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Water productivity of aquatic systems

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Contents

List of Acronyms

ATTZ	Aquatic/terrestrial transition zone
CC	Carrying capacity
CGIAR	Consultative Group on International Agricultural Research
CIFA	Central Institute of Freshwater Aquaculture
CPUE	Catch per unit of effort
CPWF	CGIAR's Challenge Program on Water and Food, hosted by IWMI
Dai	Cambodian word for the bagnet, a gear used in Cambodia
DRIFT	Downstream response to imposed flow transformation
DRM	Desktop reserve mode
EARO	Ethiopian Agricultural Research Organization
FAO	Food and Agriculture Organization of the United Nations, Rome, Italy
GTZ	Gesellschaft fur Technische Zusammenarbeit (Technical Cooperation Agency, Germany)
IHE	Institute for Water Education, Delft, The Netherlands
ILRI	Institute for Land Reclamation and Improvement, The Netherlands
IRD	Institut de Recherche pour le Développement, France
IWMI	International Water Management Institute, Colombo, Sri Lanka
IBGN	L'Indice Biologique Global Normalisé (Global Normalized Biological Index)
LCA	Life cycle assessment
MEFA	Materials and energy flow analysis
MEI	Morphoedaphic index
MEWREW	Middle East and Africa Water Review, published by SOAS Geography Department, Water Issues Group
MoWR	Ministry of Water Resources, Addis Ababa, Ethiopia
MSY	Maximum sustainable yield
ORSTROM	Office de la Recherche Scientific et Technique d'Outre-Mer, Paris, France
PROFA	Protection of Forests around Akwaya, Cameroonian-German Project
RUE	Rain use efficiency
RVA	Range of variability approach
SASS	South African Scoring System
SIFRA	Source Book for the Inland Fishery Resources of Africa
SOAS	School of Oriental and African Studies, University of London, U.K.
TC	Transpiration coefficient
UNESCO	United Nations Educational Scientific and Cultural Organization
USDA	U.S. Department of Agriculture
WP	Water productivity
WUE	Water use efficiency

Summary

It is now clear that fulfilling agricultural demand for water will soon become a challenge in most parts of the world. This has led to a renewed interest in water productivity (WP) as a potentially useful concept to identify where improvements in agricultural production can be made. A number of other concepts, such as virtual water, have recently been proposed in the literature, which allow for water accounting on different scales, from the basin to the individual plant. The management of water resources would, however, be greatly facilitated if all water-consumptive productive processes in a basin could be accounted for through their WP. The purpose of the present study is to analyze how fish-related activities, fishing and fish culture can be integrated within this WP framework.

Water productivity is usually estimated as the amount of agricultural output produced per unit of water consumed. The difficulty is to determine water consumption properly, which is of course dependent on the environment. Water considered as consumed is largely site-specific, as some of it may be re-utilized in other production processes.

The productivity of aquatic systems has been given two meanings in the literature: either the transfer of matter or energy through the food web, or the quantity of fish that may be captured in a sustainable way per unit of time. A number of short-cuts may be used to estimate the sustainable fish catch. These are discussed in the text, mostly in an African context.

On the one hand, the few scientific publications related to fisheries and WP do not allow for a consensus on water consumption associated with fish catch in a water body, and thus for an estimation of fisheries production in relation to WP. Only a marginal WP can be calculated when a change in fish catch is associated with a change in water allocation. In this study, the case of the River Niger Inner Delta in Mali is used as an example.

Fish culture production and water needs, on the other hand, are well documented, and allow calculations of WP estimates. In this case, as in agriculture, WP is highly site-specific and dependent on the water that is re-used. Depending on the production process and the species produced, WP in fish culture varies widely, from 0.01 to 1.6 kg dry weight per cubic meter.

The comparison between fisheries and fish culture leads to the conclusion that, although a continuum exists between fishing (as a gathering activity) and fish culture (as fully controlled agricultural production), there is a limit below which WP cannot be estimated for fishing systems, as by the very nature of this gathering activity, no water is specifically allocated to the fisheries system.

1. Introduction

Societies have to make the best use of the limited resources in our world. For agricultural production, solar irradiance, area of arable land, water availability, potential environmental impact, energy costs and economic returns are some of the main limiting factors.

For a long time, yield, as kg/ha, has served as the most commonly used indicator of the output for a given area of arable land. Given the fact that agriculture *largo sensu* is the main consumer of water on a global scale, and considering the scarcity of water, there is now a wide consensus that increasing production per unit of water is one of the global challenges that require urgent attention. Where energy is limited, due either to lack of manpower in low technology rain-fed systems in semi-arid developing countries, or to high oil prices in more developed environments, another concept based on production per energy unit should be used to explain farmers' strategies. Recently, following the concept of sustainability, more attention has been paid to the environmental costs of food production (Bartley et al. 2007).

At the UN Millennium Summit in September 2000, UN Secretary-General Kofi Annan echoed a decade of IWMI research when he said that we need a "Blue Revolution" in agriculture that focuses on increasing productivity per unit of water: "*more crop per drop.*" This has led to a renewed interest in the use of the concept of "water productivity" (WP) as a tool to analyze agricultural production and to identify ways by which agricultural production can be improved (Molden et al. 2003; CPWF 2008; FAO 2008a and 2008b; WorldWatch Institute 2008).

Related to this concept of water productivity are those of "virtual water" and "water footprint." These are also useful in assessing the environmental impact of human society on water resources, and are therefore described briefly in section 2.

Water productivity has been given different definitions by different authors, often according to the scale of the plant, plot of land or watershed they were investigating or the purpose of their study. After a review of the literature available on productivity and water productivity in aquatic systems (section 3), we will try to identify when it is appropriate to consider fisheries literature in the context of the general debate on food production dependent-livelihoods, and to include it in a unified WP metrics. Although fish culture seems more appropriate for WP estimates than most fisheries systems, section 4 will show that there remains a very large range of variation of WP values, depending on site conditions.

A general conclusion of this report (section 5) is that the WP concept, initially developed for irrigated agriculture and later applied to other agricultural activities, does apply to fish culture, but does not apply in all instances to gathering activities, such as fisheries. Nonetheless, the concept of marginal water productivity may be useful for water allocation decisions at the basin or catchment level.

2. The concept of water productivity and related variables

2.1 Water productivity

Plant production is closely linked to transpiration. Under given ecological conditions, a plant species has a genetically determined *transpiration coefficient* (TC). This coefficient, which is measured as the ratio of the weight of water absorbed to the weight of dry matter produced, was introduced by Briggs and Shantz (1913, 1914) and is expressed as m^3/kg.

The concept of *water use efficiency* (WUE), introduced later by Viets (1962) to describe the relation between production and water loss, is the ratio between dry matter produced and the amount of water evaporated and transpired. WUE has the dimension $M L^{-3}$, and is usually expressed as g/kg or kg/m^3 (Le Houérou 1984). WUE has the same meaning as water productivity (WP) when an agricultural field is considered (see below).

For practical use in rain-fed agriculture, *rain use efficiency* (RUE) has been proposed (Le Houérou 1984). It is defined as the ratio of annual production to the amount of annual rainfall received by the field, and expressed as kg/m^3. It is relatively easy to estimate and indicates the ecological functioning of a field, in relation to its primary production, to the amount of rainfall needed to grow the crop.

Water use efficiency or water productivity are two measures of agricultural efficiency that may be adopted to reduce water consumption for agriculture. Initially, they were developed for irrigated crops, for which a robust measure of the ability of agricultural systems to convert water into food was required (Le Houérou 1984; Molden et al. 2003). Later, they were used (i) to include other types of livelihood support, such as mixed cropping, pasture, fisheries or forestry, and (ii) to define viable goals of agricultural water management for poverty alleviation (Kijne et al. 2003; Cook et al. 2006a, 2006b; Hussain et al. 2007).

In a recent review of agricultural WP values in a number of countries, Hussain et al. (2007) came to the following conclusions, which should be borne in mind when dealing with WP indicators:

- The WP indicators based on crop output do not reflect the full range of benefits and costs associated with agricultural water use.
- The value of agricultural water may not be as low as generally perceived or estimated when all major uses and direct and indirect benefits of water are accounted for properly.
- The value of water varies across time and space, and the value to stakeholders on various scales (farmer, system manager, basin planner and national policy maker) can be quite different. As a consequence, management schemes may be potentially misguided if key dimensions of water value are not considered on the right temporal and spatial scales.
- Efforts should be directed not only to increasing WP in terms of the mass of output per unit of water, but also to the overall benefits or value of water at various levels for increased growth and poverty alleviation impacts, considering the sustainability of the systems.

