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AN INTERACTIVE WATER INDICATOR ASSESSMENT TOOL TO SUPPORT LAND USE PLANNING†

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ABSTRACT

This paper presents an interactive web-based rapid assessment tool that generates key water related indicators to support decision making by stakeholders in land use planning. The tool is built on a consistent science based method that combines remote sensing with hydrological and socioeconomic analyses. It generates transparent, impartial, and verifiable information regarding the impact of land use changes on water productivity, water consumption, water availability, and employment. The usefulness of the tool was demonstrated in the Inkomati River Basin in Southern Africa, where the tool was used to assess the impact of converting land use on the water resources to prioritize areas for conversion and to track required changes in land use to comply with tripartite water allocation agreements. This contributed to confidence building and to strengthening the process of conscientious land use planning, which is an extension of conventional work in this field. Copyright © 2011 John Wiley & Sons, Ltd.

KEY WORDS: land use planning; water productivity; remote sensing; economic analysis; water indicators

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RÉSUMÉ

Cet article présente un outil d'évaluation rapide basé sur internet: il génère des indicateurs clefs liés à l'eau pour faciliter la prise de décision des différents acteurs de l'aménagement du territoire. L'outil s'appuie sur des méthodes scientifiques très cohérentes qui combinent la télédétection avec des analyses hydrologiques et socio-économiques. Il génère des informations transparentes, impartiales et vérifiables sur les impacts de changements dans l'utilisation des terres sur la productivité de l'eau, sa consommation, sa disponibilité et son utilisation. L'utilité de l'outil a été démontrée en Afrique du Sud dans le Basin du fleuve Inkomati où il a permis d'évaluer l'impact de la conversion de l'usage des terres sur les ressources en eau, d'établir des priorités et de tracer les changements requis pour respecter des accords tripartites d'allocation d'eau. Ceci a permis d'établir la confiance et a renforcé le processus d'une planification consciencieuse de l'usage des terres, qui est une extension du travail classique dans ce domaine. Copyright © 2011 John Wiley & Sons, Ltd.

MOTS CLÉS: aménagement du territoire; productivité de l'eau; télédétection; analyse économique; indicateurs de l'eau

INTRODUCTION

Land and water resources in many of the world's river basins are under unprecedented pressure resulting from population growth, socio-economic development (e.g., the liberalization of the world food markets), socio-cultural developments (e.g., changes in lifestyle and diet), and climate change. These developments are leading to increasing competition for land and water resources. To deal effectively with these competing claims, there must be good communication between stakeholders in river basins. This applies especially to large basins, because stakeholders are from various sectors, regions, and countries. Furthermore, the information that is communicated must be impartial and transparent.

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† Un outil interactif pour évaluer la planification des terres par des indicateurs liés à l'eau.

Hydrological regimes and the availability of water resources largely depend on land use and management in the river basin. Land development in upstream areas impact on the availability and quality of water in downstream areas, and may thus limit the development potential of the latter areas. As land use is generally not planned and managed at the river basin level, suboptimal conditions often emerge. That is, the favourable economic or ecological prospects of downstream areas are not being fully utilized due to water scarcity or pollution, while less favourable areas located upstream use the water resources sub-economically or sub-ecologically. This is especially valid for transboundary river basins such as the Nile and Kagera basins. Integrated water and land management at the river basin scale is therefore imperative to deal effectively with competing claims on land and water. Although the integration of land and water management is an important topic in the Comprehensive Assessment of Water Management in Agriculture (2007), it is dealt with mainly in terms of water and agriculture. The broader scope of land and water management, namely incorporating both cultivated lands and nature, has been less subject to integrated studies.

The Water Evaluation and Planning (WEAP) tool (Yates *et al*., 2005) allows for the analysis of various water allocation scenarios but not for the evaluation of water based land use planning. More integrated land and water models (e.g., SWAT) not only require large efforts in terms of data and model development, but also tend to have a strong hydrological approach. A common problem is that data and models are not transparent and objective, which hinders their acceptance by stakeholders; in land and water management issues, such acceptance is generally more critical than the generation of accurate information.

This paper presents an interactive tool that can provide rapid assessments of the impact of changes in land use on water resources in river basins. The tool was developed to support discussions among stakeholders in river basins. It can be applied in multistakeholder meetings and workshops and by individual stakeholders. The tool can instantly generate key indicators for land and water management, and this can help stakeholders and decision makers identify development scenarios. Because the concept and assumptions are relatively simple, the data are objective and transparent and the results can be easily verified (through own calculations by the user); the tool is very suitable for application in meetings with stakeholders from various sectors, regions, and countries.

The tool has already been used in the Inkomati River Basin, which is a transboundary river basin shared by South Africa, Swaziland, and Mozambique. The Inkomati River Basin was chosen to demonstrate the usefulness of the interactive tool, as the basin is a typical example of one that is experiencing water scarcity, over-exploitation of water resources, population growth, economic development, and socioeconomic reforms (which include the transfer of land to emerging farmers in South Africa under the National Water Act of 1998). It also has a wide applicability to land use and farming system, including subsistence farming, irrigated sugar cane, pasture, natural vegetation, alien plants, Kruger National Park, and commercial forest plantations.

