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Short communication

Can water productivity metrics guide allocation of freshwater to inland fisheries?

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ABSTRACT

Key-words: *extraction, watershed management, ecosystem services*

Water productivity (WP) metrics have proven useful in comparing production efficiency of various crops. Recently, it has also been proposed to facilitate more equitable allocation of scarce freshwater resources between irrigated agriculture and fisheries. Parameterizing water productivity metrics, however, proves to be very difficult in the real world of inadequate data and complex aquatic ecosystems, and is usually impossible to calculate for exploitation strategies, such as fisheries, that harvest products, but do not in and of themselves reduce the natural resource base from which those products were derived. In special cases, marginal water productivity (the variation in production for each unit variation in available water) can be estimated, but the complexity of its use under-values the social, ecological and economical importance of fisheries and so cannot be recommended for making inter-sectoral comparisons.

RÉSUMÉ

Peut-on utiliser la métrique de la productivité de l'eau pour définir l'allocation de l'eau aux pêches continentales ?

Mots-clés : *usage de l'eau, gestion de bassin, écosystèmes aquatiques*

L'utilisation de la métrique utilisée pour la productivité agricole de l'eau (PE) s'est avérée utile pour comparer l'efficacité de cultures différentes. Cette approche a été récemment proposée pour faciliter une répartition plus équitable de ressources en eau limitées entre agriculture irriguée et pêche. La généralisation de la métrique utilisée pour la productivité de l'eau s'est cependant révélée difficile dans un contexte de données inadaptées et d'écosystèmes complexes. Elle n'est, en général, pas applicable à des systèmes d'exploitation tels que les pêcheries qui relèvent de la cueillette et ne sont pas en eux-mêmes consommateurs de la ressource dont ils dépendent. Il est possible de calculer dans certains cas particuliers une productivité marginale de l'eau (PME, la variation de la production par unité de variation de l'eau disponible). Mais la difficulté de sa généralisation fait qu'il en résulte une sous-estimation de la valeur sociale, écologique et économique des pêches. L'approche ne peut donc être recommandée pour des comparaisons entre secteurs de production différents.

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INTRODUCTION

Freshwater allocation in an environment of increasing demand and declining quality and availability is a major societal challenge in the 21st century. Traditionally, revenues have been used to reduce complexity and prioritize alternative uses of scarce water resources (Bakker, 1999), but this approach has proven to be laden with biases in favor of distant urban stakeholders who benefit disproportionally compared to local people and environments. Ideally, maximization of water use efficiency in terms of supply of food, raw materials and income should be tempered by considerations of equity, the preservation of biodiversity and the continued delivery of environmental goods and services from natural ecosystems. This short communication explores the concept of water productivity metrics in the allocation of freshwater among heavily managed and natural food production systems, specifically irrigated agriculture and inland capture fisheries.

> *WATER USE METRICS*

A range of measures has been proposed to guide wise use of water in comparing food, mostly field crop, production systems (Molden, 2007). A transpiration coefficient was proposed by Briggs and Shantz (1913, 1914) to calculate the amount of water consumed by plants per kilogram of production. Viets (1962) added evaporation to transpiration to describe water use efficiency. Le Houérou (1984) defined rain use efficiency as the ratio of annual crop production to the amount of annual rainfall received by a field, less runoff and groundwater recharge, representing the first attempt to include ecosystem function (in this case, of a farmed field) in the determination of the amount of water needed to produce a crop. Refinements to these general metrics have attempted practical valuation and comparison of water use among alternatives. Allan (1998) proposed the concept of virtual water, which allows for the calculation of water savings realizable by purchasing food from areas with greater water endowment, rather than growing it oneself. The water footprint (or ecological footprint when non-water resources such as land are included) is the total water (or natural resources) used to sustain a given human population and represents an effort to include non-food or material production uses (*e.g.*, the absorption or transformation of wastes) into the water equation (Wackernagel and Yount, 1998; Hoekstra and Hung, 2002).