If water productivity could be applied to all rural activities, and especially to the array of food production systems, then a common metrics would allow comparisons of the different production systems within a single unit system. This would facilitate the formulation of water allocation policies. In the case of the fisheries sector, which has so far often been overlooked, this would allow better integration of fisheries in the general debate and lead to appropriate policy options.

In summary, WP is a ratio that is largely scale dependent and topic dependent. It is expressed as kg/m^3. Different figures may be proposed for the same production, according to the object or purpose of WP evaluation. The *numerator* for primary biomass should be dry matter, but it is usually expressed as the edible weight of food crops. Total above-ground biomass is used mostly for fodder. When related to animal production, WP is generally given as the fresh weight of a carcass or edible meat or fish. Identifying the numerator is usually straightforward for single crops, but may be less so for mixed crops or other products. Caloric or protein content (as nitrogen) may then be used. Monetary value can also be used in a common numerator metrics. The *denominator* is the water consumed in the production process, that is, the volume of water made unavailable for other existing or potential uses (i.e., the "opportunity costs" of water consumed in the production process).

Water consumption has been given quite a variety of definitions and has to be defined in each situation. If we are dealing with a field in rain-fed agriculture, the water consumed may be:

- the quantity lost through evapotranspiration, although it can argued that the "consumed" water lost to the atmosphere contributes to rainfall in other places. In that case, WP is the same as WUE.
- the quantity of rain received by the field, assuming that this quantity is needed for the ecological functioning of the field system. With lower rainfall, the field would not produce the same crop or the same quantity. In that case, WP equals RUE.

It should be noted that the difference between WUE and RUE lies in the fact that runoff and groundwater recharge are accounted for and included in the RUE denominator (but not in the WUE calculation).

In irrigated cultivation, irrigation water is added to rain in the denominator. For a large irrigation scheme, irrigation water is the water entering the scheme. Water lost on the way to the field is not included if only the field is considered. If some water is drained, it returns to the river and may be subtracted if its quality has not been altered along its way through the field. Some authors claim that if drained water is polluted, it should be considered as "consumed." Others compute how much water would be needed to restore (by dilution) acceptable water quality. In that case, the capacity of "water quality self-restoration" by natural rivers should be considered.

As for unfed fishponds dedicated to fish production, the water is consumed through evaporation E, seepage S, and drainage D when the pond is emptied for maintenance. If natural water is used, the water consumed is E+S+D, if D is not used for other purposes. The WP is directly computed as production/loss of water. However, if some of the water used to fill or maintain the pond is sewage or wastewater, which is usually returned to the environment in a better condition, D is at worse nil and may be negative when the gain in quality can be quantified. In this case, the consumption of sewage may be considered a benefit, not a cost.

In livestock or aquaculture production, fishmeal from marine fisheries is considered a non-water consumable. More generally, oceanic fish production is considered to have zero water cost. To the contrary to primary producers (plants, cereals and trees), fish and livestock do not use water directly, except for drinking, which represents a very small part of their total direct or indirect water needs: 30 litres of drinking water per day for a head of cattle versus 3 m^3 to produce its daily fodder needs (Peden et al. 2003). For livestock, the production in the numerator also extends to other benefits or goods (transport, draft power, leather and livelihood security) that are more difficult to include in the analysis, but are important to herders in developing countries. For fisheries, when water consumption is not identified, counting the water content of the fish catch (about 66 to 75 percent of fresh weight) as the water consumed has been proposed.

In many instances, the water needed by fish and livestock is shared with other types of production. For example, a hydroelectric scheme is usually not managed to provide the best environment for fish in the reservoir or downstream from the dam. Similarly, cattle in developing countries often feed on stubble and crop residues after harvest. Thus the WP denominator is shared by different items, and the absolute value of water productivity is difficult to assess. We may consider here *marginal (incremental) water productivity*, where the increase in production for one given production can be assessed, as opposed to changes in overall water use. We may, for instance, want to increase fish production in a valley downstream from a reservoir by creating an artificial flood. In this case, a certain amount of water will have to be dedicated to fish reproduction and fisheries. In that case, marginal water productivity can be assessed by evaluating the increase in fish production. Marginal water productivity is also useful in irrigated crops, when the value added by an increase in irrigation water is compared to the increase in yield.

2.2 Virtual water and the water footprint

The concept of virtual water relies on estimates of water productivity and allows for a real application of WP in water management on different scales. The amount of water consumed in the production process of a product is the "virtual water" contained in the product (Allan 1998). The *virtual water* content of 1 kg of agricultural product is 1/WP.

The concept of virtual water is useful when considering transporting or trading products between regions with different water endowments, and in answering such questions as: How much water was consumed to produce the product? How much water can be "saved" by buying it, instead of producing it? These two quantities may, however, be different in some instances, as the conditions to produce the same product are not necessarily similar in different environments.

Ideally, virtual water trade between nations and even continents could be used as an instrument to improve global water use efficiency, to achieve water security in water-poor regions of the world and to alleviate the constraints on the environment by using the best-suited production sites (Turton 2000; World Water Council 2004).

Also, virtual water trade can be considered at the local or river basin level. The challenge is to stimulate and direct investments in the agricultural sector to enable activities beyond subsistence farming, which is probably the only way out of poverty. This requires managing water resources in a socially acceptable way and where optimum economic returns generate the financial means to purchase food (Turton 2000).

The concept of the *water footprint* was introduced by Hoekstra and Hung (2002) in order to create awareness of the amount of water needed to produce various goods and provide an individual or a country with commodities. This water footprint may be larger than the water consumed locally if some high water-demand products are imported. The water footprint is a better estimate of a nation's actual appropriation of global water resources. For example, an average US male citizen has a water footprint of about 2,300 m^3/year, of which 1,200 m^3 is used for food production, including 600 m^3 for meat, and 900 m^3 for domestic use and industrial products. On the other end, the average Chinese citizen was estimated to use only about a third of this total figure, i.e., 700 m^3/capita/year, during the period 1997-2001 (Chapagain and Hoekstra 2004).

The *ecological footprint* is similar in its approach to the water footprint, except that it incorporates not only the water resource, but also land resources. In essence, it is a resource management tool that measures how much land area and water a human population requires to produce the resources it consumes and absorbs under the prevailing technology (Global Footprint Network 2008). Also, it can be applied to a single type of production.

Both water and ecological footprints emphasize the *major challenges to sustaining* renewable resources and represent the benefits provided by the natural systems. The depletion of many ecological assets systematically undermines the well-being of people. This depletion is exacerbated by the growth in human population and the changing lifestyles, which place greater demands on natural resources (Global Footprint Network 2008).

A recent FAO expert consultation focused on comparative analyses of the environmental cost of aquatic food production in relation to other terrestrial food production sectors (Bartley et al. 2006). Tools such as life cycle assessment (LCA), material and energy flow analysis (MEFA) and biophysical accounting have also been proposed for this approach, but problems in making valid comparisons arise from the differences between aquatic and terrestrial environments, and the tremendous diversity of farming systems used in both (Haberl and Weisz 2007; Prein 2007; Tyedmers and Pelletier 2007).

2.3 Green, blue and other water states

The main denominator in WP is the amount of water consumed to produce biomass. Can we give a proper definition of water consumption?

On a global scale, there is no loss of water from the earth/atmosphere system, although a certain amount of water is polluted and may be considered as consumed, i.e., temporarily unavailable for use. At the basin level, much of the rainwater received is released back into the atmosphere by evapotranspiration. Although part of the evaporated water is recovered in the form of rain, we may consider that the evaporated water has been consumed by the vegetation to produce primary biomass.

There are differences in the benefits that a given quantity of water can provide. The distinction between green and blue water was introduced to address this difference. It has been estimated that two-thirds of total continental precipitation is lost through evapotranspiration during biomass production in terrestrial ecosystems, while only one-third flows to the sea (World Water Council 2004). We refer to this liquid water as "blue water," in contrast to "green water," which represents plant transpiration or field evapotranspiration. Rain-fed agriculture contributes two-thirds of the food produced in the world and consumes green water (Falkenmark and Rockstrom 2004).

Green water can rarely be employed for any of the practical uses provided by blue water. If a plant is watered, it transpires vapor (green water) and is said to have consumed this amount of water, which is not available for other uses, although it still exists. In fact, blue water is changed to green water.