The comprehensive basin wide Interim IncoMaputo Agreement (IIMA), which was signed in 2002, recognizes the right of all riparian states to specific volumes of water. Water demand and use, however, are currently in excess of available water resources, certainly if the water requirements of Mozambique and the Ecological Reserve are taken into account. The Ecological Reserve is not met and the cross-border flow to Mozambique is often less than agreed upon in the IIMA. Moreover, water assurance to the irrigation sector is very low in certain areas, especially in the lower reaches of the Crocodile River.

The tool was used in stakeholder meetings to identify potential policy options, one of which is the current plan to convert 25 000 ha of bushland into sugar cane for biofuel production in Mozambique. The tool allows for the assessment of the impact on water productivity, water consumption, and water availability for downstream uses. The tool can also be used to track strategic adjustments in land use or farming systems (cropping pattern) to comply with the tripartite water allocation agreements. To embark on a water reallocation process, either among the three states or in accordance with the water supply objectives and priorities laid down in the National Water Act (Act 36 of 1998) and the National Water Resource Strategy, a better understanding of current water use and available water resources at a regional (river basin) level is required. The IWAAS study (2008) provides insight into water availability but only limited insight into actual water use by land use types. This paper explains the concepts behind a new, interactive water-based land use planning tool and shows its application in strengthening of stakeholder discussions. The tool is used to elaborate two scenarios:

1. Conversion of 25,000 ha of bushland into sugar-cane for biofuels in Mozambique;
2. Prioritization of areas for zero replant of forest plantations in the upstream areas.

The first scenario was proposed by the stakeholders during an interactive workshop. The second was added to illustrate differences among areas in the cost-effectiveness of streamflow enhancement. The results of the tool's application are presented. The accuracy of the various variables will be discussed and some conclusions will be drawn.

METHOD AND MATERIALS

The interactive tool builds upon earlier studies in which remote sensing and economic analysis were combined to support decision making in the Inkomati River Basin in South Africa (Soppe *et al*., 2006; Hellegers *et al*., 2009, 2010) and in the Krishna River Basin in India (Hellegers and Davidson, 2010). The land and water indicators in the decision making process will be elaborated as well as data to quantify these indicators and details concerning the setup and functionalities of the tool.

Indicators

The tool quantifies key land and water management indicators. These indicators can help identify and evaluate land development options that best serve policy objectives and priorities. Discussions on future land uses can be better structured and more to the point by using water related indicators for existing and alternative land uses and by evaluating tradeoffs between various land use options. The tool enables the assessment of four indicators, each of which addresses a specific policy objective as follows:

Policy objective	**Indicator**	**Description**
Food security	Crop water productivity	Beneficial biomass per unit of water consumed
Income security	Economic water productivity	Net private benefits per unit of water consumed
Social security	Job water productivity	Employment per unit of water consumed
Equitable water allocation	Water availability for downstream uses	Volume of water for downstream uses

Crop water productivity

The agricultural production per unit of water is an important indicator for the allocation and management of scarce water resources (Kijne *et al*., 2003; Molden *et al*., 2007). The concept has been discussed extensively in the literature, especially within the framework of the challenge of producing more food with less water (Molden *et al*., 2010). The biophysical crop water productivity (CWP) ($kg\,m^{-3}$) is calculated by dividing the beneficial biomass (yield) by the volume of consumed water (Eq. 1). The yield of a crop is calculated by multiplying the gross biomass production by the crop's harvest index (Eq. 2). CWP is relevant only for agricultural land uses and forest plantations.

$$CWP_i = Y_i/10 * ET_{acti} \quad (1)$$

$$Y_i = k_i * M_i \quad (2)$$

with $Y_{i,}$ beneficial biomass or yield of crop i ($kg\,ha^{-1}$); $ET_{acti,}$ actual evapotranspiration of crop i (mm); $k_{i,}$ harvest index of crop i (−); $M_{i,}$ gross biomass of crop i ($kg\,ha^{-1}$).

The actual evapotranspiration and gross biomass production can be quantified through remote sensing techniques. The harvest index is generally determined based on historical yield data and/or the literature. As with evapotranspiration and biomass production, the harvest index can vary spatially, as certain areas are more suitable for specific crops than others. The harvest index may also vary between years, as climatic conditions and related yields vary from season to season.

Economic water productivity

Economic water productivity (EWP) expresses the monetary returns on water, namely the monetary value of the produced product per unit of water. EWP has been used in studies by Hellegers and Perry (2006), Soppe *et al*. (2006), and Hellegers *et al*. (2009, 2010). Here, the South African rand (ZAR) is used as the monetary unit. EWP can be calculated if the prices of commercial (agricultural and forestry) inputs and outputs are known. It is calculated by multiplying the beneficial biomass (yield) by the market price, subtracting the financial production costs of all inputs except water, and dividing the figure by the volume of consumed water (Eq. 3). A negative EWP means that the financial costs of production exceed the gross production value (benefits). This approach, which is known as the residual method (Young, 2005), relies on the principle that the value of a good (its price times its quantity) is equal to the sum of the quantity of each input multiplied by its average value. The value of the consumed water (or the 'value of water' or 'net return to water') can be calculated if the other inputs and outputs and their values are known (Hellegers and Davidson, 2010).

$$EWP_i = (P_i * Y_i - B_i * Y_i - C_i)/10 * ET_{acti} \quad (3)$$

with $Y_{i,}$ beneficial biomass or yield of crop i ($kg\,ha^{-1}$); $P_{i,}$ market price of crop i (ZAR kg^{-1}); $B_{i,}$ variable financial production cost of crop i (ZAR kg^{-1}); $C_{i,}$ fixed financial production cost of crop i (ZAR ha^{-1}); and ET_{acti}, actual evapotranspiration of crop i (mm).