Writing on water productivity Molden *et al.* (2003) expand upon water use efficiency in an attempt to understand total water budgets at the basin, watershed or catchment level, including inter-basin transfers (through precipitation and/or groundwater) and in addition to row crops has been used to relate production in fisheries, forestry, animal husbandry and mixed or integrated cropping systems to the setting of targets for poverty alleviation and local food security (Kijne *et al*., 2003; Cook *et al*., 2006a, 2006b; Hussain *et al.*, 2007). Leaving aside economic and social values of various water use alternatives, agricultural water productivity (WP) is generally expressed as:

$$\text{WP} = \text{produce (as kg or kcal or \$)/m}^3 \text{ of water consumed } (T + L + P)$$

where T is the amount of crop transpiration lost by the system, L the portion of evaporative, seepage and mechanical loss incurred in holding and delivering water to the crop, and P the volume of water fixed in harvested produce, which is assumed to be lost from the system.

While of theoretical value in understanding water budgets, in practice, the use of WP and the other metrics so far elaborated as comparators for water allocation is complicated by the fact that a good estimation of ($T + L + P$) only applies to managed systems (Zoebl, 2006). WP comparisons are valid only in cases where the water consumption can be estimated with no ambiguity. This is not the case for gathering activities such as hunting and fishing where products are extracted from a natural system without undermining the resource base that generated those products. Gathering and agriculture (and other activities which reduce water available for other uses) cannot be evaluated with the same metrics (Lemoalle, 2008).

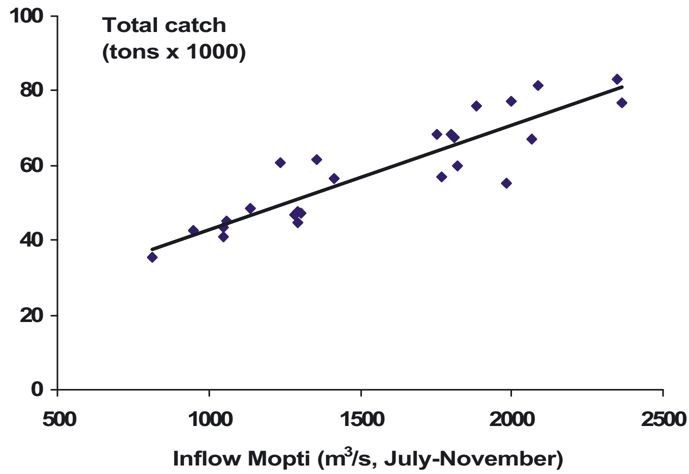

Figure 1
Relationship between fish catch and flood riverine input to the floodplain of the Inner Delta of the River Niger in Mali (from Laë and Mahé, 2002).

Figure 1
Relation entre les captures annuelles et l'apport de la crue fluviale dans le Delta Intérieur du Niger au Mali (d'après Laë et Mahé, 2002).

Natural ecosystems, on the other hand, produce substantial food and other benefits while taking out of the system only water incorporated in the harvested product. In addition to producing food, fiber and building materials, natural ecosystems are critically important in maintaining habitat for biodiversity, erosion control, the dilution and processing of inorganic and organic wastes, the huge recreation and tourism industries, and the general well-being of the biosphere.

Because there are no water losses to the system induced by the gathering activity, water efficiency as the guiding criterion should favor the allocation of all available water to natural ecosystems. This, of course, is never done, as agriculture is needed to provide food to the larger population, the concerns of which for economic development, coupled with the inability of resource managers to present cost-effective options for maintaining the functional integrity of their natural ecosystems, has led to the alarming rate at which these are being degraded globally (Lemoalle, 2008).

> MARGINAL WATER PRODUCTIVITY: THE COST OF FAILURE

Because inter-basin flows and the water needs for complex ecosystems are virtually impossible to properly parameterize over any meaningful period of time, WP cannot be used in comparing efficiency of managed and natural systems for purposes of attributing relative value. What can be done is to calculate the value of what could be lost or gained when fisheries are affected by other developments in the watershed: a marginal water productivity, MWP (Lemoalle, 2008).