To characterize different water qualities or possible urban and domestic uses, a few other qualifying terms have been proposed, for example:

- "White water" applies to groundwater or potable water;
- "Grey water," sometimes also called "spilled grey water," is non-industrial waste water generated by domestic processes such as dish washing, laundry and bathing (but not water from toilets). It can be used for landscape irrigation; and
- "Black water" applies to heavily polluted water. Black water is distinct from grey water in the amount and composition of its chemical and biological contaminants (from faeces or toxic chemicals).

All these classifications point to the benefits that can be provided by water. They are sometimes largely overlooked when dealing with water use, water productivity and water consumption.

2.4 Water consumption: a case-dependent definition

If water consumption is the volume of water made unavailable for other existing or potential uses, there seems to be no general definition, and the scale or limits of the system will play a major role in calculating the water consumed. Two examples illustrate this.

A fishpond loses water through evaporation. Usually, this water is considered a loss, and thus as consumed water. As part of the fish production process, it may also produce a volume of polluted water. If this water, rich in organic matter and nutrients, is used for irrigation, it is not considered "consumed," but rather "improved" by the fishpond. However, if it is released as such into the river, we may have to calculate the necessary dilution rate before water quality is sufficiently restored. The total quantity of water "consumed" may then be very important and the "benefit" that fish farm effluents can provide is, therefore, a major determinant of the denominator in the computation of water productivity, as well as the scale considered, including:

- the fishpond, where the water consumed is the evaporated volume plus the polluted outflow,
- the (pond + irrigated field) system, where the consumption is pond evaporation plus field evapotranspiration and irrigation; and
- the (pond + river) system, with consumed water equal to evaporation plus polluted outflow plus dilution water.

Hydroelectric reservoirs provide another good example of the importance of accounting for water benefits when calculating water consumption. If it is assumed that water quality is not altered in a reservoir, then the water consumed is the volume lost only through evaporation. The reservoir's inflow and outflow is blue water. However, some water may be needed for irrigation at some elevation between the reservoir surface and the turbine outlet. This was, for instance, the case of an irrigation project near the Lake Volta dam in Akosombo, Ghana. The water in the reservoir could provide gravity irrigation, while the water downstream would have required additional energy input to lift it up. The benefits of irrigation provided by the lake or the downstream river water are quite different if we consider these two systems as separate.

Both examples illustrate how the computation of water consumption and water productivity depends on the combination of benefits effectively provided by a given volume of water. This may be one of the reasons why water productivity figures are so different for apparently similar types of production.

2.5 Livestock and water productivity

Livestock water productivity may be estimated based on rangeland carrying capacity (CC) in arid and semi-arid developing regions. The concept of rangeland carrying capacity has been applied to pastoral systems in Africa where livestock are primarily dependent on grazing. Livestock production systems in other regions, such as intensive dairy or beef production in Western Europe, use feed originating from diverse remote areas. The virtual water content of the feed should therefore be used here instead of the CC concept (Dijkman 1993).

In theory, if the CC and the rainfall are both known, the theoretical WP can be calculated. However, the CC of a rangeland is difficult to determine accurately, as is the herd's productivity, and a number of approximations or hypotheses have to be made regarding the herder's strategy (risk avoidance or optimization of productivity, sale of young or adult animals, and age and sex structure of the herd). For instance, in the arid Alice Springs County in Australia (100 to 300 mm rainfall per year), the livestock WP is estimated to be 0.15 kg/m^3 in the best alluvial plains and 0.01 kg/m^3 in the shrub land (Bertram et al. 2006). The order of magnitude of WP for the pastoral system in the Volta Basin in West Africa is 0.005 to 0.01 kg/m^3 when only meat is accounted for in cattle production (BFP Volta, unpublished). When dairy products or other benefits (transport) are significant production components, monetary units have to be used to combine the different items.

3. Fisheries productivity: a short literature review

Estimating the fisheries productivity, or the health of an aquatic system, with general rules or equations, may explain the relationship between the water regime and the production system. Increasing fisheries productivity through some form of intervention will lead to an increase in water productivity most of the time.

3.1 Characteristics of aquatic systems in relation to productivity

The productivity of aquatic ecosystems has been studied in detail for many years, with a strong emphasis on the energy flow through the food web of the pelagic compartment, starting with photosynthesis and respiration of phytoplankton (Gaarder and Gran 1927). Estimating biological fish production was long based on population dynamics before evolving to a more comprehensive approach that includes prey-predator (fish-fisher) and other ecological relationships.

The *fisheries productivity* of an inland aquatic system is commonly measured in terms of kilograms of fresh fish per hectare (kg/ha) or per kilometre of river stretch annually. Productivity (in kg/ha/yr) has, therefore, the same dimension as yield in agriculture.

Relating fisheries production to the management of an aquatic habitat, and especially the hydrologic regime of a system, has led to the concept of fisheries' water productivity. Water abstraction and transfer have focused attention on environmental flows, but have seldom been translated into fisheries productivity or WP units (kg/m^3). The exception is floodplains, which provide probably the best examples of fisheries catch related to water volume in a number of different basins.

Fisheries' water productivity, as production per unit of water volume consumed or dedicated (kg/m^3), has been only recently used for inland aquatic systems, especially within the context of the Challenge Program on Water and Food (Brummett 2006a, 2006b, Dugan et al. 2006; Welcomme 2006; CPWF 2008). However, the term water productivity has not yet appeared as a keyword in the bibliographic databases of aquatic and fisheries sciences, where productivity is related to the food web and trophic levels (primary or secondary productivity) leading to biological production. In contrast, *aquaculture water productivity* has been studied with more attention, as water in that sector is one of the important economic components of the activity (Brummett 2006c, 2007; Sugunan et al. 2007).

The importance of fisheries

Fish and other aquatic resources of inland aquatic ecosystems are beneficial, especially in developing countries, but remain largely undervalued and poorly taken into account in water-related policies. Recent publications underline the high potential of small-scale fishing activities for economic development at local and national levels. However, they also highlight how poorly their true economic value is reflected in official statistics, food security and livelihoods appraisals (Cowx et al. 2004; Neiland and Béné 2006). In Africa, which provides about 25 percent of the world's inland fisheries landings, there is such a lack of data that FAO had to provide estimates of the total catch for half of the African countries where inland fishing is known to take place (FAO 2007). Better data are needed if fisheries are to be adequately accounted for in water allocation/conservation policies and thereby escape the vicious circle generated by the present situation (Figure 1).

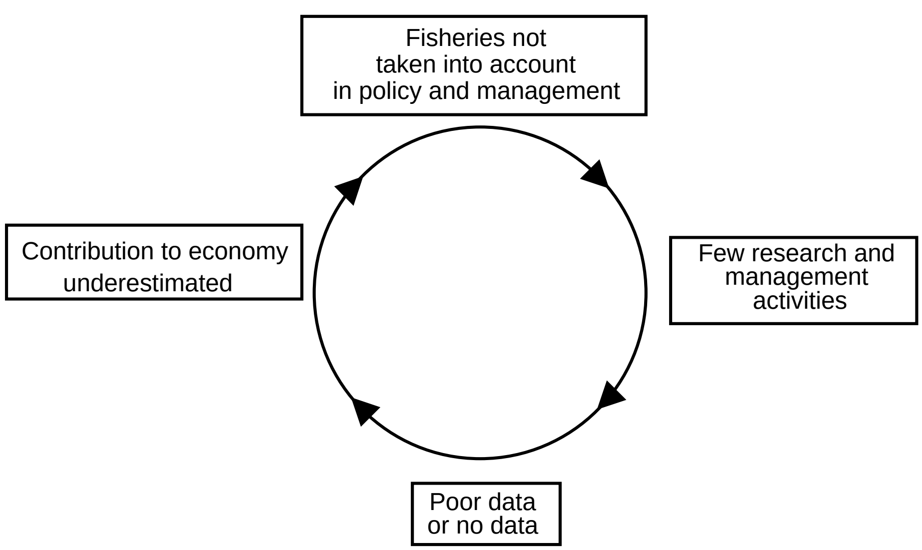

Figure 1. Vicious circle resulting in the continued undervaluation of inland fisheries.

Since competition for water and modification of aquatic habitats are the main threats to fisheries resources, the water productivity approach may prove useful to formulate adequate water allocation policies for sustainable fisheries and aquatic ecosystems (Sugunan et al. 2007).

