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Aqueous Productivity: An enhanced productivity indicator for water

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SUMMARY

Increasing demand for scarce water supplies is fueling competition between agricultural production and other municipal and environmental demands, and has heightened the need for effective indicators to measure water performance and support water allocation and planning processes. Water productivity (WP), defined as the 'ratio of the net benefits from crop, forestry, fishery, livestock, and mixed agricultural systems to the amount of water required to produce those benefits', is one such indicator that has gained prominence, particularly in research-for-development efforts in the developing world. However, though WP is a framework well-suited to systems where water use is directly attributable, particularly via depletion, to definitive benefits, the suitability of the approach becomes questionable when these conditions are not met, such as in multiple use systems with high re-use and non-depleting uses. These factors furthermore make WP highly scale-dependent, complicating comparative studies across scales and systems. This research forwards 'aqueous productivity' (AP) as an alternative indicator that addresses some inherent limitations in the WP approach and enhances productivity estimates for water in integrated systems. Like WP, AP is expressed as a ratio of benefit to water volume. However, AP uses a systems approach and is based on the concept that elements within a hydrologic system are linked via water flow interactions, and that those elements either 'extract' value from associated water flows or 'infuse' value into them. The AP method therefore calculates the 'aqueous productivity', a ratio indicating the 'dissolved' production-related economic value of all downstream uses of an individual water flow, for each inter-element and cross-boundary flow in the system. The AP conceptual framework and analytical methodology are presented. The method is then applied to two example hydroeconomic systems and compared to equivalent WP analysis. Discussion compares and contrasts the two methods, with a particular focus on how the AP approach addresses limitations in the WP method through its treatment of multiple uses of water and water re-use, seamless integration of depleting and non-depleting water uses, explicit cross-scale linkages, and incorporation of water storage and other temporal aspects in the analysis. Appropriate contexts of application for AP in decision support and in contrast to other water valuation methods are consequently considered.

1. Introduction

Water is becoming an increasingly scarce global resource (CA, 2007; Pimentel et al., 2004; Rijsberman, 2006), fueling competition for water between agricultural production and other uses (Kijne et al., 2003b). This competition, especially poignant in the developing world where the poor are typically the most affected (Kijne et al., 2003a), has fostered the use of indicators to assist in allocating water optimally and to identify management and policy alternatives that would lead to more efficient and productive water use.

Agricultural research-for-development efforts in particular have focused much attention on improving the use of irrigation supplies, using a progression of indicators (Bessembinder et al., 2005; Zoebl, 2006). Early research utilized the concept of 'water use efficiency' (WUE) at the field level, estimated as yield mass per unit volume of water transpired (Bessembinder et al., 2005; De Wit, 1958; Viets, 1962). The assumption behind WUE was that efficiency improvements in crop management would either lead to the ability to produce more with a given amount of water, or enable a given production level to be sustained with less water, thereby freeing any remaining water for other beneficial uses (Kassam et al., 2007). However, though helpful in estimating production improvements in the former case, WUE could not inform or quantify the downstream benefits realized in increases in available water in the latter (Seckler et al., 2003).

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Molden (1997) then formalized the broader performance metric of 'water productivity' (WP). Like WUE, WP was defined to be a ratio of agricultural output per unit volume of water, but values for both the numerator and the denominator varied according to the application and scale of analysis. Field-level WP definitions included 'crop water productivity' or 'physical water productivity', expressed in yield mass per unit of evapotranspiration (ET) (Kijne et al., 2003b; Tuong et al., 2005). Irrigation managers utilized service-level definitions of WP, generally given in yield mass or economic value per unit of either applied irrigation water or in total water supplied via irrigation and rainfall (Bouman et al., 2007; Molden et al., 2003).

The utility of using WP as a performance indicator stems from its simplicity. The slogan "more crop per drop" (Giordano et al., 2006; Kijne et al., 2003a; Seckler, 2003; Seckler et al., 2003) used to describe agricultural WP is a concept easily grasped by stakeholders and decision-makers across all scales. Its appeal has increased the scope and scale of WP application (CA, 2007; USAID, 2009) and precipitated diversified definitions that have moved far beyond the indicator's origins in the agricultural field (Bessembinder et al., 2005; Bluemling et al., 2007; Cook et al., 2006; Molden et al., 2007; Rockstrom et al., 2003), including those for livestock (Peden et al., 2007; Tilahun et al., 2009a,b), aquaculture (Nguyen-Khoa et al., 2008), agroforestry (Ong and Swallow, 2003), and others. In reformulating the WP concept into a framework for assessment of multiple-use production systems, Molden et al. (2007) provide the broadest definition of WP: "the ratio of the net benefits from crop, forestry, fishery, livestock, and mixed agricultural systems to the amount of water [used]... where water use means either water delivered to a use or depleted by a use". Regional- or basin-scale analyses thus utilize 'economic water productivity' to capture multiple-use benefits, where the WP ratio is expressed in monetary units per unit of water used (Molden, 1997).