For example, Figure 1 illustrates the general relationship between water inflow to the Niger River Inner Delta in Mali and the fish catch. Across this mid-range of inflow rates, catches increase with the volume and duration of the floods, which primarily impacts production by means of increasing food availability and juvenile survival when young-of-the-year juvenile fishes move into shallow water on the floodplain seeking refuge from predators (Junk and Wantzen, 2004). From this data, marginal water productivity (MWP) across this mid-range of inflow rates is the slope of the relationship between the annual fish catch and the mean river discharge during the flood (Figure 1): a change of 1 $m^3{\cdot}s^{-1}$ in the discharge rate or a total of 13 Mm^3 in the flood discharge (from July to September) to the Inner Delta, would induce

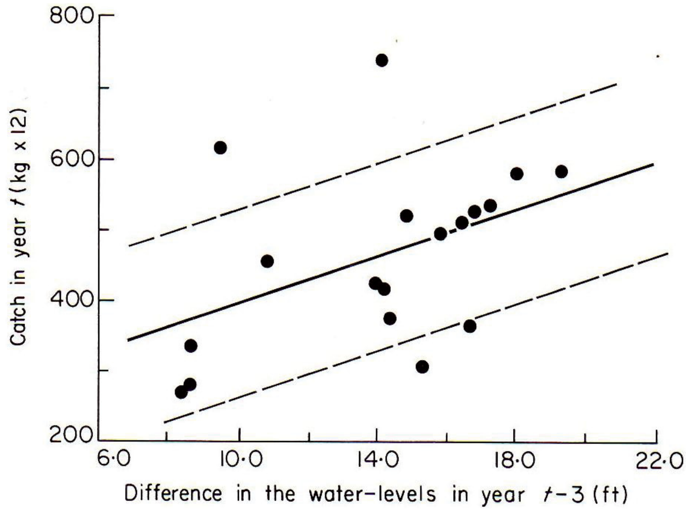

Figure 2
Relationship between Oreochromis mossambicus *catch per fisher per year and change in mean monthly water level in the Parakrama Samudra reservoir in Sri Lanka (from De Silva, 1985).*

Figure 2
Relation entre les prises d'*Oreochromis mossambicus* par pêcheur et par an (année *t*) et les variations du niveau dans le Réservoir Parakrama Samudra au Sri Lanka au cours de l'année *t*−3 (d'après De Silva, 1985).

a variation of 27.8 tonnes in the fish catch of the region (Laë and Mahé, 2002). In the river water budget, the marginal WP is

$$\text{MWP} = 0.0021 \text{ kg (fresh weight)/m}^3 \text{ water.}$$

Figure 2 illustrates another example of how changes in reservoir level can be used to estimate MWP. In this case, catches of introduced *Oreochromis mossambicus*, which represent 70% of the total, respond significantly to water fluctuations three years later, largely as a result of corresponding changes in reproductive habitat. De Silva (1985) calculated that:

$$Y = 232.2 + 16.2x \tag{1}$$

where Y is the yield in kg per fisher in year t and x is the change in water level in the reservoir three years earlier ($t - 3$ in feet) ($r = 0.48$; $p < 0.05$). When full, the reservoir is 2662 ha with an average depth of 7.62 m (ILEC, 2009). The relationship between surface area and average depth is virtually linear down to the last 1000 ha at which point the water is about 2.7 m deep (Amarasinghe *et al*., 2001). The average surface area over the difference of 16 feet (4.9 m) in depth at the point in the curve where the data is richest and closest to the regression line is about 1800 ha, corresponding to a difference in water volume of some 88 million m^3 and a catch per fisher of 5892 kg per year. Multiplied by the 40 boats working Parakrama Samudra in 1985 (Amarasinghe, 1997), this equals 236 tons total captures. If the water only fluctuates 14 feet (4.3 m), the catch is only 3624 kg per fisher per year, meaning that 12.4% more water stored seasonally in the reservoir produced 2268 kg of extra catch per fisher per year or 90.72 tons for the entire fishery per year, thus:

$$\text{MWP} = 90\,720 \text{ kg/11 million m}^3 = 0.0082 \text{ kg}\cdot\text{m}^{-3}.$$

While useful for illustrating the MWP concept, the Niger Inner Delta model is rather unusual in that the main exploited species are harvested as one year olds and virtually the entire stock is replaced annually, hence the linear relationship between production and river discharge in any given year (Laë, 1995; Laë and Mahé, 2002). Similarly, the MWP estimate for Parakrama Samudra is valid for only one species and then only if the water in question is the top 5 m.