Global inland fisheries and aquaculture (including China) contributed 9.6 and 28.9 million tonnes, respectively, of fresh weight in 2005, amounting to about 27 percent of the world's total marine and inland production (FAO 2007). If China's figures are excluded, in 2005 inland capture and aquaculture produced 7.0 and 8.8 million tonnes, respectively. The contribution of fish to total animal protein intake is significant (about 20 percent) and probably higher than indicated by official statistics, given the unrecorded contribution of subsistence fisheries. An estimated 68 percent of total landings from inland fisheries occurs in developing countries, where they contribute significantly to the livelihoods of many rural households. National statistics are usually considered as underestimates, since part of the catch is either not commercialized or delivered through informal channels. Where data are "reconstructed," however, evidence suggests small-scale fisheries are important in the developing world. Neiland and Béné (2003, 2007), for instance, have produced tentative but, nevertheless, informative estimates of the importance of actual and potential basin-wide fisheries in West and Central Africa, from Senegal to Congo-Zaïre. Although some of their figures for actual catch may be underestimates (e.g., Lake Chad and Lake Volta), they also show that the potential catch, as derived from the general relationships described later in this study (section 3.2 below), is expected to be much higher that the actual estimated catch in most basins (Table 1).

Table 1. Volume of fisheries production in some African basins (modified from Neiland and Béné 2003).

Basin		Production (t/yr)			Potential fisheries production (t/yr)
	Lake	Rivers	Lake	Total	
Senegal-Gambia	Manantali	30,500	??	> 30,500	112,000
Volta	L. Volta	13,700	> 40,000	> 53,700	62,000
Chad	L. Chad	32,200	> 60,000	> 92,200	165,000
Niger-Benue	L. Kainji + Lagdo	236,500	6,000	242,500	205,000
Congo-Zaïre	-	312,900	-	>418,900	520,000

Bernacsek (1988) estimated the overall potential annual fish yield of small systems in Africa (lakes, rivers, swamps, reservoirs and coastal lagoons) to be between 1 and 2.3 million tonnes. Fish processing and fish trade activities involve many people, especially women, for whom these activities provide a crucial source of cash income.

Finally, as far as aquaculture is concerned, the annual growth rate of the world's inland aquaculture has been 8.8 percent since 1970, compared to 2.8 percent per year for terrestrial farmed meat production systems. Africa remains of minor importance in this activity though, with only about 1 percent of the world's fish farmers and 0.16 percent of global production (FAO 2007).

Ecosystem health, environmental flows and fish production

Increasingly, river scientists are asked to provide recommendations on the amount, timing and quality of water flows needed to support ecosystem health. The emphasis is most often on the ecological quality of the river and the benefits to society, among which fish production is not the main component.

It may be hypothesized that, in general, a river's "good health" is a requisite for fish production, at least for fish diversity, if not for quantity. Actual cases of increasing productivity as a result of river management are, however, lacking. The short bibliographic review below provides a few examples of river flow management and discusses whether these have had implications in terms of fish production.

The most convenient, and often the only available, indicators of a river's "health" are hydrologic (Matthews and Richter 2007; Mazvimavi et al. 2007). A range of environmental flow assessment methods has been derived from hydrologic data, such as the "range of variability approach" (RVA) and the South African "desktop reserve mode" (DRM). Nevertheless, despite considerable progress in understanding how flow variability sustains or improves a river ecosystem, there is a growing temptation to ignore the natural system's complexity in favor of using simplistic, static, environmental flow "rules" to resolve pressing river management issues (Arthington et al. 2006; Kashaigili et al. 2007). Indeed, a knowledge gap remains in linking hydrologic and bio-economic objectives with the optimum use of all water resources under conflicting demands (Hirji and Panella 2003).

A recent global review of environmental flow methodologies revealed the existence of 207 individual methodologies, applied in 44 countries within six world regions. These could be differentiated into hydrological, hydraulic rating, habitat simulation and holistic methodologies, with a further two categories representing a combination-type and other approaches (Tharme 2003). Recent advancements include the consideration of ecosystem-dependent livelihoods and a benchmarking process suitable for evaluating alternative water resource developments in a basin, usually in relatively poorly known systems. Holistic methodologies may be especially appropriate in some developing countries where environmental flow research is in its infancy and water allocations for ecosystems must be based, for the time being at least, on scant data, best professional judgment and risk assessment.

The description of the diversity of invertebrate riverine communities has been developed in different countries as an indicator of river health, based on the habitat preferences of these animals. Examples are found in the South African Scoring System (SASS) (Chutter 1995; Dickens and Graham 2002) or in the "Global Normalized Biological Index" (IBGN 2008). These tools generate information on the distribution of the health of a stretch of river over time, as measured by the invertebrate community, but no relation with fish production was observed.

Attempts at more comprehensive or multi-criteria approaches have been published, including water quality data and other biological components, such as phytoplankton, macrophytes or periphyton (Brown and Joubert 2003; Palmer et al. 2005). The DRIFT (Downstream Response to Imposed Flow Transformation) method is presented as a holistic methodology for advising on environmental flows in rivers targeted for water-management activities. It was developed in a semi-arid, developing region of Zimbabwe, where water supply problems are pressing, and uncertainties about river-linked ecological and social processes are high (King et al. 2003; Love et al. 2006).

The structure of fish communities, as an indicator of the health of a river system, has been studied in many countries and developed into fish biotic indices that are routinely used for environmental monitoring. Since these indices apply to specific hydro-eco-regions, a variety of formulae is available, for example in the USA (Karr 1981; Fausch et al. 1984; Fayram et al. 2005) and France (Oberdorff and Hughes 1992; Lemoalle et al. 2001; Oberdorff et al. 2002). For river restoration, the ability to predict fish responses to environmental flow is still quite limited. Further monitoring of fish communities is necessary. In addition, contingency flow allocations can be used to test fish responses to altered environmental flows directly (Growns and Gehrke 2005). For example, habitat requirements for fish in direct relation with fisheries production have been published for salmon in North America and Norway (Halleraker et al. 2007; Moir et al. 2006).

Although some environmental flows have been implemented in an attempt to maintain or increase riverine fish communities, it seems that the effects of such interventions have not been given much publicity in the scientific literature, except for salmon (Halleraker et al. 2007). In contrast, the decrease in fish catch resulting from the alteration of a river's regime due to the construction of a dam is better documented (FAO 2001). Most often, the change in catch below a dam does not, however, result necessarily from a decrease in water volume, but from a modification in the river's hydrological regime. In other words, the change in water volume is not the main cause of the change in the amount of fish caught.

When productivity is modified by external interventions

The yield or productivity of a fisheries system can be modified by external interventions, which may, or may not, involve a change in water volume. When a water volume has been dedicated to this purpose, a marginal WP can be calculated.

As mentioned above, cases of associating the extent of environmental flows in a river with the fish catch (increase or decrease) are poorly documented. Other examples of possible interventions are:

- artificial flooding to restore floodplain inundation;
- fish pass and weirs; and
- management of reservoir water level.

The construction of two dams—the Diama dam in the estuary and the Manantali dam on the Senegal-Mali border—has modified the lower valley of the Senegal River and affected the euryhaline and freshwater fish communities. Although part of the flood in the Senegal River below the Manantali Reservoir has been maintained artificially to allow for recession cultivation in the floodplain in the valley, sharp decreases in the number of fishers and in fish catch have been observed and attributed to a decrease in the area flooded (Albaret and Diouf 1994). However, the quantitative relationship does not seem to have been established.

In most cases, the river discharge below a hydroelectric reservoir is closely regulated and does not allow for floodplain inundation, at least not close to the downstream reach. Further downstream, floodplain productivity can be totally or (more often) partially lost, and so is the capacity of fish to migrate to spawning grounds to reproduce. Fish passes and weirs may be adopted to address and mitigate this impact.

3.2 Estimating fisheries productivity

The productivity of inland fisheries systems results from the interaction among three main types of variables; these are related to human activity, the aquatic habitat and fish communities. In their analyses, fisheries scientists usually identify different classes of habitat and then look for variables that could explain fluctuations in the fish catch in different water bodies belonging to the same type of habitat. The observed relationships are being improved as more data sets become available. They have proven very useful in estimating the productivity of fisheries systems for which very few data are available.

