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A novel approach to estimate direct and indirect water withdrawals from satellite measurements: A case study from the Incomati basin

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ABSTRACT

The Incomati basin encompasses parts of South Africa, Swaziland and Mozambique, and is a water stressed basin. Equitable allocation of water is crucial to sustain livelihoods and agro-ecosystems, and to sustain international agreements. As compliance monitoring of water distribution by flow meters is laborious, expensive and only partially feasible, a novel approach has been developed to estimate water withdrawals using satellite measurements. Direct withdrawals include pumping from rivers, impoundments and groundwater, for irrigation and other human uses. Indirect withdrawals include evaporation processes from groundwater storage, unconfined shallow aquifers, seepage zones, lakes and reservoirs, and inundations, in addition to evaporation from pristine land surface conditions. Indirect withdrawals intercept lateral flow of water and reduce downstream flow. An innovative approach has been developed that employs three main spatial data layers inferred from satellite measurements: land use, rainfall, and evaporation. The evaporation/rainfall ratio was computed for all natural land use classes and used to distinguish between evaporation from rainfall and incremental evaporation caused by water withdrawals. The remote sensing measurements were validated against measured evaporative flux, stream flow pumping volume, and stream flow reductions. Afforested areas in the whole basin was responsible for an indirect withdrawal of 1241 Mm^3/yr during an average rainfall year while the tripartite agreement among the riparian countries specifies a permitted total withdrawal of 546 Mm^3/yr. However, the irrigation sector is responsible for direct withdrawals of 555 Mm^3/yr only while their allocated share is 1327 Mm^3/yr – the long term total withdrawals are thus in line with the tripartite agreement. South Africa withdraws 1504 Mm^3/yr while their share is 1261 Mm^3/yr. The unmetered stream flow reduction from the afforested areas in South Africa represents the big uncertainty factor. The methodology described using remotely sensed measurements to estimate direct and indirect withdrawals has the potential to be applied more widely to water stressed basins having limited availability of field data.

1. Introduction

A river basin is the management and planning unit for many different users of water. The available water in river basins is gradually exploited to full capacity and the competition for utilizable water resources is getting fiercer (e.g., Vorosmarty et al., 2000; Oki and Kanae, 2006). Water competition requires more regulation and compliance monitoring of withdrawals. Water

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users withdraw and consume water, and return non-consumed recoverable flow to the downstream hydrological system, often at a degraded quality (Perry, 2007). The consumers of water from rivers, groundwater and impoundments in the basin are among others irrigated agriculture, households, industries, livestock, groundwater dependent ecosystems, wetlands, reservoirs, aquaculture and inter-basin transfers.

The Incomati river basin is a typical example of a highly stressed basin with international disputes that requires a transparent regulation of its resources and withdrawals (e.g., Carmo Vaz and van der Zaag, 2003; Waalewijn et al., 2005). The basin covers approximately 46,500 km^2 shared by South Africa (28,600 km^2, 61.5%), Swaziland (2600 km^2, 5.6%) and Mozambique (15,300 km^2, 32.9%). The Kruger National Park is an internationally recognized hotspot for wildlife, and covers a large part of the Incomati basin. Note that throughout this paper, we use the term evaporation as suggested by Savenije (2004) to express the evaporation from soil, water, vegetation and interception.

The political responsible decision makers for water in the three countries agreed in 1991 upon a minimum cross-border flow at Ressano Garcia of 2 m^3/s averaged over a cycle of three days. Later in 2002 a more formal Tripartite Interim Agreement (TIA) was signed. Each country drew up its own water allocation plan based upon the agreed withdrawals for each country. The three riparian countries of the transboundary Incomati river are member states of the Southern African Development Community (SADC). SADC has developed several regional laws, including one on water, i.e., the SADC Protocol on Shared Watercourses. This protocol, which came into force in revised form in 2003, provides a legal framework which SADC member states should adhere to when managing shared watercourses. The revised SADC Protocol adopts the main principles codified in the UN Convention on the law of non-navigational uses of international watercourses (McCaffrey, 2001), and urges riparian countries to develop cooperative agreements over particular shared watercourses (van der Zaag, 2009).

