Water Productivity at Different Scales under Canal, Tank and Well Irrigation Systems

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Introduction

Generally speaking, the term 'water productivity' refers to the magnitude of output or benefit resulting from the input quantum of water as applied on a unit base. In the domain of agriculture, it is expressed as the net consumptive use efficiency in terms of yield per unit depth of water consumed per unit area of cultivation. If the field water conveyance, application, storage and distribution efficiencies are accounted to depict the seepage, runoff and deep percolation losses (not consumed by plant; evapotranspiration loss is included as an implicit component of field water balance) it would be termed as the gross irrigation water use efficiency. When isolated as 'water productivity' it becomes a partial productivity of one factor viz., water, irrespective of the land unit but in reference to the scale of production in the range of a single plant's effective root zone to a basin or system of irrigation command. As more and more water losses are incurred when the scale of reference expands, the apparent or relative water productivity is bound to decrease. However, for an increasing scale, the chances of recovering the so called 'losses' of water are bound to increase and at one stage, may be a project or basin scale, the loss at one point will be a gain at another point (as deep percolation leading to groundwater recharge or runoff leading to surface detention and storage) for recycling. In other words, the basic net input of water required in the effective root zone of a plant scale is subsequently reckoned as a gross input of water incorporating the irrigation efficiencies (h) at farm/field level and fixing the flow duty (D), field duty (D) and storage duty (S) at a system/project/basin/command level. The overall conceptual framework should account for all these transformation parameters from scale to scale.

Agricultural Water Productivity

Agricultural water productivity can be expressed either as a physical productivity in terms of the yield over unit quantity of water consumed (tonnes per ha.cm of water or kg yield per kg water consumed) in accordance with the scale of reference that includes or excludes the losses of water or an economic productivity replacing the yield term by the gross or net present value of the crop yield for the same water consumption (rupees per unit volume of water).

Water productivity is defined as 'crop production' per unit 'amount of water used' (Molden 1997). Concept of water productivity in agricultural production systems is focused on 'producing more food with the same water resources' or 'producing the same amount of food with less water resources'. Initially, irrigation efficiency or water use efficiency was used to describe the performance of irrigation systems. In agronomic terms, '*water use efficiency*' is defined as the amount of organic matter produced by a plant divided by the amount of water used by the plant in producing it (De Wit 1958). However, the used terminology '*water use efficiency*' does not follow the classical concept of '*efficiency*', which uses the same units for input and output. Therefore, International Water Management Institute (IWMI) has proposed a change of the nomenclature from '*water use efficiency*' to '*water productivity*'. Water productivity can be further defined in several ways according to the purpose, scale and domain of analysis (Molden et al. 2001; Bastiaanssen et al. 2003).

Stakeholder	Definition	Scale	Target
Farmer	Yield / irrigation	Field	Maximize yield
Irrigation engineer	Yield / canal water supply	Irrigation scheme	Maximize water allocation
Policymaker	$ / available water	River basin	Maximize profits

Scales of Reference and Water Productivity Transformations

The definition of water productivity is scale-dependent. Increasing water productivity is then the function of several components at different levels viz., the plant, field, irrigation system and river-basin. An increase in production per unit of water diverted at one scale does not necessarily lead to an increase in productivity of water diverted at a larger scale. The classical irrigation efficiency decreases as the scale of the system increases (Seckler et al. 2003). In India, the on-farm irrigation efficiency of most canal irrigation systems ranges from 30 to 40 % (Navalawala 1999; Singh 2000) whereas, the irrigation efficiency at basin level is as high as 70 to 80 % (Chaudhary 1997). Basin water productivity takes into consideration beneficial depletion for multiple uses of water, including not only crop production but also uses by the nonagricultural sector, including the environment. Here, the problem lies in allocating the water among its multiple uses and users.

Methodology to Workout Water Productivity

The assessment of water productivity would involve a sequence of mathematical operations that may be in accordance with the scale of reference. The scale based models are to be integrated for the final quantification of agricultural water productivity on an ultimate regional scale for the purpose of planning.

Plant/Crop Scale Water Productivity (WP [p]):

Here, the effective root zone of the plant/crop is the reference or datum over which the crop consumptive use exclusive of the inevitable gravitational irrigation system losses (seepage, runoff and deep percolation) is considered as the input for the single plant/crop output. In case of using micro-irrigation systems (drip or sprinkler) these losses are reduced to zero and the root zone gets exact replenishment through irrigation to meet the soil moisture deficit. The physiological processes such as photosynthesis, nutrient uptake and water stresses also contribute over to productivity. Hence,

total consumptive use (CU) in cm = (number of irrigations)* (depth of irrigation in cm).