River basins

At the basin level, variables pertaining to habitat size are often used to describe the system. Welcomme (1976, 1985) proposed several relationships regarding the total fisheries catch in African river basins. The first equation (Welcomme 1 in Figure 2) gives the fisheries total catch (tonnes/year) as a function of the basin area (km^2) in 20 river basins with high to moderate fishing activity:

$$\text{Catch (tonnes/year)} = 0.03\ (\text{Area})^{0,97} \qquad (N = 20,\ r = 0.91)$$

This relationship has been slightly modified for basins where extensive floodplains contribute to an increase in productivity (Welcomme 2 in Figure 2):

$$\text{Catch (tonnes/year)} = 0.044*(\text{Area})^{0.90} \qquad (\text{N and R not specified})$$

From Figure 2, it is evident that the second relationship produces slightly higher estimated values (as expected, since it accounts for floodplain production). Crul (1992), drawing upon the Source Book for the Inland Fishery Resources of Africa (SIFRA) (van den Bossche and Bernacsek 1990) with information on more than 900 inland waters of Africa, revisited the existing equations on the productivity of rivers and lakes. The updated relationship for African basins with or without floodplains is shown below (Crul in Figure 2):

$$\text{Catch (tonnes/year)} = 0.048\ (\text{Area, km}^2)^{0.93} \qquad (R = 0.95)$$

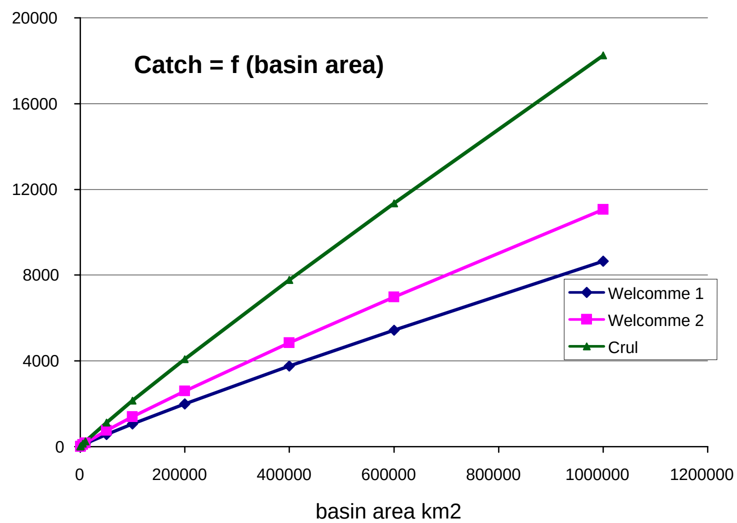

Figure 2. Productivity of African river basins (data from Welcomme 1976 and 1985, and Crul 1992).

Considering that there is a general homogeneity in basin shape, in the sense that the length of the main channel is proportionally related to the basin area, the following empirical relationship has been proposed (Welcomme 1985):

$$\text{main channel length} = 4.95\ (\text{basin area})^{0.45}$$

Based on this, Welcomme's equation 1 can be translated into the main river length L (km) as

$$\text{catch (tonnes/year)} = 0.0032\ (L)^{1,98} \qquad (N=20, R= 0.90)$$

or, broadly:

$$\text{catch (tonnes/year)} = (L)^2/300$$

This equation has been derived further to state that each kilometre of river reach, at a distance L from its source, would produce 2×L/300 tonnes of fish (Welcomme 2006). The appropriateness of the latter relationship is, however, questionable, as the original relation applies to the basin's area and not to the main river's length. The derivative used here would mean that each extra basin area corresponding to a one-kilometre increase in river length would produce a predictable amount of fish. However, the productive system is actually the basin area, not the main channel of the river.

Factors regulating fish production in a river system remain poorly studied and understood. Published catch data for African rivers are often estimates derived from the above equations (e.g., Neiland and Béné 2008) and do not contribute new information. Deviations from the theoretical yield in an individual river system arise from differences in both edaphic and morphological characteristics. In addition, the production of a very large number of smaller streams and tributaries has not been recorded yet.

The first order rainforest streams have been estimated as a major aquatic ecosystem in Africa, providing fish to a widely dispersed and protein-deficient population (Welcomme 1976; Brummett and Teugels 2004). Estimates from southern Cameroon put the productivity of capture fisheries in a forest river basin at 1.1 tonnes/km^2/yr (du Feu 2001). This translates into more than twice the value of all other non-timber forest products combined. Accordingly, average fish consumption in Cameroon's rainforests is around 47 kg/person/year, compared to 10 kg for the general population (Obam 1992).

Floodplains

Productivity of tropical floodplains may be quite variable because they depend on annual river flooding and, partially, on the fish community in the river. Drawing upon data from 25 tropical floodplains (of which 14 are in Africa) in different continents, Welcomme (1985) proposed the following relationship (Figure 3):

$$\text{Catch (tonnes/yr)} = 4.23 * (\text{floodplain area, km}^2)^{1.005} \quad (N = 25; \text{r not given})$$

Although the best fit is a power curve, the exponent is sufficiently close to 1 to make the relationship almost linear, with about 43 kg/ha/yr (Welcomme 1985). Crul (1992) proposed an updated relationship for tropical floodplains (Figure 3):

$$\text{Catch (tonnes/yr)} = 8.78 (\text{floodplain area km}^2)^{0.90} \quad (r = 0.93).$$

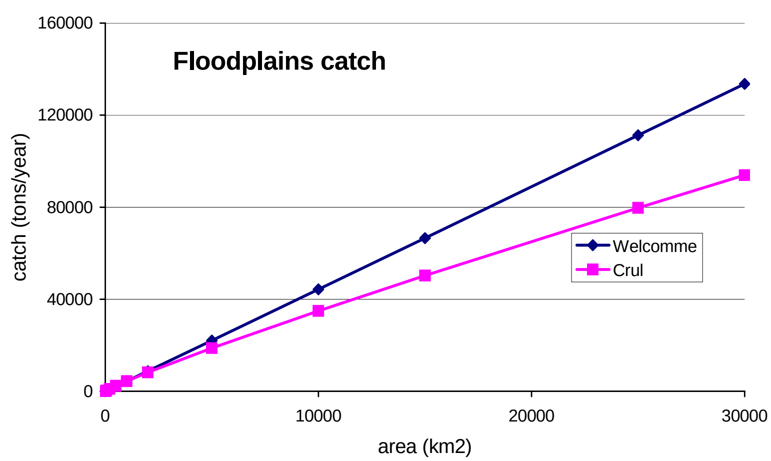

Figure 3. Floodplain catch based on the flooded area (data from Welcomme 1985 and Crul 1992).

Total production in a given floodplain is closely dependent on the magnitude of the flood, which can be described either by the maximum extent of the flooded area or by the inflow volume. It is generally assumed that floodplains provide shelter and food for juvenile fish during their first months of life. A "good" flood is one that provides an early spawning period, a large amount of food as well as longlasting shelter and growth before the fish enter the mainstream. Such relationships between fish catch and annual inflow have been described in various contexts. Some tropical examples are:

- the Inner Delta of the Niger River (Laë 1992; Quensière 1994; Laë and Mahé 2002) (Figure 4);
- the El Beji outlet of the Yaere floodplain in Northern Cameroon in the Chad Basin for the period 1974-79 (Bénech and Quensière 1983); and
- the maximum water level in the Great Lake and fish catch of the *dai* fisheries in the Tonle Sap River linking the Mekong River to the Great Lake in Cambodia. The *dai* fisheries is only a part of the total fisheries in the Great Lake, which is one order of magnitude larger. The relationship nevertheless shows the importance of the inundated area (van Zalinge et al. 2003; Kummu et al. 2006) (Figure 5).
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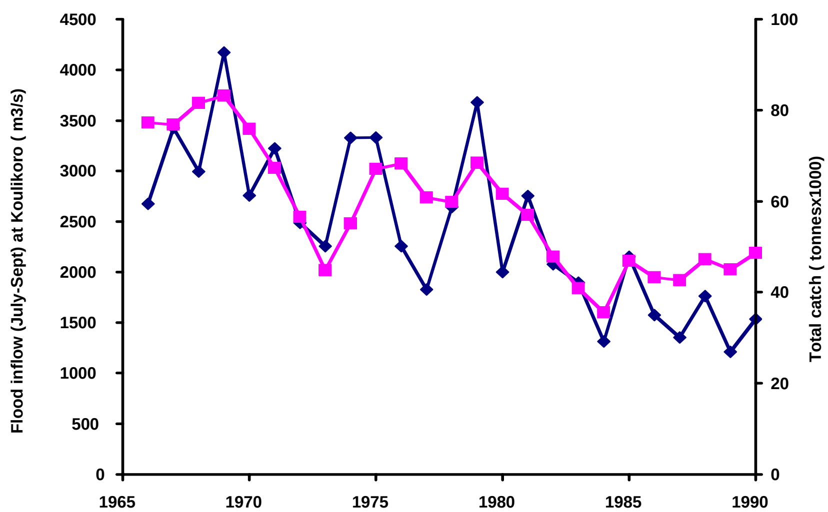

Figure 4. Relation between flood river inflow as measured at Koulikoro (diamonds; m^3/s from July to September) and annual catch (thousands of tonnes) in the Inner Delta of the River Niger (squares) (data from Laë and Mahé 2002).

