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# PROPOSAL FOR THE INTEGRATION OF IRRIGATION EFFICIENCY AND AGRICULTURAL WATER PRODUCTIVITY

**B. Blümling[*], H. Yang[**], C. Pahl-Wostl[***]**
[*] Institute of Environmental Systems Research, Barbarastraße 12, 49076 Osnabrück, Germany; Bettina.Bluemling@usf.uni-osnabrueck.de
[**] EAWAG, Dübendorf, Switzerland; Hong.Yang@eawag.ch
[***] Institute of Environmental Systems Research, Barbarastraße 12, 49076 Osnabrück, Germany; Pahl@usf.uni-osnabrueck.de

**SUMMARY –** In this paper, we provide a concept for the integration of the engineering and agronomic definitions of irrigation efficiency into the concept of Water Productivity. After "Water Productivity" has entered the water policy and research arena, there has been some confusion in its use and delineation from "Efficiency". We will therefore first make a clear differentiation between the terms, and then actually integrate the different kinds of efficiency into what we call "Agricultural Water Productivity". "Agricultural Water Productivity" then sets the boundaries within which efficiency indicates the smoothness of the water use process which itself is directed towards high Agricultural Water Productivity. The latter denotes at which points a process has to be efficient in order to get the highest overall value out of water. Applying this system perspective of Water Productivity to agriculture allows going beyond "yield" as the only output from irrigation water use, but considers different outputs with differing values. The conceptualisation of Agricultural Water Productivity provides a sound basis for a harmonized application of irrigation and water use efficiency and water productivity to decision making.

**Key words:** Water Productivity; Agricultural Water Productivity; Classical Efficiency; Irrigation Efficiency.

## INTRODUCTION

The importance of increasing and securing food production for a growing world population, while at the same time limiting agricultural water use, has been extensively discussed among practitioners and researchers (see for example Rosegrant 1997; IFPRI 2001; FAO 2003; Qadir et al 2003; SIWI-IWMI 2004). The debate for a long time focussed on "(agricultural) water use / irrigation efficiency" as the core concept to indicate the successfulness of water policy that aims at increasing the "crop per drop" ratio. In the course of the discourse, many researchers have made an appeal to change the perspective on and thereby modify the conceptualisation of dealing with water resources in agriculture (e.g. Carruthers et al 1997; Perry 1999; Gleick 2000; Molden et al 2001b; Postel 2003). Molden's concept of "water productivity" was one response to this plea, and was added to the discussion in 1997. With this concept he framed the idea of a group of researchers who thought that "efficiency" underlies a "conceptual blindness" since, what is "waste" from the "efficiency" point of view may be used beneficially elsewhere in the hydrological system. When water is used, not all of it is lost but parts return to the system and may provide input to other uses.

There were also other attempts to label the idea which stands behind the "water productivity" definition by Molden. Carruthers et al in 1997 proposed a differentiation into "real" water savings and "paper" water savings for the same phenomenon. Seckler (1996) previously advocated for the terminology of "dry" and "wet" water savings. Keller et al (1996; 1998) put forward the term of "effective irrigation efficiency". Taking a look at literature, "water productivity" is the concept which some researchers have tried to improve or to apply to their research and therewith seems to be accepted by the community (see for example Sakthivadivel et al 1999; Renault et al 2000; Droogers & Kite 2001; Hamdy et al 2003; Peranginangin et al 2004; Dong et al 2004; Bessembinder et al 2004; Ahmad et al 2004; Kijne et al (without date); Kijne et al. 2004).

At the same time, there seems to be a differing use of the term Water Productivity. For some, it is just a new name for what was "originally referred to in literature as 'water use efficiency'" (Zwart & Bastiaanssen 2004: 116 in their thorough literature review). But the two terms do have different underlying etymologies and concepts, and the one may not just be re-named into the other[1]. We will come to this point under the paragraph about classical efficiency in relation to water productivity.

Not only that Water Productivity is used in two different ways, but one may also ask what the one or other meaning may add? Why introducing a term like "Water Productivity" when there are already "irrigation efficiency" and "water use efficiency" which are widely applied? In parallel to Water Productivity entering the water policy and research arena, "efficiency" remains the indicative term to other researchers for the evaluation of water use in agriculture (see for example Skaggs and Samani 2005, Rosenzweig et al 2004, Mo et al 2004; Hatfield et al. 2001)[2].

There hence seems to be a need for clarification. We will in the following make a clear differentiation between irrigation and water use efficiency on the one hand and Water Productivity on the other. We then will integrate efficiency into Water Productivity. The system perspective of Water Productivity as defined by Molden is proven to be very useful for meeting the new challenges in agricultural water policy, and applying the concept to irrigation water use allows going beyond "yield" as the only output from irrigation water use. This "Agricultural Water Productivity", as we call it, sets the boundaries within which efficiency indicates the smoothness of the water use process which itself is directed towards high Water Productivity. By integrating efficiency into the concept of Water Productivity as defined by Molden, we add to the latter and at the same time clarify the difference between Water Productivity and irrigation and water use efficiency.

Whereas Molden focuses on definitions of Water Productivity depending on the scales of investigation and their interlinkages (Molden et al 2003), we remain on the scale of a field and make Water Productivity, through the integration of efficiency, a more operational term. Our incorporation of the system perspective refers to a single water user, whereas Molden focuses on various system users and their interrelations on different scales. We will start with outlining three kinds of irrigation efficiency, the so-called "Classical Efficiency", Water Use Efficiency and Irrigation Water Use Efficiency. We then contrast one of it, "Classical Efficiency, with the concept of Water Productivity. Since the upcoming of Water Productivity to some extent can be regarded as a reaction to "Classical Efficiency", we will focus on the comparison of these two concepts. We nevertheless will also discuss the relation of Water Use Efficiency to Water Productivity.

After a detailed description of the concept of Water Productivity, we come to its modification for irrigation water use. We will show that the different concepts of efficiency and that of Agricultural Water Productivity do not compete against each other, but can be used synergistically. This conception, as we will see, provides a very helpful link to policy making.

## DEFINITION OF TERMS - "IRRIGATION EFFICIENCY" AND "WATER PRODUCTIVITY"

Engineers as well as agronomists use the term "irrigation efficiency", but denoting two different meanings. The concept of Water Productivity can be seen as a response and critique to the definition by irrigation engineers and practitioners, which is often referred to as "classical efficiency" or "CE" (see Wichelns 2002; Seckler et al 2002). Some "agronomic definitions" seem to be very close to Water Productivity, but, as we will see, only in their parameters, not in their conceptualisation.

[1] It is moreover interesting that a definition which previously had been named out of an engineering terminology, now should be replaced by a term out of an economic context. This may also allow for a discussion about who takes the lead of discourse in the domain.

[2] According to the advocates of the water productivity approach, when speculating on the reasons for the persistence of what they call "classical efficiency" (CE), they regard it as a matter of training of current irrigation practitioners, the orientation of their professional interests and positions around CE, and also the institutional establishment around CE, as well as the fact that "CE serves the interest of other professions and groups as well. Economists can use low CE as justification for pricing water and water markets; and environmentalists can use it in their battles against large dams, transbasin diversions and other water-development projects." (Seckler et al 2002: 47f)

**Two Terms of Efficiency**

The “classical” irrigation efficiency, as for example defined by ICID, at each stage of an irrigation scheme relates the volume of incoming water to the volume coming out of the scheme[3]. For the whole irrigation scheme, the amount of water stored in the root zone is related to the amount of water delivered for irrigation. Across different scales, “irrigation efficiency is defined for: irrigation conveyance (farm supply/main system supply), farm irrigation efficiency (field application/farm supply), field irrigation efficiency[4] (rootzone storage/field application), and overall irrigation efficiency (rootzone storage/main system supply)” (Kassam, Smith 2001: 15). To its users, the term has an operational function; it is a management ratio which can be taken for management decision support[5].

