservoir). Overall the total number of species at risk of mainstream dam development is likely to be greater than 100 but is not precisely known.

The mainstream projects are likely to result in serious and irreversible environmental damage, losses in long-term health and productivity of natural systems and losses in biological diversity and ecological integrity. The largest impact on the riverine terrestrial system would affect wetlands. Almost 40 percent of the Mekong River's wetlands lie within reaches of the river where projects are located - 17 percent of which would be permanently inundated by the LMB mainstream projects.

The MRC's BWDS Report estimated that the 20-Year Plan scenario would result in wetland losses valued at US$225 million. This is because changing hydrology and sediment flows resulting from the dams in China and the tributaries will alter the river morphology and the productivity of different parts of the river channel in the mainstream. Raised dry season water levels and decreasing sediment coming down the river will tend to reduce the diversity and productivity of the Mekong mainstream (TCEB, 2010). It is estimated that the cascade of 8 dams planned for Yunnan Province and the tributary projects of the LMB will reduce the sediment load of the Mekong River by 50 percent at Kratie and in the order of 80 percent in Chiang Saen-Vientiane. A significant load of nutrients is attached to these sediments resulting in a significant reduction in nutrient loads, which will further reduce the productivity of the Mekong system.

3.2.4 Carbon fixation

Although there is no scientific report regarding carbon fixation in LMB, a study conducted in the Amazon River, similar climatic conditions to Mekong River, shows that the river plume supports nitrogen fixation far from the river mouth and provides important pathways for atmospheric carbon dioxide sequestration in the western tropical North Atlantic. It was found that the dominant species change as the water moves away from the mouth of the river. Diatoms, which are large chain-forming cells, sink rapidly when they die and carry organic carbon – incorporated into their cells when they were alive as part of the photosynthesis process – down to the sea floor. Phytoplankton thus becomes a vector, or long-term sink for atmospheric carbon dioxide (Dumé, 2008). Therefore any reduction in sediment load and flooding will lead to a decrease in associated nutrient replenishment for phytoplankton and thus reducing potential of C fixation (see more in nutrient cycling section).

3.2.5 Green House Gas

Hydropower projects and reservoirs are considered as a source of greenhouse gasses (carbon dioxide, methane and nitrous oxide) from the decomposing of organic matter.

The "fuel" for these emissions is the decomposing of organic matter from the vegetation and soils flooded when the reservoir is first filled. The carbon in the plankton and plants that live and die in the reservoir, the detritus washed down from the watershed above, and the seasonal flooding of plants along the reservoir fringes, ensure that emissions continue for the lifetime of the reservoir. Emission levels vary widely between different reservoirs depending upon the area and type of ecosystems flooded, reservoir depth and shape, the local climate, and the way in which the dam is operated. For instance, China's reservoirs are often deep but sludge-filled, while Brazil's reservoirs are shallow and in a tropical zone. Both cases can lead to high emissions (**Figure 12**).

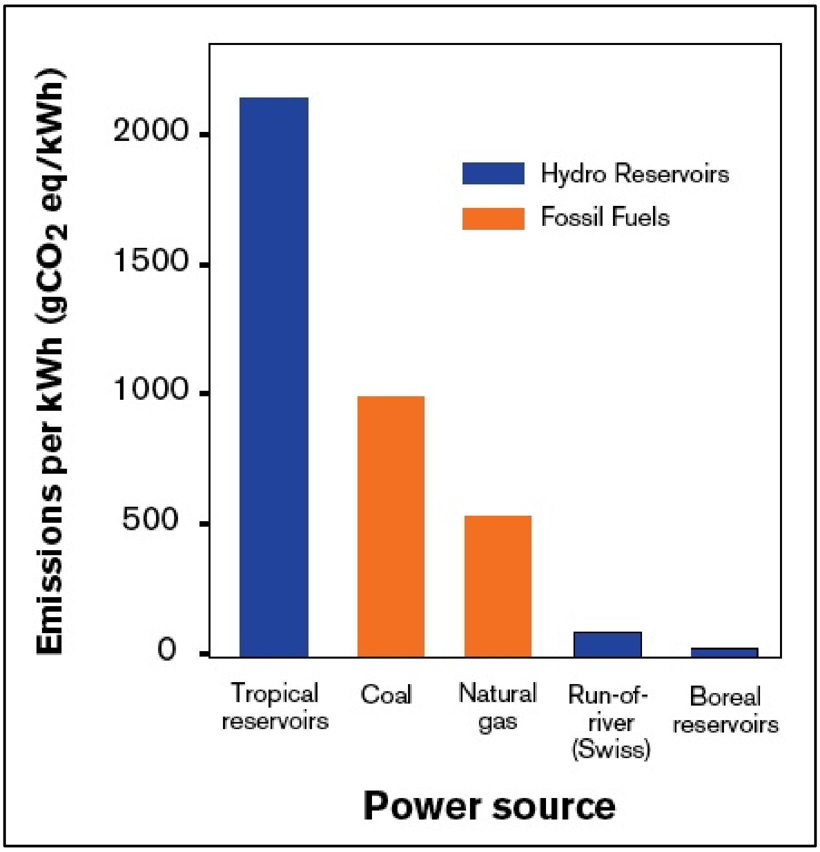


Figure 12 Greenhouse gases emissions from different power sources
Source : International Rivers (2008)

Therefore, increases of inundated land (minimum of 9 000 hectares) due to hydropower development of LMB can result in greenhouse gas emissions.

However, the 11 LMB mainstream reservoirs have the potential to reduce the emissions of the regional power sector too. The MRC's BWDS Report estimates that if 11 dams were built along the mainstream Mekong, emissions from the electricity sector would be reduced by up to 50 million tonnes of CO2 per year by 2030. The MRC's SEA Report estimates a similar amount and estimates that the net impact will be within a range of 40–50 million tonnes per year (Knowles, 2014).

3.2.6 Nutrient cycling

Any reduction in sediment load and flooding (nutrients are part of these sediments) will lead to a decrease in productivity and in associated nutrient replenishment measured as loss of phosphates due to sediment trapping at each of the dams.

According to ICEM (2010), in the 2030 with LMB mainstream scenario, sediment load will be reduced by 75 percent (25 percent due to mainstream dams) or to ~6 600 tonnes/year. The reduced sediment load will have critical impacts on the natural and human systems which rely on these nutrients, including primary production, flooded forests, floodplain fisheries and agriculture, specifically:

- Cambodian floodplain: the Cambodian Floodplain is naturally fertilised by nutrients attached to suspended sediments, the mainstream dams will reduce loading from 4 000 tonnes/year to less than 1 000 tonnes/year.

- Mekong Delta floodplain: the Mekong delta freshwater area relies on overbank siltation for enriching agricultural land adjacent to the delta channels and primary canal network, the mainstream dams will reduce loading from 4 000 tonnes/year to 1 000 tonnes/year.

- Tonle Sap productivity: there is a correlation between sediment load and aquatic productivity in the Cambodian floodplain and the Tonle Sap system. If mainstream dams halve nutrient input on top of the reductions expected by tributary and Chinese hydropower (from ~5 500 tonnes to 2 250 tonnes to 1 200 tonnes per year) an impact on primary production is to be expected. This will in turn have an impact on Tonle Sap fish resources (60 percent of Cambodia's yield), in addition to the loss of at least 309 000 ha of floodplains forecasted by 2030 if all dams are constructed.

Significant reductions in the transport of fine material, because of the operation of reservoirs with large storage in China and on major tributaries will also impact on the nutrient load in the Mekong marine sediment plume. This is because the productivity of the Mekong delta coastal fishery is due to the shallow coastal shelf, preponderance of estuarine environments and the deposition of approximately 60 percent of the Mekong sediment load. Coastal fishery zones will experience reduced primary production with implications for the whole marine fisheries and industries that rely on these fisheries (ICEM, 2010).

The LMB and tributary dams will induce a 50 percent reduction in the arrival of sediments and nutrients to the coastal zone. This will have a significant impact on marine fisheries, though the magnitude and time-scales remain unclear.

The load of suspended sediment in the Mekong River is estimated at 160–165 million tonnes/year. In the order of 50 percent of the load will be removed by storage hydropower projects in China and the 3S rivers. With all 12 LMB mainstream dams the sediment load would be halved again – i.e. at Kratie it would be 25 percent of the current load (~42 million tonnes/year). This reduced suspended load will have significant implications for the transport of nutrients which naturally fertilize the Tonle Sap system and 23 000 – 28 000 km^2 of floodplain in Cambodian and Viet Nam, as well as destabilizing the river channels, floodplains and coastline of the Mekong Delta.

The 2030 trend without LMB mainstream dams is for the supply of fine sediments and nutrients to the floodplains and delta of the Mekong River will be halved. This will impact on some 18 000 km^2 of Cambodian floodplain and 5 000-10 000 km^2 of Mekong Delta floodplain as well as reducing the nutrient load in the Mekong marine sediment plume.

Table 26 Indicative changes to the fate of sediment downstream of Kratie: the 20Y foreseeable future is predicted to halve the sediment load arriving at primarily due to trapping by the dams.
Source: TCEM (2010)

Site of Deposition	Average Annual Deposition Volume	
	Baseline	**20Y without LMB mainstream dams**
	Sediment (Mt/yr)	**Sediment** (Mt/yr)
Kratie : annual sediment transport rate	165	88
Cambodian floodplain	25	13
Tonle Sap flood pain	9	5
Mekong Delta floodplain	26	14
Mekong river mouth	5	3
Ca Mau Peninsula	<1	0
Offshore coastal shelf (<20km from the coast)	100	53

3.2.7 Income and livelihood support

Hydropower projects are likely to affect the way of life since most (80 percent) of the Mekong riverine communities are dependent on the natural resources of the Mekong River for their livelihoods (ICEM, 2010). The changes predicted for the mainstream projects would require changes in farming, fishing, and transportation practices as well as recreational activities. People living in the dam area may also have relocate to new areas, principally due to inundation for reservoirs but also due to riverbank erosion (Knowles, 2014).

For the definite future scenario combined impacts of principally reservoir construction and wetland productivity reduction are estimated to put the livelihoods at risk of some 4 360 000 people within the LMB (Lao PDR - 907 000; Thailand - 516 000; Cambodia – 1 212 000; Viet Nam – 1 725 000.

People in LMB rely mainly on fish which are the main source of protein. A report of Dugan (2010) states that the hydrological and sedimentation schemes are fundamental for the habitat where fish live and reproduce and therefore altering the hydrological and sedimentation schemes and blocking fish migration will potentially cause the reduction and loss of inland fish production and change of fish composition in the Mekong River, and lead to food security and livelihood risks. Furthermore, the reduction of sedimentation deposit and the seawater intrusion will affect the highly productive agricultural and rice fields in the region, which depend on the nutrients that the Mekong River transports in its sediment, and therefore create even bigger challenges in food and livelihoods of the people in LMB.

ICEM (2010) also shows that loss of river bank gardens (RBGs) in the reservoir areas, and for some distance below dams would affect 450 000 households, with some significant impacts on livelihoods of riparian communities including the loss of an important rural food source.

Health issues related to water resource management in LMB are likely to affect livelihood of people in the LMB. In particular, the transmission of schistosomiasis in the lower Mekong Basin is of concern and has occurred due to the snail intermediate host *(Neotricula aperta)*. In the Pak-Mun dam in Thailand it is suggested the dam may have affected a spike in population density immediately after its completion (Attwood and Upatham, 2013).

Although dam construction projects appear to have adverse effects, mainstream hydropower is likely to increase the navigability of the river as it will increase the depth of the river along significant stretches (ICEM, 2010). Large hydro-electricity projects also reduce flood problems and increase land productivity and rice production in some areas due to irrigation projects associated with the hydropower developments (ICEM, 2010).

3.2.8 Cultural ecosystem services

Significant changes to cultural ecosystem values of the river would affect the social, cultural and religious structure of communities along the river, especially those adjacent to the reservoirs or immediately downstream of the dams. For example, changes and loss of relevance may be expected in festivals and cultural events associated with the river and its seasons (ICEM, 2010). In term of tourism, the perception and willingness to pay for river based activities of visitors and tourists to the Mekong region would be affected, especially during the construction period, and tourism products and marketing would have to be changed once the dams and reservoirs have been created to redevelop river based tourism. The negative impacts of hydropower on tourism can also be large due to the degradation of natural assets that already generate, or have the potential to generate tourism revenue.

Impacts on transport could also be negative if dams make trips along the Mekong more difficult, due to the hindrance of dam walls or due to unpredictable water flows (Knowles, 2014). On the other hand large hydro-electricity projects also attract (mainly domestic) tourism (for example Hoa Binh dam in northern Viet Nam)**.** The MRC estimates that between 20 000 and 25 000 tourists a year take trips on the upper Mekong. More than 85 percent of these tourists travel by boat between Houei Sai and Luang Prabang in Lao PDR. This is part of a popular longer route between Chiang Mai and Luang Prabang, that involves land travel. The boat trip itself has been reported as costing US$30, with accommodation costing US$10 and land transport required for the trip costing a further US$10. Based on this, we can estimate that Upper Mekong tourists have direct trip expenditure (not counting other incidental purchases) in the magnitude of US$1 million per year (Knowles, 2014).

4. SUMMARY, CHALLENGES AND AVENUES FOR FUTURE RESEARCH

The Mekong River is a trans-boundary river that flows through six countries including China, Myanmar, Lao PDR, Thailand, Cambodia and Viet Nam. In addition, the river is ranked the world's 12th longest river (4 350 km) and the world's 8th average annual discharge (457 km^3/year) and can be divided into two basins (the Upper Mekong Basin (UMB) and the Lower Mekong Basin). The Lower Mekong Basin encompasses Myanmar, Lao PDR, Thailand, Cambodia and Vietnam (76 percent). A wide variety of natural resources support local people in term of food sources, shelters and medicine. There are 60 million people living in the LMB and the livelihood of people relies on goods and services provided by the LMB ecosystem. The LMB is among the most biologically rich and diverse places on earth.

This report gives an overview on the value of ecosystem services in the Lower Mekong River basin at the current situation and assesses the impacts of proposed hydropower development projects to ecosystem service values based on the review of published literature. The services provided by ecosystems are categorized as: provisioning services, regulating services, cultural services and supporting services. Future scenarios were used to estimate the potential changes of ecosystem's goods and services that are likely to be affected by dam development projects within the LMB. Several hydropower dams are being/will be constructed in the main stream and tributaries of the Mekong River by 2030. Overall, our assessment shows that their impacts on ecosystems, fisheries productivity and livelihoods, including nutrition, will be negative.

