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ORIGINAL PAPER

Combining remote sensing and economic analysis to support decisions that affect water productivity

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Abstract In this paper, an innovative method—that combines a technical and socio-economic analysis—is presented to assess the implications of policy decisions on water productivity. In the technical part, the variability in crop water productivity (CWP) is analyzed on the basis of actual water consumption and associated biomass production using the Surface Energy Balance Algorithm for Land (SEBAL). This generates input for the socio-economic analysis, which aims to quantify the foregone economic water productivity (EWP) of policy decisions to allocate water in a social optimal way. The basis for arguments to transfer water between categories of users will be strengthened and be more objective when the productivity in existing and alternative uses is known. The usefulness of such an approach is shown in the South African part of the Inkomati Basin, where according to the Water Act, water has to be reserved for basic human needs and to protect aquatic ecosystems. The opportunity costs, in terms of foregone EWP, of decisions to divert water away from agriculture are assessed. The results show that diverting water away from crops with a low CWP is not always the most cost-effective way in terms of foregone EWP.

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Introduction

Nowadays, a wide variety of driving forces is leading to new claims on water enhancing the competition for water. The liberalization of the world markets triggers the production of crops in many water scarce basins, disregarding water availability and the effect on local livelihoods.

Trade-offs have to be made between the water management objectives: economic efficiency, social equity, environmental sustainability and security. A social equitable allocation is often not efficient, while an efficient allocation is often not equitable. This means that a social equitable allocation may result in productivity losses. This is a dilemma that policy makers face.

That water is not always allocated in the most productive way in order to meet all kinds of socio-political objectives can best be illustrated on the basis of some examples. In Indonesia, the government encourages rice production, despite its low economic returns, for food security reasons. In the Yemen, an exceptionally water-short country, groundwater is allowed to be unsustainably used for Qat production, as it is an important source of income for the poor. In South Africa water is reallocated from commercial to emerging farmers for equity reasons. In Egypt, water is transferred to 'new lands' for rural development and employment reasons. The 'new lands' in the middle of the dessert are less fertile and less productive than lands along the Nile; however, niche crops, like cantaloupes, are grown with a high economic return to water.

So, from a social welfare point of view, water is allocated in an optimal way, but not from a technical and economic point of view. This means that productivity, output per unit input, can be defined in various ways. In this study, three water productivity indicators are distinguished:

'crop water productivity' (CWP): beneficial biomass per unit of water (kg/m^3).
'economic water productivity' (EWP): net economic benefits per unit of water (\$/m^3);
'socio-optimal water productivity' (SWP): socio-optimal value per unit of water.

The CWP has extensively been discussed in the literature, especially the challenge of increasing the CWP, to produce more food with less water, (Zwart and Bastiaanssen 2004, 2007). The EWP has been studied by Hellegers and Perry (2006) and Immerzeel et al. (2008)It has lately gained attention in the context of payment for environmental services (PES). Substantially less can be found in the literature about the SWP. Hellegers (2006) shows that disregarding social values in allocation decisions causes market failure. Although it has been widely acknowledged that water allocation is essentially political in nature (Savenije and Van der Zaag 2002; Hermans and Hellegers 2005; Hoekstra 2005; Hermans et al. 2005), social values have so far hardly been quantified. This is due to the fact that the values society attaches to achieving political objectives are hard to quantify.

This study aims therefore to develop and demonstrate a method that derives an implicit minimum social value on the basis of economic productivity losses, which is an extension of conventional work in this field. This can strengthen policy decisions, as the value society attaches to achieving a certain objective must at least be equal to the opportunity costs. Besides, it can show the most cost-effective way of achieving that objective.

To achieve this aim, a combined technical and socio-economic analysis is developed. The technical analysis quantifies variability in CWP, actual water consumption and biomass produced using the SEBAL algorithm and satellite images (Sect. "Remote sensing in combination with SEBAL"). The socio-economic analysis quantifies the economic productivity losses of policy decisions (Sect. "-Socio-economic indicators"). The usefulness of combining remote sensing and socio-economic analysis to assess variability in CWP and EWP is demonstrated with data from the Inkomati Basin in the eastern part of South Africa, where—according to the Water Act—water has to be reserved for basic human needs and to protect aquatic ecosystems (Sect. "How can it strengthen policy decisions in the Inkomati Basin?"). Finally, some conclusions are drawn (Sect. "Conclusions").