Then, water productivity on a plant/crop scale WP (p) = Y/CU and the water use efficiency becomes WUE (p) = WP (p)/A, where 'A' is the effective area commanded by the plant. In accordance with the crop-crop spacing (Sc) and the row-row spacing (Sr), A = Sc*Sr. The unit of WP(p) can be kg yield per kg of water consumed or cm of water consumed and that of WUE(p) can be kg yield per cm of water consumed per square meter crop area.

Field/Farm Scale Water Productivity (WP [f]):

At a field scale, processes of interest are different: nutrient application, water conserving tillage practices, field bunding, puddling of paddy fields etc. Water enters the field domain by direct rainfall, subsurface flows and irrigation from a source of storage. Rainfall alone is considered in case of rain-fed agriculture. A field or farm scale water productivity (WP [f]) is influenced by the inevitable irrigation conveyance, application, storage and distribution losses/efficiencies. Hence, the total water diverted from storage accounting for these losses is taken as the consumptive usage. Technically,

WP (f) = WP (p)/ (η), where (η) is the overall irrigation efficiency of the farm with gravitational irrigation system layout. In case of a micro-irrigation layout, the value of (η) will be more than 95 % and almost 100 % if the design is perfect.

Since the scale of reference expands, the unit may be chosen as tonnes per cm of water consumed (t/cm).

Conveyance Efficiency	$\acute{\eta}_c$	= Wdf/Wds X 100
Application Efficiency	$\acute{\eta}_a$	= Wsr/Wdf X 100
Storage Efficiency	$\acute{\eta}_s$	= Wsr/Wnr X 100
Distribution Efficiency	$\acute{\eta}_d$	= (1-Y / d) X 100
Water Use Efficiency	WUE	= (Y/A)/Wdf

Where,

Wds = Volume of water diverted from the irrigation source, in m^3 or ha.cm; the source may be a well, canal distributory outlet, tank sluice outlet etc.

Wdf = Volume of water delivered on to the field, in m^3 or ha. cm

Wro = Volume of run off, m^3 or ha. cm

Wdp = Volume of deep percolation m^3 or ha. cm

Wsr = Wdf – (Wro + Wdp) = Volume of water stored in the effective root zone m^3 or ha. cm

Wnr = Volume of water needed in the root zone, m^3 or ha. cm = AX d
d = design depth of irrigation, cm

The overall field irrigation efficiency $\acute{\eta}e = \acute{\eta}_c \text{ X } \acute{\eta}_a$

Project/Command Area Scale

In Tamil Nadu, three distinct kinds of command areas are in vogue viz., canal (or reservoir) command, tank (system and nonsystem) command and well (groundwater) command. While the canal and tank commands mostly fall intact under a project operation, well commands occur in a scattered fashion (Figure 1). When water is distributed in an irrigation system at a major scale like this, the important processes include allocation, distribution, conflict resolution and drainage. Allocation and distribution of irrigation water are primarily for irrigation besides meeting the nonagricultural demands like domestic, industrial, livestock and fisheries.

For canal command areas, irrigation scheduling cannot be done on a micro-scale calculating the depth of irrigation required, frequency of irrigation and the duration of irrigation owing to a larger areal extent with different crops and a different system of irrigation supply throughout the season on a rotational basis. Here, irrigation scheduling refers to the quantum of water to be stored or diverted for meeting the overall command area crop and allied demands. The water productivity concept shall be redefined by way of incorporating the overall irrigation efficiency and the duty of water at storage, flow and field level. The base period (B) over which irrigation flow is continuous through the canal network with suitable time rotations at outlets for distribution, also decides the productivity.

Canal Command / Project Water Productivity (WP(c))

The overall productivity of this scale of reference depends ultimately on the total quantum of water released from storage over the base period, the area covered and the project yield. The storage duty (S) includes the losses during conveyance, distribution and application over and above the field duty (Δ) in a canal network project.

Field duty (Δ) is expressed as the seasonal water requirement for crop and related activities, in cm, at the tail most end area of the canal network.

$\Delta = CU/\eta$ where, η represents the farm/field efficiency

Then, the storage duty (S) = $\Delta / \eta(c)$ where $\eta(c)$ represents the overall conveyance efficiency of the canal network/project.