The development projects of hydropower within the LMB potentially put pressure on all ecosystem goods and services, but especially inland fisheries. The overall prospects of inland capture fisheries and fresh water aquaculture in the region are reduction of fish production and a loss of the number of fish species due to physical barriers, changes in river flow patterns and sediment loads, deteriorated environmental conditions and losses of fish habitats. The expected losses of inland fisheries production are also high. Losses directly due to LMB mainstream dams are expected to be worth US$476 million/year, which is far from the gains from reservoir fisheries of US$14 million/year in the constructed reservoirs. The net losses in fisheries are valued at more than US$450 million/year. The reduction in sediment load would have an impact on agricultural productivity; the value of fertilizer to replace the losses is estimated to be US$24 million/year. There are both gains and losses in agriculture production, the losses due to inundated paddy fields is estimated around US$4.1 million/year while the gains from increased irrigation area is higher at US$15.54 million/year. The impacts of development projects on regulating, supporting, and cultural values of ecosystem service are hard to predict and estimate e.g. biodiversity, water purification, and tourism. The rough estimated ecosystem service function losses due to loss in wetland area range between US$4 million/year to US$13.8 million/year. Although some people will gain from the project, most of the people will incur losses. Considering how to compensate the losses due to the dam development is very important.

The most important trade-offs in ecosystem dependency and provisioning in the region are fish production and fish biodiversity (the second most diverse river in the world with 877 species of fish) that the ecosystem provides to millions of people in this region. Moreover, fisheries and aquaculture are believed to have enormous potential to provide poor people with more jobs, more food with better nutrition and increased incomes. Fisheries and aquaculture also stimulate economic growth and offer greater diversification of livelihoods (Sinh et al., 2014). There are many rare and endangered fish species such as the world largest Mekong giant catfish (*Pangasianodon gigas*) that are already at risk.

Agricultural production would also be reduced due to changes in land use and water flow patterns. A minimum of 9 000 hectares of suitable agricultural land is expected to be inundated. Losses of agricultural land and river bank gardens would be around US$ 5.4 million/year and US$ 20.7 million/year, respectively. The expected losses of inland fishery production are also high. The losses in fisheries directly due to LMB mainstream dams are expected to be worth US$ 476 million/year, excluding coastal and marine fishery production. Water quality conditions of the Mekong River are likely to be poorer during construction and operational phases. Constructed barriers and reduction of sediment loading could also have adverse and cumulative effects on nutrient cycling and biodiversity, especially fish species. In the 2030 with LMB mainstream scenario, it is estimated that sediment load will be reduced by 75 percent or approximately 6 600 tonnes/year. Reduction in sediment load will lead to a decrease in associated nutrient replenishment for phytoplankton and thus reducing potential of C fixation. Hydropower projects and reservoirs are also considered as a source of greenhouse gasses from the decomposing of plants in the reservoirs. Due to losses of agricultural land, biodiversity and other services, hydropower projects are likely to negatively affect the Mekong riverine communities in term of quality of life, income and health as well.

Low income people are possibly the most vulnerable party and mostly affected by the dam development since they do not have many other options in life. Most poor people (e.g. households in the Tonle Sap area) rely mainly on natural resources and therefore destruction of resources due to development would lead to problems of local people. A study of TCEB (2010) reported that poor households would be adversely affected by the direct impacts of hydropower development including resettlement, loss of land, and impacts during the contraction period. Loss of fisheries and associated proteins would also lead to declines in nutritional health in LMB populations.

It is worth noting that the main limitation of this study is lack of scientific and economic research specific to the conditions in the LMB. Missing data that are needed included economic values of nutrient cycling, biodiversity, GHG emission and water quality. In addition, there are also only a few and limited case studies available. The secondary data available were obtained from specific areas but not at the landscape level, thus it might not always be representative data of the whole river basin. More information on the linkage between the ecosystem structures/situations and the ecosystem services and the benefits they provide is needed before the valuation process. Most of the studies reviewed were done a long time ago and the socioeconomics, behaviors, attitudes, and life styles of people in the LMB are likely to have changed substantially. Additionally, prices and markets for most ecosystem services do not exist, and more primary ecosystem services valuation studies are needed for more accurate estimations of values at basin level and better quantification of degrees of uncertainty in trade-off analyses.

Potential impacts from the hydropower development projects must be analyzed at regional level using an integrated system approach. The data analysis should take into account the individual country and transboundary areas as well as the landscape level. There is a need to reassess several of the dams planned. To this end, the new regional agreement on tributary development of the Mekong River Data at basin level should be taken into account (Ziv et al., 2012). Adaptation and mitigation strategies need to be identified where the potential risks are critical and seriously affect the local livelihoods. Other sources of renewable and clean energy production from wind and sunlight may also be an alternative for securing energy consumption and the demand of people in the region in return of sustainable ecosystem good and services in the LMB. In addition, regional experts, scientists and other parties should carry out research/studies together to fill research gaps in the mentioned topics in order to provide data that could support strategic decisions. Regular monitoring of the environment and ecosystem services in the LMB should also be conducted to detect any changes that might occur along the dam development projects. The assessment of ecosystem service of the LMB is critical for supporting the decisions on the potential impacts of hydropower development to ensure the sustainable development of the region.

5. CONCLUSION

The Lower Mekong Basin is a source of ecosystem goods and services to 60 million people that live within the basin. People have relied on the Mekong's resources, for thousands of years, especially from inland capture fisheries and more recently from aquaculture, and the river forms an integral part of local culture. However, several hydropower development projects have been proposed and these may pose major threats to people's livelihoods and the ecosystems in the basin. Therefore, effective management of the transboundary Mekong River is needed including integration of science and technology, society and political aspects. International cooperation for sustainable development in Mekong river basin can play a key role among member countries in optimizing the contribution of these projects in a sustainable way.

Every nation in the region has to sit together to discuss and to reach consensus on every single development project based primarily on sustainability of the Mekong River. In addition, expanding civil society engagement in the development of LMB is one of the key successes to sustainability of the LMB. Successful management also requires benefit-sharing mechanisms that encompass all institutional means for distributing equal benefits from any development projects within the Mekong Basin. Indeed, there are still research gaps and limited information on ecosystem services (production of fishery resources in rice fields, nutrient cycling, carbon fixation, GHG emissions) and socioeconomic conditions, particularly in projecting future scenarios. Therefore we urgently need more research and studies to bridge the knowledge gap and data.

REFERENCES

Amornsakchai, S., P. Annez, S. Vongvisessomjai, S. Choowaew, Thailand Development Research Institute (TDRI), P. Kunurat, J. Nipupanon, R. Schouten, P. Sripapatrprasite C. Vaddhanaphuti, C. Vidthayanon, W. Wirojanagud and E. Watana. 2000. *Pak Mun Dam, Mekong River Basin, Thailand.* A WCD Case Study prepared as an input to the World Commission on Dams, Cape Town, www.dams.org

Attwood, S.W. and S. Upatham. 2013. A population growth trend analysis for *Neotricula aperta*, the snail intermediate host of *Schistosoma mekongi*, after construction of the Pak-Mun Dam*. Negl. Trop. Dis*. 2013 Nov; 7(11): e2539.

Baran, E., T. Jantunen and C.K. Chong. 2007 *Values of inland fisheries in the Mekong River Basin*. World Fish Center, Phnom Penh, Cambodia. 76 p.

Barlow, C. 2002. *Size and value of the fishery in the LMB*. Textbox p. 13-14 in Sverdrup-Jensen, S. (ed.). *Fisheries in the Lower Mekong Basin: status and perspectives.* MRC Technical Paper No. 6, Mekong River Commission, Phnom Penh. 103 pp.

Barros, N., Cole, J.J., Tranvik, L.J., Prairie, Y.T., Bastviken, D., Huszar, V.L.M., del Giorgio, P. and Roland, F. (2011) Carbon emission from hydroelectric reservoirs linked to reservoir age and latitude. *Nature Geoscience Letters online*, 4: 593-596.

Beasley, I, B., Lars, and M, Helene. 2010. *Dolphin-Watching Tourism in the Mekong River, Cambodia: A Case Study of Economic Interests Influencing Conservation*. Accessed 24/6/15, www.researchgate.net/publication/242575795

Belton, B., D.C. Little and L.X. Sinh.2011. The social relations of catfish production in Vietnam. *Geoforum*, 42(5): 567–577.

Bosma, R., P.T. Anh, and J. Potting. 2011. Life cycle assessment of intensive striped catfish farming in the Mekong Delta for screening hotspots as input to environmental policy and research agenda. *International Journal of Life Cycle Assessment*, 16: 903–915.

Cacaud, P. & Latdavong, P., (2009). *Fisheries and aquaculture in the Lao PDR – a legislative review*. FAO Regional Office for Asia and the Pacific, Bangkok, Thailand. RAP Publication 2009/05, 71 pp.

Camber, Z. NA *The role of low value fish in aquaculture in Cambodia after ban on the cultivation of Giant Snakehead- Socio-economic impact assessment*. Master Degree project thesis in Ecotoxicology, Department of Systems Ecology, Stockholm University.

Chen, H., Y. Wu, X. Yuan, Y. Gao, N. Wu, and D. Zhu (2009) Methane emissions from newly created marshes in the drawdown area of the Three Gorges Reservoir. *Journal of Geophysical Research*, 114, D18301. doi:10.1029/2009JD012410

Chong, J. 2005. *Valuing the role of wetlands in livelihoods: constraints and opportunities for community fisheries and wetland management in Stoeng Treng Ramsar Site, Cambodia*. IUCN Water, Nature and Economics Technical Paper No. 3, IUCN — The World Conservation Union, Ecosystems and Livelihoods Group Asia, Colombo.

David J.H. Blake (WA). NA. *Integrated rice and fish culture/capture in the lower Songkhram River basin, northeast Thailand*. pp 97-107.

Duchemin, É., Lucotte, M., St-Louis, V. and Canuel, R. (2002) Hydroelectric reservoirs as an anthropogenic source of greenhouse gases. *World Resources Review*, 14: 334–353.

Dugan, P.J., C. Barlow, A.A. Agostinho, E. Baran, G.F. Cada, D. Chen, I. G. Cowx, J. W. Ferguson, T. Jutagate, M. Mallen-Cooper, G. Marmulla, J. Nestler, M. Petrere, Economist. 2015. *Hydropower in Vietnam: full to bursting*. Accessed 24/6/15, www.economist.com/news/asia/21638178-hydro-electric-projects-can-spell-trouble-rural-poor-full-bursting

Dumé, B. 2008. *Tropical rivers enhance carbon sequestration*. Accessed 24/6/15. http://environmentalresearchweb.org/cws/article/news/35489

Fisher, M.J. and S.E. Cook. 2012. *Water, food and poverty in River Basins: defining the limits*. Routledge, Oxon.

Fougeirol, D. 2007. *Mekong River transboundary water quality monitoring (learnings from a case study*). Accessed 24/6/15, http://www.inbo-news.org/

Fredén, F. 2011. *Impacts of dams on lowland agriculture in the Mekong River catchment*. Department of Earth and Ecosystem Sciences Lund University. 37 pp.

Frenken, K. (2012). *Irrigation in Southern and Eastern Asia in figures*.

Garaway, C. and K. Lorenzen. 2001. Developing fisheries enhancement in small Water bodies: lessons from Lao PDR and Northeast Thailand. In: *Reservoir And Culture-Based Fisheries: Biology and Management*. Edited by S.S. de Silva. 2001. ACIAR Proceedings 98. Canberra: ACIAR. pp. 227-234.

GiZ. 2014. Training Manual on Hydropower and Economic Development.

Guttman, H. 1999. *Rice fields fisheries – A resource for Cambodia*. Naga, the ICLARM Quarterly 22 (2): 11-15.

Henriksson, P.J.G., Zhang, W., Nahid, S.A.A., Newton, R., Phan, L.T., Dao, H.M., Zhang, Z., Jaithiang, J., Andong, R., Chaimanuskul, K.,Vo, N.S., Hua, H.V., Haque, M.M., Das, R., Kruijssen, F., Satapornvanit, K., Nguyen, P.T., Liu, Q., Liu, L., Wahab, M.A., Murray, F.J., Little, D.C., Guinée, J.B., 2014. *Final LCA Case Study Report - Results of LCA Studies of Asian Aquaculture Systems for Tilapia, Catfish, Shrimp, and Freshwater Prawn.* SEAT Deliverable Ref D 3.5. Leiden, Netherlands, 165 pp.

Hortle, K.G., S. Lieng and J. Valbo-Jorgensen. 2004. *An introduction to Cambodia's inland fisheries.* Mekong Development Series No. 4. Mekong River Commission, Phnom Penh, Cambodia. 41 pages. ISSN 1680-4023

Huysveld, S., T. Schaubroeck, S.D. Meester , P. Sorgeloos, H.V. Langenhove , V.V. linden,and J. Dewulf. 2013. Resource use analysis of Pangasius aquaculture in the Mekong Delta in Vietnam using Exergetic Life Cycle Assessment. *Journal of Cleaner Production* 51: 225-233

ICEM. 2010. *MRC Strategic Environmental Assessment (SEA) of hydropower on the Mekong mainstream,* International Center for Environmental Management Hanoi, Viet Nam.

Ikeguchi, A., M.L., Lam, and N.L. Duong. 2008. The rice-fish aquaculture system and marketing in the Mekong delta, Vietnam. *The Social Sciences, Journal of the Faculty of Education and Human Sciences,* Yokohama National University, no 10, February. P 11-17.

International Rivers. 2013. *A Transboundary Water Crisis*. Accessed on 24/6/15. www.internationalrivers.org

International Rivers. 2008. *Dirty Hydro: Dams and Greenhouse Gas Emissions*. Accessed on 24/6/15. www.internationalrivers.org

International Rivers. Nd. *Environmental and Social Impacts of Lancang Dams. Accessed* 24/6/15 www.internationalrivers.org/files/attached-files/ir_lancang_dams_researchbrief_final.pdf

International Rivers. 2008. *Power Surge; the impacts of rapid dam development in Laos*. Accessed 24/6/15 file:///C:/Users/Admin/Downloads/intl_rivers_power_surge.pdf

International Rivers. 2008. *Reservoir Emissions*. Accessed on 24/6/15. http://www.internationalrivers.org/campaigns/reservoir-emissions

Kamoto, M. and M. Juntopas. 2011. *Lower Mekong Basin -Existing environment and development needs- In* S. Haruyama. 2011. *Human and Natural Environmental Impact for the Mekong River*, pp. 25–42.

Khonchantet, Y. 2007. Valuation of fishery and non-timber forest products of seasonally flooded forest in the Lower Songkhram River Basin, Nakhon Phanom. *Environment and Natural Resources Journal*, 5(2): 173-181.

Knowles,T. 2014. *Training Manual on Sustaining River Basin Ecosystems*. German Federal Ministry for Economic Cooperation and Development (BMZ).

Kristensen, J. (2001, February*). Food security and development in the Lower Mekong River Basin: A challenge for the Mekong River Commission*. In Asia and Pacific Forum on Poverty: Reforming Policies and Institutions for Poverty Reduction held at the Asian Development Bank, Manila (pp. 5-9).

Kummu, M. and O. Varis. 2007. Sediment-related Impacts Due to Upstream Reservoir Trapping, the Lower Mekong River*. Geomorphology* 85: 275-293.