Remote sensing in combination with SEBAL

Not all biomass produced is beneficial biomass. For example, by fruit bearing plants and trees, the interest is in the fruits, and not the stem or the leaves. The beneficial biomass or crop yield (Y) is a fraction of the total amount of biomass produced. Crop water productivity is defined in this paper as the amount of beneficial biomass per unit of water consumed.

The terms, consumed water and actual evapotranspiration (ET_{act}) are used interchangeably. A high production of beneficial biomass per unit of water consumed is an indication of efficient water use by the plant, indicating the potential for improved management where the CWP is low, either through reducing the evaporative part of ET_{act}, or by improving crop growing production factors, like fertilization, or by inducing limited water stress through irrigation scheduling. Note that efficient water use by the plant is not at all related to the concept of irrigation efficiency, since the irrigation efficiency is a measure of how well water was delivered to the plant. Irrigation efficiency is the fraction of irrigation water applied that is beneficially consumed by the crop and can be increased by modern irrigation technologies (Perry 2007).

To avoid the use of ill-defined concepts of efficiency, the terminology used in this paper is clarified below. It avoids the word efficiency and relies instead on the hydrological framework that defines component water flows (as adopted by the ICID and described in Perry 2007):

1. *Water use*: irrigation water applied and use of direct rainfall, comprising:
2. *Consumed use*: water evaporated or transpirated, comprising:
   - 2.1 *Beneficial consumed fraction*: water consumed for the desired purpose,
   - 2.2 *Non-beneficial consumed fraction*: other evaporation or transpiration,
3. *Non-consumed use*: water not lost to the atmosphere, comprising:
   - 3.1 *Recoverable fraction*: water that can be recovered and re-used,
   - 3.2 *Non-recoverable fraction*: water that cannot be economically recovered.

It is important to note that total consumed water ET_{act} is studied in this paper (including ET from both irrigation and direct rainfall), while only the ET from irrigation can be managed by re-allocation of water.

Although the volume of water diverted from a source (river or aquifer) is widely used as the basis for water management, this might be a misleading concept on a basin scale since recoverable losses can be re-used elsewhere in time or space. On a basin scale, the actual consumed water should be used instead as the basis of management, since in case of a large recoverable fraction, measured diversions at basin scale might be higher than the available water.

The Surface Energy Balance Algorithm for Land (SEBAL) (Bastiaanssen et al. 2002, 2005) is used in this study. It is a robust remote sensing model based on the physics of the energy balance that calculates the available energy for actual evapotranspiration (ET_{act}). This model was extended to produce estimates of crop biomass production, so that crop yield, actual water consumption and crop water productivity can be obtained in an integrated way on a pixel by pixel basis. The energy balance can be calculated for each date that satellite images are available, and the resulting values are therefore variable in space as well as in time. It allows assessment of consumptive water use and biomass produced and CWP for all types of evapotranspirative use: from rangelands, natural and planted forests, rainfed and irrigated agriculture, and wetlands. The data can be assembled relatively quickly, based on uniform analytical procedures that have been internationally tested.

The key input data in the remote sensing component of the study consists of Landsat, MODIS and TRMM (Tropical Rainfall Measuring Mission) images. The former two data sources are used for ET_{act} estimations. The latter one for rainfall. In addition to that, routine weather station data has been used from a limited number of stations. This data consists of solar radiation, air temperature, air humidity and wind speed. The weather data has been gridded for acquiring estimates of the lower atmospheric boundary conditions.

Bastiaanssen et al. (2005) investigated the error margins in ET maps prepared by SEBAL. Their conclusion is that errors at the field scale for a single day can be as large as 10–20%. A single day regional scale value for accuracy will be better. This estimate was recently confirmed by independent researchers from Nebraska (Singh et al. 2008). Four years of ET field measurements over irrigated fruit crops in Brazil confirmed this accuracy with SEBAL to be attainable (Texeira 2008). A compilation of earlier SEBAL research results on grapes in Spain, Turkey and Brazil showed that the model performance is very consistent between rainfed rosins and intensely irrigated table grapes (Bastiaanssen et al. 2008).