In this paper, EWP is applied only to commercial land use. The EWP of Kruger National Park, which generates revenue from tourism, is not considered, as the relation between water consumed by nature and monetary returns from tourism is much more ambiguous than the relation between water consumed by agriculture and forestry and the monetary returns from these sectors.

Job water productivity

Job water productivity (JWP) (jobs m^{-3}) is less extensively discussed in the literature, yet is very relevant to Southern Africa. It can be calculated by dividing the number of jobs (employment) per ha of a certain land use by the volume of water consumed by that land use (Eq. 4):

$$JWP_i = J_i/10 * ET_{acti} \quad (4)$$

with $J_{i,}$ number of jobs required to manage the land use i (jobs ha^{-1}) and $ET_{acti,}$ actual evapotranspiration of land use i (mm).

Here, JWP is applied only to commercial land uses.

Water availability for downstream uses

Water availability for downstream use is an important indicator for the ecological reserve (environmental flow requirements), water assurance commitments (water rights) or licenses for certain water uses, and international agreements. Water availability for downstream use is determined by assuming that water resources are ultimately represented by precipitation and that water consumption is represented by actual evapotranspiration. Inter-basin transfers were not incorporated in the tool, but can be easily accounted for. Water availability is then assumed to equal the rainfall surplus (rainfall minus actual evapotranspiration). Using the tool in any area or sub-area, water availability for downstream use is calculated as:

$$Q_{out} = Q_{in} + 10^{*}\sum\left((P \text{ 0.5em- } ET_{acti})^{*}Ai\right) \quad (5a)$$

$$\text{for } Q_{in} + 10^{*}\sum\left((P \text{ 0.5em- } ET_{acti})^{*}A_i\right) > 0 \text{ and } Q_{out} = 0 \quad (5b)$$

$$\text{for } Q_{in} + 10^{*}\sum\left((P \text{ 0.5em- } ET_{acti})^{*}Ai\right) < 0$$

with $Q_{out,}$ water availability for downstream areas (m^3); $Q_{in,}$ water available from upstream areas (m^3); $P_,$ rainfall (mm); $ET_{acti,}$ actual evapotranspiration of land use i (mm); and $A_{i,}$ area of land use i (ha).

The tool assesses periods of one year, thus covering a hydrological cycle. Equation 5b makes a provision for the temporary use of water from storage, for example in dry years. The calculated water availability for downstream use should not be misinterpreted as river discharge. Part of the rainfall surplus is stored in the soil profile, aquifers, and reservoirs (dams), and is therefore not immediately available. For relatively long periods, changes in storage are relatively small in comparison with the groundwater and surface water discharges; however, these changes in storage should not be overlooked due to the large interannual variability of rainfall. Percolation losses (e.g., from irrigation systems) and domestic and industrial waste waters are regarded as internal (recoverable) flows and volumes, as they remain within the system. The actual domestic and industrial consumptive water uses can be ignored, as most domestic and industrial uses are non-consumptive recoverable uses (Perry, 2007).

Data

Land use. A reliable land use map is critical to relate geographically the actual evapotranspiration and biomass production data from remote sensing to the different land uses. The land use map was created using NLC2000.

Rainfall. Rainfall data were retrieved from the Tropical Rainfall Measurement Mission (TRMM), which carries a precipitation radar. Data are available at 3-hour intervals. The spatial resolution of the data is 0.25°, which corresponds with a pixel size of approximately 25 km^2. The TRMM satellite rainfall model can have accuracies of between 70% and 99% (Huffman *et al*., 2007). The accuracy of rainfall radar technologies was recently tested by Schuurmans *et al*. (2007). Detailed background information about the retrieval of rainfall data from satellites is provided by Barrett (1988), Barrett and Beaumont (1994), Petty (1995), Petty and Krajewski (1996), Kummerow *et al*. (1996), Smith *et al*. (1998), Kidd (2001), and Huffman *et al*. (2007). The major advantage of using TRMM rainfall data is that the data are impartial (they can be applied without spatial processing, which can sometimes be ambiguous) and are free of charge.

Actual evapotranspiration and biomass production. The actual evapotranspiration and biomass production are calculated using the surface energy balance algorithm for land (SEBAL) applied on MODIS images. These images have a spatial resolution of 250 x 250 m. SEBAL (Bastiaanssen *et al*., 2002, 2005) has been in use for 20 years. The model uses remote sensing data and the physics of the energy balance to estimate actual and potential evapotranspiration (ET_{act}, ET_{pot}) from net available energy. In periods of water stress, the actual evapotranspiration is less than the potential evapotranspiration. The model was extended to produce estimates of crop biomass production (Bastiaanssen and Ali, 2003), so that crop yield and crop water productivity could be obtained on a pixel by pixel basis. Energy balance and biomass production are calculated approximately twice a month. If land use maps are available, the consumptive water use can be calculated for each land use. The geographical distribution of water consumption for particular land uses can also be determined. Field measurements of ET_{act} over natural vegetation surfaces and irrigated mango plantations in Brazil recently showed that the annual ET_{act} values of SEBAL deviated 4.4% and 0.5%, respectively, from the eddy correlation measurements (Teixeira *et al*., 2009).