Kummu, M and J. Sarkkula. 2008. Impact of the Mekong River flow alteration on the Tonle Sap flood pulse. *Ambio.* 37(3):185-92.

Lamberts, D. 2001. *Tonle Sap fisheries: a case study on floodplain gillnet fisheries in Siem Reap, Cambodia*. FAO Regional Office for Asia and the Pacific, Bangkok, Thailand. RAP Publication 2001/11, 133 p.

Liu, M. 2011. Fish species composition and distribution in Lancang River in Yunnan. *Journal of Fishery Sciences of China*, 18(1): 156-170.

Lu, X. X. and R.Y. Siew. 2006. Water discharge and sediment flux changes over the past decades in the Lower Mekong River: possible impacts of the Chinese dams. *Hydrology and Earth System Sciences* 10: 181-195.

Navy, H. and M. Bhattarai. 2009. Economics and livelihoods of small-scale inland fisheries in the Lower Mekong Basin: a survey of three communities in Cambodia. *Water Policy*. 11 (Supplement 1): 31–51.

Mekong River Commission. 2008. *An assessment of water quality in the Lower Mekong Basin*. MRC Technical Paper No.19. Mekong River Commission, Vientiane. 70 p.

Mekong River Commission. 2002. *Fisheries in the Lower Mekong Basin: Status and Perspectives*. MRC Technical Paper No. 6 (May).

Mekong River Commission. 2009. *MRC's role in agriculture and agricultural water management strategy paper*

Mekong River Commission. 2010. *State of the Basin report 2010*. In: Taylor, R. (ed.). Mekong River Commission. Vientiane.

Mekong River Commission. 2010. *Summary of the final report, Strategic environment assessment of hydropower on the Mekong mainstream*.

Ministry of Fisheries and the World Bank. 2005. *Vietnam Fisheries and Aquaculture Sector Study. Final Report*, Ministry of Fisheries and The World Bank, February 16.

Nam, S. and S.L. Song. 2011. *Fisheries Management and Development in Tonle Sap Great Lake, Cambodia.* Fisheries Administration, Phnom Penh, Cambodia.

Office of Agricultural Economics. 2014. Agricultural Statistics of Thailand 2014.

Oopatham Pawaputanon Na Mahasarakarm, 2007. *An Introduction to the Mekong Fisheries of Thailand.* Mekong Development Series No. 5 Mekong River Commission, Vientiane, Lao PDR. 54 Pages

Open Development Cambodia. 2015. *Hydropower.* Accessed 24/6/15 www.opendevelopmentcambodia.net/briefing/hydropower

Orr, S., J. Pittock, A. Chapagai, and D. Dumaresq. 2012. Dams on the Mekong River: Lost fish protein and the implications for land and water resources. *Global Environ. Change* 22: 925-932.

Pagdee, A., S. Homchuen, N. Sangpradab, C. Hanjavanit and P. Uttharak. 2007. Biodiversity and economic value of wetland resources at Nong Han, Udonthani province, northeast Thailand. *Natural History Bulletin of the Siam Society*, 55(2): 323-339.

Perera, K., Herath, S., & Tateishi, R. (2013, November). *Mapping Mekong River Basin land cover to support food production.* In Conference of Japan Society of Remote Sensing 2013 (pp. 59-60). Japan Society of Remote Sensing.

Phomikong, P., M. Fukushima, B. Sricharoendham, S. Nohara and T. Jutagate. 2014. Diversity and community structure of fishes in the regulated versus unregulated tributaries of the Mekong River. *River Research and Applications* 31(5). DOI: 10.1002/rra.2816

Phong, L.T., I.J.M. de Boer, and H.M.J. Udo. 2011. Life cycle assessment of food production in integrated agriculture–aquaculture systems of the Mekong Delta. *Livestock Science* 139: 80–90.

Kruijssen, R.F., Satapornvanit K., Nguyen P.T., Liu Q., Liu L., Wahab M.A., Murray F.J., Little D.C. and Guinée J.B. 2014. *Final LCA case study report: Results of LCA studies of Asian Aquaculture Systems for Tilapia, Catfish, Shrimp, and Freshwater prawn.*

Ratner, B.D. 2003. The politics of regional governance in the Mekong River Basin, *Global Change, Peace & Security*: formerly Pacifica Review: Peace, Security & Global Change, 15:1, 59-76, DOI: 10.1080/0951274032000044522

Ringler, C. 2001. *Optimal Water Allocation in the Mekong River Basin*, ZEF – Discussion Papers On Development Policy No. 38, Center for Development Research, Bonn, May 2001, pp. 50.

Royal Irrigation Department. 2010 (in Thai). Summary report, Basin development planning targeting on 60 million rai of irrigated lands.

Van Zalinge, N. 2002. *Update on the status of the Cambodian inland capture fisheries sector with special reference to the Tonle Sap Great Lake*. Mekong Fish Catch and Culture 8 (2): 1-6

Sinh, L.X., H. Navy and R.S. Pomeroy. 2014. Value Chain of Snakehead fish in the Lower Mekong Basin of Cambodia and Vietnam. *Aquaculture Economics & Management*. 18:1: 76-96.

Sjorslev J.G. 2001. *Assessment of consumption of fish and aquatic animals in the Lower Mekong Basin.* Unpublished draft report for the MRC Technical Report Series. 35 pp.

Smajgl, A. and J. Ward. 2013. *The Water-Food-Energy Nexus in the Mekong Region Assessing Development Strategies Considering Cross-Sectoral and Transboundary Impacts*. Food and Agriculture Organization of the United Nations, Rome. 213 pp.

Status of cage mariculture in Vietnam. 2000, Accessed 24/6/15, http://agris.fao.org/agris-search/search.do?recordID=PH2002001149

Sy Van, N. and Thanh Luu, L. 2000. Status of Reservoir Fisheries in Vietnam In De Silva, S.S. 2000. *Reservoir and Culture-based Fisheries: Biology and Management.* Proceedings of an International Workshop held in Bangkok, Thailand from 15–18 February.

Syaukat, Y. (2012). Irrigation in Southern and Eastern Asia in figures.

The Guardian. 2015. *Multiple dams are an ominous threat to life on the Mekong River*. Accessed 24/6/15 www.theguardian.com/sustainable-business/2015/may/06/dams-hydropower-mekong-river-thailand-laos-don-sahong-xayaburi

The Living Aquatic Resources Research Centre (LARReC) and the Network of Aquaculture Centres in Asia-Pacific (NACA). 2001. *A Report on Cage Culture in Lao PDR.* LARReC Research Report No.0002 (ISSN 1608-5604)

Van Zalinge N., P. Degen, C. Pongsri, S. Nuov, J. Jensen, V.H. Nguyen and X. Choulamany. 2004. *The Mekong River system*, p. 333-355. In R.L. Welcomme and T. Petr (eds.) *Proceedings of the Second International Symposium on the Management of Large Rivers for Fisheries*, Vol. 1. FAO Regional Office for Asia and the Pacific, Bangkok, Thailand. 356 pp

Voss, M., D. Bombar, J. Dippner, J. Grosse, D.N. Hai, F. Korth, N.N. Lam and I. Liskow. 2009. *Nutrient cycling in the Mekong River plume*. Workshop and Conference on Biogeochemical Impacts of Climate and Land-Use Changes on Marine Ecosystems. 2 - 10 November 2009.

van Zalinge, N., N. Thuok, T. S. Tana & D. Loeung, 1998. *Where there is water, there is fish?* Cambodian fisheries issues in a Mekong *River Basin perspective*. MRC Phnom Penh.

Weimin, M., C.V. Mohan, W. Ellis and B. Davy. 2013. *Adoption of aquaculture assessment tools for improving the planning and management of aquaculture in Asia and the Pacific*. RAP PUBLICATION 2013/11.

Welcomme, R.L. and K.O. Winemiller. 2010. Fish migration, dams, and loss of ecosystem services in the Mekong Basin. *AMBIO* 39: 344–348.

William, S. and D. Pearse-Smith. 2012. The impact of continued Mekong Basin hydropower development on local livelihoods. Consilience: *The Journal of Sustainable Development* 7(1): 73-86.

World Wildlife Fund. 2013. *The economic value of ecosystem services in the Mekong basin*. 60 p.

World Wildlife Fund. 2015. *Magical Mekong: new species discoveries 2014*. Accessed 24/6/15, www.panda.org

World Wildlife Fund, 2015. *First contact in the Greater Mekong: New Species Discoveries*. www.worldwildlife.org/about/news-press

Xue, Z., Liu, J.P. and Ge, Q. 2011. Changes in hydrology and sediment delivery of the Mekong River in the last 50 years: connection to damming, monsoon, and ENSO. *Earth Surface Processes and Landforms*, 36 : 296-308.

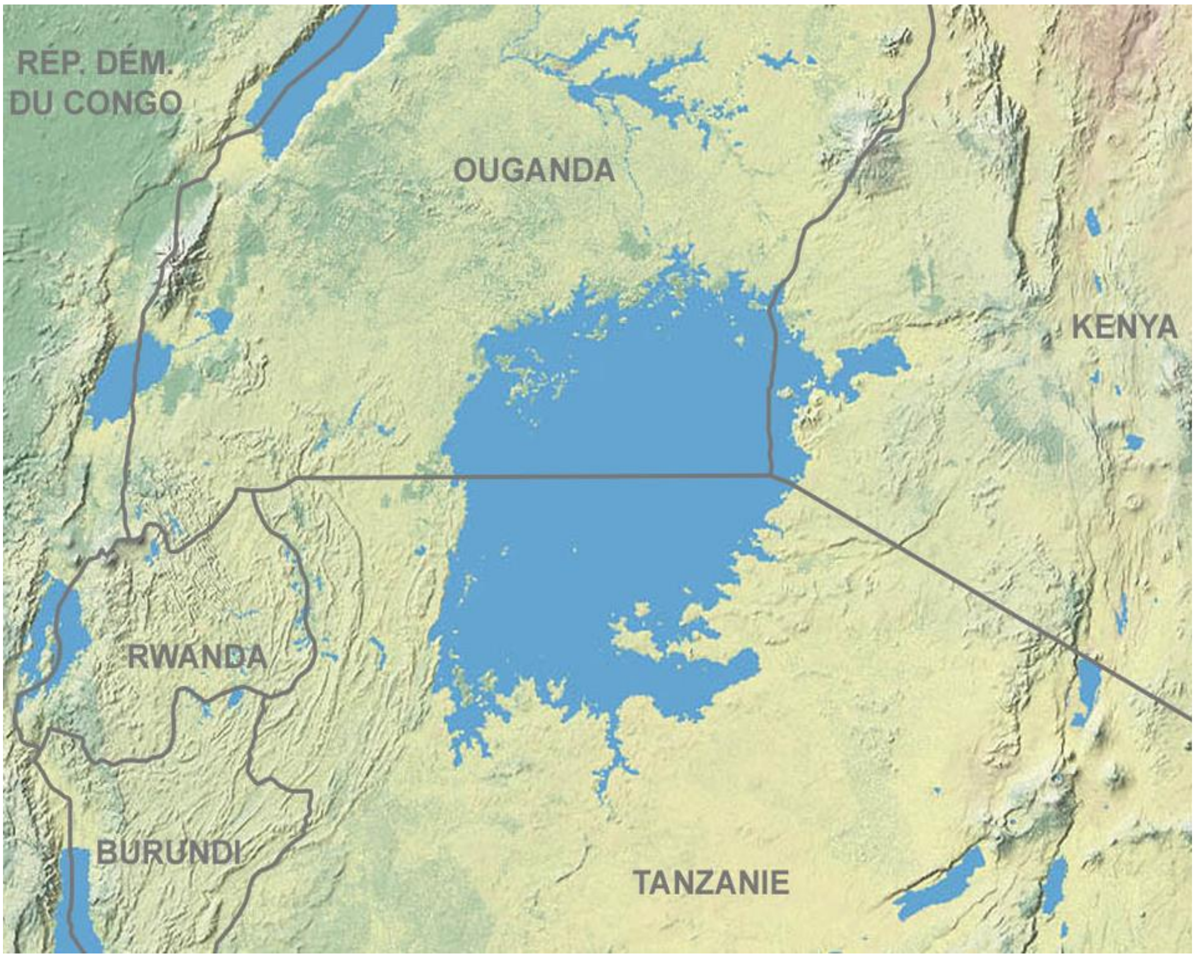
Yoshimura, C., M. Zhou, A.S. Kiem, K. Fukami, H.H.A. Prasantha, Hi. Ishidaira and K. Takeuchi. 2009. 2020s scenario analysis of nutrient load in the Mekong River Basin using a distributed hydrological model. *Science of the Total Environment,* 407(20) : 5356–5366

Yuan, D., Y. Yi, and J.S. Diana. 2006. *Walking Catfish Production in Thailand, Hybrid Species Helped Hybrid Species Helped Fuel Culture Boom Fuel Culture Boom*. Global Aquaculture Advocate J. 59-61.

Ziva, G., E. Baran, S. Nam, I. Rodríguez-Iturbed, and S.A. Levin. 2012. Trading-off fish biodiversity, food security, and hydropower in the Mekong River Basin. *Proc Natl Acad Sci*. 109(15): 5609–5614.

4.5: Case study 3: Lake Victoria

Case study 3 is an assessment of the value of ecosystem services in a set of fish production systems and main water management practices in Lake Victoria.



EXECUTIVE SUMMARY - LAKE VICTORIA

This report presents both the capacity of Lake Victoria to provide a range of ecosystem services and also measures the actual use of those services in economic terms specifically the industrial fisheries (Nile perch) and cage aquaculture production systems and main water management practices. The report gives a brief description of Lake Victoria as a complex social ecological system interacting with one another, a valuation of the Lake Victoria ecosystem services under the current use and management, trade-offs in ecosystem services under different management scenarios

Lake Victoria in East Africa is used as a case study of the value of ecosystem services, specifically industrial fisheries (Nile perch) and aquaculture (Cage culture). These two key production systems are set within competing water management practices such as irrigation and waste assimilation and wetland uses. From the social-ecological interactions originating from the industrial fisheries and the recent cage culture services, the report brings out exogenous variables (e.g. population growth, wastewater discharges and agricultural practices impacting wetland buffers and water quality for fisheries) and other endogenous variables (e.g. other fishes, biodiversity) relevant to the value of the two fish production systems.