The accumulated ET for a season was acquired with the help of a set of MODIS images. On average, one individual MODIS image per 14 days has been used. The time integration between consecutive images was accomplished by means of the one-layer Penman–Monteith energy balance combination equation for ET_{act}. The bio-physical parameters required for this equation was taken from MODIS overpass days, i.e., surface albedo, surface emissivity, surface roughness, Monin–Obukhov length, Leaf Area Index and the bulk surface resistance. The daily variation in ET was included by the temporal variations of the routine weather data. The error for accumulated ET fluxes is smaller than for individual days. This can be ascribed to cancelling of random errors that occur during individual days. Whereas a certain semi-empirical relationship is good to describe the average condition, it may be less accurate to describe single events on individual days. ET across a season is therefore more accurate than for a MODIS overpass day. The downscaling of 1-km MODIS results to a 30-m Landsat grid was established by running SEBAL for a selected number of Landsat images in parallel to the MODIS images.

SEBAL estimates the actual evapotransipiration (2.1), which is a combination of beneficial consumption (2.1.1) and non-beneficial consumption (2.1.2). Evaporation from soil surfaces, does not directly contribute to biomass production. Transpiration, where it has a function of transporting nutrients through the plant, is usually beneficial for biomass production. However, it appears that there is not always a direct relation between water transpired and biomass produced.

A standard method to estimate actual evapotranspiration is through the use of the FAO 56-Penman–Montheith method (Allen et al. 1998), which is based on point measurements. Using this equation, the reference evapotranspiration (ET_{ref}) can be calculated based on an assumed standard grass coverage and available meteorological data. The ET_{ref} must be multiplied by a crop coefficient (k_c) to obtain the potential evapotranspiration (ET_{pot}) of a specific crop. To obtain the actual evapotranspiration (ET_{act}), the ET_{pot} must be adjusted for stress, indicated by a stress factor (k_s). The difficulty in this process is that the k_c is usually taken as a fixed value per crop (only variable over time, depending on growth stage) and that the determination of a stress factor for a selected period is almost impossible (the stress factor not only depends on available water, but also on fertility, insect pressure and possible heat stress).

Unlike conventional bases for analyzing evapotranspirative consumption, the SEBAL technique is not point specific (and hence challengeable at any other point). Allen et al. (2007) have adopted this spatial estimation of evapotranspiration (ET_{act}). Once demonstrated to be accurate (validated), the data from these analyses are very useful for monitoring and predicting future water use based on trends. In addition to the technical strengths of remote sensing, the uniformity of the analysis also may have legal implications.

This study is based on qualitative ground-truthing only. The verification has been done with interviews. At this

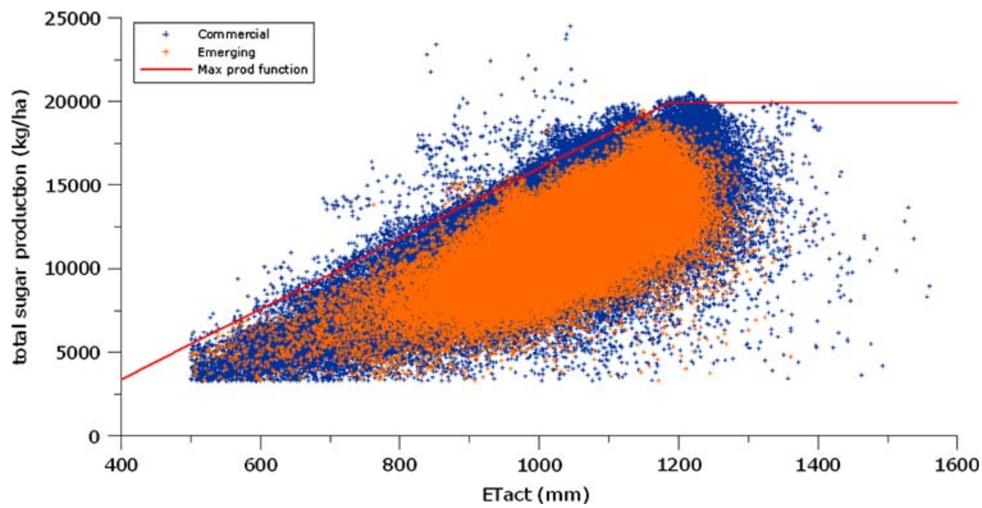


Fig. 1 Sugar cane production per pixel as a function of actual water consumption for commercial (*black cloud*) and emerging farming (*grey cloud*). Water consumption below 500 mm and sugar cane production below 7,500 kg/ha are not taken into consideration