Publications on the accuracy of crop yield estimates are less common. Zwart and Bastiaanssen (2007) showed that reported wheat yields in the Yaqui irrigation district (Mexico) were on average 10% lower than remote sensing estimated yields. With the installation of GPS systems on harvesters, it will soon be easier to validate remotely sensed maps of crop yields. The role of remote sensing algorithms in estimating ET_{act} has been reviewed by Moran and Jackson (1991), Kustas and Norman (1996), Courault *et al*. (2005), Kalma *et al*. (2008), and Verstraeten *et al*. (2008). The applicability of a satellite based energy balance for mapping evapotranspiration has been assessed by Allen *et al*. (2005, 2007). The usefulness of remote sensing data to provide spatial information about water resources has also been demonstrated by Chowdary *et al*. (2008) and Casa *et al*. (2008). The latter applied a spatially distributed simple water balance model, which allows the estimation of temporal and spatial variation of crop water requirements.

Harvest and socio-economic data. Biophysical crop characteristics such as harvest indices and yields, and socioeconomic data such as fixed and variable financial production costs of crops and the market prices of crops (including commercial forestry), largely determine the outcomes of the tool. A main difference between these variables and the ET is, however, that the user can specify the socioeconomic variables and thus has direct control over their accuracy.

Tool setup and functionalities: spatial resolution. A number of geographical land management areas were identified to allow for the spatial assessment of changes in land use. Land use planning occurs at the level of these land management areas and the land and water indicators are calculated for these units. In the current version of the tool, the Inkomati River Basin was subdivided into 24 land management areas (Fig. 1), of which 18 are located in South Africa, one in Swaziland and five in Mozambique. A total of 15 land uses are distinguished. These include nine commercial land uses (cultivated areas and commercial forestry, in which consumptive use of water produces beneficial biomass) and six other uses (nature and built areas). The land management areas do not refer to existing administrative units but were created to visualize the spatial variability of land and water indicators over a perceivable number of spatial units.

Temporal resolution. To facilitate dynamics in land use planning, the tool was developed to assess a recent average year (2003–2004), a relatively dry year (2002–2003), and a relatively wet year (2005–2006). These years were

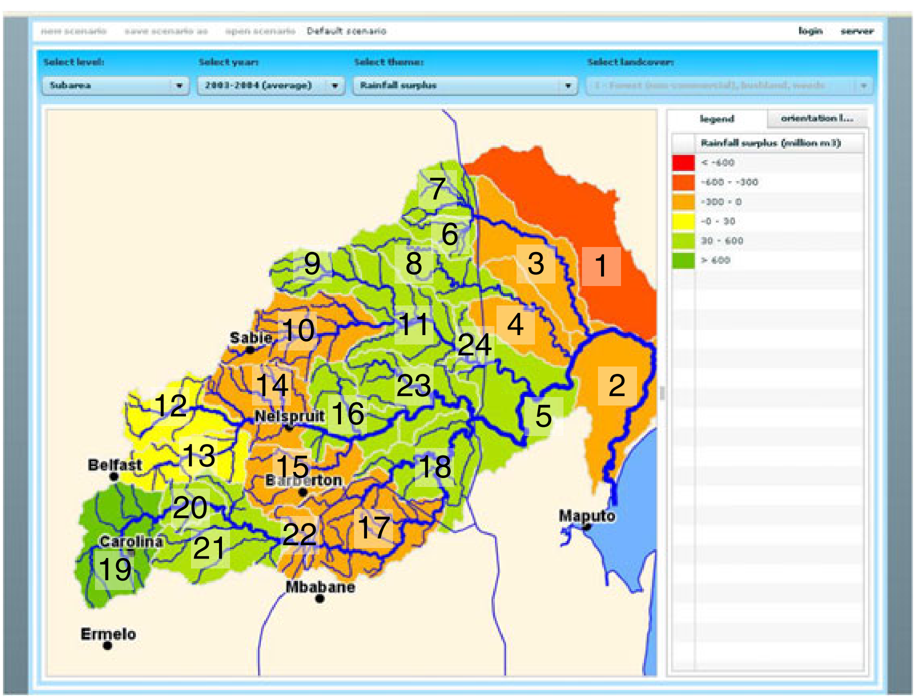

Figure 1. Land management areas. This figure is available in colour online at wileyonlinelibrary.com/journal/ird

selected on the basis of rainfall data covering the past 10 years. The use of older climatic data is not desirable, as the utilized land use data refer to 2000. Combining data of the year 2000 with old climate data could introduce significant errors.

Functionalities. The current version of the tool can instantly show for each land management area the implications of land use changes anywhere in the river basin for:

- crop water productivity;
- economic water productivity;
- total water production value (in million ZAR);
- water use related jobs;
- volume of water available from upstream areas;
- actual evapotranspiration (consumptive water use);
- volume of water available to downstream areas;
- water taken from storage (in the case of a negative rainfall surplus).

In addition, rainfall, total area under commercial land use, biomass production, socioeconomic background data, and other general data are presented. The average actual evapotranspiration and biomass production is calculated for each of the 15 land uses in each of the 24 land management area, and for each of the three years. If a certain land use does not occur in any of the land management areas, values from the neighbouring land management area are taken. These average values (ET_{acti} and M_i in equations 1–5) are considered characteristic (non-variable) data of a land management area. If any change in land use is introduced in a land management area (in a certain year), the actual evapotranspiration (consumptive water use) in that area is recalculated to: $\sum_{i=1}^{15}(ET_{acti} * A_i)$. Thereafter, CWP, EWP, and JWP are recalculated as previously described.