For agronomists, there are various definitions of irrigation efficiency. Basically, efficiency relates the agricultural yield to water consumption. Therefore, whatever may be integrated into the definition of efficiency as used by agronomists, at the core of it lays “(Crop) Water Use Efficiency”. It is the ratio of crop yield to the water consumed to produce the yield, that is, evapotranspiration or, better, transpiration.

$$\text{Water Use Efficiency} = \frac{\text{Yield}}{\text{(E)T}}$$

This definition is still widely used (Viets 1962; Hatfield et al 2001; Kang et al 2002[6]; Yuan et al 2003[7]; Zhang et al 2004[8]). The only difference in its use lays in the framing of the nominator, whether yield may be crop dry matter (either total biomass or aboveground dry matter), the economic yield (including the crop price), etc. For the denominator, evapotranspiration is often taken, since the calculation of transpiration is considered difficult.

Water Use Efficiency varies with crop species, available energy from sunlight, atmospheric pressure, etc. This definition hence expresses the property of a plant at a certain location, that is, the characteristic of a crop, and therewith is much related to plant breeding. Water Use Efficiency in its strictest sense does not take into account the role of irrigation. It hence is a genuinely agronomic term.

Some agronomists include opportunity costs into the definition of what they then call “economic efficiency”, focussing on financial aspects of irrigation. “Economic efficiency of irrigation water use refers to the economic benefits and costs of agricultural water use in agricultural production. As such, it includes the cost of water delivery, the opportunity cost of irrigation and drainage activities, and potential third-party effects or negative (and positive) externalities [...]. Economic efficiency can be expressed in various forms, for example, as total net benefit, as net benefit per unit of water, or per unit of crop area and its broader approach compared to physical efficiency [which is here referred to Classical Efficiency, the authors] allows an analysis of private and social costs and benefits“ (Cai et al 2001: 6). Since irrigation plays a role only as a cost factor, “economic efficiency” may go too much into the direction of economics.

3 The International Commission on Irrigation and Drainage uses about the same definition: “The water used in irrigation passes through successive stages of storages (possible), conveyed up to the head of the area, distributed among the fields and finally applied to each field. During each stage, there is loss of water and the volume coming out is less than the volume entering. The efficiency at each stage is equal to the ratio: volume coming out/volume entering ” (ICID 2000)

4 which often is also referred to as “application efficiency”

5 We thank M.G. Bos for this remark, who also emphasized that efficiency was never intended to carry out, and therewith did not include parameters of a water balance. It would be a term which currently would be disused, “ratio” may taking the lead.

6 “WUE, defined as the ratio between grain yield and total growing season evapotranspiration” (Kang et al 2002: 204)

7 “Water use efficiency (WUE) is the relation between yield or dry matter produced and the quantity of water consumed” (Yuan et al 2003: 164)

8 “Water use efficiency is generally defined in agronomy as the ratio of crop yield (usually economic yield) to water used to produce the yield” (Zhang et al 2004: 113) They set the yield in relation to evapotranspiration.

The definition of "Irrigation Water Use Efficiency" by Howell seems to be more suitable from an agronomic perspective. It specifies the above Water Use Efficiency in order to take the benefits of irrigation into account. "Irrigation Water Use Efficiency" (Howell 2003: 471; Howell 2001: 285) is calculated by first subtracting the yield which would be achieved without irrigation from the yield which is produced with the help of irrigation. The same applies for the water fraction in the denominator where evapotranspiration of precipitation input during the growing season is subtracted from evapotranspiration of irrigation water input.

$$\text{Irrigation Water Use Efficiency} = \frac{\text{Yield}_{\textit{with irrigation}} - \text{Yield}_{\textit{without irrigation}}}{\text{ET}_{\textit{irrigation water}} - \text{ET}_{\textit{precipitation}}}$$

This definition of irrigation efficiency incorporates agronomic aspects of plant characteristics as well as the management of irrigation (e.g. irrigation scheduling or irrigation system).

When further referring to the agronomic definition of irrigation efficiency, we will refer to this Irrigation Water Use Efficiency. We will understand the "genuinely" agronomic Water Use Efficiency (WUE) as integrated in Irrigation Water Use Efficiency (IWUE). Whereas WUE considers the variation in the yield of different species of a crop, or even among different crops, under the same input of water, Irrigation Water Use Efficiency looks at the variance of the yield of the same specie / crop under different applications of water. This integration will be of importance when we further below will set the two terms in the frame of Agricultural Water Productivity. Irrigation Water Use Efficiency and Classical Efficiency are relating to "Water Productivity" in different ways, which we will see in the following section.

**Efficiency in Relation to Water Productivity**

As mentioned before, there exists mix-up in the naming of Water Use Efficiency as Water Productivity, and we will first shortly address this question under the chapter about Water Use Efficiency in relation to Water Productivity. But since Classical Efficiency is the definition which is criticized by the advocates of Water Productivity, we will in the following focus on this discussion of distinguishing Water Productivity and Classical Efficiency. Irrigation Water Use Efficiency actually to some extent has the same "conceptual blindness" as CE in that it focuses on the in- and outputs of agricultural production only. The critique under the chapter about Classical Efficiency in relation to Water Productivity hence does not only address Classical Efficiency but implicitly is also related to WUE / IWUE.

*(Irrigation) Water Use Efficiency in Relation to Water Productivity*

Some of the confusion in the definition of Water Productivity comes from the fact that researchers use it interchangeably with Water Use Efficiency (see before Zwart & Bastiaanssen 2004). Belder et al (2004) define Water Productivity as "the amount of harvested product per unit water use" (Belder et al 2004: 170), and also Cantero-Martinez (2003) talk about the "water productivity of barley", when actually referring to Water Use Efficiency in their article. Cabangon et al (2004) differentiate between "irrigation water productivity" (WPI, kg/m3), and "calculated from grain yield divided by the volume of irrigation water input during the crop season" (Cabangon et al 2004: 197) and "water productivity with respect to the total water input (WPI+R, kg/m3), the denominator was the total water input (I + R)" (ibid). This shows that what previously was, and actually still is, defined as Water Use Efficiency, has been renamed in "Water Productivity".

Though the concept of yield per defined unit of water is very useful, the double naming of Water Productivity in two different, yet related scientific communities suggests to return to Water Use Efficiency when it comes to the relation of yield to water consumption, since this term for a long time has been proved useful, as well as the renaming in Water Productivity actually does not add much to it. Applying "Water Productivity" as defined here in contrast will enhance the concept of irrigation water use and agricultural produce. This is why we encourage returning to Water Use Efficiency and leaving Water Productivity for taking a new perspective on irrigation water use.

*Classical Efficiency In Relation to Water Productivity*

Taking a step back and looking at the semantic meaning of the term, “productivity” focuses on the result of an action. Being productive implies “yielding or furnishing results”[9], while the term at the same time has a positive connotation of “resulting in or providing a large amount or supply of something”[10]. “Productivity” is a term which is used in an economic context where it means “The rate at which goods or services are produced especially output per unit of labor”[11]. In being defined as the "rate of output per unit"[12], that is by referring to a unit, productivity incorporates system boundaries in its definition, as well as it has the notion of getting the most out of a defined limited base, that is the notion of (profit-) maximization. In summary, productivity is result-orientated and focuses on the maximization of output based on a certain unit of input.