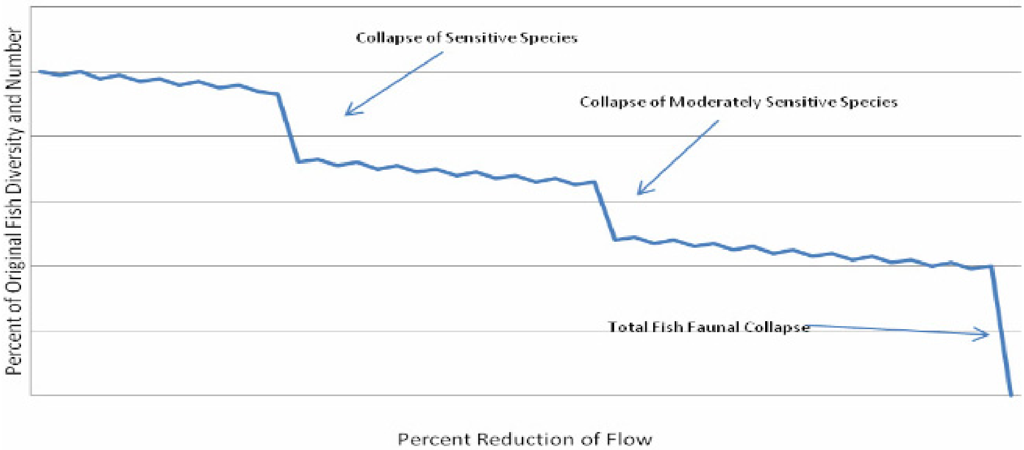

Figure 3
A theoretical model of serial fish stock collapse as water flow rates decline in a river.

Figure 3
Un modèle théorique d'effondrements successifs des populations de poissons lorsque le débit du fleuve diminue.

The bottom 5 m is far more valuable in that if the reservoir dries completely, the entire stock will be lost.

In fact, most systems are even more complicated with numerous species with a wide range of life histories and spawning migrations that occur at different times of year and which rely on differing flow regimes (Collares-Pereira and Cowx, 2004). In this case, the relationship between hydrology and catch is likely to look more like the theoretical depiction in Figure 3. Progressively lowering the flow rate below the tolerance of each species results not in a steady decline in catch, but collapse of one stock after the other, with increasingly unpredictable consequences for the integrity of the entire ecosystem (Eisworth and Haney, 2001).

To apply MWP to such a system might be theoretically possible; models have been proposed for establishing the base-flows needed to maintain various fish species above their respective stock collapse thresholds based on dissolved oxygen, food resource (*e.g.*, macroinvertebrates) and spawning habitat requirements (*e.g.*, Brown and King, 2000). Though base-flow models have achieved some success in terms of maintaining single stocks of high economic value (Gibbins *et al.*, 2001), the complexity of parameterizing the more typical multi-species stocks and restoring something approaching full functionality to ecosystems, limits their usefulness in making WP comparisons (Nelson and Lieberman, 2002; Arthington *et al.*, 2006).

In any case, the MWP of the Niger Inner Delta and Parakrama Saumudra fisheries compares poorly to the WP of cultivated crops, which are one to two orders of magnitude larger (Table I), even without considering that fish average about 76% water (Brummett, 2007). Translated into economic terms, even the higher value of fish per unit of weight still favors irrigated crops by up to 4 to 1 (Renwick, 2001). If the objective of the comparison is to support reallocation of water in favor of fisheries, the MWP of fisheries is probably too small to justify significant sacrifices on the part of any society preoccupied with basic food security and poverty alleviation.

In fact, various permutations of the MWP approach have been used to argue against the loss of fisheries resulting from the transformation of natural into managed ecosystems many times, usually to no avail (WCD, 2000). Even where a convincing case for prioritizing a fishery over the construction of a hydropower dam or development of an irrigation system can be made, to the majority of stakeholders and outside observers, the national benefits of having reliable electricity or cheap and reliable food supplies far outweigh the locally accruing benefits of a functional fishery.

WP has a clear role to play in water allocation decision making within the realm of agriculture (Molden, 2007; Kumar and Amarasinghe, 2009). However, the scale of the difference

Table I
Water productivity of some crop production systems (adapted from Brummett, 2007).

Tableau I
Productivité de l'eau (kg poids sec·m^{-3}) de quelques cultures (d'après Brummett, 2007).