It is important to note that ET_{act} is not only dependent on land use but also on the prevailing climatology of an area. Hence, the tool has a deficiency when sugar cane is planted in areas that are climatologically different then the reference areas for sugar cane that are used to determine the spectrum of ET_{act} values. This discrepancy in atmospheric conditions could create a systematic deviation from the average ET_{act} value found for existing sugar cane areas if sugar cane is not cultivated in nearby areas. One way to solve this issue in the next version of the model will be to include the concept of reference ET and a crop coefficient. Another limitation is that ET_{act} also depends on agricultural practices. Water productivity can, for example, be increased through efficient irrigation systems that minimize evaporation losses. By analyzing the statistical characteristics of water productivity for each land use in a certain area, the scope for more efficient water use and saving can be assessed. The option of water saving might be included in the next version of the tool.

Water availability to downstream areas is calculated with a routing procedure that takes into account the hydrological structure of the river basin. Water availability to downstream areas is calculated as the sum of water availability from upstream areas plus rainfall surplus in the area. In the case of a calculated negative water availability to downstream areas (due to rainfall deficit), it is assumed that the water debit is taken from storage and that water availability to downstream areas is nil. The conversion of land towards even more water consuming land use in upstream areas that have already a negative rainfall surplus is not restricted by the tool. The tool, thus, does not consider biophysical system limitations. Details are also given in the online tool manual.

Analysis and interactive use

The current version of the tool consists of a viewer and interactive mode. The viewer mode enables the display of all basic data on thematic pixel maps: land use, biomass production, actual and potential evapotranspiration, and rainfall (mostly at a spatial resolution of 250 m). The viewer mode can also show the indicators and the basic data aggregated for the land management areas. Data are presented in the form of both tables and maps. In the interactive mode, the user can introduce and assess land use changes in each of the 24 land management areas and for each of the three years. Market prices, production costs, and harvest indices can be specified and altered. After each adjustment, the tool instantly recalculates the land and water indicators, displays them in tables and maps, and compares them with the current (reference) situation.

To allow for the application of the tool at any time and anywhere, it has been developed as a web-based application. For interactive use and for defining, saving, and reopening scenarios, the user needs to log in. The tool works in a GIS environment. It uses open source software to enable license free hosting, and application and open standards to ensure compatibility, easy further development, maintenance, and any future extension of functionalities without being dependent on developers or vendors. Although the interactive tool is accessible only to authorized users, non-authorized users may browse through the existing data presented in the tool. The viewer mode contains hundreds of base maps, while a virtual unlimited number of additional maps with land and water indicators can be generated (online) in the interactive mode. Maps are continuously updated while the user works with the tool.

INTERACTIVE PLANNING AND EVALUATION OF SCENARIOS

Scenarios of land use planning can be identified and evaluated either interactively (e.g., in stakeholder meetings) or individually. In this section, two potential land development scenarios in the Inkomati River Basin in Southern Africa were evaluated to demonstrate the usefulness of the tool.

The Inkomati River Basin

The Inkomati River Basin incorporates six sub-basins: the Komati, Crocodile, Sabie Massintonto, Uanetze, and Mazimchopes rivers (Fig. 2). The Komati River originates in the southwest of the basin, flows from South Africa to Swaziland, then re-enters South Africa before crossing into Mozambique at Komatipoort and Ressano Garcia. The Crocodile River is located in the centre of the basin. It joins the Komati River just before it flows into Mozambique, where the river is called the Incomati. The Sabie River originates in the northwest of the basin. It flows through Kruger National Park towards Mozambique, where it eventually joins the Incomati River. In the north, three relatively small rivers (Massintonto, Uanetze, Mazimchopes) also cross Kruger National Park and flow towards Mozambique. As the discharges of these three rivers are very limited, land and water planning and management mainly concern the area covered by the Komati, Crocodile, and Sabie basins.

Scenario development. Approximately 12% of the basin (638 000 ha) is used for rainfed agriculture, forest plantations, and livestock (grazing areas), and about 5% (260 000 ha) is used for irrigated agriculture. Thus, 17% of the land is managed while 83% is not. Some of the unmanaged land could be converted into managed land; for example, bushland and natural grassland could be converted into agricultural areas. The scope for land use adaptation, however, is limited. Conversion depends not only on the availability of water resources but also on the agricultural potential and the existing and planned economic and ecological functions. For example, it is not realistic to convert part of Kruger National Park into irrigated agricultural land. Land use planning should, of course, involve both regional and local knowledge from planners and stakeholders.

As a showcase, two scenarios are evaluated and discussed in this section:

- conversion of 25 000 ha of bushland into cultivated area for sugar cane for biofuel production in Mozambique;
- prioritization of areas for zero replant of forest plantations in the upstream areas on the basis of, for example, the cost-effectiveness of streamflow enhancement.