South Africa's 1998 National Water Act requires water users to obtain a water right in order to withdraw water from rivers and aquifers. But the South African water act also makes provision for what is called "stream flow reduction activities (SFRAs)" to be declared as "water users". Stream flow reduction activities pertain to agro-ecological systems that consume more water than the original land use, and hence reduce stream flow at the same level of rainfall. Water rights thus need to be acquired for land use changes that enhance the historic level of consumptive use of water (Jewitt, 2006). Afforestation with exotic eucalyptus and pinus plantations (371,900 ha) is common in the mountain areas of the Incomati, and was introduced in the sixties and seventies. These plantations in South Africa and Swaziland evaporate more water than the natural vegetation that they replace (Bosch and Hewlett, 1982; Brown et al., 2005), which is grassland or scrubland in most cases (Albaught et al., 2013; Geldenhuys, 1997). This is also what Vertessy (2001) found when researching eucalyptus and pinus plantations replacing grasslands in Australia. The stream flow was reduced and in addition to that, the recharge rate of the groundwater appeared to be lower. Forest plantations are therefore considered to be a component of the withdrawals from the Incomati river.

The implementation of the TIA agreement needs to be monitored, and this is usually achieved with a network of flow meters. Withdrawals for irrigation are measured by meters on pumps at streams or ponds. However, not all water withdrawal points are measured, and compliance to quotas for irrigation purposes is therefore difficult to monitor. This is also the case in Australia: Australia has embarked on extensive programs to measure the water delivered at a point of entry (farm gate) to every farming unit for achieving their natural water accounts. Yet it is difficult to get the data systematically and on time (Vardon et al., 2012).

Hellegers et al. (2010) suggest that consumed water exceeds the volumetric entitlement at commercial farms in Komati and Lomati (SA). The current study investigates a novel approach to utilize satellite measurements of evaporation to estimate withdrawals and monitor compliance to permitted quotas of water use as an alternative method to in situ flow measurements. The following