Though not explicitly stated in WP definitions (Molden, 1997; Molden et al., 2003, 2007), WP can be effectively applied at any scale when benefits are clearly attributable to an unambiguously defined set of water uses. However, as will be described in this study, the suitability of the approach becomes questionable when these conditions are not met, such as in multiple-use systems with significant re-use and non-depleting uses (van Halsema and Vincent, 2012). These factors furthermore make WP highly scale-dependent, complicating comparative studies across scales and systems (Molden, 1997; Molden et al., 2003). Subsequent perspectives on the WP concept and its implementation have ranged from application focused on less-limiting WP definitions, e.g. Mainuddin and Kirby (2009), to qualification of its use (Bessembinder et al., 2005; van Halsema and Vincent, 2012), to criticism of its use as an indicator altogether (Zoebl, 2006).

This research forwards 'aqueous productivity' (AP) as an alternative indicator that addresses some inherent limitations in the WP approach and enhances productivity estimates for water in integrated hydrologic systems. Like economic WP, AP is expressed as a ratio of benefit per unit volume of water. However, unlike WP, AP is defined systemically and the benefit/volume ratio for each component of a water use system is determined by its interactions with other components. AP seamlessly integrates multiple water uses, non-consumptive uses, and recycling and re-use. Scales can be explicitly linked in an AP framework, and unlike WP analysis, negative scale effects diminish as system components are defined with increasing resolution and decreasing scale.

After an overview of WP and definition of the AP concept, two example systems are used to demonstrate the difference in approaches and results between the two indicators. The ensuing discussion highlights their capabilities and limitations, and describes AP's potential effectiveness in contrast to WP and in view of other water valuation and hydroeconomic modeling approaches. Appropriate contexts for application are subsequently considered. Because AP is by definition an economic indicator, all subsequent references to WP in this study imply economic rather than non-economic definitions of WP.

2. Theory

2.1. WP and AP as productivity indicators

Water uses can be demarcated into those in which water is a 'final good', such as drinking water supplies, and those in which water is an input to a production process and is therefore considered an 'intermediate good' (Harou et al., 2009; Seckler et al., 2003; Ward and Michelsen, 2002; Young, 2005). As the concept of productivity links the output of a production process to associated inputs, it is these intermediate uses of water that are the focus of WP and AP as productivity indicators.

In economic parlance, 'total factor productivity' relates the value of the output of a production process to the aggregate value of all inputs for that process, while 'partial factor productivity' (PFP) instead typically assigns the output value to only one input resource, such as land, labor, or water (Barker et al., 2003). Though a simplification that neglects the reality that all inputs actually contribute to the output value, a PFP indicator can nevertheless provide meaningful insight into the effects of an input resource on the economic performance of a production process, particularly if that input resource is scarce or limiting (Barker et al., 2003; Molden et al., 2007). WP is one such PFP metric that correlates gross or net benefits from a production process only to the water utilized in that process (Barker et al., 2003; Molden et al., 2003). AP, though calculated differently, is essentially an extension of the WP concept and can also be classified as a PFP measure.

PFP indicators can be differentiated from other economic valuation methods for water. WP and AP cannot be equated with marginal valuation measures (Seckler et al., 2003) such as willingness-to-pay, due to their simplified structures, their equivalency to average valuation rather than marginal valuation for water (Ward and Michelsen, 2002), and their typical exclusion of some costs and benefits associated with production processes such as opportunity costs for water and other production inputs (Barker et al., 2003; Young, 2005). WP and AP therefore may not describe the 'true' economic value of intermediate uses of water that may be more accurately determined by more complex nonmarket water valuation methods, such as those described in Young (2005) and Harou et al. (2009), but may be helpful within the scope of their intended purpose: to provide 'snapshots' of water system performance.

In the formalization stage of the WP concept, distinctions were not drawn between methods and conceptual approaches such as water productivity, the productivity of water, and partial factor productivity of water, and terms were often equated or used interchangeably (Barker et al., 2003; Molden, 1997; Molden et al., 2003). For clarity, this research differentiates between the formalized definition of WP as described below and a generic definition of the 'productivity of water' as the PFP of water that can be estimated using indicators such as WP and AP. WP refers to both the formalized conceptual approach and the indicator value, e.g. a WP analysis of an agricultural field produces a WP of \$1 m^{-3} of water. Conversely, AP is defined as a conceptual approach where AP values, or aqueous productivities, are generated for system water flows using a formalized Aqueous Productivity Method (APM).

2.2. Water productivity theory

A detailed description of WP and its various sub-definitions is provided in Molden et al. (2003) and rephrased by others