Development of sugar cane in Mozambique

During an interactive workshop, stakeholders proposed assessing the conversion of 25 000 ha of bushland into agricultural land for the cultivation of sugar cane. The proposed area is located in Mozambique, in the area where the Incomati and Sabie rivers join. The 25 000 ha represents 9% of the total area (Fig. 3). Table 1 shows that in an average year, this land conversion would cause a 52 million m^3 decrease in the rainfall surplus (from 62 to 10 million m^3), as sugar

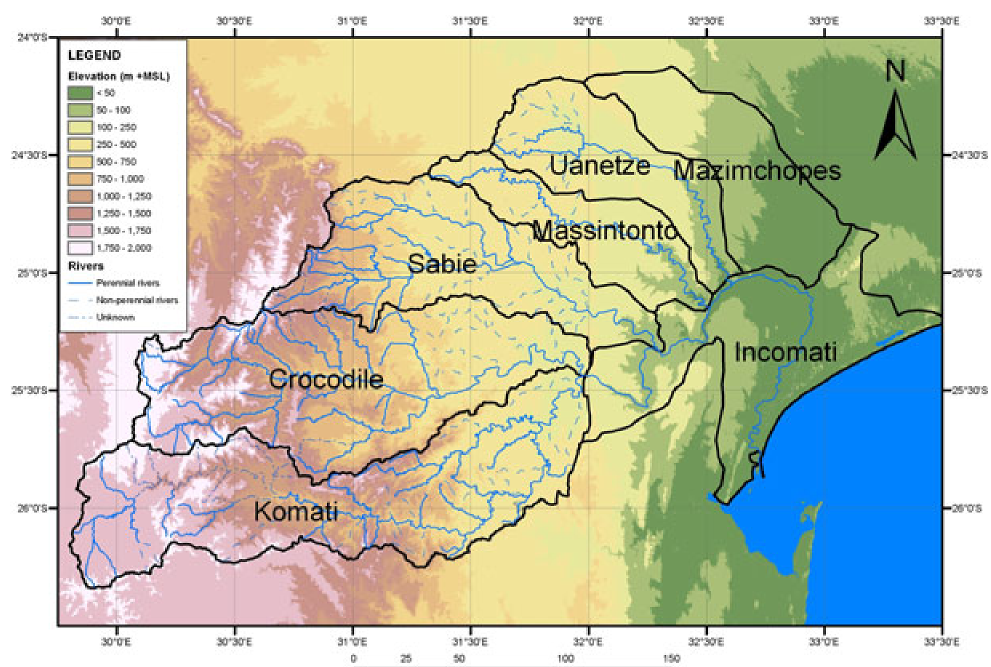

Figure 2. Inkomati River Basin with sub-basins. This figure is available in colour online at wileyonlinelibrary.com/journal/ird

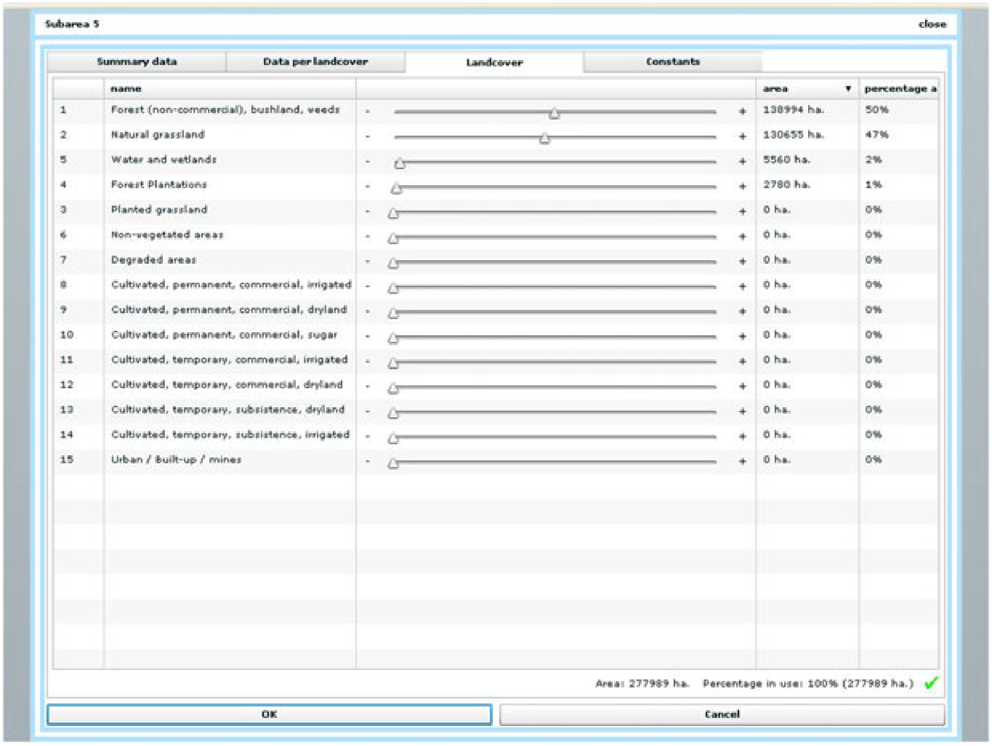

Figure 3. Land cover in the baseline situation (before conversion) in area 5

cane consumes 867 mm of water and bushland only 639 mm. Water availability to downstream areas would therefore decrease by 3% (from 1730 to 1680 million m^3 per year).

In a dry year, there is already a rainfall deficit of 479 million m^3. The development of sugar cane would increase the deficit by 85 million m^3 (towards a deficit of 564 million m^3). As in a dry year there is no water available from upstream areas, this scenario is only feasible if provisions are made to cover the water shortage in the form of, for example, surface water reservoirs or boreholes, or arrangements with upstream water uses to release more water. Both CWP and EWP of the area would, however, increase considerably. The production value of the area would increase from 6 million to 283 million ZAR/year in a dry year and to 321 million ZAR/year in an average year.