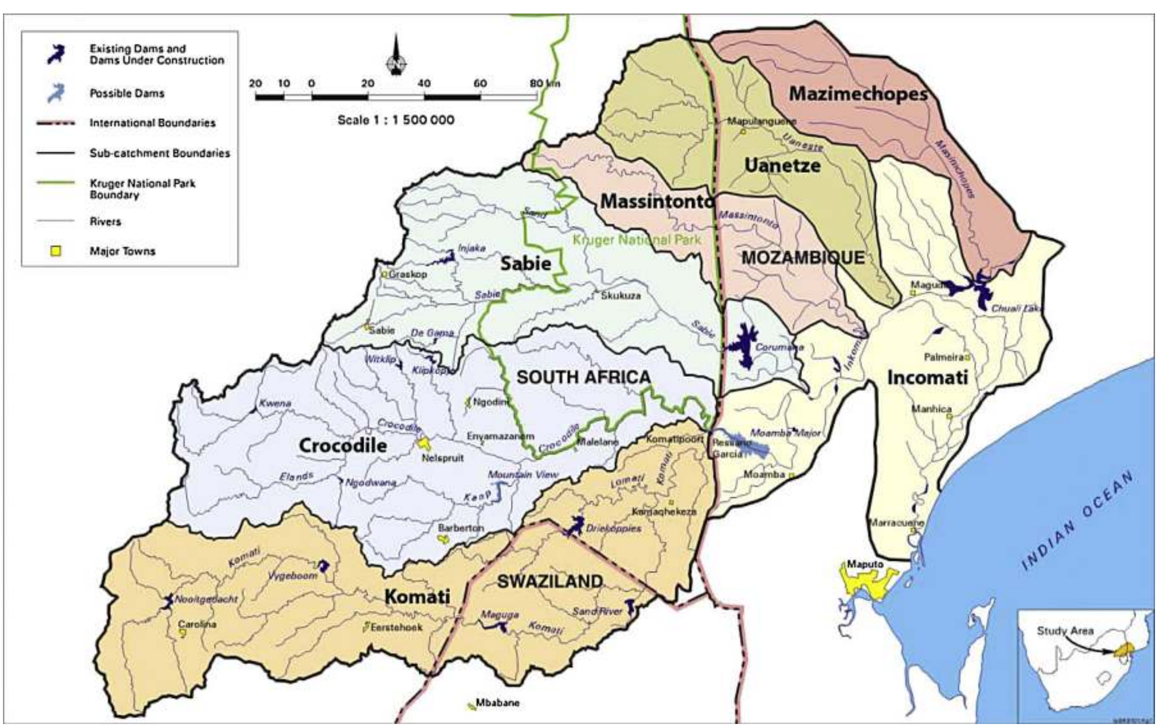

Fig. 1. The Incomati basin and all sub catchments (source JIBS, 2001).

research questions are answered: is it possible to determine the evaporation induced from rainfall? Can the consumptive use originating from water withdrawals be computed? And can we estimate the gross withdrawals from this incremental evaporation? Also the political question on what degree the volumes from the trilateral agreement are met in the Incomati will be addressed. If all these question are answered affirmatively, then this research presents a promising alternative system to assess withdrawals without reliance on ground data.

2. Materials and methods

2.1. Study area

The Incomati river has six main tributaries: the Komati, Crocodile, Sabie, Massintonto, Uanetze and Mazimechopes rivers (Fig. 1). The elevation ranges from 2000 m above sea level in the mountains and plateau in the western part of the basin near the town of Belfast and the Kwena reservoir to sea level at the homogeneous flat coastal plain to the east of the Lebombo mountain range (Fig. 2). All of the major tributaries originate on the plateau on the west except the Mazimechopes. The Incomati river discharges into Maputo Bay. The area is home to about 2 million inhabitants. Most of the urban area is situated along the western boundary of the Kruger National Park. The city of Maputo is not part of the Incomati basin but may soon require water from the Incomati to satisfy the growing water demand. In the TIA, 87.6 Mm^3/yr of water is reserved for domestic and industrial allocations (Table 1). The Incomati river system supports a vast river ecosystem, riparian ecosystems, mangrove ecosystems, and others, with a large variety of plant, and animal species including a number of threatened species. The basin also includes a number of areas with conservation status including the Kruger National Park and part of the Great Limpopo Transfrontier Park.

The Triparti Interim Agreement (TIA) is the result of international negotiations and describes the entitled amounts of water to be withdrawn for different purposes (see Table 1). A total water withdrawal by human activities, directly or indirectly from the Incomati basin and its tributaries, of 2338 Mm^3/yr was agreed upon. If the countries exceed these volumetric allocations, the TIA will be violated, and tension between upstream and downstream countries can arise. Hence, it is of essence to develop a transparent monitoring system based on independently gathered measurements that all parties trusts.

2.2. Existing satellite data of Incomati

2.2.1. Land use map

Since the core of this paper is the development of a novel approach to estimate withdrawals, the background and scientific aspects of existing remote sensing data available prior to the start of the current study will not be discussed exhaustively. The contents of the existing images is part of the materials used, and therefore discussed in the current section. The land use map was prepared by a conventional pixel based image classifier, object-based modelling and direct image photo-interpretation (Jarmain et al., 2013). Various data sources (SPOT-5, UK-DMC, Deimos satellite imagery and aerial photography) were used together with other spatial datasets (e.g., polygons of sugarcane field boundaries and location of dams). Mapping the agricultural land use was done in two steps. First, fields were mapped into three broad categories consisting of annual crops, horticultural and sugarcane crops. The field boundaries were mapped using manual interpretation of SPOT-5 images at 1: 10.000 scale. Secondly, a supervised classification was used to identify crop types for each individual field and was based on the description of crop phenology using multi-temporal UK-DMC and Deimos imagery acquired between November 2011 and October 2012. Field visits