The flow duty (D) in ha/cumec is devised in accordance with S and Δ to cover the given command area (A) over the base period (B) of the project water supply, as,

$D = (864B) / \Delta$, and $S = A.\ \Delta / \eta(c)$

As the command area/project scale is expanding, the apparent losses like runoff and/or deep percolation would be considered for recycling or conjunctive use with canal flows. Then, the water productivity will be based on the total volume of water diverted from the irrigation source or simply the storage duty (S).

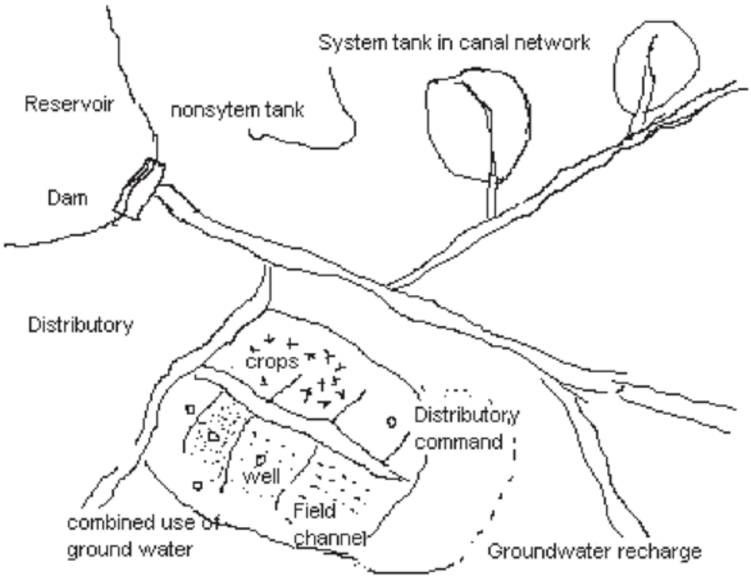
$WP(c) = Y / S$ Where,

Y = project yield, in tonnes and S = Storage duty, in ha.cm

If S is expressed in cm as S’ then, S’ = S/A

So that WP(c) = Y / S’

Figure 1. Water productivity at project/ command area scale.



Tank Command Water Productivity WP (t):

Nearly 39,000 tanks exist in the Tamil Nadu State as natural surface water harvesting structures since the olden kings’ regimes for the purpose of irrigation and other water use. Earlier the tank system had clearly defined channel network originating from the storage outlet point and in due course of time these channels have disappeared owing to encroachments and other formidable reasons. The tanks commonly come under a *nonsystem* (isolated or interconnected battery) with independent or combined catchments or a *system tank* arcade hooked along rivers or streams or canals, in which water at select points is diverted into the tank. The gross volume of water depleted from the tank storage (Sd) or the equivalent depth (Sd’) in cm, over the crop growth season forms the base (denominator) for productivity calculations.

WP (t) = Y/Sd

where,

Y = the overall tank command yield in tonnes

Sd = depleted volume of water from tank storage, ha.cm or Million cubic meters

Sd’ = equivalent depth in cm of water depleted from tank storage

Well Command Water Productivity WP (w)

Unlike the canal or tank commands, well commands are isolated and scattered and may also occur within a canal command or tank command. Absolute water productivity from an area fed by wells alone can be worked out if that area is away from a canal or tank command. But if the wells function within a canal or tank command, the conjunctive water productivity will be assessed on the premise that losses from canal or tank flows, contribute to groundwater recharge over a certain lag period, i.e., loss is transformed into a gain. Recycling this gain of water as a conjunctive use of groundwater with surface waters will help increase the irrigation area thereby increasing the absolute productivity of the region. Water table fluctuations are periodically assessed to determine if the area comes under a dark zone or gray zone or a white zone for having exploited the groundwater potential and leading to a critical stage of minimum or controlled pumping with possibilities for introducing artificial recharge means and structures. Water table fluctuations, pumping hours, discharge variations, power of pumping unit, mode of conveyance and application, type of crop and method of irrigation would contribute to the fluctuations in productivity. The productivity can be improved if lined channels or pipelines are used for conveyance and micro-irrigation systems are used for application.