Culture species	Production system	Edible dry matter per m^3 water
Maize (*Zea mays*)	Rainfed	0.16
	Pivot irrigated	0.65
	Furrow irrigated	0.27
Sorghum (*Sorghum bicolour*)	Rainfed	0.23
	Pivot irrigated	0.53
	Furrow irrigated	0.42
Wheat (*Triticum* spp.)	Rainfed	0.12
	Furrow irrigated	0.59
Tomato (*Lycopersicon esculentum*)	Greenhouse (drip irrigated)	1.34
	Furrow irrigated	0.05
Cucumber (*Cucumis sativus*)	Greenhouse (drip irrigated)	1.50
Onion (*Allium cepa*)	Furrow irrigated	0.95
Citrus (*Citrus* spp.)	Furrow irrigated	0.01

in accrual of national benefits between agriculture and fisheries and the difficulty of fully parameterizing fisheries ecology models constrains the use of both WP and MWP in making intersectoral comparisons for purposes of prioritizing water allocation. More generally, agricultural and gathering systems should be considered separately when dealing with water productivity except when marginal WP may be evaluated.

REFERENCES

Allan J.A., 1998. Virtual water: a strategic resource. Global solutions to regional deficits. *Groundwater*, *36*, 545–546.

Amarasinghe U.S., 1997. Observations on the trends in the cichlid fishery in an ancient reservoir in Sri Lanka. *Journal of the Sri Lankan National Aquatic Resources Agency*, *35*, 57–68.

Amarasinghe U.S., Nissanka C. and De Silva S., 2001. Fluctuations in water level in shallow irrigation reservoirs: implications for fish yield estimates and fisheries management. *In*: De Silva S. (ed.), Reservoir and Culture Based Fisheries: Biology and Management, Australian Center for International Agricultural Research, Canberra, 101–110.

Arthington A.H., Bunn S.E., Poff N.L. and Naiman R.J., 2006. The challenge of providing environmental flow rules to sustain river ecosystems. *Ecol. Appl.*, *16*, 1311–1318.

Bakker M., 1999. Valuing the multiple uses of water. *In*: Bakker M., Barker R., Meinzen-Dick R. and Konradsen F. (eds.), Multiple Uses of Water in Irrigated Areas: a Case Study from Sri Lanka, SWIM Paper *8*, International Institute of Water Management, Colombo, 26–31.

Briggs L.H. and Shantz H.L., 1913. The water requirements of plants. I. Investigations in the Great Plains in 1910 and 1911, U.S. Department of Agriculture, Bureau of Plant Industry Bulletin *284*, Washington D.C.

Briggs L.H. and Shantz H.L., 1914. Relative water requirements of plants. *Journal of Agricultural Research*, *3*, 1–77.

Brown C. and King J., 2000. Environmental flow assessments for rivers; a summary of the DRIFT process, Information Report 01/00, Southern Waters Ecological Research and Consulting, Mowbray, South Africa.

Brummett R.E., 2007. Comparative analysis of the environmental costs of fish farming and crop production in arid areas: a materials flow analysis. *In*: Bartley D.M., Brugère C., Soto D., Gerber P. and Harvey B. (eds.), Comparative Assessment of the Environmental Costs of Aquaculture and other Food Production Sectors, *Fisheries Proceedings*, *10*, FAO, Rome, 221–228.

Collares-Pereira M.J. and Cowx I.G., 2004. The role of catchment scale environmental management in freshwater fish conservation. *Fish. Manag. Ecol.*, *11*, 303–312.

Cook S., Gichuki F. and Turral H., 2006a. Agricultural water productivity: issues, concepts and approaches, Challenge Program on Water and Food – Basin Focal Project Working Paper *1*, http://www.waterandfood.org/publications/basin-focal-projects.html.

Cook S., Gichuki F. and Turral H., 2006b. Agricultural water productivity: estimation at plot, farm and basin scale, Challenge Program on Water and Food – Basin Focal Project Working Paper *2*, http://www.waterandfood.org/publications/basin-focal-projects.html.

De Silva S.S., 1985. Observations on the abundance of the exotic cichlid *Sarotherodon mossambicus* (Peters) in relation to fluctuations in the water-level in a man-made lake in Sri Lanka. *Aquaculture and Fisheries Management*, *16*, 265–272.