Lake Victoria with a surface area of 68 800km^2, is the world's second largest freshwater body and it is a transboundary resource shared by the republic of Kenya, Tanzania and Uganda. With fisheries and aquaculture as key provisioning services from the lake, the three countries established the Lake Victoria Fisheries Organisation (LVFO) as a coordinating body for its vast fisheries. Located within a much larger 193 000 km^2 drainage basin occupied by at least 30 million people many of whom derive livelihood from its fisheries, Lake Victoria is one of the world's largest inland fishery producing an estimated 1 000 000 metric tons of fish per annum valued at an estimated US$1.56 billion beach value and US$500 million in exports. Out of the more than 500 fish species found in the lake, three species (the introduced Nile perch, *Lates niloticus* and Nile tilapia, *Oreochromis niloticus*; and the native "dagaa/mukene/omena" *Rastrineobola argentea*) comprise over 95percent of the total fish catch providing almost one million people with employment in several aspects (e.g. fishers, boat owners, fishing gear operators) in the fisheries bringing the total direct household livelihood dependency to at least four million people.

The report analyses other ecosystem services in relation to their interactions with Nile perch and aquaculture, and as sources of threats to the industrial fisheries and aquaculture. Practiced mainly on the Uganda part, lake-based cage culture has since 2012 emerged to overtake traditional pond-based fish farming, and from the estimated 2 000 cages, this new ecosystem service is valued at about US$7.5 million. Apart from provisioning, other supporting and regulating ecosystem services from Lake Victoria affect the fisheries. Other than Nile perch, other fishes (e.g. Nile tilapia and *R. argentea*) are important for food security and income. Thus, the unsustainable (over)fishing historically leading to Nile perch introduction is partly a threat to biodiversity, with other threats coming from eutrophication due to waste assimilation, wetland conversion for agricultural use and resurgence of water weeds such as water hyacinth.

Through economic valuation of different ecosystem services, findings of the report indicate that the fisheries worth based on Nile perch export earnings (US$545 million in 2014) and employment are still under-valued. For example, this figure does not take into account the losses due to illegal fishing methods (IUUs). While some studies factored wetland provisioning services such as breeding and nursery grounds for key commercial fishes, a sample breeding area (107 833 ha) was valued at US$673 956 which, when considered in this study, was under-valued by at least 50 times. The area usually regarded as fish breeding and nursery grounds is not a thin strip of wetland but one that stretches from wetland fringes out towards open water by as much as 500 meters. However, accessibility to other wetland services (e.g. papyrus, crafts, domestic water) was valued at US$1.4 billion from an equivalent area.

A major conclusion from this study is that despite the importance of industrial fisheries (Nile perch) and cage aquaculture as key ecosystem services, there are key ecosystem functions that feed into intermediary ecosystem services that lead the final beneficial uses of the lake. As the analysis suggests, the factors governing fish production (provisioning, supporting and regulating) cannot be traded-off to increase fish production. Two key management practices may compete directly with the fisheries production system: increased water use for irrigation agriculture alongside further wetland buffer degradation, and, nutrient cycling/pollution. It is important to improve our understanding of the full value of ecosystem services and the economic implications of the threats/production constraints.

1. DESCRIPTION OF LAKE VICTORIA AS A COMPLEX SOCIAL-ECOLOGICAL SYSTEM

Lake Victoria, the world's second largest freshwater lake, is located in the upper reaches of Africa's Nile River system, with a surface area of about 68 800 km^2. It is a transboundary resource shared by the Republic of Kenya, the United Republic of Tanzania, and the Republic of Uganda. The lake basin is comprised of 11 river basins and a lake-edge area that drains directly into the lake. The largest river basin is the Kagera, which drains parts of the Republic of Rwanda, the Republic of Burundi, Tanzania and Uganda. The next largest basins are the Mara (Kenya and Tanzania), Gurumeti (Tanzania) and Nzoia (Kenya) (Awiti and Walsh 2000). Rwanda and Burundi are a part of the upper watershed that drains into Lake Victoria through the Kagera River. The lake is also part of the Nile River basin system, shared by ten countries[15].

The immediate catchment, also known as Lake Victoria Basin (LVB), covers an area of 193 000 $km^2$and is shared by the five countries: Burundi (7 percent), Kenya (22 percent), Rwanda (11 percent), Tanzania (44 percent), and Uganda (16 percent) (*Kayombo* and Jorgensen 2006). The Lake Victoria Basin is crucial for the 25-30 million residents of Kenya, Uganda, Tanzania, Rwanda and Burundi who live in the lake basin and for the larger downstream Nile river system (UNEP, 2006).

For purposes of this analysis, the Lake Victoria Basin (**Figure 1**) is used as representing the Lake Victoria ecosystem. However, apart from the wider basin influences such as hydrological factors (rainfall and water balance as key inputs into the lake proper), pollution (due to land use practices), the human population in the catchment and related impacts, the analysis focuses on the immediate lakeshore boundaries including wetland buffers and inflowing rivers as part of lake fisheries (e.g. migration, breeding and nursery areas for fish), in addition to factors related to water management (e.g. irrigation and hydropower generation).

[15] Burundi, Democratic Republic of Congo, the Arab republic of Egypt, the Federal Democratic Republic of Ethiopia, the State of Eritrea, Kenya, Rwanda, the Republic of Sudan, Tanzania, and Uganda

Figure 1. The Lake Victoria basin with an inset map showing its location in Africa.
Source: Kayombo and Jorgensen, 2006

The LVB ecology, use and management have been extensively documented, in particular in relation to the impact the introduction of the Nile perch (*L. niloticus*) has had on the lake ecology and on the economies of its riparian countries. More recently, Hakansson et al. (2012) highlighted the impacts of a shift from a cichlid (*haplochromines*) dominated regime to a Nile perch dominated in combination with another major driver of change on the lake – eutrophication – on social groups and the overall ecological health of the system.

The interactions of the Nile perch fishery with the broader social-ecological system supported by the lake are described in **Figure 2**.

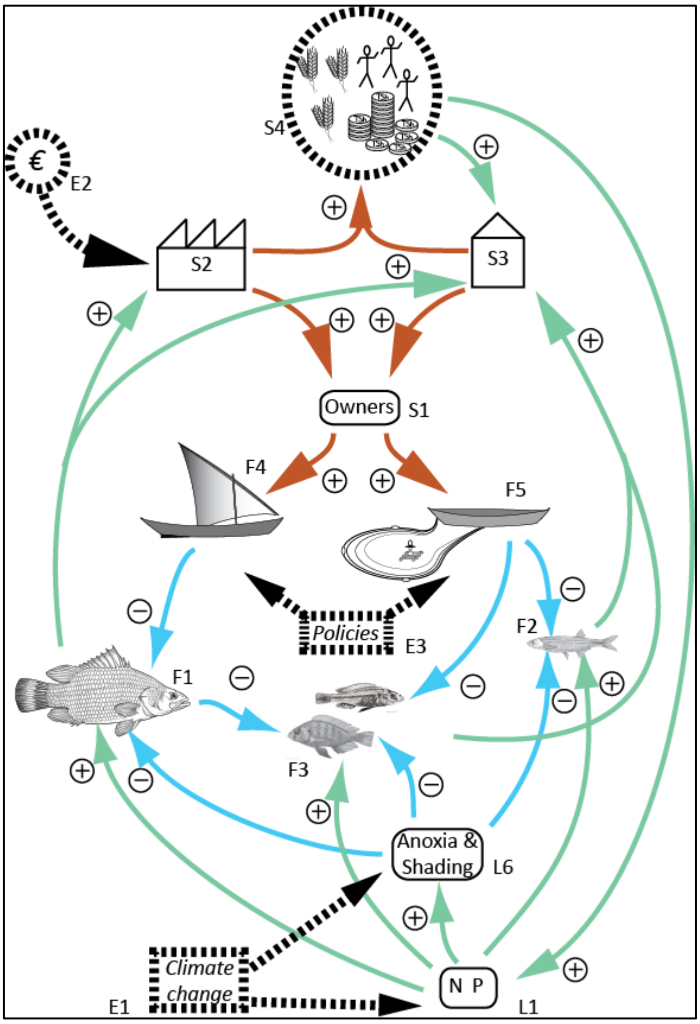


Figure 2: Social-ecological system interactions in Lake Victoria.
Source: Downing et al. 2014.

Narrative for Figure 2: Green arrows represent growth processes (also identified by + sign); blue arrows represent mortality processes (associated with - signs); rust arrows represent investment; thick dotted lines and arrows represent complex systems/interactions not further developed. E1 = climate change; E2 = international economy; E3 = policies; F1 = Nile perch; F2 = Rastrineobola argentea; F3 = haplochromines; F4 = Nile perch fishing effort; F5 = R. argentea fishing effort; L1 = nitrogen and phosphorus; L6 = anoxia and shading; S1 = boat and camp owners; S2 = international market; S3 = local and regional market; S4 = local and regional economy and society. A positive feedback loop reflects a “reinforcing” process, where an increase in one element causes it to increase further: positive feedback loops are therefore destabilizing. A negative feedback loop, on the other hand, is self-regulating: an increase in an element’s value leads it to limit itself; a negative feedback loop is stabilizing.

What **Figure 2** does not show however, is the effect of exogenous variables such as population growth, wastewater discharges and runoff caused by agriculture expansion and deforestation in the wider basin[16]. These factors, as is described in the next section, have combined to modify the functions and services of the lake, with important consequences on fish production, the main ecosystem service of the lake a strong basis for reference to the LVB.

[16] A figure combining all these factors is in the making.

2. DESCRIPTION AND VALUATION OF LVB ECOSYSTEM SERVICES UNDER CURRENT USE AND MANAGEMENT

LVB supplies a wide range of ecosystem services, summarised in **Table**. Many of them are under threat due to: **(I)** land, wetlands, and forest degradation; **(II)** overfishing in general (including the use of illegal unregulated gears, capture of immature fish, summarized as IUU-Fishing (LVFO, 2007); **(III)** increased pollution and eutrophication; **(IV)** resurgence of invasive weeds; and **(V)** fluctuating water levels and climate change. This section aims to both complement the description of the overall system by providing more information on the ecosystem services LVB supplies, and, by doing so, to estimate their value under the current use and management of the lake.

Table 1: Lake Victoria's ecosystem services.
Source: developed from Upton et al. 2013 using information from the case study

Ecosystem Service category	Goods and services		In Lake Victoria
Provisioning services	Water for consumptive use	Drinking water	✔
		Irrigation water	✔
	Water for non-consumptive use	Hydropower	✔
		Transport, navigation	✔
		Fisheries	✔
		Cage aquaculture	✔
	Aquatic organisms for food and other uses	Fish and shellfish	✔
		Plants, fibres	✔
	Minerals, fuel etc.	Sand, gravel	✔
Supporting services	Nutrient cycling		✔
	Primary production		✔
	Biodiversity		✔
	Habitat for fish, birds etc.		✔
Regulating services	Waste assimilation		✔
	Flood moderation		✔
	Climate regulation		✔
Cultural services	Recreation, tourism		✔
	Cultural, spiritual, existence		✔
	Education, research		✔

2.1 Provisioning services

The main provisioning service provided by the LVB is fish. This fish comes from both capture fisheries and aquaculture. A recent and extensive review of the status, trend and management of the Lake Victoria fisheries is provided in Kolding et al. (2014).

Fish supply – in terms of output, jobs, revenue

Lake Victoria supports a large fishing industry for export and local consumption.

From capture fisheries:

The lake produces an estimated 1 000 000 metric tonnes per year[17]. Three commercial fish species: Nile perch (*L. niloticus*), Nile tilapia (*O. niloticus*) and 'dagaa' (*R. argentea*), constitute

[17] The annual total reported catch to FAO for Uganda, Kenya and Tanzania amounts exactly to 888,490 tonnes (FAO FishStat J 2015) (Editors' notes).

over 95 percent of total fish catch in Lake Victoria[18]. The fishery provides employment directly to about 200 000 fishers and indirectly 600 000 others and when dependants are included, the fisheries as a whole support some 4 million people (Mkumbo and Marshall, 2015). The income generated from the fishery provides food security, and supports the livelihoods of approximately three million people. Fish processing and fish meal industries around the lakeshore towns and cities provide employment to thousands of people. The Lake Victoria fishery has remained the dominant source of fish makes an important contribution to national economies of the riparian countries. The Lake fishery contribution to the GDPs of the riparian countries is: - Kenya, 2 percent; Tanzania 2.8 percent; and Uganda, 3 percent and the value of Nile perch landings in 2014 and Nile perch export (foreign exchange earnings) in 2013 were estimated at as high as US$545 and US$300 million respectively (LVFO, 2014). Although Nile perch is no longer the dominant species in the fishery in terms of weight (27 percent), having been replaced by small pelagic species, it is still the most important in terms of value, and in 2014, it accounted for about 65 percent of the total landed value of fish from Lake Victoria (LVFO, 2015; Mkumbo and Marshall 2015).

Industrial fisheries are largely Nile perch-driven and export led to overseas markets. Nile tilapia has entered the overseas markets after the Middle-East. Recent additions to this trade are Nile perch maws (swim bladders) exported to the Asian markets (China) as a separate by-product. Tilapia, catfishes (*Clarias gariepinus, Bagrus docmak*) and silver fish (*Rastrineobola argentea)* fisheries serve domestic markets. However fisheries targeting the regional markets emphasize silver fish *R. argentea* "dagaa" and juvenile Nile perch. Still, "dagaa" is a major input to the livestock/poultry feed industry and has become a major raw material in the production of fish feeds for the emerging commercial scale aquaculture.

According to the 2014 Lake Victoria fisheries stock assessment (LVFO 2015), the total catches have continued to decrease in the lake, but there are fluctuations in the catches of individual species (Figure 3). For example, the total estimated catch of Nile perch has continued to decline between 2000 and 2014, from its peak in the 1999. This is coupled with a shift in contribution of catches from higher trophic level species (Nile perch) to lower trophic level (*dagaa*) species. In the case of the Nile perch fishery, the Catch per Unit Effort (CPUE), which is an index of stock abundance, declined, exhibiting characteristics typically observed with heavily exploited fisheries.

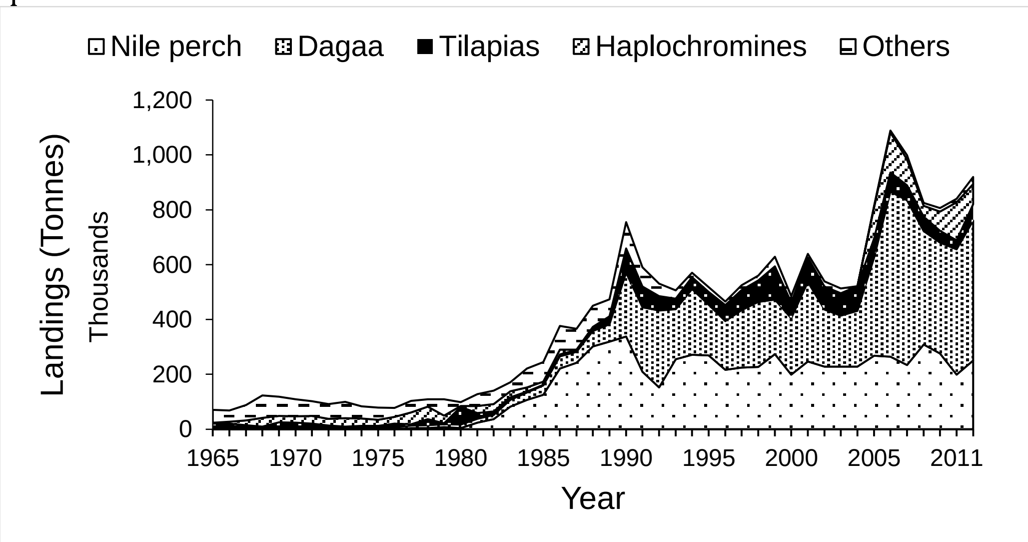


Figure 3: The changes in fish landing from capture fisheries by species from 1965-2014.
(Source: Payne et al 2006, LVFO surveys, 2005-2014)

[18] This contrasts with figures reported to FAO which suggest that these three species would only constitute 67% of the total catch (editors' notes).