“Efficiency” as the quality of being efficient may also be expressed as being “productive without waste”[13] or “acting or producing effectively with a minimum of waste, expense, or unnecessary effort”[14]. In this sense, the term focuses on the quality of a process, like using water well without wasting any. Efficiency is expressed in a ratio, that is, as “the ratio of the effective or useful output to the total input in any system”[15]. In irrigation, Classical Efficiency stems from an ideology of technological process optimization. For irrigation engineers, since “‘efficiency’ is per definition related to comparing input with output during a given process, the same units for input and output should be applied” (van Dam and Malik 2003: 13). Focussing on making the process within the system smoother (or: less wasteful), Classical Efficiency therefore does not necessarily have a fixed reference unit like “water productivity” which relates the yield to, for instance, a cubic meter of water (output of a system per unit of input[16]). At any scale of Classical Efficiency, one may increase the ratio by means of technological innovation and better irrigation practices, but, and this is the critique by those using “water productivity”, without referring to system boundaries (see Molden 1997: 2; Perry 1999: 46f). An increase of efficiency simply implies more total water savings within the system. The expansion of the system boundaries, the irrigation scheme, that is, the expansion of efficient irrigation, can only be welcomed. Increasing efficiency in some cases then may even lead to the overexploitation of the resource. A common example for this is that farmers, when increasing their application efficiency by utilising irrigation efficient technologies, most likely extend their irrigated land surface and therewith the overall water use[17].

[9] Webster’s Revised Unabridged Dictionary, © 1996, 1998 MICRA, Inc.; http://dictionary.reference.com/search?q=productive, viewed December 2004

[10] Cambridge Advanced Learner's Dictionary, Cambridge University Press 2004, http://dictionary.cambridge.org/define.asp?key=63151&dict=CALD, viewed December 2004 see also for “productive”: “producing or capable of producing (especially abundantly); ‘productive farmland’; ‘his productive years’; ‘a productive collaboration’ [...] marked by great fruitfulness; ‘fertile farmland’” WordNet ® 2.0, © 2003 Princeton University, http://dictionary.reference.com/search?q=productive, viewed December 2004

[11] The American Heritage® Dictionary of the English Language: Fourth Edition, 2000. http://www.bartleby.com/61/12/P0581200.html, viewed December 2004; see also: “The ratio of the quantity and quality of units produced to the labor per unit of time.” Ultralingua.Net. http://www.ultralingua.net/index.html?service=ee&text=productivity, viewed December 2004

[12] Online Etymology Dictionary, © November 2001 Douglas Harper, http://www.etymonline.com/index.php?term=productive, viewed December 2004

[13] Merriam-Webster Online Dictionary, viewed December 2004 http://www.m-w.com/cgibin/ dictionary?book=Dictionary&va=efficiency, viewed December 2004

[14] The American Heritage Dictionary of the English Language: Fourth Edition. 2000 http://www.bartleby.com/61/98/E0049800.html, viewed December 2004

[15] The American Heritage Dictionary of the English Language: Fourth Edition. 2000. http://www.bartleby.com/61/95/E0049500.html, viewed December 2004

[16] see also: “productivity, in economics, the output of any aspect of production per unit of input. […] Output can be measured in output per acre for land, per hour for labor, or as a yearly percent...” Encyclopedia.com © 2004, http://www.encyclopedia.com/searchpool.asp?target="productivity", viewed December 2004

[17] (Perry 1999: 48) gives an example of a “water scarce country in the Middle East [in which] on-farm investments were made to increase measured ‘efficiency’ from 40 – 50 % to 60 – 70 %, releasing water for further expansion of the irrigated area. Measurements to date show that the improved technology results in increased crop yields and increased water consumption – a direct confirmation of the many existing studies showing the positive relationship between yield and evapotranspiration, but not the hoped-for saving in water!”

The main differences between Water Productivity and Classical Efficiency are provided in Table 1. In general, Water Productivity takes the hydrological system as a reference unit to set the system boundaries, whereas Classical Efficiency refers to the irrigation scheme, the infrastructure, as the system boundaries, within which efficiency shall be increased.

Table 1: Comparison of Water Productivity and Classical Efficiency

| Term / Attributes | Water Productivity | Classical Efficiency |
|---|---|---|
| stakeholders using the term | professional use by economists | professional use by engineers |
| etymology of the main term | "yielding or furnishing results"<br>"The rate at which goods or services are produced especially output per unit of labor" | "productive without waste"<br>"acting or producing effectively with a minimum of waste, expense, or unnecessary effort" |
| focus | focus on the (value of the) output; value can be given by prices, nutritional values, etc. | focus on the quality of a process (e.g. using water well without wasting any) |
| denominator | the denominator is set as the reference unit water; the unit depends on the scale of examination | the denominator is not a reference unit; the fraction is a simple ratio of input to output |
| components of the fraction | nominator: yield; economic return of the yield; nutritional value of the yield<br>denominator: quantity of water | nominator and denominator: quantity of water |
| system boundaries | hydrological unit | technical infrastructure which is processing the water |
| levels of the system incorporated in the definition | not defined | main system supply<br>farm supply<br>field application<br>rootzone storage |
| stakeholders of the system | all water users of a hydrological unit | Farmers of an irrigation scheme |
| object of action | maximization of the output | optimization of the process |
| water losses | water is not lost to the system, but captured and recycled elsewhere in the system | water is lost from the system |

Thus, efficiency as "being able to function without wasting resources" may not be a concept integrative enough for dealing with the potential conflicts around scarce water resources, since actually, what is "left over" may be productively used by other stakeholders. "Water Productivity" then again seems to be a suitable terminology in the discussion of how much food or "value" may be secured based on limited water resources. It underlies a more integrative view on water resource use.

## THE IDEA BEHIND WATER PRODUCTIVITY

Coming from the semantics of "efficiency" and "productivity", we now want to present Molden's (1997) concept of Water Productivity and dwell on two points which we consider important. On the one hand, this is the system perspective (see chapter *Differentiation of a River Basin's In and Outflows*) which allows differentiating diverse "products" out of irrigation water use. The latter then have to be valuated out of the context of a river basin's water scarcity and water use situation in the chapter *Getting the Highest Value Out of Water*.

### Differentiation of a River Basin's In- and Outflows

The Water Productivity terminology was developed in parallel with the emergence of the "IWMI water resources paradigm" (see Perry 1999)[18]. The IWMI-paradigm states, among others, that water

[18] See also (van Dam and Malik 2003: 13) "The International Water Management Institute (IWMI) has started a strong lobby to change the nomenclature from water use efficiency into water productivity, which is now also followed by other Consultative Group on International Agricultural Research (CGIAR) institutes and the Food and Agricultural Organization of the United Nations (FAO).

is not lost to a larger system though it may be lost to a smaller system. As Seckler et al put it: "One of the cardinal features of water use is that, when water is used, not all of it is 'used up'. Most of the water remains in the hydrological system, where it is available for reuse or recycling. As water is recycled through the hydrological system, the efficiency of use increases. Thus, while every part of the system may be at low levels of water-use efficiency, the system as a whole can be at high levels of efficiency" (Seckler et al 2002: 37f). Molden and de Fraiture give the following example: "In some cases, when 18" irrigation efficiency is improved downstream users (often the environment) can actually get less water because water gained from farm-level efficiency increases is used upstream. In southern Sri Lanka, cement lining of canals led to reduced groundwater recharge and consequently several shallow drinking-water wells dried out [...]. These shallow wells provide better quality drinking water than fluoride-laden deep wells in the area" (Molden and de Fraiture 2004: 9).