Eisworth M.E. and Haney J.C., 2001. Maximizing conserved biodiversity: why ecosystem indicators and thresholds matter. *Ecol. Econom.*, *38*, 259–274.

Gibbins C.N., Soulsby C., Jeffries M.J. and Acornley R., 2001. Developing ecologically acceptable river flow regimes: a case study of Kielder reservoir and the Kielder water transfer system. *Fish. Manag. Ecol.*, *8*, 463–485.

Hoekstra A.Y. and Hung P.Q., 2002. Virtual water trade: a quantification of virtual water flows between nations in relation to international crop trade. *Value of Water Research Report Series*, *11*, IHE, The Netherlands.

Hussain I., Turral H., Molden D. and Ahmad M.D., 2007. Measuring and enhancing the value of agricultural water in irrigated basins. *Irrig. Sci.*, *25*, 263–282.

ILEC, 2009. Parakrama Samudra, http://www.ilec.or.jp/database/asi/asi-45.html, International Lake Environment Committee, Kusatsu.

Junk W.J. and Wantzen K.M., 2004. The flood pulse concept: new aspects, approaches and applications – an update. *In*: Welcomme R.L. and Petr T. (eds.), *Proceedings of the Second International Symposium on the Management of Large Rivers for Fisheries*, FAO and the Mekong River Commission, Bangkok, 117–140.

Kijne J.W., Barker R. and Molden D. (eds.), 2003. Water productivity in agriculture: limits and opportunities for improvement. *CABI Series Comprehensive Assessment of Water Management in Agriculture Series*, *1*, CABI Publishing, Wallingford.

Kumar M.D. and Amarasinghe U.A. (eds.), 2009. Strategic analyses of the National River Linking Project (NRLP) of India, series 4. Water productivity improvements in Indian agriculture: potentials, constraints and prospects, International Water Management Institute, Colombo.

Laë R., 1995. Climatic and anthropogenic effects on fish diversity and fish yields in the Central Delta of the Niger River. *Aquat. Living Resour.*, *8*, 43–58.

Laë R. and Mahé G., 2002. Crue, inondation et production halieutique ; un modèle prédictif des captures dans le delta intérieur du Niger. *In*: Orange D., Arfi R., Kuper M., Morand P. and Poncet Y. (eds.), Gestion intégrée des ressources naturelles en zones inondables tropicales, Éditions de l'IRD, Paris, 865–882.

Le Houérou H.N., 1984. Rain use efficiency: a unifying concept in arid-land ecology. *J. Arid Env.*, *7*, 213–247.

Lemoalle J., 2008. Water productivity of aquatic system. Final Report, Improved Fisheries Productivity and Management in Tropical Reservoirs, CP-PN34, CGIAR Challenge Program on Water and Food, WorldFish Center, Penang.

Molden D. (ed.), 2007. Water for food, water for life; a comprehensive assessment of water management in agriculture, Earthscan, London.

Molden D., Murray-Rust H., Sakthivadivel R. and Makin I., 2003. A water productivity framework for understanding and action. *In*: Kijne J.W., Barker R. and Molden D. (eds.), Water Productivity in Agriculture: Limits and Opportunities for Improvement, CABI Publishing, Wallingford, 1–18.

Nelson S.M. and Lieberman D.M., 2002. The influence of flow and other environmental factors on benthic invertebrates in the Sacramento River, USA. *Hydrobiologia*, *489*, 117–129.

Renwick M.E., 2001. Valuing water in irrigated agriculture and reservoir fisheries: a multiple-use irrigation system in Sri Lanka. Research Report *51*, International Water Management Institute, Colombo.

Viets F.G., Jr., 1962. Fertilizers and efficient use of water. *Advances in Agronomy*, *14*, 223–265.

Wackernagel M. and Yount D., 1998. The ecological footprint: an indicator of progress toward regional sustainability. *Environ. Monitor. Assess.*, *51*, 511–529.

WCD, 2000. Dams and development: a new framework for decision-making, World Commission on Dams, EarthScan Publications.

Zoebl D., 2006. Is water productivity a useful concept in agricultural water management? *Agric. Water Manage.*, *84*, 265–273.