moment, quantitative verifications of sugarcane yield and ET are under execution in the study area. The verification of crop yield and ET from SEBAL has been completed in 20 different countries, and considering the general physics of the model, it seems that it can be applied trustworthy in the case of South Africa. This was confirmed during a recent experiment held in the Winelands region of the Western Cape (Jarmain et al. 2007).

Plotting beneficial biomass produced as a function of actual water consumption (Fig. 1) shows for instance the variability in CWP of sugar cane.[1] The maximum CWP is represented by the red line. It shows that farmers below the red line can potentially increase beneficial biomass with the same amount of water or maintain their beneficial biomass with less water.

This non-productive water use means that water can be diverted away without adversely affecting the beneficial biomass production in two ways. First, limit water consumption to a maximum quota of 1,200 mm/year, since it produces no additional biomass. Second, reduce the non-beneficial consumed fraction by means of improved water management. The large variability of CWP was also found by Zwart and Bastiaanssen (2004), who show values of 0.6–1.7 kg/m^3 for wheat, 0.6–1.6 kg/m^3 for rice, and 1.1–2.7 kg/m^3 for maize. They ascribe the large variability to (1) climate, (2) irrigation water management, and (3) soil (nutrient) management. It shows opportunities for maintaining or increasing production with 20–40% less water resources.

[1] The beneficial sugar cane production found in this study (calculated by multiplying the average harvestable total sugar cane biomass production of 55.0–59.1 ton/ha with the Harvest Index of 0.22) matches with the results of Bezuidenhout et al. (2006), who estimated 14.1 ton sugar per hectare for an ET of 1016 mm in Komati.

Socio-economic indicators

Economic water productivity (EWP) is defined in this paper as net production value (direct benefits) per unit of water consumed (\$/m^3). In case of a negative EWP, costs of production exceed benefits of production. It can also be used to determine the economic most productive crop. It is, however, important to note that the EWP is rather sensitive to market prices, and that growing solely the most productive crop is usually not desirable for a number of reasons. Market prices may vary and might drop as a result of a substantial increase in production due to market and supply–demand economics. Besides farmers do not prefer monocultures, as they like to spread price risks and disease risk. It is also not desirable from a crop rotational point of view.

The CWP is calculated by dividing beneficial biomass by water consumed (Eq. 1). The EWP is calculated by multiplying beneficial biomass and the market price minus variable and fixed production costs divided by water consumed (Eq. 2).

$$\mathrm{CWP_i} = \mathrm{Y_i}/\mathrm{ET_{acti}} \quad (1)$$

$$\mathrm{EWP_i} = (P_\mathrm{i} \times Y_\mathrm{i} - B_\mathrm{i} \times Y_\mathrm{i} - C_\mathrm{i})/\mathrm{ET_{acti}} \quad (2)$$

With

Y_i Yield of crop i (kg/ha)
P_i Market price received for crop i (\$/kg)
B_i Variable production cost of crop i (\$/kg)
C_i Fixed production cost of crop i (\$/ha)

This approach, of subtracting cost of production from the gross production value, is the one employed by most analysts and known as the residual method. Young (2005) provides an extensive review of the residual method, detailing its theoretical foundations, uses, benefits and limitations. The basic approach relies on the fact that the value to a producer from producing a good is exhausted by the summation of the values of the inputs required to produce it. If the value of one input is unknown, then the value of that input (which in this study is the value farmers place on water) can be found by simply rearranging terms so the unknown value is a function of the price by quantity of the output, less the prices by quantities of all known inputs, all divided by the quantity of the unknown input (Eq. 2). Young (2005, p. 61) describes this as the 'value of water' or the 'net return to water'.

Production costs (including costs of machinery, labor, fertilizer, pesticides, seeds and land) vary in practice among farmers, but this can not be derived by remote sensing. It is therefore assumed that part of the production costs are fixed and part is proportional to the yield. Although it is an oversimplification of reality, it is uniformly applied, transparent and easy to correct.