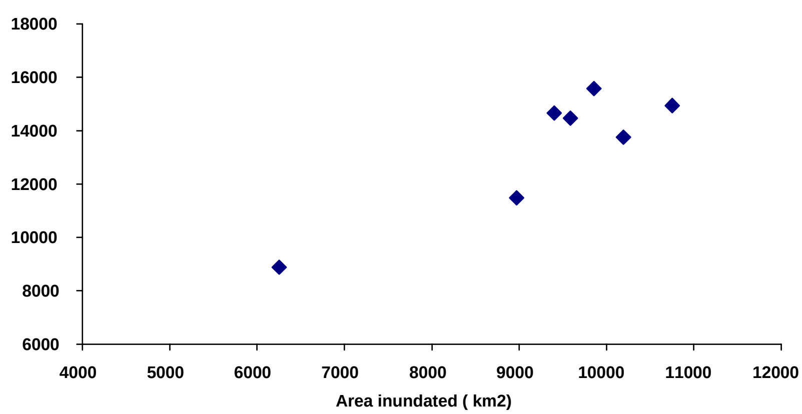

Figure 5. The *dai* (bagnet) fisheries catch in Tonle Sap as a function of total inundated area in the Great Lake, Cambodia (data from van Zalingue et al. 2003).

These examples indicate that there is a quantitative relationship between the volume of water delivered to the floodplain and the fish catch. Using this relationship would allow the computation of a marginal WP when planning water management strategies.

Lakes and reservoirs

The fisheries productivity of tropical lakes and reservoirs varies over a very large range. Jackson and Marmulla (2001) give the following figures from different authors for African water bodies of different sizes:

- large reservoirs subject to moderate to heavy fishing: from 27 to 65 kg/ha/year (Kapetsky 1986);
- medium-sized reservoirs: around 80 kg/ha/year (van der Knapp 1994); and
- a variety of small sub-Saharan water bodies: around 329 kg/ha/year (Marshall and Maes 1994).

General relationships have been proposed to describe such diversity, based on the characteristics of some lakes. It should be remembered, however, that fish catch is also dependent on fishing activity and techniques. A striking example is that of Lake Kinneret in Israel: the mean yearly catch of Kinneret fish increased 6.5-fold, from 265 tonnes during 1936-40 to 1,748 tonnes during 1969-73. The annual catch per fisher has increased from 1.5-2.0 tonnes during the initial period to a value of approximately 9.7 tonnes. This augmentation is the result of changes in environmental conditions, fishing regulations, technological development of fishing methods, increased marketing possibilities and the stocking of new species (Reich 1978).

The *morphoedaphic index (MEI)* is the ratio of total dissolved solids (or conductivity) to mean depth. Ryder (1965) proposed it as a possible index of a lake's biological productivity. The relationship is valid to compare lakes within a given category (i.e., in a given geological region), but it should not be used for lakes differing in their water ionic composition or having non-comparable basins. It has, however, been overused, with little consideration of the geological setting (Ryder 1982). Biological fish productivity in a given class of lake is usually given as a direct function of the MEI:

$$\text{Fish productivity (kg/ha)} = k \times \text{MEI} = k \times \text{(Conductivity)/(mean depth)}$$

The relation indicates that decreasing lake depth should induce an increase in productivity, if water quality is not modified. The lake's total production (area × productivity) would then depend on its shape (i.e., change in area as a function of water level). In some of Africa's closed shallow lakes, such as Lake Chad and Lake Chilwa, when local droughts cause a decrease in water level and an increase in conductivity through evaporation (resulting in a strong increase in MEI), increases in biological productivity per unit area have indeed been observed (Kalk et al. 1979; Lemoalle 1979). Matuszek (1978) used the components of the morphoedaphic index, mean depth and total dissolved solids concentration, as a set of two independent variables to explain 70 percent of the variability of the maximum sustainable yield (MSY) of a series of large North American lakes. Crul (1992) proposed a series of relationships to estimate the order of magnitude of productivity for African lakes and reservoirs.

Based on 71 pooled African lakes and reservoirs:

$$\text{Catch (tonnes/year)} = 8.32\ (\text{water body area, km}^2)^{0.92} \qquad (R^2 = 0.93)$$

It should be noted, however, that the confidence limits are quite wide: the fish catch of a 100-km^2 lake would be 585 tonnes/year, with a 95 percent probability to lie between 152 and 2,253 tonnes/year.

Based on 46 African lakes:

$$\text{Catch (tonnes/year)} = 8.93\ (\text{lake area, km}^2)^{0.92} \qquad (R^2 = 0.92)$$

Based on 25 African reservoirs:

$$\text{Catch (tonnes/year)} = 7.09\ (\text{reservoir area})^{0.94} \qquad (R^2 = 0.94)$$

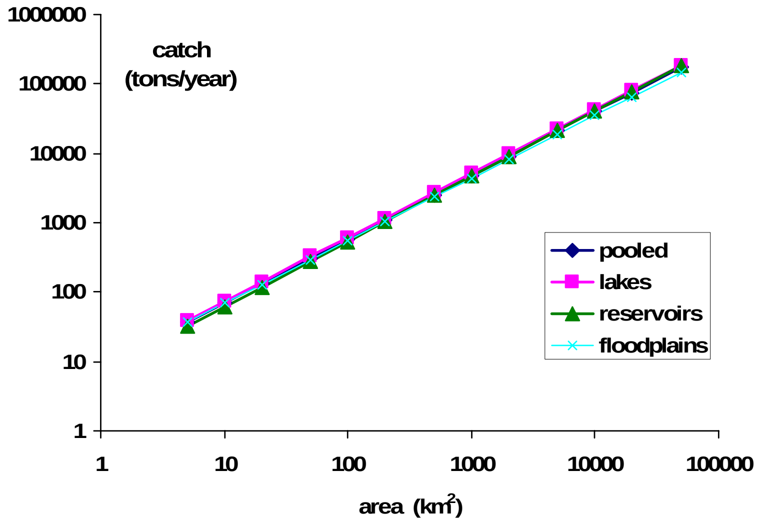

Figure 6. Relationships between area and annual catch in African lakes, reservoirs, lakes and reservoirs pooled together, and floodplains (from Crul 1992). On a log-log scale, all the productions are remarkably similar.

Taking into account the uncertainty of these correlations, the three equations do not show any significant difference (Figure 6). In fact, the overall model indicates an average catch of 60 kg/ha/yr in African lakes and reservoirs, with values in large lakes slightly lower than in smaller ones, but with considerable uncertainty when applied to a single water body. This uncertainty severely limits the application of the relationships to make effective predictions or to manage a specific water body (Laë 1997).

A number of fisheries studies use catch per unit of effort (CPUE) as a measure of fish density or potential total fish catch, and this has proved very useful to determine trends in the productivity of a water body and the need for fishing regulations. However, CPUE is often difficult to estimate when the fishing activity is poorly understood, as it requires estimates of both landings and fishing effort. Rough figures to check for consistency with other productivity estimates have been proposed by Henderson and Welcomme (1974) and Crul (1992) when both total production and number of fishers (as a proxy for fishing effort) are given for a lake or reservoir. The relationship proposed by Henderson and Welcomme (1974) is a combination of physico-chemical characteristics of the lake and of the density of fishing activity. It relates the catch per fisher (tonnes/year) and the morphoedaphic index (measured as the ratio of water conductivity in micro Siemens/cm to mean depth in meters) as follows:

$$\text{Catch per fisher (tonnes)} = 14.3136\ (\text{MEI})^{0.4681}$$

Laë (1997) also found that the highest correlation between catch per fisher and the morphoedaphic index (R^2= 0.42) occurs when the fishing effort involves more than two fishers per km^2. This is the condition of a "normally" exploited lake, where the CPUE is not too high, resulting from the catch of large individual fish in an underexploited fish community. Theoretically, the two empirical equations seem to be very close to the improper use of the morphoedaphic index as quoted by Ryder (1982). They may prove inadequate for some lakes in specific geological locales and for reservoirs with a very short residence time.

More generally, Crul (1992) has proposed a mean yield per fisher of around 2.3 tonnes/year for the combined series of lakes and reservoirs and 2 tonnes/year for reservoirs only. Jul-Larsen et al. (2003) have found a mean value of 2.8 tonnes/fisher/year in another series of African lakes, irrespective of fisher density. In these lakes, the catch per unit area increases with fisher density, up to 20 tonnes/km^2/year in lakes Chilwa and Mweru or Malombe, with 5 to 6 fishers per km^2.