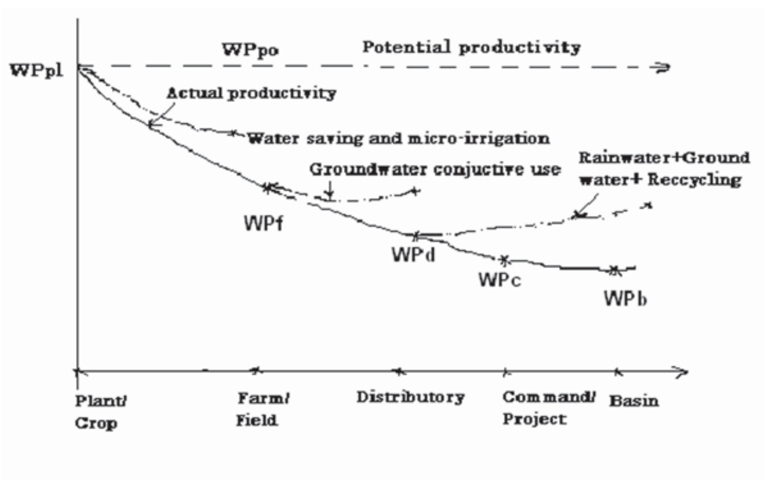
WP (w) = Y/Wd

Where,

Wd = volume or equivalent depth in cm of water depleted from well storage by pumping = (pump discharge * total duration of pumping over the crop growth season) / area of cultivation

All the above scales of reference shall be suitably formatted for input data, processing models and output units of productivity. The overall physical or economic productivity of a region shall then be worked out integrating the above scales.

Figure 2. Implications for integrated system water productivity.



Implications for Integrated System Water Productivity

- The physical water productivity (WP_p) tends to decrease at a drastic rate towards the scale expansion to farm/field level from the ideal plant/crop level with the potential productivity (Figure 2). The reason attributed is runoff and deep percolation losses, resulting in reduced efficiency levels and an increased water demand at the field inlet for diversion from the irrigation source.
- From farm/field scale the rate of reduction in productivity decreases towards a distributory scale and thereupon it may attain constancy due to the effects of the groundwater conjunctive use and recycling from the water harvesting structure for supplemental irrigation. Productivity can be improved upon by these effects.

Water Productivity Vs Scale of References under Different Irrigation Systems

Water productivity under different scale levels viz., plant, field and distributory level was studied in three different irrigation systems viz., canal, tank and well irrigation. In canal irrigation system, four river basin areas of Tamil Nadu viz., Parambikulam Aliyar Project (PAP), Lower Bhavani Project (LBP), Periyar Vaigai and Tampiraparani river basins were taken to work out the water productivity at different scales of references. Data were collected using field visits to the canal commands and also necessary information was collected from the project records. Wherever possible measurements were taken and verified. The details of water productivity under different scale levels in various irrigation systems are presented in Table 1. In canal irrigation system, groundnut is a predominant crop in Parambikulam Aliyar Project (PAP), whereas in the other three river basins rice is the major crop.

From the results, it is clearly understood that there was a considerable reduction in water productivity under field level (0.20 kg groundnut/ m^3 of water in PAP, 0.40 kg rice / m^3 in Lower Bhavani Project (LBP), 0.24 kg rice / m^3 in Vaigai and 0.27 kg rice / m^3 in Tampiraparani River basin) as compared with individual plant/ crop level (0.39 kg groundnut/ m^3 of water in PAP, 0.73 kg rice / m^3 in LBP, 0.70 kg rice / m^3 in Vaigai and 0.60 kg rice / m^3 in Tampiraparani River basin) mainly due to losses through seepage, deep percolation and runoff in the canal irrigation systems. Among the four canal irrigation projects, Lower Bhavani Project was recorded to have higher productivity at the plant level (0.73 kg/m^3) as well as at the farm level (0.40 kg/m^3) compared to other projects. At distributory level, conveyance losses caused reduction in water productivity, which means that a more quantity of water is being used for crop cultivation. So water productivity has a negative relationship with the scale of reference that is the expansion of the boundary of the command area (Figure 3).

In the case of tank irrigation, Srivilliputhur Big Tank in Ramanathapuram District of Tamil Nadu was taken for the study as the data on most of the parameters of water productivity calculations were available. The results showed that there was a reduction in water productivity when the scale of reference is increased. The physical water productivity of rice was higher under individual plant level (0.47 kg / m^3) followed by field level water productivity (0.30 kg / m^3) and comparatively lower water productivity was recorded under tank system level.

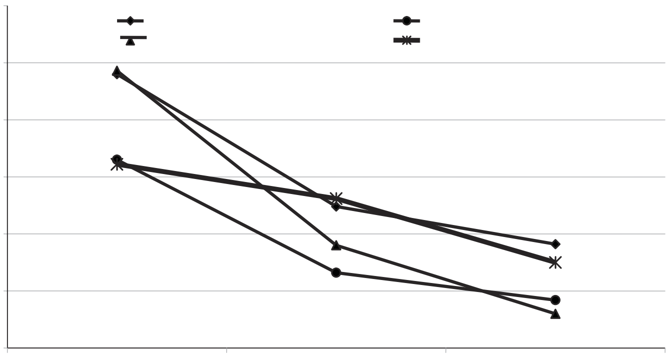
In sum, among the different irrigation systems, the well system has comparatively higher water productivity both in physical and economic terms due to controlled irrigation application, comparatively higher crop yields and multiple crops/ enterprises combinations. In canal and tank systems, mono-cropping, uncontrolled irrigations, and scarcity of water during critical crop periods result in lower water productivity.