This more integrative view on water use as being situated in an overall context of a river basin certainly is a main improvement by the concept of Water Productivity. The idea actually had been existing for some time (see for example Palacios-Vélez 1994[19]), but had not been formulated into a concept. It results in new ways of assessing water use: water accounts are proposed across sectors within a defined hydrological unit, the "receipts" and the "outgoings" of the balance being the inflows to and the outflows from the water body.

On the sides of the outflows of a water use, according to Molden (Molden 1997: 7), Classical Efficiency as well as the agronomic definition of irrigation efficiency would only take into consideration water which is lost to the system through transpiration or evapotranspiration during the growth stages of plants. "Water Productivity", on the other hand, would in addition integrate the water fractions to the outflows which, though even allocated to irrigation, are not consumed by the crop. The conventional definitions of irrigation efficiency would consider this part as something which "is left" when irrigation efficiency would not be high, that is, as a loss for the system. But according to the Water Productivity concept, water is only then lost from the system when it e.g. is deteriorated in its quality, flows to saline sinks or evaporates into the air. The output of a water use, the "left over" according to the efficiency definition, thus is much more differentiated: All fractions of water which deplete from the irrigation site should be integrated; no matter whether they further may render benefits or not.

Looking at the inflows to a system, the critique addresses the same "conceptual blindness". Seckler et al (Seckler et al 2002: 43) criticize that "in all the definitions of efficiency up to this point, precipitation only enters the analysis as effective precipitation (Pe). The difference between total precipitation (P) and Pe(P-Pe) – the amount of 'ineffective precipitation', as it were – is lost; it simply vanishes from the system, much like the 'water losses' in CE. This is unacceptable in terms of the water balance of the hydrological system as a whole".

The Water Productivity concept hence integrates different kinds of in- and outflows into the water use balance for a defined hydrological unit. Molden structures the flows into a water flow diagram which is reproduced in the illustration below (Fig. 1). We will shortly explain each fraction.

Available water is the amount of water available to a service or use, which is equal to the inflow to the system less the share of outflow which is committed to other uses. The inflow is split into gross and net inflow. Gross inflow is defined as the total amount of water flowing into the system (precipitation, surface and subsurface inflows), whereas net inflow includes changes in the storage of the system, that is: net inflow adds water to the gross inflow if water is removed from the storage, or it subtracts water from the gross inflow if water is added to the storage. Depleted water comprises that share of water of the net inflow which becomes unavailable for further use by the system. Molden distinguishes between process depletion and non-process depletion. The former refers to water which gets unavailable for further use in the system during its processing for the production of a certain good (e.g. when it comes to irrigation water use: transpiration during plant growth and water incorporated into plant tissues). Non-process depletion comprises depletion of water from the system without fulfilling a specified use (e.g. evaporation of water from the soil and free water surfaces; water flowing into the sea or into saline groundwater which makes it further unavailable to the system, or

[19] Palacios-Vélez (1994) who states in a talk at a seminar held in 1991: "In many cases, however, part of that water can be reused, either in the same system or downstream in another system (…) when considering actions to improve water use efficiency, care must be taken that such actions do not have harmful effects in other parts of the system"

water as much polluted that it is not usable anymore). Non-process depletion is further subdivided into beneficial or non-beneficial. A beneficial non-process depletion may be that of fruit trees consuming irrigation water. A non-beneficial non-process depletion may comprise water which is lost to sinks as well as water rendered unusable because of pollution. But it non-beneficial non-process depletion can also be caused by weed which is using up water for evapotranspiration. Hereby, the consideration of how beneficial the depletion may be is defined by the stakeholders in the system. If stakeholders may find out that a plant which was previously considered a weed has beneficial uses in their agriculture or as an herb, the water depletion may then be considered as beneficial. The water still remains defined as “non-process depleted” since depletion by these plants was not the main reason why water was diverted from the system.

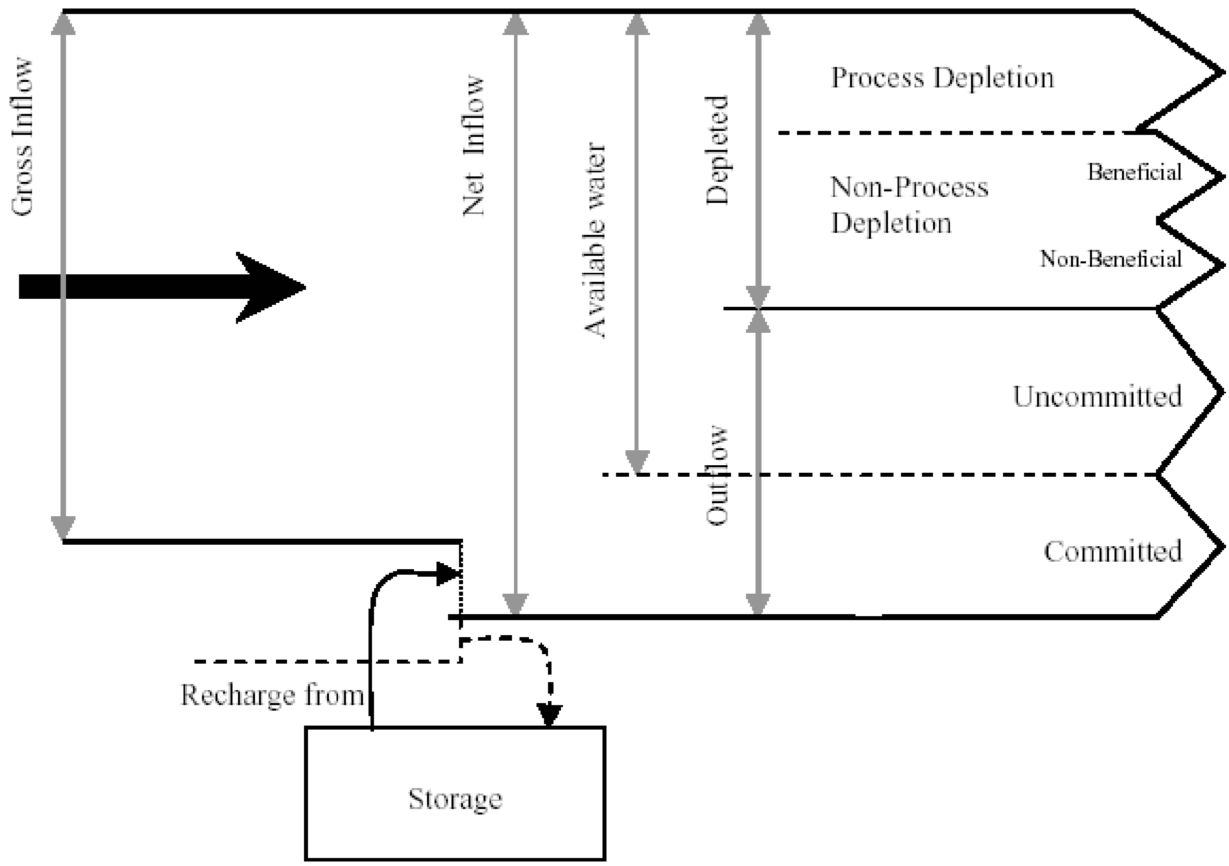


Fig. 1: Water Flow Balance (after Molden 1997: 5)

The outflow is additionally split into committed and uncommitted outflow. This distinction is important for the integration of the context into the evaluation of the water productivity of a water use. Committed outflow comprises the fraction of water which is allocated to further uses in the system. Uncommitted outflow is further divided into utilizable and non-utilizable. Outflow is utilizable if existing facilities or the improved management could make further use of it but actually doesn’t. Non-utilizable uncommitted outflow then is the fraction which leaves the system since the facilities in any case could not capture it for further use.