The basis for arguing for transfers of water among categories of uses: crops, farmers, sectors, upstream and downstream, states and over time in order to meet socio-political objectives will be considerably strengthened when the water productivity in existing and alternative uses is known. This enhances the ability of decision-makers to evaluate trade-offs between water policies and courses of social actions that alter water use and the multiple services it provides.

What is socially optimal depends on the country specific objectives. In a food-scarce system, the goal can be to maximize the CWP, while in an open-market system, the goal can be to maximize the EWP. In many systems, the goal has been for a long time to maximize social welfare disregarding the productivity of water. Given new claims on water, there is an increasing need to consider productivity implications in order to harmonize policies. This study does not promote to allocate water in the economic most productive way, but aims to simulate productivity changes as a result of meeting social objectives. It is important to note in this respect that reallocations are usually conditional upon the size of productivity gains compared to the transaction costs involved in such a transfer.

The large variability in CWP and EWP values among farm land is spatially depicted in Fig. 2, which is the area along the South African part of the Komati river before the border of Mozambique. It shows that there is not a strong correlation between the CWP and EWP. This means that diverting water away from crops with a low CWP is not always the most cost-effective way in terms of foregone EWP. Figure 3 shows that for low CWP values there is indeed no strong relationship between the CWP and EWP. This can be explained by the rather high fixed production costs, which is a relatively heavy burden for low-productive users.

How can it strengthen policy decisions in the Inkomati Basin?

The usefulness of the methodology presented in this paper has been demonstrated in the South African part of the Inkomati Basin where, according to the Water Act, past inequalities have to be redressed, while encouraging productive use and sustainable resource management. The implementation of the principles implied by the Act presents many challenges. Under section 27.1, the Act specifically requires that the socio-economic implications

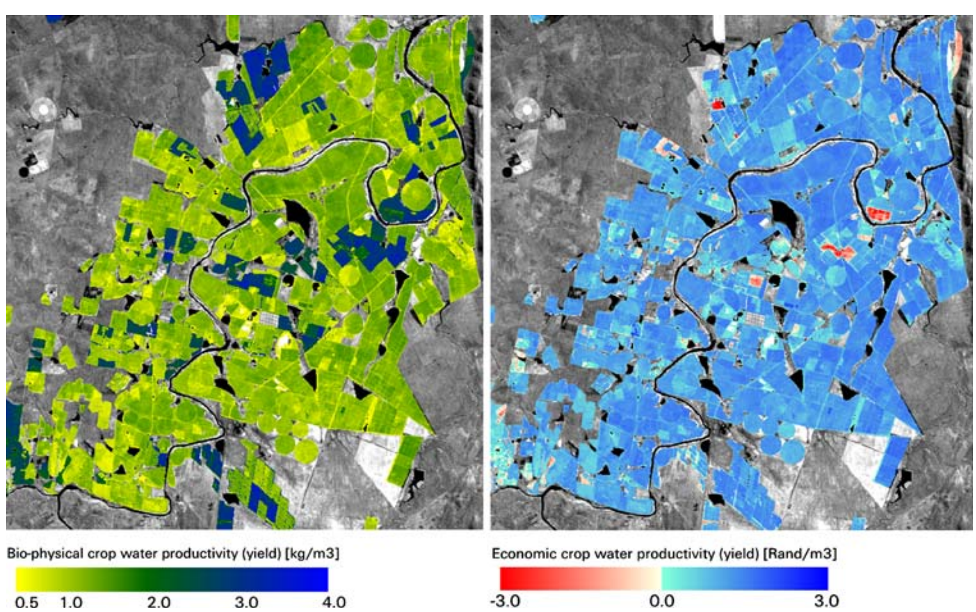


Fig. 2 Crop water productivity (kg/m^3) and economic water productivity (R/m^3) of bananas and sugar cane at commercial farms along the South African part of the Komati river