Table 1. Physical and economic water productivity under different irrigation systems with the different scale of reference in Tamil Nadu.

Scale of references	Total water used (m^3)	Output		Water productivity	
		Physical (Rs.)	Economic (kg/m^3)	Physical ($Rs./m^3$)	Economic (kg)
I. Canal system					
1. Parambikulam Aliyar Project (PAP)					
Plant/ crop level	0.013	0.0051	0.0312	0.39	2.40
Field level (0.4 ha)	3,388.8	680	4,160	0.20	1.23
Distributory level	1,335,283.7	1,85,661	1,135,810	0.14	0.85
2. Lower Bhavani Project (LBP)					
Plant/ crop level	0.0180	0.0131	0.029	0.73	1.61
Field level (0.4 ha)	5,473.5	2,200	7,000	0.40	1.28
Distributory level	8,33,824.4	2,13,796	6,21,952	0.26	0.75
3. Vaigai River Basin					
Plant/ crop level	0.020	0.014	0.033	0.70	1.65
Field level (0.4 ha)	6,931.25	1,650	4,390	0.24	0.63
Distributory level	2,486,534.4	3,96,000	1,053,600	0.16	0.42
4. Tampiraparani River Basin					
Plant/ crop level	0.028	0.017	0.068	0.60	2.43
Field level (0.4 ha)	7,909.4	2,100	7,100	0.27	0.90
Distributory level	37,647,968.0	3,549,038	12,066,949.5	0.09	0.30
II. Tank system					
Plant/ crop level	0.0202	0.0095	0.007125	0.49	0.35
Field level (0.4 ha)	11,608.1	3,160	2,375	0.27	0.20
System level	3,099,174	8,21,000	9,54,750	0.26	0.30
III. Well system					
Plant/ crop level					
Maize	0.048	0.050	0.21	1.04	4.38
Banana	6.6	8.5	59.70	1.28	8.99
Field level					
Crops alone (0.9 ha)	12,003.0	15,833.33*	1,15,752	1.31	9.64
Crops + Dairy (1.0 ha)	10,068.4	32,116.67**	1,15,752	3.19	11.27
Crops + Fishery (1.20 ha)	16,352.0	72,045.83*	6,78,350	4.41	41.43

Note: * banana equivalent yield ** maize equivalent yield

Figure 3. Economic water productivity and scale of references in four river basins of Tamil Nadu.



Water Productivity Improvement Measures and Future Challenges

Water productivity could be improved either by reducing the water losses that occur in various ways during water conveyance and irrigation practices or by increasing the economic produce of the crop through efficient water management techniques. Principle factors that influence water losses and water productivity of a command area are the design and the nature of construction of the water conveyance system, type of soil, extent of land preparation and grading, design of the field, choice of irrigation methods and skill of irrigators.

The scale and boundary of the area over which water productivity is calculated greatly affect its value. This is because that the outflow 'losses' by S, P and runoff at a specific location (or field) can be reused at another location within the area under consideration. Data on water productivity across scales are useful parameters to assess whether water outflows upstream are effectively reused downstream. The limited data suggest that water productivities at scale levels vary widely. The paucity of data on water productivity at scale levels higher than the field level is the major constraint (Jacob et al. 2003). In this context, increasing crop water productivity is a challenge at various levels which is briefly outlined below:

The first challenge is to continue to enhance the marketable yield of crops without increasing transpiration. The second challenge is at field, farm and system levels to reduce as much as possible all outflows that do not contribute to crop production. The third challenge is to increase the economic productivity of all sources of water, especially rainwater but also wastewater of various qualities and saline (ground) water. Interdisciplinary team work is warranted.

The study results thus help to derive the following policy recommendations:

a) Introduction of modern water management technologies should be taken up by the extension department of the government and nongovernmental organizations to minimize the wastages.

b) Agricultural technology transfer programs should be strengthened to increase the technical efficiency, which in turn will help increase the rice production further from 25 % to 32 % in the canal irrigation systems.

c) Wherever possible, multiple uses of water should be exploited in order to increase the water productivity.

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