Water input to, e.g. an irrigation scheme, thus is considered to have many outflows, and not only the one to which it is allocated. Several products out of an allocated water input result, and these products have to be given a value.

### Getting the Highest Value Out of Water

Since the term of productivity concentrates on what may result out of a water use, the labelling of this output is of additional importance. It opens up the discussion about what the value of a produce actually is to different stakeholders, like for different sectoral products that originate from the same source of water such as industrial products, bird habitats or tourism.

In Classical Efficiency, since in- and output are of the same entities, no further value would be given to the output. The result of Classical Efficiency is always that the processing is more or less efficient. In Irrigation Water Use Efficiency, the value of agricultural produce of course differs for, e.g. farmers and the government. But the comparison of the value remains within the sector. For Water Productivity, in its broadest sense, an increase "means obtaining more value from each drop of water—whether it is used for agriculture, industry or the environment. Improving agricultural Water Productivity generally refers to increasing crop yield or economic value per unit of water delivered or depleted"(Molden, de Fraiture 2004: 9). But even within one sector, there are different understandings of what the value may be. Should agricultural water use be set into relation with economic values, should Water Productivity be a nutritional concept indicating how much nutritional value is produced out of a certain amount of water (see Renault, Wallender 2000), or should one simply refer to the yield, without assigning a nutritional or economic value? Seckler et al (2002) decide this question by making three distinctions of the Water Productivity terminology. "Pure physical productivity" would be defined as "the quantity of the product divided by the quantity of AWS [available water supply, the authors], diverted water or depleted water, expressed as kg $m^{-3}$" (Seckler et al 2002: 46). "Economic productivity" would be the net present value of the product divided by the net present value of the amount of available water supply, or the water which is diverted or depleted, which can be defined in terms of its value, or opportunity cost, in the highest alternative use [20](Seckler et al 2002: 47). And as a "hybrid" definition, „combined physical and economic productivity is defined in terms of the net present value (NPV) of the product divided by the amount of water diverted or depleted. Thus, the quantity of the product is productivity times the amount of AWS or water depleted" (Seckler et al 2002: 47). According to Kijne et al, the question of the output of Water Productivity can be dealt with flexibly. "Within one context of water productivity (physical or economic), the choice of the denominator (depleted or diverted water) may vary with the objectives and domain of interest of the study" (Kijne et al 2003: 5). As we understand it here, the choice of the denominator will be subject to the interests and values of the respective groups or organisations having a stake in water use, not so much of the study itself. If the value which different stakeholders denote to certain agricultural products differs, new issues of conflicts of interest enter the water policy arena.

## THE APPLICATION OF WATER PRODUCTIVITY TO IRRIGATION WATER USE

The concept of Water Productivity up until now has been applied to whole river basins (see, for example, Molden et al 2001a, Peranginangin et al 2004) but not to the detailed analysis of a single user's Water Productivity. But the systematisation of a river basin's Water Productivity is also valuable for the single water use irrigation. As we will see, Agricultural Water Productivity proves to be very useful to encompass different kinds of benefits out of irrigation water use under the respective natural resources conditions.

We will in the following make Modifications in the theoretical concept of Water Productivity for its applicability to irrigation water use. A general adjustment addresses the differentiation of system flows, while the later integration of the two kinds of efficiency into the concept of Water Productivity improves it considerably for its application to irrigation water use.

### Adding "Non-Beneficial Process Depletion" To The Water Balance For The Case of Irrigation Water Use

[20] "water used in one place has an opportunity cost in terms of the value of its use in another place within the system. The concepts of efficiency and productivity need to reflect the values of all the uses and alternative uses within the system." (Seckler et al 2002: 45)

Whereas Molden splits the fraction “non-process depletion” further into “non-beneficial” and “beneficial” in his definition of water productivity, the fraction “process depletion” is not. “Process depletion” – in the context of irrigation water use – for us describes the water rendered unusable to the system in the process of crop growth. As soon as water is used by other processes or leaves the field and then is used by other processes, it is rendered to the fraction of non-process uses. From this perspective, process depletion is the minuend for the calculation of non-process depletion. After the subtraction of non-process-depletion, water is returned to the fractions of committed or uncommitted outflow.

Under “beneficial process depletion”, we then understand the portion of water that is lost to the system because of a special function it fulfils, that is, in the case of irrigation water use, the water transpired by the crop. “Non-beneficial process depletion” would comprise the fraction of water which e.g. evaporates from the soil surface.

Figure 2 illustrates the application of this water productivity systematization to the farm level. On this scale, “available water” defines the Gross Inflow. Inflows at the field level are irrigation application, precipitation, subsurface contributions, and surface seepage flows. The “storage change” in the hydrological system is expressed in soil moisture change in the active root zone. Beneficial process depletion at the field level is set equal with crop transpiration. Non-beneficial process depletion comprises the fraction that evaporates from the soil surface, or water rendered unusable due to the degradation of quality. Non-beneficial non-process depletion for example comprises weed evapotranspiration, beneficial non-process depletion comprises the evapotranspiration from useful plants.