During the same period the fishing efforts increased tremendously e.g., number of fishers and fishing crafts increased by 63 percent each, boats with outboards engines by over 400 percent number of gillnets by 68 percent, and long-line hooks by over 300 percent (Table 2). Noteworthy are also the use of illegal gears (Table 2) and the known use of bed nets (Minakawa et al. 2008) with even smaller mesh size.

Table 2: The numbers (in thousands) of some components of the fishery on Lake Victoria, 2000-2014. Gears that target Nile perch exclusively are marked with an asterisk (*). Note that gillnets of <5" are illegal while those of ≥5" are legal. (Source: LVFO, 2015).

Component	2000	2002	2004	2006	2008	2010	2012	2014
Fishers	129	176	153	196	199	194	205	210
Total fishing crafts	43	52	52	69	68	66	69	70
Crafts with outboard motors*	4	7	10	13	14	16	20	21
Total No. of gillnets <5"	113	178	143	215	208	159	200	234
Total No. of gillnets ≥5"	538	725	1091	1007	806	709	826	859
Total No. of all gillnets	651	903	1 233	1 222	1 014	867	1 033	1 093
Total No. long line hooks	3 496	8 098	6 096	9 044	11 267	11 472	13 257	14 244

Alarming results from past Nile perch stock assessments were however based on steady-state stock assessment applications, which ignored the constantly changing environment of the lake, including the steady increase in nutrient levels. Recent analyses, on the other hand, relativize the over-exploitation of the fishery and suggest that its management could benefit from a relaxation of some of the top-down, drastic measures that are under implementation (Kolding et al. 2014). Still, the changing environmental factors such as nutrient enrichment and other form of pollution and degradation are primarily due to human activity separately managed from fisheries management regimes.

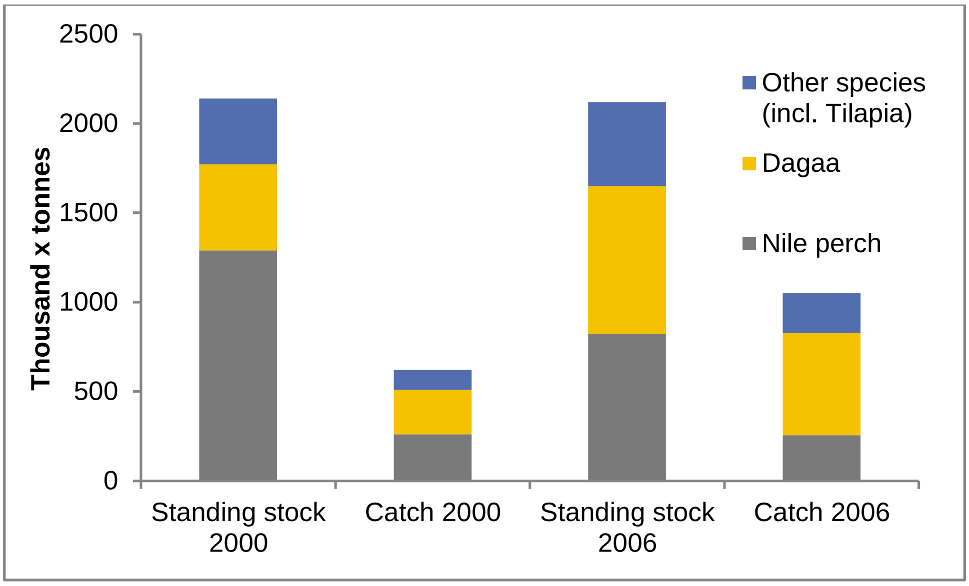


Figure 4. Comparison between standing stock and catches in Lake Victoria for the years 2000 and 2006 (Source: LFVO, 2015)

Still, hydro-acoustic surveys have revealed that the standing stock of fish in Lake Victoria has remained fairly constant over the years. The mean standing stock for Lake Victoria was estimated at 2.17 million tonnes in 1999/2001 and 2.12 million tonnes in 2005/2006 (LFVO

2015; Figure 4)). However, the mean standing stock of Nile perch is observed to have declined from 1.29 million tonnes in 1999/2001 to 0.82 million tonnes in 2005/2006 surveys. Meanwhile the mean standing stock of *dagaa* is estimated to have increased from 0.48 to 0.83 million tonnes and that of other species from 0.37 to 0.47 million tonnes during the same period (*ibid*).

From cage aquaculture[19]:

Lake-based cage aquaculture has emerged to overtake traditional pond-based fish farming in the region (Figure 5). On Lake Vitoria cage aquaculture is more pronounced on the Ugandan part of the lake focusing on culturing the Nile tilapia (*Oreochromis niloticus*). Pilot cage practices[20] are capable of producing one ton of fish in 6 to 8 months (cage size 2.5m x 2.5m x 2.5m (12.5m^3)). The pilot trials developed into to use of larger cages[21] in various parts of the lake in Uganda. There are at present an estimated 2,000 cages on Lake Victoria (Uganda part) of small (10 m^3 to 60 m^3) low volume high density (LVHD) cages. Based on the production estimates of about 1 600 tonnes of Nile tilapia in 2014 from the cage pilot project all located in Napoleon Gulf, Lake Victoria Cage aquaculture alone was valued at about US$7.5 million (Personal Communication). 150 people are directly employed by Lake Victoria aquaculture with about 90 employed under cage farming and the rest by the hatcheries located around the shores named above, while many others (un-assessed) are engaged in supplying inputs and equipment for the industry. As in production figures however, the general lack of accurate data from small-holder farmers remains an outstanding challenge (NaFIRRI unpublished data). Here it is estimated that small cage (15 m^3 to 40 m^3) scattered in various parts of the lake employ at least 200 workers. Therefore, livelihood figures from those employed in the emerging cage industry might be as high as 1 000 (assuming a ratio of one to three four family members per employee).

Figure 5. Cage farming in Lake Victoria.
Source: www.lvfo.org/images/carousel2/cage_farming.jpg

[19] Pond aquaculture is not included here. Despite the current low pond productivity, the recent increased uptake of commercial aquaculture (increased numbers and sizes of ponds, DFR, 2010/11) coupled with improved supply and availability of quality fish feeds has resulted in the recent upsurge in estimated total aquaculture value in Uganda from less than US$20 000 in 2004 to about US$140 000 in 2009 (Hyuha et al., 2011).

[20] Source of the Nile (SON) fish farm Limited and the cage demonstration facility by the National Fisheries Resources Research Institute and the Uganda China Friendship Agricultural demonstration Centre-Kajjansi NaFIRRI/Uganda-China Agricultural Technology Dissemination Centre (NaFIRRI/UCATDC)

[21] 3.5m x 3.5m x 2.5m; 3.5m x 3.5m x 3.0m (20m^3 to 30m^3)

Fish supply – in support of food security

Fish from Lake Victoria feed around 22 million people in the region with their annual fish intake making a significant contribution to regional food security (LVFO 2015.) In Uganda it was estimated in 2010 that fish fed up to 17 million people (50 percent) of the total population in Uganda annually and at least 10 percent of the consumed fish directly came from Aquaculture (MAAIF, 2011). However, per capita fish consumption (8 kg) is considered quite low in comparison to FAO's recommended 17 kg.

Wetlands provide key breeding and nursery grounds for some key taxa in Lake Victoria that directly contribute the consumed fish in the basin. In three wetlands of Uganda (Nangabo, Mabamba and Mende) representing the Lake Victoria crescent agro ecological zone the monitory economic value of wetlands in terms of availability for fish breeding/spawning and fish production was estimated at US$673 956 and 372 300 respectively. Adding on other wetland ecosystems services from crop farming, livestock grazing/pastures, livestock watering, value added through milk production, wetland grass for mulching); Accessibility (papyrus, papyrus crafts); services/functions (domestic water supply nonuse values) gives an estimated net economic value to food availability of about US$1 424 476 711 (Kakuru et al. 2013).

The analysis by Kakuru et al. (2013) considered the following acreages for the different uses and values: 20 751 ha under papyrus valued at US$1 660 080 while 107 833 ha for fish spawning was valued at US$673 956. Three landscape features have to be factored into these estimates: (a) the acreage given in each case represents less than 5 percent of the total area of Uganda's Lake Victoria shore wetlands, illustrating how low the services are ranked, (b) the area given as fish spawning excludes a much larger area of fish nursery grounds that is considered to stretch from within the papyrus fringes to at least 300 to 500 m out towards open water indicating that the area and value of fish breeding and nursery services are under-estimated by as much as 50 times.

The sustained supply of fish is dependent upon the sustained supply of most, if not all, the other ecosystem services supplied by the lake. Variations in one or more of these will have knock-on effects on other ecosystem services. Due to their interlinked nature, this will ultimately bear on the fish production systems embedded in the lake, although, as will be described further, the Nile perch fishery, combined with increased water pollution and overfishing, is also responsible for creating imbalances in the LVB social-ecological system.

Quality water supply - ** UNDER THREAT **

Lake Victoria is an important source of water for domestic, industrial and is also a repository for human, agricultural and industrial wastes. Approximately 5 million people live in the major cities around the lake, such as Kampala, Entebbe, and Jinja (Uganda); Kisumu, Homa Bay, and Migori (Kenya); and Mwanza, Musoma, Bukoba, Shinyanga, and Kahama (Tanzania).

Discharge of untreated domestic and industrial wastewater and agricultural effluents in the lake through drainage channels and rivers causes pollution by increasing the Chemical Oxygen Demand (COD), and the concentration of total phosphorus (TP), total nitrogen (TN), and Chlorophyll-a, and results in eutrophication.

Energy (hydropower) supply

The waters originating from the lake provide hydropower through its only outlet, the Victoria Nile River, in Uganda, and other power plants further downstream. The LVB boasts of significant hydropower potential with the lake itself acting as the world's largest "reservoir". There exists considerable potential for the hydropower production within and downstream of the basin. Uganda's installed hydropower systems include the 180 MW Nalubaale (formerly Owen Falls) and the Kiira with 200 MW power stations on the mouth of the Victoria Nile. The Bujagali hydropower station located about 8 kilometers downstream Nalubaale and Kiira, generate an additional 250 MW. Additionally preparations are underway for the Rusumo Hydropower station of 62 MW, and other power stations on the Kagera and the Victoria Nile rivers. These future developments of the low-cost power generation options and electricity trade in the Nile Equatorial Lakes (NEL), are critical for the regional economic development.

Hydropower provide low production cost of electricity, which makes electricity affordable to the urban and rural poor and presents real opportunities for reducing pressure on woodlands and forests (presently heavily relied on as a source of energy) and protecting critical watersheds needed for sustained flows of the Nile tributaries.

The benefits associated with hydropower include: a renewable source of energy pollution free and eligible for carbon credits, are labour intensive and provide huge employment opportunities during construction and operation. Other additional benefits include flood control and river flow, regulation, irrigation, transport and navigation, aqua farming, capture fisheries, recreation, industrial and domestic water supply.

Hydropower dams are also usually accompanied by auxiliary infrastructure projects such as roads, electrification, telecommunication, schools, health centres and other government services that provide added benefits to riparian communities.

The water levels of the Lake Victoria have fluctuated and are causing serious economic and environmental impacts on the riparian and downstream countries since 2000, the Lake level had dropped by about 1.6 meter, bringing it to a level of 1 133.26 meters above sea level2 in October 2006, which was very close to the lowest ever recorded level of March 1923. This fall has been partially attributed to a three-year drought period (2001– 2004), and partially to over-abstraction of water beyond the agreed curve[22] by Uganda hydropower generating company. However, the lake levels increased to approximately 1 134.31 meters above sea level in March 2007 due to the above normal rainfalls received in the Lake basin.

The riparian countries are cognizant that lake water management is crucial for the economy of the region, protection of biodiversity and wetlands, as well as maintaining the environmental integrity of the LVB. In response to concerns about the declining water levels, Uganda reduced hydropower output from Nalubaale and Kiira dams' complex from 270 MW in 2002 down to 120 MW since August 2006. In addition, short-term thermal generation capacity of 50 MW each was installed at Lugogo, Kiira and Mutundwe to alleviate power shortages (Table 3).

[22] Stipulates an outflow between 600–1 100 m3/depending on lake level.

Table 3: The location of hydropower station and completion status in Uganda 2012
(Source: The State of River Nile Basin Report 2012)

Hydroelectric power station	Location (Coordinates)	Type	Capacity (MW)	Year completed or completion expected
Nalubaale	0.443611°N 33.185°E	Reservoir	180	1954
Kiira	0.4506°N 33.1858°E	Reservoir	200	2000
Bujagali	0.4975°N 33.1400°E	Run of river	250	2012
Isimba	0.9400°N 32.9650°E	Run of river	183.2	2018
Karuma	2.2430°N 32.2450°E	Run of river	600	2018
Ayago	2.3630°N 31.9200°E	Run of river	600	2023

STATE OF THE RIVER NILE BASIN 2012

Irrigation water supply for agriculture and livestock

The lake is the source of the White Nile and is therefore an important asset for all countries within the Nile River Basin. The LVB water resources are also important for both irrigated and rain-fed agriculture, particularly for export crops, such as horticulture (cut flower and green vegetables), sugarcane, and tea industries. Kenya is the leading exporter of green tea in the world, and one of Africa's largest exporters of cut flowers to the European Union market. The largest sugar producer in Kenya, Mumias, is located in the basin. Almost all major tea and sugarcane plantations and factories in Uganda are located within the basin. The LVB also has the largest concentration of livestock in EAC countries, which consume a significant amount of water on a daily basis.

Navigation routes

Lake Victoria is important for navigational processes. Shipping is still the cheapest means of transport for the three riparian countries. The main Lake Victoria transport routes included Mwanza – Port Bell/Jinja, Mwanza – Bukoba, Mwanza – Musoma, Port Bell/Jinja –Bukoba,and Kisumu – Bukoba. The local networks are: Kisumu – Kendu Bay – Kuwor – Homa Bay – Mbita – Rusinga – Mfangano, and Asembo – Kowu/Homa Bay in Kenya; Mwanza – Nansio, Mwanza – Bukakata – Kalangala, Nakiwogo – Kalangala, and Jinja – Bugala in Uganda. These navigation routes are very important for the basin economy.