Uncertainty of fish catch: the case of Lake Volta

Lake Volta provides a good example of the uncertainty associated with catch estimates in a huge reservoir (8,500 km^2) with a large number of fishing villages (1,329) and about 80,000 fishers (Braimah 2000). The published fish catch estimates derived from field observations vary widely, as follows:

- mean catch of 40,000 tonnes/year during the period 1969-77 for the whole lake (Braimah 1995);
- 31,000 ± 3,000 tonnes/year in 1996 for stratum VII only, one of the lake's eight strata (De Graaf and Ofori-Danson 1997); and
- a recent (unpublished) estimate for year 2000: close to 215,000 tonnes/year.

This last figure may seem an overestimation with a catch of 253 kg/ha/yr and would indicate a high, but not impossible, annual catch per fisher of 3 tonnes/year. It should be compared to an estimate for the whole lake from the equations cited above: with a lake area of 8,500 km^2, the catch would be around 35,000 tonnes/year (with a 95 percent confidence interval ranging from 9,000 to 140,000 tonnes) according to Crul (1992).

These values may be compared to two other large African reservoirs. The fisheries production of Lake Kainji (1,270 km^2) is between 6,000 and 36,000 tonnes/year, depending on the period and fishing effort (Nigerian-German Kainji Project 1998; Ovie and Raji, pers. comm.). The annual catch per hectare ranges from 47 to 283 kg/ha; the highest values are obtained when capture of pelagic clupeids is allowed. The fish catch in Lake Nasser (6,216 km^2) ranges from 15,700 to 34,000 tonnes per year, while its productivity ranges from 25 to 55 kg/ha/yr (Crul and Roest 1995).

3.3. Water productivity in inland fisheries

Water productivity of fisheries: marginal water productivity

While the productivity of aquatic systems is measured through the catch per unit of water area (kg/ha/yr), the water productivity of fisheries (fisheries WP) is the fish catch per unit volume of water consumed by, or dedicated to, the fisheries system.

In their present state, most fisheries are non-consumptive users of water. As noted above, this is the case for marine fisheries. As a result, the virtual water content of marine fish and of the fish meal used in aquaculture may be considered as zero (Brummett 2006c). However, the aquatic communities that support the fisheries in rivers, lakes and wetlands require particular characteristics, especially in terms of the hydrologic regime, water quality and seasonality. Consequently, there is a water requirement for fisheries in order to maintain or increase production.

Where this requirement does not exist, the fisheries WP cannot be properly evaluated because the denominator is nil. This is the case of the world's oceans, even though there are signs that human activities impact the water budget, for instance with the predicted and observed rise in sea level. This may be the case for large lakes, such as the African Rift lakes in East Africa, Lake Chad in Central

Africa and the North American Great Lakes, where the water budget or the hydrologic regime is not impacted by water abstraction in the basin. Riverine and floodplain fisheries may also be included in the "no water cost" category, as long as no water is committed to the maintenance of fish communities, which is usually the case.

If some water volume (Δ Water) is dedicated to increase or maintain fish production, a certain amount of the fish catch (Δ Prod) may be related to the water cost. The water volume (Δ Water) is diverted from other potential uses. It is then possible to calculate the fisheries' marginal water productivity:

$$\text{Marginal Fish WP} = \Delta \text{ Prod}/\Delta \text{ Water}$$

A case study: the Inner Delta of the Niger River

Detailed multi-year observations on the fisheries catch in the Inner Delta of the River Niger in Mali have resulted in a relationship between total inflow and catch (Figures 6 and 7). This relationship remains valid as long as the shape of the flood hydrogram is unchanged, i.e., the flooded area and flood duration in the floodplain are directly related to total inflow.

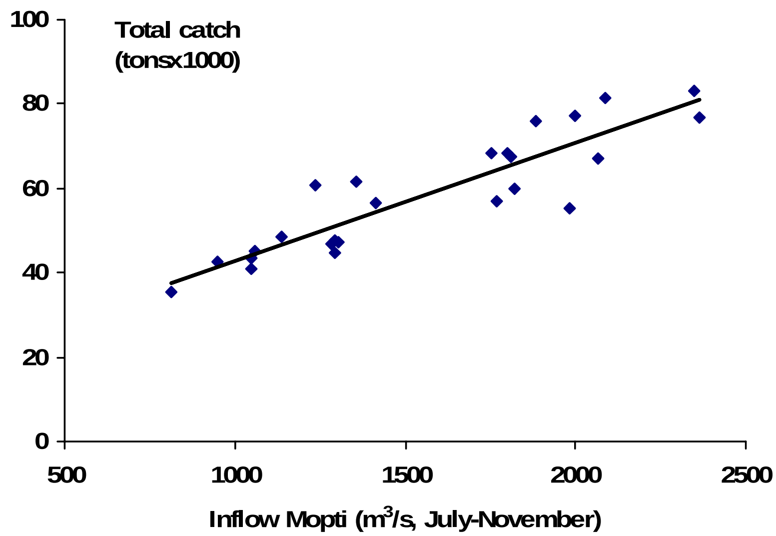

Figure 7. Relationship between fish catch (thousands of tonnes per year) and flood riverine input (July to November) in the floodplain of the Inner Delta of the River Niger in Mali (data from Laë and Mahé 2002).

This relationship is explained by the ecology and fish behavior in the river and floodplain. Whereas it is usually assumed that the fish catch in a floodplain is related to the floods of the two or three preceding years, in the case of the Inner Delta, the fish catch is related to the flood of the same year, as very few fish survive at the end of the dry season, due to high mortality rates associated with capture fisheries and predation by birds. Nevertheless, this very limited stock at the end of the dry season has so far been sufficient to ensure reproduction of the stock and recruitment in the fisheries, mainly of one-year-old fish (Laë and Mahé 2002).

Assuming that some water abstraction occurs upstream without modifying the shape of the inflow hydrogram, we can then compute from Figure 7 the change in the fisheries catch. For a given volume of water, a corresponding quantity of fish can be estimated. In particular, Figure 7 indicates that an abstraction of 1 m^3/s between July and November (equivalent to 13×10^6 m^3 during the flooding season) would result in a loss of 27.8 tonnes of fish catch in the observed domain of the flood discharge. This relationship allows us to estimate the impact of the planned Fomi reservoir on the fisheries of the Inner Delta.

The flood pulse concept revisited

The general equations described above (section 3.2) indicate that a 1,000-km^2 lake or reservoir would generate a fish catch of 4,800 tonnes/year, while a floodplain of the same area would produce close to 4,400 tonnes/year. If we consider that the floodplain is inundated only part of the year, and that it provides other benefits such as agricultural cultivation and cattle grazing during the rest of the year, it appears that floodplains are highly productive systems. The high productivity of floodplains has been attributed to a number of processes associated with the oxydo-reduction cycle in the aquatic/terrestrial transition zone (ATTZ). The flood pulse concept incorporates those processes occurring at the wet/dry interface along the moving littoral over the whole area of the floodplain (Junk et al. 1989).

The fish production of a floodplain is partly derived from the riverine system, especially when the catch is composed of fish less than one year old (0^+) and less than 2 years old (1^+) that have spent part of their lives in the river system. In floodplains where the catch consists mainly of 0^+ fish, as in the Inner Delta of the Niger River or the El Beji outlet of the Yaere in the Chad Basin, biological productivity is fully derived from processes occurring in the floodplain during its inundation.

Marginal water productivity of such a floodplain could be computed, but it would have to include all the benefits provided by the system, namely the fish, and also cattle fodder and cultivated crops, rice being the most important.

4. Aquaculture productivity

For physiological reasons, fish are by far the most efficient animals, when we consider the energy transfer from food to body weight. Being poikilothermic, fish do not use energy to heat or cool their bodies. Since they excrete ammonia, fish use a minimal amount of energy in protein catabolism and excretion. In addition, because they generally float in water, fish do not need heavy bones. Aquatic animals are thus well suited as energy converters. Channel catfish (*Ictalurus punctatus*), for example, gain up to 0.85 g of weight for every gram of feed consumed, compared to 0.48 g in chicken, the most efficient warm-blooded animal, and 0.13 (or much less, according to the nature of the feed) in beef cattle (Renault and Wallender 2000).

However, most aquatic ecosystems cannot use solar energy as efficiently as terrestrial systems due to the reflection of light on the water's surface and its absorption within the water mass. Only the aquatic helophytes can compete favorably with terrestrial plants. The most efficient energy transfer may, therefore, be a combination of fish reared in fertilized ponds, supplemented by terrestrial products. When energy transfer is considered through the whole food web, it should also be noted that primary consumers, such as carp or tilapia, are more efficient than top predators, such as salmonids or Nile perch. The same area of a tropical natural water body can produce much more tilapia than Nile perch.