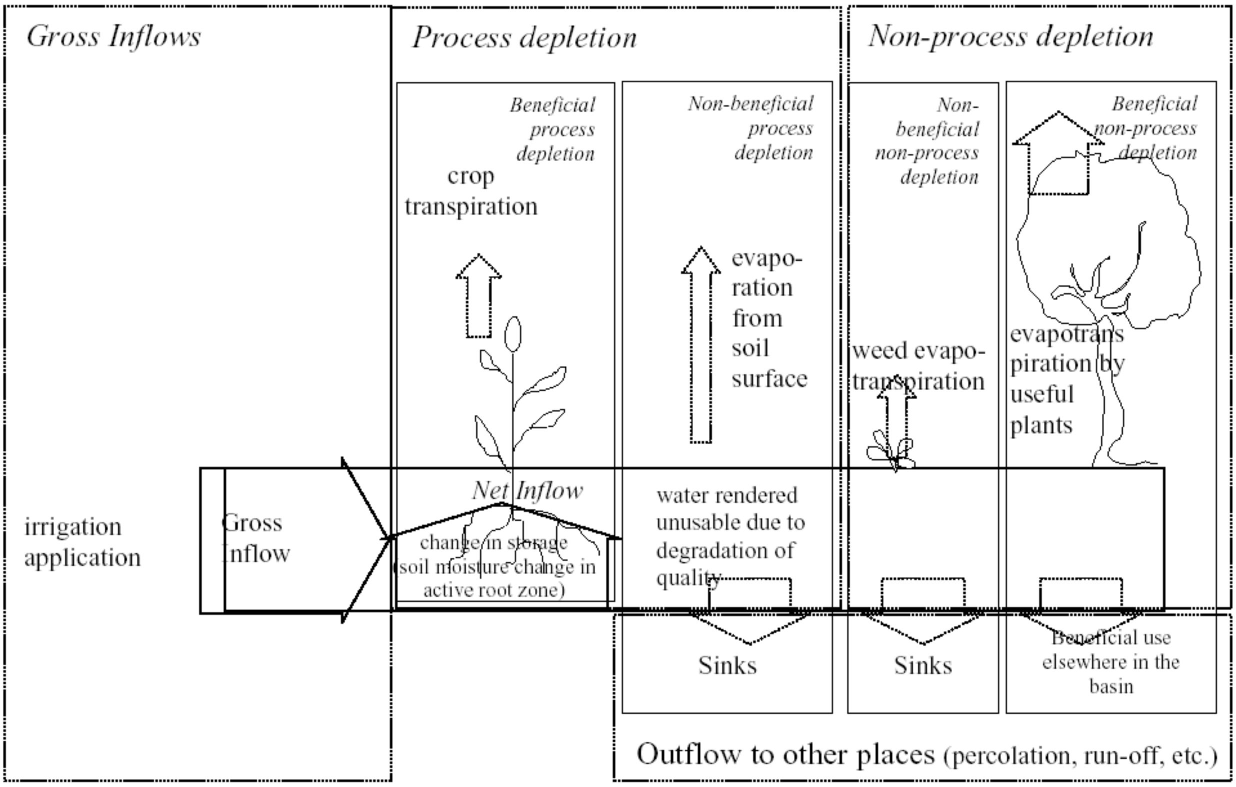


Fig. 2: Water flow balance for irrigation water use[21]

The subdivision of water fractions is not necessarily something new for irrigation water use. The American Society of Civil Engineer’s On-Farm Irrigation Committee in 1978 defined irrigation efficiency as the ratio of the volume of water which is *beneficially* used to the volume of irrigation

[21] terms taken from Molden 1997 and Kijne et al., 2003

water applied. Beneficial uses would e.g. include crop evapotranspiration, deep percolation for salt control, crop cooling, frost control, or would take place in combination with pesticide or fertilizer applications. The denominator also in this case represented the total volume (which means beneficial as well as non-beneficial uses) of irrigation water. By extending the range of beneficial uses, efficiency still remains high though the water is not used for transpiration only. Still, the definition does not see agriculture as embedded in a context of other water users and therewith does not allow for the valuation of the water fractions.

**Problems With The Differentiation of Beneficial / Non-Beneficial Process Depletion**

Whereas evaporation and transpiration in this conceptualisation are indicated as the fractions "non-beneficial process depletion" and "beneficial process depletion", respectively, they generally are integrated into "evapotranspiration", that is, a crop is considered together with certain management practices under which a certain amount of water evapotranspirates. But we need to make a differentiation here since it is important to know how much water the crop itself takes to grow (transpiration), to then examine in how far soil and water conservation practices may change the evaporation of water from the soil. Different human decision making processes and activities are linked to the respective depletion fraction, and, as we will see, efficiency and water productivity are linked to them in different ways.

Crop transpiration basically is a result of plant breeding, and on the farm level a consequence of crop and species selection. A change in the amount of transpiration more likely requires making decisions about which crop to grow and which species to select (since transpiration can change across the species of a crop with their respective production-biomass ratios, the length of the growing season, etc.). A farmer here basically has to decide whether he wants to grow a crop which he can use for his livelihood or not, whether he wants to take the risk of producing it (which is also linked to the selection of certain species of a crop), whether he wants to take the time to manage it, whether it is easy to sell etc. Since transpiration stands for how much water a crop needs to produce yield, it can be indicated by Water Use Efficiency as defined before[22].

"Evaporation is always a component related to crop specific growth, tillage and water management practices" Zwart, Bastiaanssen 2004: 116), thus, a reduction in evaporation requires an alteration in management practices, and here, a farmer most likely has to spend more time on agriculture, or invest in infrastructure to reduce this actual water loss. The surplus value out of the management then likely is to play a role if a farmer is a main-income farmer, but maybe not so much if he is a side-income farmer. Evaporation then is a side-effect / -loss during the course of a water use, that is, non-beneficial process depletion occurs in connection with an allocation of water to a water use[23]. The potential amount of water loss from soil evaporation may best be indicated with a ratio of evaporation to (potential) evapotranspiration (E/ET).

To support our argument for a separation of evaporation and transpiration despite the common integration into evapotranspiration, we will give examples of Zwart and Bastiaanssen's thorough literature search by which the variety of evapotranspiration values depending on crop management practices should get clear[24]. They found out that the variability of the yield for actual crop evapotranspiration of wheat ranges between 0.6 and 1.7 kg $m^{-3}$ [25]. The values with the most efficient

[22] Actually, also here exists confusion of terms. What we call "Water Use Efficiency" is also labelled "Transpiration Efficiency" by researchers of a biological science / plant breeding community (Byrd 1997; Turner 2004; Condon et al 2004). To them, Transpiration Efficiency is the the weight of dry matter or biomass produced per unit of water transpired. Since this paper addresses researchers dealing with irrigation, we will stick to Water Use Efficiency as yield per water consumed by transpiration.

[23] Precipitation of course does not happen for the sake of watering the crop. Still, non-beneficial process depletion also in the case of precipitation input describes the part of the rain which evaporates from the soil in the proximity of the crop after a precipitation event. It is lost to further use, though it could have been captured by soil and water conservation methods.

[24] As mentioned above, Zwart and Bastiaanssen use "water productivity" interchangeably with water use efficiency, which in their research is measured as amount of yield per amount of evapotranspiration. We therefore describe the results listed in their article with "yield per unit evapotranspirated". We take "actual evapotranspiration" since their listed examples deal with limited water supply.

[25] The value of the FAO study by Doorenbos and Kassam ranged between 0.8 – 1.0 kg $m^{-3}$

water use were found by Jin et al (1999) where the application of manure allowed for higher production and straw mulching again improved soil water and soil temperature conditions, reducing evaporation[26]. The variability of cotton lint yield again ranged between 0.14 to 0.33 kg $m^{-3}$. The best values were found in China and Israel, and for China, they were the result of experiments in which cotton was planted in furrows and the soil was covered with plastic leaving holes for the infiltration near the plants (see Jin et al. 1999). By this method, soil evaporation was reduced and the soil water status of the root zone was improved.

From these results we conclude that a differentiation into evaporation and transpiration makes sense in two regards: the differentiation shows in how far there is scope for a reduction of the non-beneficial process-depletion fraction, as well as it provides the opportunity to denote which kind of action the respective farmers should take in order to achieve this reduction, may it be by changing to a different crop (in case of a high transpiration), or by investment in irrigation technologies or effort for crop-, water- or soil-management practices in case of a naturally given high ratio of evaporation.

**Integration of Terms In a Concept of "Agricultural Water Productivity"**

As stated above, irrigation efficiency as a single indicator for water use may not respond to contemporary requirements of harmonized water use planning in water scarce river basins. But the fact that the two terms of irrigation efficiency may not match current needs does not mean that they are not important. In fact, Water Productivity can set the boundaries within which efficiency indicates the smoothness of the process which itself is directed towards high Water Productivity. Water Productivity then denotes at which points a process has to be efficient in order to get the highest overall value out of water. Setting this benchmark does not so much orientate at agriculture, but looks at the context of water use in order to evaluate the respective Water Productivity of agriculture (see Figure 3).