2.2 Regulating services

Climate and water cycle regulation

The large size of Lake Victoria influences the hydrological cycle i.e., weather and climate modulation in the basin. Approximately 85 percent of the water entering the lake comes from direct precipitation, and about 15 percent from stream flow and Basin runoff (Bootsma & Hecky 1993). The lake also serves as the natural storage for the White Nile River, and sustains large expanses of downstream wetlands, including the Sudd in Sudan, and other natural ecosystems along the river system.

The wetlands that fringe the lake are closely connected to its ecological health and quality of its waters. The many functions and ecosystem services provided by wetlands have been extensively described in previous TEEB studies (e.g. TEEB for Water and Wetlands, Russi et al. 2013). A primary product of the wetlands bordering Lake Victoria is papyrus (*Cyperus papyrus*) (Morrison et al. 2012). These wetlands also constitute refugia and sites for fish breeding. Wetlands are also involved in the exchange of nutrients with the lake and act as filters, trapping incoming sediments and pollutants. Extensive wetlands around Lake Victoria are being destroyed or degraded through conversion to agricultural land, excavation for sand and clay, and use as disposal sites. It is estimated that 75 percent of Lake Victoria's wetlands area has been affected significantly by human activity, and 13 percent is severely damaged which leads in the reduction of nutrient absorption by those lake margin wetlands.

A spatially explicit approach in the Yala catchment discharging water and nutrients and into the Kenyan part of Lake Victoria made it possible to model interactions of agriculture and fisheries as mediated by the margin wetlands. The model specially estimated the value of the forgone nutrient retention resulting from conversion of the wetland to agriculture and the scope for providing same services through other land use change elsewhere in the catchment would require to compensate farmers for on farm nutrient buffering at a cost of US$3.68 million year^{-1} equivalent to 35 percent total gains from crop production (Simonit and Perrings, 2011). The study also estimated that a 60 percent reduction in margin wetland would increase the nutrient load to the lake from 34 tonnes phosphorus year^{-1} to 96 tonnes phosphorus year^{-1} and this loss in wetland buffering capacity would lead to an expected loss of 2 666 tonnes phosphorus year^{-1} worth US$1.98 million and an estimated loss in fishery production valued at US$216 ha^{-1}year-1 (Simonit and Perrings, 2011).

Waste assimilation - ** UNDER THREAT **

Lake Victoria is an important repository of wastewaters. Yet, as was indicated above, this function is under threat by the discharge of wastewater effluents in the lake, which is overwhelming the natural treatment capacity of the lake's fringing wetlands and has knock-on effects of its capacity to maintain the supply of its other ecosystem services.

Many rivers and streams draining into Lake Victoria and the near-shore areas are heavily polluted, particularly by: (i) raw and partially treated municipal and industrial effluents; (ii) contaminated urban surface/stormwater runoff; (iii) unsanitary conditions of the shoreline settlements (e.g. lack of latrines due to high water table and absence of sewerage services); and (iv) pollutants carried in eroded sediments, particularly nitrogen (N) and phosphorus (P), synthetic pyrethroids, and organorphosphates. These pollutants bring into the lake coliforms of faecal origin; oxygen demanding organic substances; heavy metals, such as chromium, lead and mercury; and pesticide residues. The increased inflow of nutrients, particularly N and P, has resulted in changing lake chemical and bio-physical characteristics, increased eutrophication, nutrients balance problem, health problems to riparian communities, and proliferation of w hater hyacinth. The pollution effect is clearly seen in the littoral areas and the increased algal biomass and phosphorus loading is noticeable. There are a number of "hotspot" areas with high eutrophication such as Murchison Bay in Uganda.

2.3 Supporting services

Biodiversity - ** UNDER THREAT **

Lake Victoria and its satellite lakes are important for fisheries resources both in terms of diversity and numbers. The lake and associated ecosystems harbor more than 200 different fish species, including the predatory introduced Nile perch, *Oreochromis tilapias* and endemic herbivorous *cichlids*, several riverine fish species, such as *Labeo victorianus* and *Barbus altianalis*. A major threat to the biodiversity of the lake has been the intertwined increase of the Nile perch population and the eutrophication of the lake (Hecky et al. 1994, Hakasson et al. 2014). Close monitoring of the fishery in the 1980s indicated that the explosion of the lake's Nile perch population also coincided with a fivefold increase in the economic value of the fishery (Reynolds et al. 1995) and simultaneous halving of the lake's 500-species haplochromine cichlid flock (Ogutu-Ohwayo 1990).

The problem of unsustainable fishing in Lake Victoria has had adverse impacts on fish species diversity and the stocks of Nile perch, the most commercially important fish species. Until the 1970s, Lake Victoria supported a multi-species fishery dominated by *tilapiine* and *haplochromine cichlids*. The fishery has undergone drastic changes in its recent history. It is thought that some 200 endemic *haplochromine* species, which previously comprised about 90 percent of the fish biomass, had become extinct from the lake due, in part, to predation by the Nile perch (*L. niloticus*) introduced in the lake in the late 1950s and early 1960s. However, much of the haplochromine biomass was not used by locals, i.e. it was not a fishery resource, but a biodiversity resource. Apart from the predation by the Nile Perch, the use of wrong fishing gears and methods are also thought to have contributed to the dramatic loss of fish biodiversity in Lake Victoria (Ochumba and Manyala, 1992).

The originally Lake Victoria diverse multispecies fishery is currently dominated by only three species: the nonindigenous Nile perch, and Nile tilapia *O. niloticus* and the native *R. argentea*[23].

Although overfishing and eutrophication (Seehausen et al. 1997) contributed the decline of the cichlid population, the intense fishing pressure on Nile perch has depressed its populations to the extent that certain species of the remnant cichlid fauna are resurging (Witte et al. 2000).

Another threat to biodiversity is caused by the resurgence of water hyacinth. Water hyacinth (*Eichhornia crassipes*) has become a major invasive weed in Lake Victoria and its tributaries since the late 1980's, and a serious threat to aquatic ecosystems, affecting fish stocks and water quality. The Kagera river system is a major source of the invasive weed. In 1998, water hyacinth weed was estimated to cover approximately 17 000 ha of waters of the Lake Victoria. By February 2000, this weed infestation had been reduced by about 80 percent, to approximately 3 400 ha, mainly through biological control using two weevils -*Neochetina eithhorniae* and *Neochetina bruchi.* In recent years the coverage of water hyacinths has remained stable in the range of 10 to 20 percent of the 1998 coverage, which is considered to be ecologically optimal level, although some areas exhibit its resurgence. The continued nutrient and sediment loading from poorly managed catchments upstream are contributing to increased water hyacinth infestation, persistence, and resurgence of the weed in some hotspots. During LVEMP I, about 36 hotspots were identified and mapped in LVB, of which 13 are located in Uganda. Infested small water bodies and satellite lakes are also sources of the weed entering the main lake.

Extensive, tightly packed water hyacinth mats along the shoreline impair environmental quality for biodiversity maintenance, fish breeding grounds, and nurseries of young fish, inshore feeding zones, and refugia for fishes, although the opposite effect of physically hampering fishing and contributing to increases in fish stocks has been reported in some sections of the lake (Kateraggo 2009). The interior of extensive mats are normally deoxygenated and/or have low levels of light and oxygen, and produce poisonous gases like ammonia and possibly hydrogen sulphide. Water hyacinth increases the cost of water treatment. It also increases the cost of hydropower generation at Nalubaale and Kiira dams in Uganda.

[23] The level of diversity of the historical fishery of Lake Victoria, i.e. before the introduction of the Nile perch, remains however a controversial topic (DM Bartley, pers.com).

2.4 Cultural services

Tourism

The LVB supports a growing tourism industry based on sports fishing and hotel industry. Tourism contributes to Uganda's annual GDP. It is one of the most important sources of foreign exchange to the basin countries. Despite the limited number of recreational activities around the lake, the consumer's surplus was estimated to US$1 044 760 per annum with an average of US$6 965 per hectare per year in the wetlands around Lake Victoria in the Musoma area (Musamba et al. 2012). Policy formulation and implementation should always endeavour to consider the use and non-use values of the lake services in order to estimate the social welfare gain or loss with respect to any proposed project or policy change. There is a large tourism potential in Lake Victoria, which could be exploited by the riparian countries.

Culture

To Lake Victoria fishers, fishing means much more than fishing for income generation or subsistence but more of the social arena that binds people together in many different ways, ethnically, economically, culturally and across genders, as an economic and social activity through which they engage with each other (Medard 2015). To them, fishing it is what makes them who they are, is a source of happiness and satisfaction, identity and meaning (Onyango 2015). Local and global dynamics, however, interact in ways that 'modern' and 'traditional' cultural repertoires continue to co-exist which create social inequality, harsh labour conditions, of dependency and the exclusion of specific groups (Medard 2015). As a social practice, fishing in changing social, economic and cultural environment may include use of witchcraft, creation of new social networks, establishment of empires, engagement in sexual relationships, working against the fisheries regulations and struggling to secure economic independence towards securing and protecting people's livelihoods.

Finally developments in the Nile perch fishery related to culture, beliefs and superstitions. Some consumers developed real or imagined allergy to the Nile perch fish flesh while others rejected for reasons such medical, taboos, odour, taste, cultural factors and bad believes about the fish to the extent, some riparian folk resent it to.

Education and research

The Lake Victoria fishery has been the subject of extensive research since the Nile perch was introduced to the lake. There may be at least 2000 scientific references and unpublished reports on the subject of Nile perch and its impacts. The cost of generating this information is in terms of the number of research projects and advanced degrees by a global audience of scholars. For example, the EU supported a EURO 45 million five years Integrated Fisheries Management Plan (IFMP) between 2004 and 2009 that among other objectives aimed at cause a recovery of Nile perch exports (**Table 4**).

As can be seen, there were many items of the intervention that would be required to be completed as this project also supported fisheries research and fisheries management institutions that collectively employ at least 1 000 staff in the region, as well as the establishment of about 1 000 Beach Management Units in the riparian districts.

Table 4. IFMP Development Objectives that in accordance with the FMP1, the three main objectives were to be achieved through activities aligned to five strategic goals and fourteen thematic areas as outlined below:

	Development objectives
1.	Earn foreign exchange for the three governments and improve the standard of living in the riparian
2.	Increase fish supply to the riparian communities (through more effective use of available fisheries
3.	Create employment opportunities, particularly for riparian communities.

#	Five Strategic Goal	14 Thematic Areas	
1.	Regulation of fishing pressure within the framework of an adaptive management approach	1.	Access Rights and Fishing Capacity
		2.	Environmental Issues
2.	Harmonizing and strengthening of the institutional environment for fisheries development, research and management	1.	Co-Management of the Fisheries of Lake Victoria
		2.	Resource and Socio-economic Monitoring
		3.	HIV & AIDS in Fishing Communities
		4.	Women in Fisheries
		5.	Safety on the Lake
		6.	Aquaculture Research and Development
3.	Establishment of an institutional environment that can sustainably manage a modified property and access rights regime using local community structures for MCS	1.	Institutional Development
		2.	Compliance to Regulations
4.	Adoption of FAO CCRF policy matrix and Integrated Development Strategy models		Policy and Legislation
5.	Developing proper handling, preservation, processing and storage of fish and fish products	1.	Landing Site Development
		2.	Fish Trade
		3.	Fish Handling and Processing

2.5 Summary of values

Industrial fisheries (Nile perch) for capture fisheries and cage culture for aquaculture are the two main fish production systems in Lake Victoria, but there are other competing services outside these. The various uses of the lake often compete and require management decisions that entail tradeoffs in pursuit of economic welfare maximization. Management decisions are further influenced by the social, cultural, environmental and economic settings. Figure 6 summarizes the interactions between Lake Victoria Basin uses and supply of ecosystem services and the production of fish, and the exogenous influences that both are subjected to. Aside the Nile perch fishing, which, due to overfishing is a case of self-inflicted externality, all externalities on the Lake ecosystem are generated by non-fish related activities.

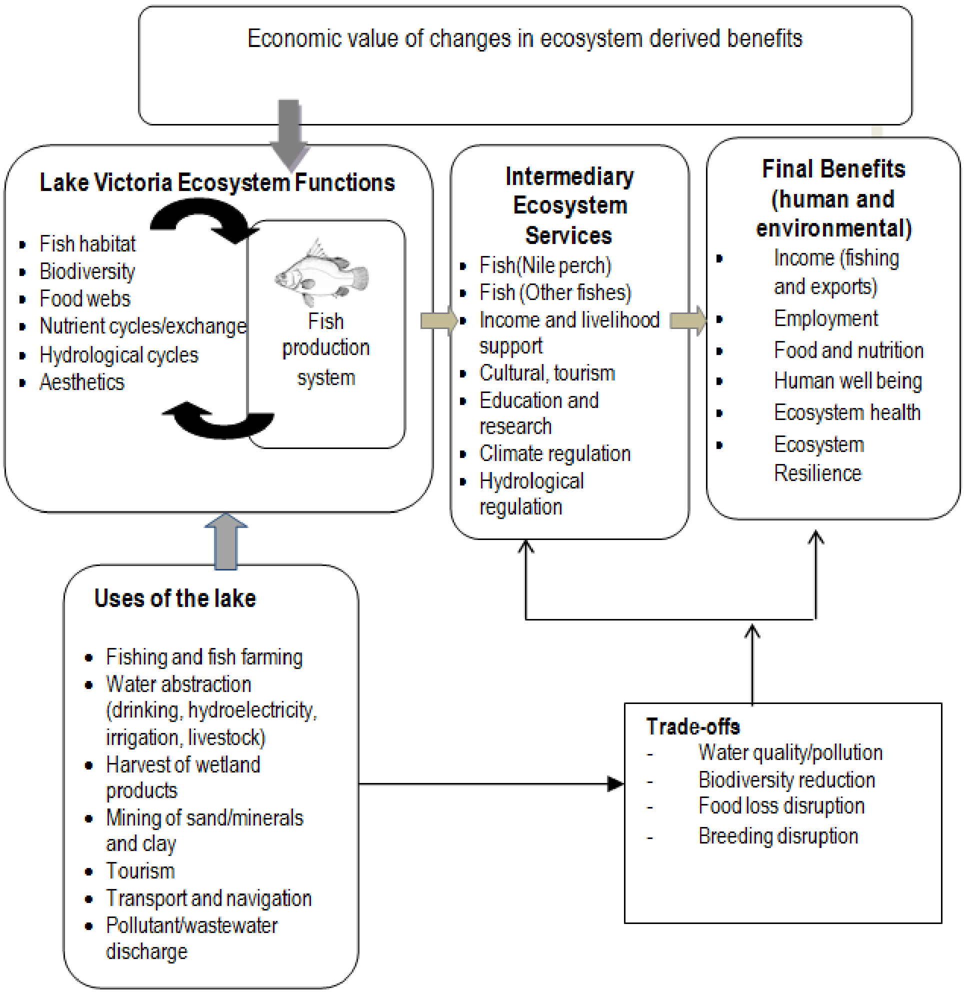


Figure 6: Ecosystem interactions between Lake Victoria ecosystem services and the Nile perch fishery.