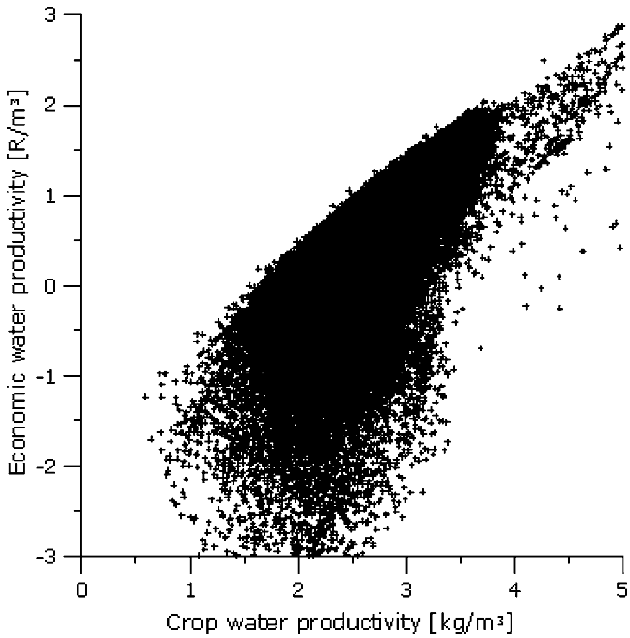


Fig. 3 Relationship between the CWP and EWP

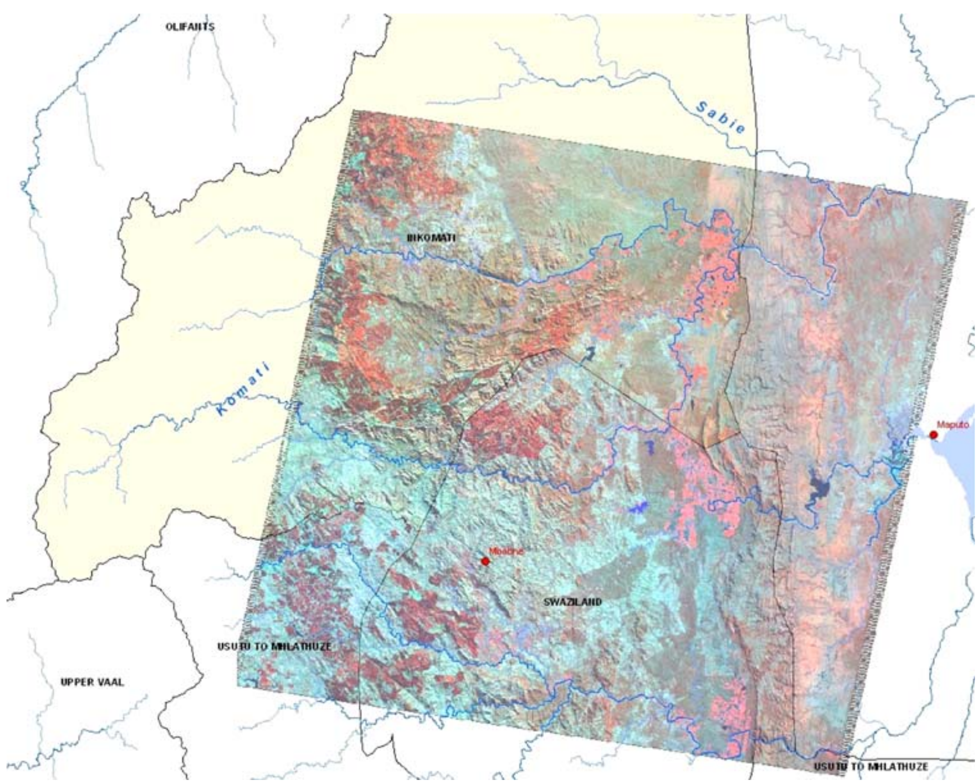
of any transfers should be evaluated before a transfer is granted. The basis for arguing for transfers of water among users (to meet social objectives) will be considerably strengthened and more objectively based when the productivity is known, which the methodology described in this paper can facilitate.

Figure 4 shows the area covered by the Landsat image relative to the Inkomati catchment used for the analysis (Path 168–Row 78). It is important to note that results presented in this section aim to demonstrate the method and that more work needs to be done to establish firmer production values.

The opportunity costs, in terms of foregone EWP, of diverting water away from agriculture—in order to comply with the Water Act—are quantified. There are, however, various ways of diverting water away. For instance, by diverting water away from agricultural areas with the lowest CWP, or lowest EWP, or proportionally or by means of a quota.