Setting the benchmark for Classical Efficiency defines the optimal relation of the water outflow fractions to each other. If we take the above mentioned example of Molden and de Fraiture (2004: 9), high Water Productivity under these conditions may imply that agriculture facilitates the percolation of irrigation water to groundwater, so that the fraction "process depletion" which leaves the system through drainage would be beneficial and its share in overall irrigation input should accordingly be high. The same is true for the case of excessive accumulation of salts in the soil. In arid areas, excess irrigation water is used to leach salt from the root zone. In this case flushing salts with additional water guarantees future fertility of the soil. From a CE perspective, efficiency would consequently be called low, but from a Water Productivity point of view, the "inefficiency" may be rather valuable. In cases in which water from agriculture would otherwise flow to sinks (like when agriculture is located close to the coast), high Water Productivity would imply increasing overall irrigation efficiency. The same holds true if excess irrigation water would leach soluble chemicals below the root zone, as well as if nitrate is carried below the root zone. Often, in arid and semi-arid areas, a gradual salinization occurs due to rising water tables where proper drainage has not been provided and too much water leached underground.

This distribution of outflow water fractions from incoming irrigation water is determined by how the *process* of irrigation is managed. To indicate the smoothness of the process of irrigation water use at the field level, we set "evapotranspiration" and "drainage below the root zone" in relation to "irrigation water input". As can be seen from Figure 3, these ratios make up the "Evapotranspiration Fraction" and the "Drainage Fraction" respectively.

A water balance would actually additionally incorporate soil moisture change and runoff. But we simply neglect soil moisture change which finds only expression in evapotranspiration, and, - if water content is beyond field capacity – drainage from the soil. Runoff would be left as a non-beneficial water fraction. In Figure 3, we additionally make the simplifying assumption that the irrigation water input does not leave the field so that the entire outflow is made up of process-depletion fractions and does not contain non-process depletion fractions.

[26] The "CWP for the experiment with straw mulching was 2.67 and 2.41 kg $m^{-3}$ for a combination of straw mulching and manure" (Zwart, Bastiaanssen 2004: 118).

Additional to the Drainage and Evapotranspiration fraction, we think that the E/ET-ratio is an important indicator (see Figure 3). The ratio requires special attention since evaporation in every case is lost to the system without benefit. Especially if a lot of the irrigation water input is allocated to the Evapotranspiration fraction, the E/ET-ratio becomes important because it shows whether there is scope for reducing its size through preventing evaporation. The more the E/ET-ratio approaches 1, the smaller the scope for action will be to reduce evapotranspiration by minimizing evaporation.

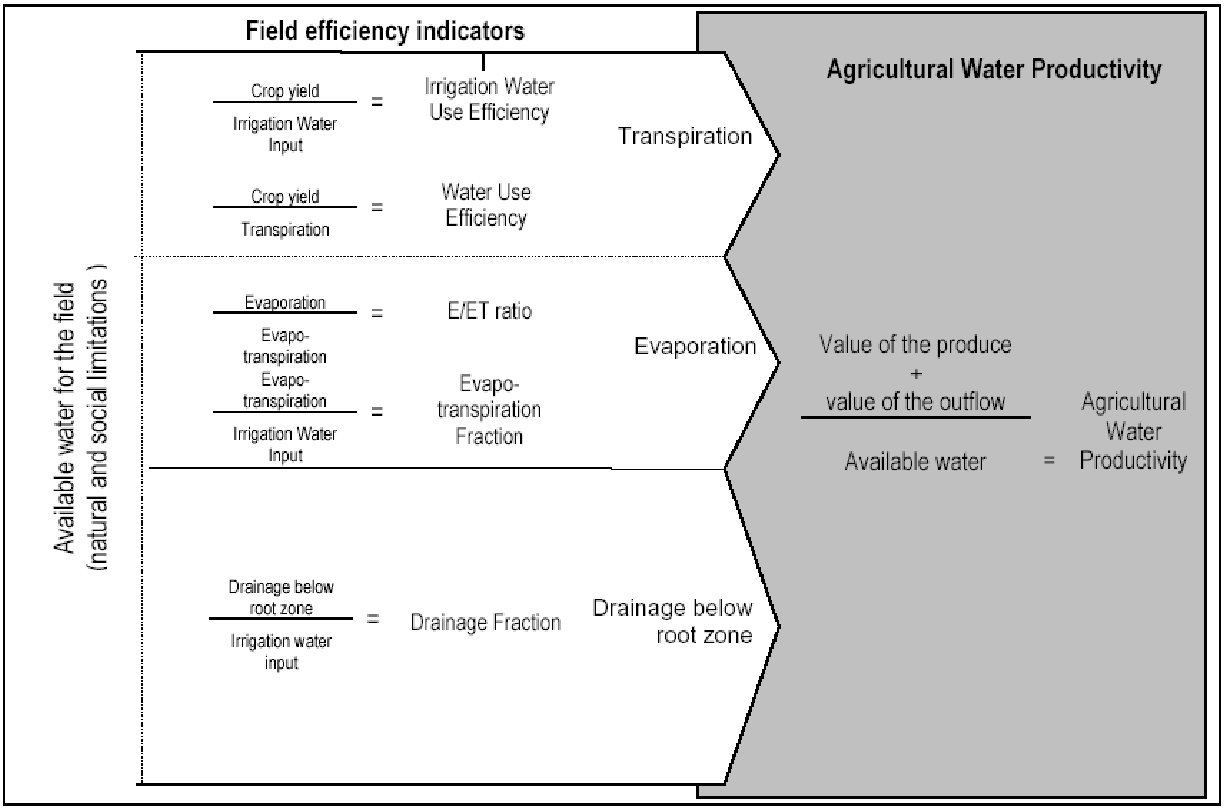


Fig. 3. Integration of Water Productivity and Irrigation Efficiency

These above efficiency indicators all relate to Classical Efficiency since they indicate the processing of different water fractions.

Setting Water Use Efficiency then into the frame of Water Productivity allocates an output to one water fraction (transpiration) already, which would have to be given a value. Efficiency in this case denotes whether this value is achieved with a high or low input of water depending on the cultivar. Irrigation Water Use Efficiency then shows the importance of irrigation to the crop. Table 2 shows the main function of the above mentioned efficiency indicators.

As Figure 3 as well as our above explanations show, the system perspective on irrigation water use allows for more products than only agricultural yield. Therewith, also the value of irrigation water use does not only relate to agricultural produce. Setting the benchmark for the efficiency of water processing out of the context in which irrigation water use is embedded thus shall provide value to the different outflow water fractions, to then allot the size of the fractions within the given water input. We will come to the point of valuation in our discussion.