Table 5: Summary table of the value of Lake Victoria's ecosystem services.

Ecosystem service	Monetary values and units	Year of valuation	Sources
Food production **Capture fisheries** **Nile perch** **Quantities** **Values** **Other main spp** **Quantities** **Values** **Cage aquaculture** **Tilapia** **Quantities** **Values**	 251,063.2 tonnes US$545 492 071 668,249.9 tonnes US$295 395 181 2000 tonnes US$6 000 000.3	 2014 2014	LVFO, 2014 and other records Nile perch exports and welfare.pdf NaFIRRI survey 2015 unpublished
Water quality **Value of wetland's regulation service (purification)**	Conversion of Yala wetland for agriculture would impact on both fish stocks and yields. Basing on the current phosphorus loading from the Yala watershed, it translates to a direct economic loss of up to US$0.7 million per year, and depending on the fishery regime, using a discount rate of 5 per cent, implies that the value of the converted wetland (its social opportunity cost) is US$14.7 million. Using the Yala catchment, to model interactions between agriculture and fisheries as mediated by conversion of 9200 ha wetland to agriculture at the lake Victoria margin. The total cost of the payments that would compensate farmers for on-farm nutrient buffering services is US$3.86 million year^{-1}, or 35 percent of the total gains from wetland conversion to crop production. In Uganda wastewater purification and nutrient retention ecosystem services of Nakivubo Swamp have a high economic value between US$ 1 million a year (using replacement cost methods) and US$1.75 million a year (using mitigation expenditures methods).	2005 2011 1999	Simonit and Perrings 2005 Simonit and Perrings 2011. Emerton, et al. 1999, Emerton 2003.
Net economic value of wetlands for food security **in three wetlands of Nangabo, Mabamba and Mende representing the lake Victoria crescent agro ecological zone**	Availability (fish breeding/spawning, fish production, crop farming, livestock grazing/pastures, livestock watering, value added through milk production, wetland grass for mulching); Accessibility (papyrus, papyrus crafts); Services/functions (domestic water supply nonuse values) Estimated net economic value to food availability of about US$1 424 476 711.	2012	Kakuru et al.2013.

Table 5 continued

Ecosystem service	Monetary values and units	Year of valuation	Sources
Biodiversity	94 percent, 79 percent and 74 percent of the lake side communities in Kenya, Tanzania and Uganda respectively perceived wetlands as a key important fish breeding and nursery ground for key fish taxa in Lake Victoria namely Tilapia sp, *Clarias sp*, *Proptopterus eathiopicus* and haplochromine species.	2011	LVBC, 2011
Carbon fixation and greenhouse gas emissions	The Kenya Agricultural Carbon Project (KACP), developed by the Vi Agroforestry programme, receives mitigation funding from the World Bank's BioCarbon Fund for soil carbon sequestration and above-ground sequestration in trees. Apart from providing farmers with a small sum of extra money, the switch to climate-smart agricultural practices has had the additional benefits of increasing crop yields as well as improving farmer's resilience to climate change. According to a recent World Bank commissioned study, the crop yield increases alone are worth US$ 200-400/ha/year. The Fund will purchase a part of the carbon credits generated by the project by 2017, estimated at US$600,000.	ongoing	biocarbonfund.org
Value of lake and wetlands' regulation service	US$4 113 750	2012	Kakuru et al. 2013.
Nutrient cycling	The Wetlands Inspectorate Division and the IUCN showed that a sewage treatment plant would cost over US$ 2 million to maintain each year. In Uganda wastewater purification and nutrient retention ecosystem services of Nakivubo Swamp have a high economic value between US$ 1 million a year (using replacement cost methods) and US US$1.75 million a year (using mitigation expenditures methods).	 1999	Emerton et al. 1999, Emerton 2003. Emerton et al. 1999, Emerton 2003.
Income and livelihood support Benefits and social and economic costs associated with: Capture fisheries (Nile perch) Cage aquaculture By social groups, e.g. large scale fishers/ fish farmers, small scale fishers/fish farmers, women, consumers etc.	Analysis of income and expenditure for 10 Nile perch fishing boats in two selected camps in Tanzania indicated that: Matajiri (Boat owner) was obtained a Average Annual income of US$12 567 and expenditure of US$ 11 171 plus crew costs of US$ 1 571 implying operating at Annual Average loss of US$ 175/year per fishing unit and while a crew member earned US$ 524 in the same period. A nullification of the claim that '*matajiri* were in the fish business not only because it was a money making activity but because they were tied to the credit markets and fish supply-tying loans' and just capitalize on cheap labour	2009-2011	Medard 2015

Recreation/ aesthetic	137 125 ha of wetland in the Lake Victoria crescent Uganda US$ 67 328 375.	2012	Kakuru et al. 2013.
	US$ 1 875 063.86 per annum about 12,500.4 US$ per ha per year and Consumer's surplus of about US$ 1 044 760 per annum with an average value of US$ 6 965 per hectare per year of the wetland around Musoma municipality, Tanzania.	2012	Musamba et al. 2012
Sports fishing	There is some undocumented sport fishing but as is known from other lakes this could form great potential especially around lake shore cities in the lake Vitoria basin	Occasionally	Personal observations (Jinja, Entebbe , Mwanza and Kisumu)
Other recreational activities?	A study of recreational activities based on responses from tourists in lake Victoria wetlands around Musoma town indicated dominance by picnic (27 percent), bird watch (25 percent), beach access (23 percent), swimming (8 percent) and boating (7 percent).		

3. TRADE-OFFS IN ECOSYSTEM SERVICES UNDER ALTERNATIVE MANAGEMENT SCENARIOS

The economic value of capture fisheries are estimated at US$550 million (Nile perch exports lake wide) and US$300 million (other fishes) and it is dependent upon the integrity of ecosystem services (e.g. supporting services such as nutrient cycling, primary and secondary production, biodiversity and habitats). The value of the ecological fish production chain (wetland buffers for nutrient cycling vs removal of wetlands for agricultural production) can be estimated from the following: cost of raising fish to market value is the cost of raising the fish through the feed conversion ratio (FCR) whether this is through primary or secondary production estimated as 1.5 kg for producing 1.0 kg of fish). Therefore sustainable capture fisheries production through the FCR is 1.5 time the fish produced which is US$850 million x 1.5 equivalent to US$1.4 billion (the cost of producing the fish). The cost of maintaining the desired water quality through waste water treatment to avoid pollution is based on the investments in waste water treatment plants which depend on the quantity of wastewater (sewage and storm water run-off entering the lake) and the cost of water treatment for domestic use. These figures are not readily available because there are far too many diverse point source inputs by-passing water and waste water treatment plants as well as the non-point sources all of which are un-quantified.

The current Nile Perch fish supply channels and networks e.g. fish handling, processing and transporting technologies have changed with the expansion of Nile Perch export, which has forced fishers to fish in distant fishing grounds. The practice makes the Nile perch fishing operation costly which has shifted to fishing other varieties including bait fish that have also entered the global basket and reduced the fish varieties available for local consumptions (Medard 2015). As a consequence, some fishers either switch from Nile Perch to *R. argentea* or fish for both in order to reduce the economic risks associated with fishing exclusively for Nile Perch. Just as in the Nile Perch fishery, processes and practices have diffused and spread in *R. argentea* fishery, with its growing economic and commercial importance (Medard 2015).

These analyses so far suggest that the factors governing fish production and are associated with provisioning; supporting and regulating services cannot be traded-off to enhance fish production for exports and for local consumption.

The different scenarios that may theoretically compete with the natural capture fisheries production system (Nile perch) in Lake Victoria include:

1. Increased water use for irrigation agriculture alongside further wetland buffer degradation may be expected to increase crop agricultural production.
2. Nutrient cycling/pollution.
3. Hydropower, transport/navigation: these are not expected to be competing uses in the short-to-medium term; hydropower generation in particular is either upstream or downstream of lake fisheries. Therefore, water management for hydropower production does not directly endanger the industrial fisheries. Instead, availability of hydropower should be regarded as a supporting service of the industrial fisheries.

4. ANALYSIS OF DIFFERENT MANAGEMENT SCENARIOS

For Nile perch, scenario development based on management changes has to consider management objectives to be addressed:

1. To earn foreign exchange for the three governments and improve the standard of living in the riparian communities.
2. To increase fish supply to the riparian communities (through more effective use of available fisheries resources at regional and national levels)
3. To increase employment opportunities, particularly for riparian communities.

According to the Fisheries Management Decision Support Tool (FMDST) developed for Lake Victoria Fisheries (LVFO 2006), management goals can broadly be classified into four, as shown in **Table 6**.

Table 6: Fisheries Management Decision Support Tool (FMDST) Nov 2006.
1 High priority, **2** Medium priority, **3** Low priority

Subset	Management Goals	Priority by Fishery		
		Nile perch	Dagaa	Nile Tilapia
Biological	Maximise sustainable fish production	1	1	1
Ecological	Minimise impacts of fishing on non-target species, particularly prey species	3	1	1
	Maintain and restore habitats (including water quality) essential for fish and their prey	2	2	1
Economic	Maximise contribution to macro-economic growth through foreign exchange generated by exports of fish products	1	3	2
	Maximise net income of artisanal fishers	1	2	1
Social	Maximise contribution to food security within national markets	3	1	2
	Maximise employment to artisanal fishers	2	1	1

4.1 Background to the geo-ecological-socio-economic factors influencing industrial fisheries (Nile perch)

The Nile perch is a native to much of the Nile system but is alien to lakes Kyoga and Victoria. However, in the 1950s and 60s, there was deliberate introductions of Nile perch and Nile tilapia into lakes Kyoga and Victoria. Following their introduction, the Nile perch population expanded rapidly and is now distributed throughout Lake Victoria with juvenile fish tending to inhabit shallow inshore waters whilest larger fish are more widely distributed.

Lake Victoria fisheries are currently dominated by three species: Nile perch (*L. niloticus*), Nile tilapia (*O. niloticus*), and dagaa (*R. argentea*). These three species are also the most commercially important ones, contributing up to 90 percent of the catch altogether. The massive population growth of the Nile perch in the 1970s and the increase in landings, coupled with fishing, has led to dramatic changes in the ecology and a reduction in biodiversity of the lake.

A report by SOFRECO (2013) on a revised Nile perch Fishery Management Plan considered three goals of the plan (biological aimed at returning Nile perch stocks to sustainable level; economic aimed at recovering foreign exchange earnings and social to diversify and improve employment opportunities for the fishing sector and associated communities). However, an analysis of the trends in fish stocks, fishing effort and market and social considerations suggest that short to medium term water management scenarios cannot be used to predict the most important trade-offs which seem to lie within the fisheries themselves; in this respect, the case for cage culture may be different from that of industrial fisheries.

State of the stocks

The yield of Nile perch reached a maximum of 338 000 tonnes in 1990. The catches have subsequently varied between 200 000 and 300 000 tonnes per year. At the time of the NPFMP, the IFMP estimated the annual catch of Nile perch at 287 000 tonnes in 2005 which fell to 234 000 tonnes in 2007. In 2008, the annual catch from Uganda fell from 95 000 tonnes in 2005 to 81 000 tonnes.

The NPFMP reported that the clearest picture of the stock state was from the acoustic survey estimating the total Nile perch biomass to be around 2 million tonnes. This fell in the period (February 2000-August 2001 to about 1.12 million tonnes. This fell again to about 650 000 tonnes by early 2007. The stock then dropped precipitately to around 300 000 tonnes for the period August 2007 to August 2009. Whilst the biomass was last estimated in 2011, the trend observed in the fishery would suggest further depletion of the biomass up to date. The safe biological limit of the stock which corresponds to the biomass at which the stock will collapse (point called B_{lim}) is estimated at 500 000 tonnes per year (approx. 25 percent of B_0). The most recent stock biomass in 2013 was predicted to be at approximately 674 000 tonnes or about 35 percent of B_0.

Action is required to halt further depletion, rebuild stock biomass to avoid compromising the reproductive capacity of the stock, and to increase yield.

Fishing effort

At the same time as the Nile perch increased in numbers, fishing effort increased tremendously from 129 300 fishers in 2000 to 199 200 in 2008, and the number of fishing boats from 42 500 to 69 400 units during the same period. By the year 2000, there were signs that commercial fish species and especially the Nile perch were under threat from both legal fishing and significant levels of illegal fishing, as reflected in the downward catches observed since then.

The fishery is characterised by small vessels, some powered by outboards, which fish with gill-nets of varying sizes and increasingly with hooks on long lines. Monofilament gillnets and smaller hooks are becoming increasingly favoured by fishers owing to their costs and catchability. Numbers of boats, engines, fishers, and gear numbers have increased between 200– 300 percent during the past decade.

Market and social considerations

The developing market for high-quality white fish meat, particularly in Europe, encouraged the establishment of processing and exporting factories around the lake during the 1980s and early 1990s. In 2005, there were 35 factories, up from 15 in 1990. By 2008, exports of Nile perch were valued at US$329.8 million with the main market being the EU (taking about 60-80 percent of the total). Other markets developed in Japan, Israel and the Middle East.

Most (60–80 percent) Nile perch are processed at lake-side plants and exported chilled or frozen fillets. Of the Nile perch consumed locally, and exported to regional markets, most is believed to comprise undersized fish. An estimated 70 000 tonnes of Nile perch may be traded "informally". There is also a subsidiary trade in processing waste: head, carcases and other material are re-processed by drying or salting. This trade is aimed at both the domestic and regional markets, including Zambia and DRC. The benefits of the fish processing industry are however not always clear. There have been reports that the reprocessing of fish frames from factories for fishmeal now accounts for a large proportion of the reprocessed waste and uses smaller fish (e.g. sardines, dagaa), which has led to rises in local fish prices and could negatively impact on local consumption (Abila and Jansen 1997).

Anecdotal evidence of the value of the developing trade in fish maws (swim-bladders) suggests that their sale price ranges from US$40– US$140 kg^{-1}. This is targeted at large fish (10 kg +).

The yield disposed via processing factories in 2009 was reported to be 48 480 tonnes (chilled and frozen fillets, headed and gutted) and 74 540 tonnes in 2012. The value of the commercial export was US$237.42 million in 2009 and US$340.7 million in 2012. An estimated 90 percent is currently sent for export, which means that the processed value of the catch would be around US$378.6 million. The decline of the catch has led to the closure of around half of the factories with those still working now operating at around $^1/_3$ capacity with only one shift a day.

The fishery is predominantly small-scale commercial with subsistence fishing. There has been a substantial migration into the fishery, especially in Kenya, by unskilled workers who are low-waged with little either incentive or means to invest in the long-term future of the fishery. There are now about 200 000 fishers. The predominant characteristic of the fishery – at all levels – is short-termism.