The choice of the most cost-effective way can be strengthened when the productivity losses are known. This requires insight into the variability of CWP, EWP and ET_{act}. Figure 5 shows the variability in *Y*, ET_{act}, CWP and EWP (top to bottom) for orchards, commercial sugar cane cane and emerging sugar cane cane (left to right) in the Inkomati Basin for year 2004–2005. The histograms, which is a graphical display of tabulated frequencies, show what proportion of pixels fall into each of the specified categories. In Table 1, the average values and standard deviations are summarized. It shows that although bananas produce on average more beneficial biomass per unit of water consumed than sugar cane cane, the average EWP is lower for bananas. This means that diverting water away from

Fig. 4 Location of the Landsat image relative to the Inkomati catchment



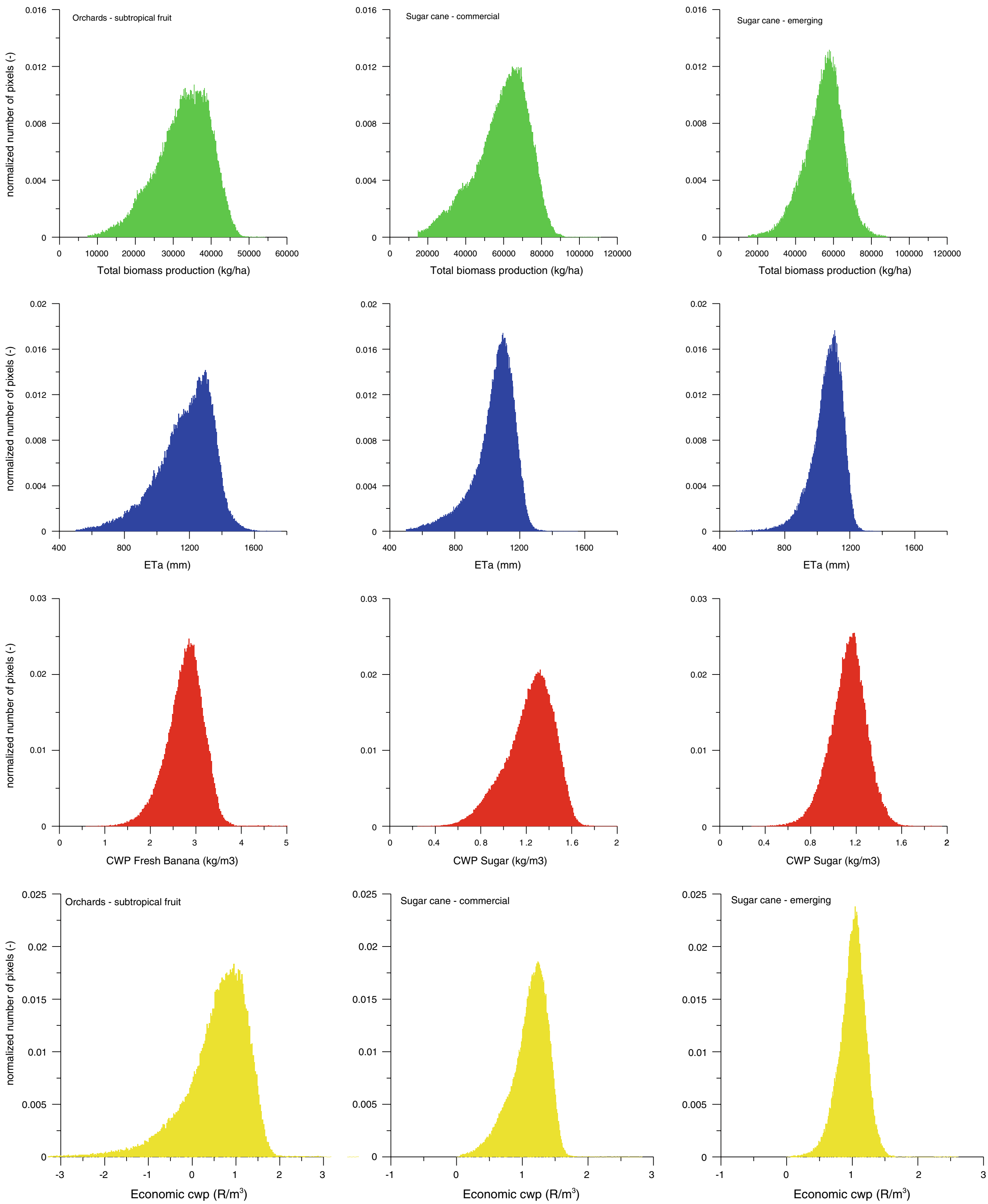


Fig. 5 Variability in beneficial biomass production, actual evapotranspiration, crop water productivity and economic water productivity (*top to bottom*) for bananas, commercial and emerging sugar cane (*left to right*) in the Inkomati 2004–2005