Table 2. Efficiency indicators

| Efficiency Indicator | Function |
|---|---|
| Evapotranspiration Fraction | shows how much of the irrigation water input meets its primary purpose |
| Drainage Fraction | indicates how much of the irrigation water input drains below the root zone and can potentially be used for other purposes than agricultural production. Whether this water fraction can be named beneficial or non-beneficial depends on the context. |
| E/ET-ratio | shows how much of the evapotranspiration is actual loss since it evaporates without returning a benefit. The ratio also indicates if there is scope for water saving through soil and water management: if the ratio is low, evaporation in overall evapotranspiration is high, so that soil and water conservation may reduce the size of the evapotranspiration fraction, considerably. |
| Water Use Efficiency | indicates how much yield a crop returns out of transpiration. It mainly depends on crop breeding (but also agronomic practices like fertilizer input, but this is beyond our subject). If WUE is low, as well as the E/ET-ratio is high, the scope for increasing the beneficial use of water would be rather limited. In this case, a change to other crop species or another crop may be advisable. |
| Irrigation Water Use Efficiency | shows how much of the total water consumption by a crop can be attributed to irrigation. It shows the dependency on irrigation by the cultivar. |

## DISCUSSION AND OUTLOOK

In this conceptualisation of agricultural water productivity as well as irrigation and water use efficiency, water productivity directs the process of optimization, that is efficiency, towards the highest overall value of agricultural water use. Process optimization applies at the system flows of the water source (Classical Efficiency), as well as at the increase of output out of the water transpired ((Irrigation) Water Use Efficiency). Efficiency thus is integrated into the framework of water productivity and therewith relates to the boundary conditions of water use.

A farmer can impact the above described efficiencies in different ways. In Figure 4, we have linked the respective efficiency indicators with two main activities: “Crop and crop species selection” will have an impact on how much a crop depends on irrigation (Irrigation Water Use Efficiency), as well as how much yield a farmer may gain out of transpiration (Water Use Efficiency). Soil and water management again will influence the size of evaporation in evapotranspiration (E/ET-ratio), and how much of the irrigation input may be used for evapotranspiration and drainage respectively (Evapotranspiration Fraction and Drainage Fraction).

Depending on the value of the agricultural produce in relation to the valuation of the drainage outflow from the field, farmers may take one or the other way in order to increase or decrease the size of the respective water fractions, and therewith raise their Agricultural Water Productivity. The valuation of the outflow will depend on the natural as well as the socio-economic conditions in which agricultural water use is embedded. The valuation of agricultural produce depends on whether it is sold or not. If it is not sold, the valuation becomes difficult since non-monetary aspects come into play. If it is sold on the market, it has a value to the consumers of a local (or global) market.

If for example the outflow is valued high since otherwise the soil may turn saline and will make future agriculture less possible, the Drainage Fraction would have to increase. Soil and water management would have to be adjusted accordingly. If a farmer in the respective context values his produce high and does not want to change it, a comparison of the Water Use Efficiency of his crop as well as the E/ET-ratio can indicate whether agronomic practices may better be changed or the respective soil and water management, in order to allow for a big Drainage Fraction and achieve a high Agricultural Water Productivity. If a farmer did not have an interest to stay with a certain crop, he may also change to another with a lower Irrigation Water Use Efficiency so that more water is set free for drainage. The dimension of Agricultural Water Productivity then would depend on the price of the crop and the monetary value of the drainage.

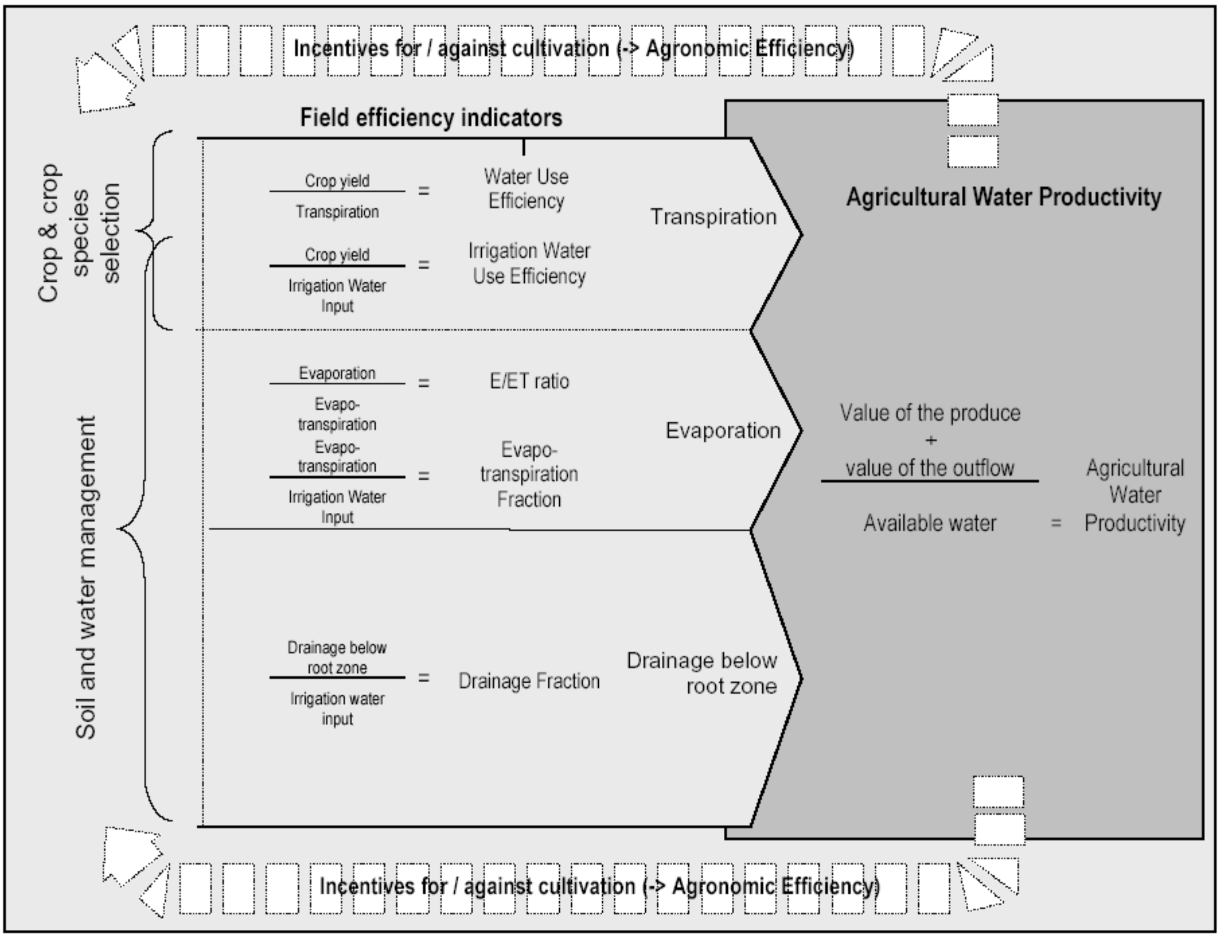


Fig. 4. Field Management Practices and their impact on Agricultural Water Productivity

This example also shows that an interesting point is who may set the value for the products of irrigation water use in a river basin. Different stakeholders will provide different meanings and hence values to outcomes, and often, these values may not be easily compared, or monetarised. Even within a sector like agriculture, stakeholders will give different meanings and values to agricultural produce.

Our conceptualisation of Agricultural Water Productivity makes it possible to operationalize this “integrative view” on irrigation water use as providing several outputs into an indication of how the different water use flows may achieve a high overall Agricultural Water Productivity. For this purpose, we made use of different kinds of efficiency indicators. We think that this conceptualisation provides a good basis for the integration of irrigation efficiency and water productivity to respond to current needs of dealing with limited water resources and increasing water demands from different sectors, as well as it provides links for policy makers to inspire the optimization of the process of water use in direction of high water productivity.

The integration nevertheless still is in its conceptualisation phase. The most prevailing question is how to really integrate values provided by the river basin to the outflow water fraction in order to guide water use flows, and which implications this may have to agriculture.

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