Table I. Situation before and after conversion of 25 000 ha of bushland into sugar cane in Mozambique

Area 5	**Dry year**		**Average year**		**Wet year**	
	Before	After	Before	After	Before	After
CWP (kg/m^3)	0.016	0.141	0.023	0.164	0.018	0.146
EWP (ZAR/m^3)	0.002	0.102	0.003	0.116	0.002	0.105
Production value (million ZAR)	6	283	8	321	7	291
Water use related jobs	1090	18 000	1090	18 000	1090	18 000
Rainfall (mm)	374	374	695	695	815	815
ET_{act} (mm)	547	578	672	691	723	743
Gross area (ha)	277 000	277 000	277 000	277 000	277 000	277 000
Commercial area (ha)	2450	27 400	2450	27 400	2450	27 400
Water available from upstream areas (million m^3)	0	0	1670	1670	3110	3110
Rainfall surplus (million m^3)	−479	−564	62	10	256	199
Water availability to downstream areas (million m^3)	0	0	1730	1680	3370	3310
Deficit/water from storage (million m^3)	479	564	0	0	0	0

Zero replant of forest plantations in the upstream area.

The cultivation of sugar cane would also create about 17 000 additional jobs in the area. These economic and social benefits could provide space for negotiations and compensation schemes with less productive upstream water uses.

In this example, the EWP in a dry and wet year are lower than in an average year. Possible explanations are lower yields in dry years, insufficient use of water in wet years, low market prices in wet years, high seasonal labour costs, etc. Such results add to the discussion and stakeholders from the area should be able to explain the results. The water related jobs do not change since with unchanged land use, the same number of people will work during a dry, average, and wet year. The job water productivity (not shown in the table) will however be different. The water related jobs do change with land use changes.

The water consumption (ET_{act}) of forest plantations is relatively high compared to other land uses. Limited or zero replant of commercial forests would therefore enhance water availability to downstream areas. In South Africa, commercial forests have been planted in various upstream areas. The tool can help prioritize areas for zero replant on the basis of, for example, the lowest decrease in economic production value per m^3 of water, which would then become available for downstream areas.

Table 2 shows the change in the land and water indicators should forest plantations be converted into bushland. Three upstream areas were assessed for an average and a dry year. In areas 9, 10, and 12, 6130, 81 900 and 18 700 ha (representing respectively, 5.7%, 33.8%, and 12.3% of the total area) were converted. The difference in ET_{act} between forest plantations and bushland that re-establishes on the site was 350, 168 and 191 mm, respectively. The resulting increase in rainfall surplus per ha converted was consequently highest in area 9, while the increase in the total rainfall surplus was highest in area 10 (due to the low share of forest plantation in the total area of area 9).

DISCUSSION

The ET values of the Incomati River Basin are computed by means of the SEBAL model. This model has been validated for energy balance measurements in various parts of the world and also inside South Africa. A summary of comparisons with field measurements can be found in Soppe *et al.* (2006). A validation with grapes in the Western Cape has been published by Jarmain *et al*. (2007), which revealed that the deviation of ET from field water balances and SEBAL surface energy balances were within the limitations of field measurement technologies.

The overall accuracy of accumulated values for ET in landscapes with pastures, bushland, sugar cane, and orchard plantations is 90 to 95%. This value typically pertains to a particular field within a certain land use class. The planning tool described in this paper considers the full spectrum of ET within a given land use class. While for certain pixels, the accuracy might be 90 to 95%, the accuracy of the land use as a total group of pixels is 95% or higher. The average ET value is thus rather accurate. Further to the validation of SEBAL against field measurements, ET data could be presented on a month-to-month basis for diverging types of land use classes. While the ET of mountainous forest remains moderate and constant throughout the year, the temporal variability of ET in the pastures exhibit a distinct seasonality. ET data does seem to be robust and consistent for the sake of land use planning.

The spatial resolution of the TRMM rainfall data was 0.25º, which corresponds to approximately 25 kilometres. The spatial resolution of the MODIS images used for the

Table II. Change in land and water indicators due to conversion of forest plantations into bushland in areas 9, 10, and 12 in a dry an average year

	Area 9 (year, y)		**Area 10 (year, y)**		**Area 12 (year, y)**	
	Dry y	Average y	Dry y	Average y	Dry y	Average y
Δ CWP of the area (kg/m^3)	−0.137	−0.148	−0.826	−0.899	−0.287	−0.338
Δ EWP of the area (ZAR/m^3)	−0.014	−0.015	−0.083	−0.090	−0.029	−0.034
Δ Production value (million ZAR)	−15	−15	−200	−218	−44	−52
Δ Water use related jobs	−257	−257	−3,440	−3,440	−785	−785
Δ ET_{act} (mm)	−18	−18	−86	−56	−24	−25
Δ Commercial area (ha)	−6130	−6130	−81 900	−81 900	1870	−18 700
Δ Water available from upstream areas (million m^3)	0	0	0	0	0	0
Δ Rainfall surplus (million m^3)	20	19	208	136	35	38
Δ Water availability to downstream areas (million m^3)	0	19	0	0	0	38
Δ Deficit/water from storage(million m^3)	−20	0	−208	−136	−35	0

Area 9 shows the lowest decrease in CWP and EWP and the lowest decrease in total production value (15 million ZAR, which is 0.75 ZAR/m^3). Whether to target area 9, 10, or 12 for zero replant also depends on the change in the land and water indicators in the downstream areas and the policy priorities that exist there.