Water productivity values of a variety of terrestrial and aquaculture products are shown in Table 2. There is, for each of these products, at least one order of magnitude in WP variability, depending on the production system, as illustrated by the difference in cereal productivity in California and the Volta Basin or by examples of WP diversity for different fish production systems (Table 3). In fed ponds, cultured tilapia and catfish do not provide higher WP than pork or chicken.

A recently published review (Brummett 2006c) of the role of aquaculture in increasing water productivity is largely used in the rest of this section. Aquaculture and, more specifically fish culture, involves a series of more or less intensive activities, from culture-based fisheries, where the natural fish stock is enhanced by the introduction of fingerlings, to high-density, open- or closed-circuit industrial schemes. The constraints for fish production and water productivity in this wide array of activities differ significantly. Examples from extensive to intensive fish culture are discussed below.

Through an effective management strategy, which involves a community mobilization and participation mechanism, culture-based fisheries can be developed in small reservoirs. Recent studies in Sri Lanka indicate good returns from culture-based fisheries in small village reservoirs. An average fish yield of about 450 kg/ha can be achieved during a single culture cycle within a year. As there are concerted efforts to develop culture-based fisheries, at least 10 percent of the total extent of village reservoirs (about 9,000 ha) may be stocked annually with fish fingerlings to enhance inland fisheries production (Amarasinghe 2006). Also in Sri Lanka, a recent evaluation has shown that a fish production of 2,000 tonnes/year can be achieved in rice irrigation reservoirs, which represents an increase of 18 percent of the total economic return (Renwick 2001). As these reservoirs have been developed for irrigation purposes (rather than for fish production), the water consumed for fisheries production is, in theory, nil. Marginal fisheries WP, however, can be calculated if we estimate the volume consumed to keep breeder fish and produce fingerlings. Cages in irrigation reservoirs or irrigation channels may also be considered non-water consumptive (except for the virtual water content of the feed), as long as there is no impact on water quality.

Table 2. Water productivity values for different types of production in different environments.

Production	WP kg/m^3	kcal/m^3	Prot g/m^3	Lipid g/m^3	Source
Millet	0.08	302	8.96	3.4	VB
Sorghum	0.10	339	11.3	3.3	VB
Wheat	0.86	2279	74	9.0	RW
Rice	0.71	1989	49	5,0	RW
Maize	1.41	3856	77	17,0	RW
Potato	9.52	5626	150	9,0	RW
Pulses (beans)	0.35	1188	76	4,0	RW
Yam	1.00	1180	15.3	1.7	VB
Cassava	1.00	1600	13.6	2.8	VB
Groundnut	0.39	2382	111	206	RW
Onion	6.83	2259	85	0.0	RW
Banana	2.00	432	11.0	0.0	RW
Bovine meat	0.074	102	10.0	7.0	RW
Pork meat	0.22	408	21.0	35.0	RW
Poultry meat	0.24	520	45.0	36.0	RW
Egg	0.37	519	41.0	36.0	RW
Milk	1.27	659	40.0	38.0	RW
Tilapia (fresh weight)	0.3	288	60.3	5.1	Br
American catfish	0.16	216	24.8	2.7	Br

Data sources: RW: Renault and Wallender (2000); VB: Volta Basin unpublished data; Br: Brummett (2007).
Note: All conversions from biomass to energy, protein and lipid contents have been computed according to the USDA Nutrient Data Laboratory data set (see URL in references).

Other beneficial ways of using poor quality water provided by extensive or intensive aquaculture are given by Brummett (2006c). They include the introduction of the filter feeding Chinese carp (*Hypothalmichthys molitrix*) in cooling reservoirs, and of common carp (*Cyprinus carpio*) or tilapia in cages in sewage ditches or untreated fishponds, that are subsequently used for crop irrigation. If some element is added to increase production, such as feed or fertilizers, the virtual content of these products may be included in the consumed water.

In intensive fed-systems, such as raceways for salmonids, a considerable volume of water is circulated (about 250 m^3 by kilogram of fish) to maintain water quality and the high dissolved-oxygen content required by the fish. The consumptive water use is, however, difficult to estimate and highly site-specific, depending on the competition for water. As these fish are fed high-energy protein feeds, the virtual water content of these products should be added to the physical volume of water used.

Table 3. Range of water productivity in fish production systems as measured by edible output (kg fresh weight) per m^3 of water, and digestible energy (kcal) per m^3 of water (modified from Brummett 2007).

Culture species	Production system	Edible output (kg fresh weight) per m^3 water	Digestible energy (kcal) per m^3 water
Tilapia (*Oreochromis spp.*)	Fertilized ponds	0.48	360
	Sewage-fed ponds	0.55	410
	Fed ponds	0.34	260
	Fed aerated ponds	0.044	34
	Fed Cages	1.26	950
	Fed biofilters	1.06	795
Sharptooth catfish (*Clarias gariepinus*)	Fed raceway ponds	0.012	8
	Fed raceways	0.27	200
Channel catfish (*Ictalurus punctatus*)	Fed ponds	0.33	250
	Fed aerated ponds	0.24	180
	Fed ponds with water reused	0.29	215
Chinese carp polyculture	Fertilized ponds	0.08	60
	Fed ponds	1.92	145
	Fed aerated ponds	0.43	320

5. Conclusion: how can we apply water productivity to fish production?

The productivity of water bodies has been the subject of numerous studies, most often with an ecological focus on the transfer of matter and energy through the food web. For a more practical approach, pragmatic alternatives have been proposed to relate fish productivity to easily accessible indicators, such as basin or lake area. More recently, the water productivity concept has been re-introduced to underline the high water cost of agricultural production and to question the sustainability of current agricultural systems and food demand. Some associated concepts, such as virtual water or the water footprint, have also proved useful in this context.

While the WP concept was initially developed for irrigated crops, recent developments have led to the inclusion of other agricultural systems, such as rain-fed cultivation or livestock rearing, in an attempt to achieve a more integrated approach, although such a possibility has been doubted (Zoebl 2006). The question now is how to link aquatic production from fisheries or fish culture to this concept of WP. This report is an attempt to analyze this possibility.

The first observation is that WP has little to do with a water body's productivity. When expressed as kilograms of fish (or other products), WP refers to volume (per m^3) consumed, while the productivity of a water body is expressed as yield (per m^2). Estimating WP requires a definition of the water consumed by, or allocated to, fish production. The literature available is insufficient to provide a corpus of data that would lead to a consensus on such a definition.

The second important point is that WP is largely dependent on scale and context, especially when dealing with fish production. Part of this is due to the fact that water consumption increases along the whole range of fish production, from natural water bodies (no consumption) to high-density aquaculture (high consumption). Some authors consider that marine fisheries or brackish and marine aquaculture are not water-consumptive because there is no demand or competition for marine or brackish water (e.g., Brummett 2006c; Welcomme 2006). Water consumption is simply identified as water content of fresh fish (66 to 75 percent of fresh weight) and used in a pseudo-WP calculation.

More generally, there is a clear distinction between two main types of activities. As long as fishing remains a gathering activity (as opposed to fish culture), we may assume there is no water allocated to a production process and, therefore, no water consumption. In that case, water productivity does not apply.

At the individual level, natural fish production in water bodies (natural or man-made), without any specific intervention may, therefore, be regarded as non-water consumptive. At the basin level, however, all aquatic systems and system activities contribute to the water budget: their production may be included in the WP numerator with all the other production sectors, e.g., agriculture (measured in calories or monetary value), while the WP denominator would be the rainfall received by the basin.

If a certain amount of water is specifically allocated to fish production, the concept of marginal water productivity can be used to evaluate the change in fish production versus the water cost, as exemplified by the River Niger Inner Delta. On the one hand, when other interventions contribute to increasing the fish catch (including fish stocking and fisheries regulations), the change from food gathering to agriculture is quite subtle, and the transition is not always clear. On the other hand, the water consumed for fish culture is highly dependent on its possible re-use and the type of system in operation (from raceways to closed recirculating systems). However, it can usually be properly estimated and allows for a WP estimation.

There is, therefore, a continuum in fish production, from fishing to fish culture, along which the water allocated for the production process is progressively identified. Only at some point is an estimation of WP possible. The same probably applies to other activities, especially in those societies that rely on wild resources, such as the collection of fruits and seeds, or on undetermined rangelands for feeding cattle.

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