Table 1 Average ET_{act}, beneficial biomass, net production value, CWP and EWP in the Inkomati Basin for year 2004–2005

	Total area planted (ha)	ET_{act} (mm)	Beneficial biomass (kg/ha)	Net production value (R/ha)	CWP (kg/m^3)	EWP (R/m^3)
Bananas	771,925	1,174 (174)	32,618 (7,132)	7,511 (8,141)	2.78 (0.42)	0.64 (0.74)
Sugar comm.	1,478,719	1,043 (130)	13,001 (3,105)	11,840 (3,652)	1.25 (0.21)	1.14 (0.28)
Sugar emerg.	576,594	1,061 (98)	12,068 (2,261)	10,660 (2,655)	1.14 (0.17)	1.00 (0.21)

Standard deviation in brackets

bananas is on average more cost-effective than diverting water away from sugarcane.

Figure 5 shows that the CWP and EWP values of emerging farming are more tightly centered on the means than those of commercial farming. This was a rather surprising result; however, during discussions in South Africa it became clear that during a dry period, water diversion restrictions were only applied on the commercial farms, which explains this finding.

Figure 5 also shows that the productivity of bananas varies more than the productivity of sugar cane. Some EWP values of bananas are even negative. The high fixed production costs of bananas are a heavy burden, making bananas a risky crop. The large, low-performing tail of the EWP histogram of bananas implies potential gains in the net production value when water is diverted away, which the CWP histogram of bananas does not reveal. It is important to note in this respect that market prices, which vary largely, are very determining for the size of the EWP.

So diverting water away from crops with a low CWP is not always the most cost-effective way in terms of foregone EWP. Rationing water use to a maximum volume per hectare and a proportional reduction in ET_{act} of all users might both be more cost-effective, as it provides users incentives to improve management practices that reduce the non-beneficial consumed fraction.

Conclusions

In this paper, remote sensing in combination with socio-economic analysis has been demonstrated to be a powerful tool to simulate changes in the productivity of water. The basis for arguments to transfer water between categories of users will be strengthened considerably and be more objective when the foregone benefits of allocating water in a more optimal instead of in a more productive way are known. These opportunity costs can be interpreted as a kind of proxy of the minimum value society attaches to allocation water in an optimal way. The usefulness of this method is demonstrated with data from the Inkomati Basin in the eastern part of South Africa, where water has to be reserved for basic human needs and to protect aquatic ecosystems. This kind of analysis can provide data for improved decision making in pursuit of social and environmental objectives, which can be considered as a starting point for further discussions. This is an extension of conventional work in this field.

This method has various strengths. Unlike conventional bases for analyzing ET_{act}, the SEBAL technique is not point specific. The data can be assembled relatively quickly, based on uniform analytical procedures that have been internationally tested. Once demonstrated to be accurate (validated), the outcome of these analyses are very useful, for monitoring and predicting future water use based on trends. In addition to the that, the uniformity of the analysis also may have legal implications. This might be helpful as it is highly likely that the process of identifying lawful and unlawful/excessive uses will be legally contested.

In summary, remote sensing offers strong tools for performing the following analysis:

– Validate volumes of water consumed historically (as a reference for water rights).
– Assess the spatial and temporal variability in crop water productivity.

Combining remote sensing with socio-economic analysis allows to:

– Assess the spatial variation in economic water productivity.
– Estimate the size of the potential gains and losses of water re-allocation.
– Detect areas with apparent excess use (where ET_{act} exceeds allocated water rights).
– Visualize accessibility by the extent to which actual water consumption and formally allocated water rights are evenly distributed among farms and plots.

Such an approach that considers changes in water productivity will become more important, for formulating more harmonized policies, as water becomes scarce.

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