calculation of the actual evapotranspiration was 250 m. Water availability was calculated as rainfall surplus, subtracting the annual actual evapotranspiration as determined by SEBAL from the annual rainfall from TRMM. Especially in relatively water scarce areas, this could result in significant inaccuracies, as the absolute value of water availability will be low. It should be noted that the TRMM rainfall data are calibrated in the Americas whereas in Africa, this is generally not the case. In the Inkomati River Basin, TRMM seems to underestimate the rainfall. The accuracy can be increased by calibrating the TRMM data, for example with topography, wind direction, land cover, and recorded rainfall. A preliminary assessment showed that calibration with meteo stations alone is not sufficient. To further increase accuracy, a more detailed downscaling method for the TRMM data needs to be developed.

As previously stated, water availability should not be interpreted as river discharge. For 13 hydrological stations, the accumulated upstream rainfall surplus was calculated based on 250 x 250 m pixels and compared with the recorded river discharges, showing low correlation. This accumulated rainfall surplus was also calculated with various downscaling methods for the TRMM data, which also showed little correlation. Obviously, the changes in storage could not be neglected over periods of one year. If reliable river discharges need to be calculated, a hydrological approach is required. For the sake of transparency and verifiability, the original non corrected TRMM data are used in the tool. As the tool does not provide detailed results, further more in-depth investigations should be carried out after the rapid assessments. In addition, as the results largely depend on the quality of the underlying data, particularly basic economic data and land use map, it is imperative to have reliable data on current land use, market prices, and production costs. It should also be taken into account that large changes in land use can affect market prices, especially if crops are produced for the local markets, since the supply will change.

CONCLUSIONS AND RECOMMENDATIONS

The tool presented in this paper enables stakeholders to evaluate the impact of alternative land development scenarios based on a number of water related indicators. The tool generates spatially distributed information about changes in water consumption, water productivity, and water availability, based on a consistent method and impartial, transparent, and verifiable information. The method is consistent in that it is applied to the entire river basin and the level of accuracy is maintained. The generation of the basic data on water resources, rainfall, evapotranspiration, and rainfall surplus excludes potentially subjective human interpretations. The tool can therefore play a role in confidence building and promote open discussions among stakeholders. It can help stakeholders evaluate tradeoffs between alternative land development options and courses of social action that could impact water resources and water use. By evaluating water related indicators, users can identify the most preferable land uses and their spatial distribution over the basin from a water resources perspective. The tool is intended for interactive use. Stakeholders can instantly investigate the impacts of changes in land use, which makes the tool particularly suitable for use in workshops and meetings. To ensure the identification of realistic land development scenarios, the tool should be used in collaboration with spatial planners. Land conversion scenarios should focus on manageable land uses.

The usefulness of the tool was demonstrated in stakeholder meetings in the Inkomati River Basin. Stakeholders became more aware of the impact of changes in land use on water resources and this resulted in lively discussions. It was also shown that the EWP is not equal among the crops, as suggested in theory. Spatial variations in water productivity can be due to management practices, random events (which cannot be controlled), and the natural productivity of the farm resources (Hellegers *et al.*, 2010). Examples of management practices are irrigation application (e.g., excessive deliveries causing non productive evaporation from wet soil), weed control, seed selection, and the use of nutrients and pesticides. Examples of random events are droughts, storms, and pest attacks. The natural productivity of farms depends on the climate, local hydrology (e.g., water tables), and soil characteristics. Because the tool also generates information on biomass production, it can be used to assess carbon sequestration policies. As some types of land use can capture and store more carbon dioxide than others, the area under such crops as trees could be expanded to reduce the accumulation of greenhouse gases in the atmosphere. Another of the tool's potential applications is the prioritization of areas for the removal of invasive alien species, thus supporting the Working for Water programme in South Africa. For this purpose, areas should be identified where excessive evapotranspiration rates are observed for certain land uses. Dye and Jarmain (2004) reported reductions in evapotranspiration of up to 600 mm following the removal of black wattle from indigenous grassland. The tool can be further developed by adding an ecological water productivity indicator, which could be used to evaluate policy priorities aimed at securing the ecological integrity of an area.

The current tool is static: it provides annual data that can promote strategic land planning. It is not designed for operational land and water management (e.g., to respond to droughts and floods), nor does it incorporate options to improve water management and water saving. To incorporate such functionalities, the calculation of the rainfall surplus in the land management areas should be replaced by more detailed hydrological calculations derived from, for example, a hydrological model. With a dynamic hydrological model, critical hydrological components such as surface and groundwater flows and changes in the soil moisture content can be quantified in time, which enables assessments for short periods during the year. Options for management practices and water saving can be evaluated by investigating the stochastic characteristics of the indicators. For example, a high standard deviation of water productivity in an area indicates that there is scope for improvement by, for example, training farmers or introducing more modern agricultural and on farm water management practices. Differences between various areas might also be investigated in more detail. This would help identify target areas to support emerging farmers, for example. In addition, location specific crop production functions (with yield as a function of ET_{act}) can be derived from data on biomass production and water consumption, which can help optimize water allocation strategies and develop strategies for fractional irrigation in times of scarcity. As operational water management, on farm water management, water saving, and water allocation are key issues in the Inkomati River Basin, it is recommended to extend the tool by adding these functionalities.

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