4.2 Cage culture

Considered a more profitable aquaculture system in many countries, cage culture is relatively new to Uganda. So far, interest has focused on Lake Victoria where there are an estimated 2 000 LVHD cages as described earlier.

According to the Development Strategy and Investment Plan (DSIP) of Uganda's Ministry of Agriculture, Animal Industry and Fisheries (MAAIF) 2011–2015, the fish gap of 300 000 tons will be met through aquaculture and cage culture is the main option. Increasing cage culture production to that level, based on present acreage (surface area), would require putting aside 150 sites (farms on the lake) of 1 500 m^{-2} each. There are diverse benefits (e.g. jobs, employment, fish production, revenue, food supply, domestic water supply, habitat biodiversity) to accrue from commercial cage culture. However, some of the services may have similar benefits, while some of cage culture benefits may impact some services (e.g. nutrient cycling, biodiversity, domestic water supply, and navigation/transportation).

A recent study suggests that cage culture causes minimal environmental changes but that caution should be exerted in planning the development of additional sites so to avoid compromising further the deteriorating water quality of the lake (Kashindye et al. 2015). In addition, beyond the state of water, cage culture depends also on quality seed (e.g. sex-reversed fast growing Nile tilapia) and quality feed (high nutrient > 30 percent protein).

The main factors to consider are summarized by Halwart and Moehl (2006) as:

1. Biological and Technical issues

- Interactions with capture fisheries, escapes and disease
- Feed and seed
- Production systems

2. Environmental issues

- Aquaculture both affects and is affected by the environment. Practices which optimize production efficiency – especially the use of feeds – can also reduce environmental impacts

3. Socio-economic issues

- Input costs, quality and supply
- Distribution and markets
- Rights and access

Key biophysical aspects of cage culture (depth, navigation/transport routes, pollution hot spots) restrict commercial scale farming to limited areas of the lake. Here there are probably more possible trade-offs than in industrial fisheries.

5. CONCLUSIONS

Predicting the impact of alternative management scenarios (drivers) from baseline i.e. current management regimes is key to sustainable returns from ecosystems but this in turn assumes availability of three requirements:

1. costing the product (e.g. fish) value chain and its linkages to related value chains (e.g. wetlands, water for irrigation, pollution) of the product;
2. whether or not trade-offs are realistic and
3. managing the scenarios in fully integrated management regimes.

To this has to be added the required information and awareness by resource users and managers of the need to understand the socio-economics of ecosystem sustainability.

In general, economic valuation of ecosystem services especially for the Lake Victoria fisheries has not been achieved to a satisfactory degree in part due to limited appreciation of ecosystem services in the region but also due to previous non-use of available tools. In the case of Lake Victoria' fisheries, the export-oriented Nile perch industry is most significant but other fisheries are similarly important in terms of local consumption and for the regional market. Using the examples from studies on the total economic value of wetland services and products cited in this report reveals that fish as food, biodiversity and associated benefits from the fisheries are grossly undervalued.

Further work should begin to address gaps in ecosystem service assessments that more closely link the productivity constraints of a service to the economic gain of removal f the constraints. For example, in the case of fish, it should be possible to predict how much economic loss may be expected from catching and trading in immature fish using the data from stock assessments and related data on fish breeding and growth to mature fish. In turn, costs of management need to be known in terms of numbers of people employed in different stages of the value chain, number of their dependants from which the actual value can be estimated.

Cage culture is an emerging industry and is only known in Uganda. There should be deliberate efforts to identify and estimate acreage of future cage sites and scenarios associated with different scales of cage culture practice. Therefore, opportunity is presented to start analysis of this recent ecosystem service in Lake Victoria.

REFERENCES

Abila, R.O. and Jansen, E.G. (1997) *From local to global markets. The fish exporting and fishmeal industries of Lake Victoria – Structure, strategies and socio-economic impacts in Kenya.* IUCN Report. https://portals.iucn.org/library/efiles/documents/1997-082.pdf [accessed 4 September 2015)

Akwetaireho S. and M. Getzner, 2010 Livelihood dependence on ecosystem services of local residents: a case study from Mabamba Bay wetlands (Lake Victoria, Uganda*). International Journal of Biodiversity Science, Ecosystem Services & Management,* 6 (1-2): 75-87.

Bootsma, H.A., and R.E. *Hecky*. *1993*. Conservation of the African Great Lakes - A limnological perspective*. Conservation Biology* 7 (3): 644—656.

Downing, A. S., E. Van Nes, J. Balirwa, J. Beuving, P. Bwathondi, L. J. Chapman, I. J. M. Cornelissen, I. G. Cowx, K. Goudswaard, R. E. Hecky, J. H. Janse, A. Janssen, L. Kaufman, M. A. Kishe-Machumu, J. Kolding, W. Ligtvoet, D. Mbabazi, M. Medard, O. C. Mkumbo, E. Mlaponi, A. T. Munyaho, L. A. J. Nagelkerke, R. Ogutu-Ohwayo, W. O. Ojwang, H. K. Peter, D. Schindler, O. Seehausen, D. Sharpe, G. M. Silsbe, L. Sitoki, R. Tumwebaze, D. Tweddle, K. E. Van de Wolfshaar, H. Van Dijk, E. Van Donk, J. C. Van Rijssel, P. A. M. Van Zwieten, J. H. Wanink, F. Witte, and W. M. Mooij. 2014. Coupled human and natural system dynamics as key to the sustainability of Lake Victoria's ecosystem services. *Ecology and Society* 19(4): 31. http://dx.doi.org/10.5751/ES-06965-190431

Emerton, L., Iyango, L., Luwum, P., and Malinga, A., 1999. *The Economic Value of Nakivubo Urban Wetland, Uganda*, Uganda National Wetlands Programme, Kampala and IUCN — The World Conservation Union, Eastern Africa Regional Office, Nairobi.

Emerton, L (2003). *Case Study in Wetland Evaluation 7: Nakivubo Swamp, Uganda. Managing Natural Wetlands for their ecosystem services. Integrating Wetland Economic Values into River Basin Management*. IUCN http://cmsdata.iucn.org/downloads/casestudy07nakivubo.pdf (last access January 19 2010)

LVFO. 2007. *Regional Plan of Action for the Management of Fishing Capacity in Lake Victoria (RPOA-Capacity)*; LVFO, Jinja. pp 28

LVFO, 2013. *Draft Revised Nile perch Fishery Management Plan (NPFMP2) for Lake Victoria*. A Report to SOFRECO. pp 10

LVFO, 2014. *Final Draft Reorgnized Nile perch Fishery Management Plan (NPFMP2) for Lake Victoria 2015-2019*. Smart Fish and Indian Ocean Commission, Programme for the implementation of a Regional Fisheries Strategy for Easterm and Southern Africa and Indian Ocean Region (IRFS PROGRAMME). LVFO, 2015 Stock Assessment Report. East African Community (EAC (Partnership Fund-Support to Resource Monitoring for Lake Victoria.

FAO, 1997*. Inland fisheries*. FAO Technical Guidelines for Responsible Fisheries. No. 6. Rome, FAO, 36p

FAO, 1995. *Code of Conduct for responsible fisheries*. Rome, FAO, 41p

Kakuru W, Turyahabwe N, and Mugisha J. 2013. Total Economic Value of Wetlands Products and Services in Uganda *The Scientific World Journal* Volume 2013, Article ID 192656, 13 pages http://dx.doi.org/10.1155/2013/192656

Kayombo and Jorgensen, 2006. *Experiences and lessons learnt brief, Lake Victoria, LVFO, 2007*. Regional Plan of Action for the Management of Fishing Capacity in Lake Victoria (RPOA-Capacity); LVFO, Jinja.

Kashindye, B.B., Nsinda, P., Kayanda, R., Ngupula, G.W., Mashfi, C.A. and Ezekiel, C.N. ,2015, *Environmental impacts of cage culture in Lake Victoria: the case of Shirati Bay-Sota, Tanzania*. Springer-Plus, 4: 475. DOI: 10.1186/s40064-015-1241-y.

LVFO, 2015. www.lvfo.org/index.php/lvfo/lvfo-secretariat/7-benefits-from-lake-victoria-fisheries

Halwart and Moehl (2006). *Cage culture in Africa*. Regional Technical Expert Workshop held on 20-23 October 2004.112p.

Hecky, R.E., Bugenyi, F.W.B., Ochumba, P.B.O., Talling, J.F., Mugidde, R., Gophen, M., and Kaufman, L. 1994. Deoxygenation of the deep water of Lake Victoria, East Africa. *Limnology and Oceanography* 39:23-36.

Hyuha T.S., Bukenya J. O., Twinamasiko J. and Joseph Molnar, 2011 Profitability analysis of small scale aquaculture enterprises in Central Uganda. *International Journal of Fisheries and Aquaculture*. 2 (15), 271-278

Kolding, J., Medard, M., Mkumbo, O. and van Zwieten, P.A.M 2014. *Status, trends and management of the Lake Victoria Fisheries*. In Welcomme, R.L, Valbo-Jørgensen, J. and Halls, A.S. (eds.). *Inland fisheries evolution and management – case studies from four continents*. FAO Fisheries and Aquaculture Technical Paper 579.

Medard, M. 2015. *A social analysis of contested fishing practices in Lake Victoria, Tanzania*. Wageningen University, Wageningen, NL. (*PhD Thesis*),

Millennium Ecosystem Assessment. 2005. *Ecosystems and Human Well-being: Synthesis.* Washington DC: Island Press.

Minakawa, N., Dida, G.O., Sonye, G.O., Futami, K. and Kaneko, S. 2008. Unforeseen misuses of bed nets in fishing villages along Lake Victoria*. Malaria Journal*, 7: 165.

Ministry of Agriculture, Animal Industry and Fisheries (MAAIF) 2010. *2011-2015. Development Strategy and Investment Plan*. Government of Uganda. Unpublished.

Ministry of Agriculture, Animal Industry and Fisheries (MAAIF) 2011. *Department of Fisheries Annual Report 2010/11*. Government of Uganda.

Mkumbo O.C and B.E Marshall, 2015. The Nile perch fishery of Lake Victoria: current status and management challenges. *Fisheries Management and Ecology* 22 (1): 56-63

Musamba E. B., Boon E. K., Ngaga Y.M., Giliba R.A. and Dumulinyi T, 2012. The Recreational Value of Wetlands: Activities, Socio-economic Activities and consumers' surplus around Lake Victoria in Musoma Municipality, Tanzania. *Journal of Human Ecology*, 37(2): 85-92

Morrison E.HJ, Odhiambo-K'Oyooh C.U.K., Harper D.M. (2012). Managing the natural capital of papyrus within riparian zones of Lake Victoria, Kenya. *Hydrobiology*, 692: 5-17.

National Fisheries Resources Research Institute (NaFIRRI), 2015. *Establishment of Aquaculture parks on Lake Victoria*. Project Progress report

NBI, 2012. *The State of the Nile Basin Report 2012*. Chapter 6.

Ntara M.M. 2015. *A social analysis of contested fishing practices in Lake Victoria, Tanzania*, 272 pages. PhD Thesis, Wageningen University, Wageningen, NL ISBN 978 94 6257-247-8

Payne, I.A., Agnew, D.J., Everson, I., Parkes, G. & Payne, A. ,2006, *Implementation of a Fisheries Management Plan for Lake Victoria* Strengthening of the Fisheries Monitoring Programme and Development of a Fisheries Management Decision Support Tool (FMDST) for Lake Victoria, September 2006, 251pp

Ochumba, P.B.O. and J.O. Manyala, 1992. Distribution of fishes along the Sondu-Miriu River of Lake Victoria, Kenya with special reference to upstream migration, biology and yield. *Aquaculture Fisheries Management*. 23:701-719.

Ogutu-Ohwayo, R. 1990. Changes in the ingested prey and the variations in the Nile perch and other fish stocks of lake Kyoga and northern waters of Lake Victoria, Uganda*. Journal Fish Biology* 37:55-63.

Onyango Luombo, 2015. Fishers' attitude towards performance of Beach Management Units (BMUs) in regulating fishery and reducing poverty: case study of two BMUs Lake Victoria, Tanzania. *International Journal of Marine Science* 01/2015; DOI: 10.5376/ijms.2015.05.0006

Reynolds JE, Greboval DF,Mannini P *.* 1995*. Thirty years on: The development of the Nile perch fishery in Lake Victoria.* Pages. 181-214. in Pitcher TJ, Hart PJB, eds. *The Impact of Species Changes in African Lakes.* London: Chapman and Hall.

Russi D., ten Brink P., Farmer A., Badura T., Coates D., Förster J., Kumar R. and Davidson N. (2013) *The Economics of Ecosystems and Biodiversity for Water and Wetlands*. IEEP, London and Brussels; Ramsar Secretariat, Gland.

Seehausen O., Jacques J. M. van Alphen, Frans Witte, 1997. Cichlid Fish Diversity Threatened by Eutrophication That Curbs Sexual Selection, *Science* 277: 5333 pp, 1808-1811

Simonit S. and Perrings, C. 2005. *Modelling the economics of ecosystem services: nutrient retention in wetlands and fisheries in Lake Victoria*

Simonit S. and Perrings, C. 2011. Sustainability and the value of the 'regulating': Wetlands and water quality in Lake Victoria. *Ecological Economics*, 70: 1189-1199.

SOFRECO, 2013. *Review and update Nile perch Fishery Management Plan (NPFMP) for Lake Victoria*. Final Technical Report. Project ref. N0EA-1.2-B3. Strengthening Fisheries Management Plan in ACP countries (EU-ACP Fish III)

The Kenya Agricultural Carbon Project (KACP) ongoing:www.biocarbonfund.org

Upton C., Ballatore T., Adgo E., Harper D., Morrison E., Ngendahayo R., Pacini N., 2013. *Ecosystem Services and Livelihoods for the African Great Lakes: Overview and Case Studies*. Produced as part of ESPA Framework Project: East African Great Lakes Observatory (EAGLO) (NERC Reference: NE/1003266/1) January 2013

Witte, F., Msuku B. S., Wanink J. H., Seehausen O., Katunzi E. F. B., Goudswaard P. C., and Goldschmidt T., 2000. Recovery of cichlid species in Lake Victoria: an examination of factors leading to differential extinction. *Reviews in Fish Biology and Fisheries* 10:233–241. http://dx.doi.org/10.1023/A:1016677515930

The Economics
of Ecosystems
& Biodiversity

The Economics of Ecosystems and Biodiversity (TEEB)
is a global initiative focused on “making nature’s values visible”.
Its principal objective is to mainstream the values of biodiversity and
ecosystem services into decision-making at all levels.
It aims to achieve this goal by following a structured approach
to valuation that helps decision-makers recognize the wide range
of benefits provided by ecosystems and biodiversity,
demonstrate their values in economic terms and,
where appropriate, capture those values in decision-making.

www.teebweb.org