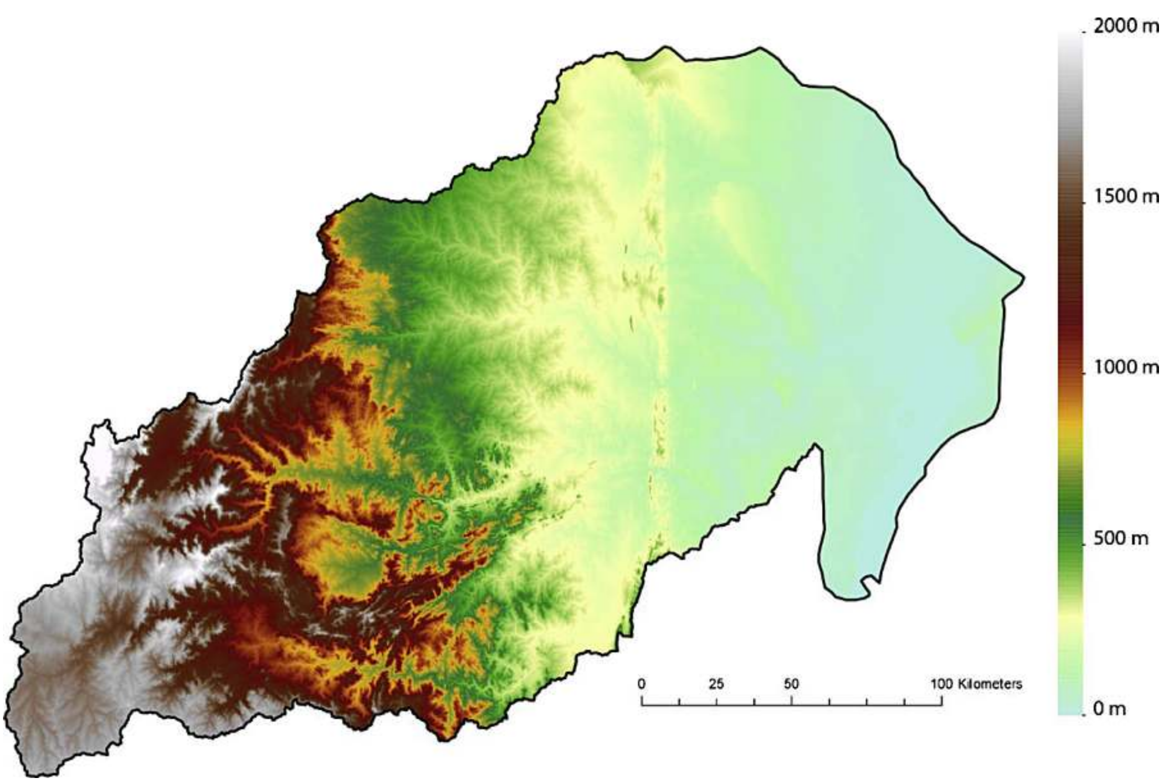

Fig. 2. Spatial variability of the terrain elevation of the Incomati basin. The SRTM digital elevation model has been used.

Table 1
Permitted volume of water withdrawals according to the Tripartite Interim Agreement (TIA) of the Incomati basin (2002) (Tripartite Permanent Technical Committee, 2002).

	First priority (domestic, livestock and industry (Mm^3/yr)	Reserved (Mm^3/yr)	Irrigation (Mm^3/yr)	Runoff reduction through afforestation (Mm^3/yr)	Total (Mm^3/yr)
Mozambique	19	87.6[a]	280	25 (25,000 ha)	411.6
South Africa	336.6		786	475 (364,975 ha)	1597.6
Swaziland	22		261[b]	46 (32,442 ha)	329
Total	377.6	87.6	1327	546 (422,417 ha)	2338.2

[a] Water reserved for the city of Maputo.
[b] This figure includes an interbasin transfer from the Incomati to the Umbelzui basin, which is estimated to be 136 Mn^3/yr (Carmo Vaz and van der Zaag, 2003).

and aerial video surveys were used to define the crop types of training sets. Natural land use classes such as wetlands, grasslands and shrubland were classified through a combination of supervised and unsupervised classification. Landscape features were identified using visual, on screen interpretation and linking to spectral classes in the images through expert knowledge of the Southern African landscape.

The most important land use classes in the Incomati basin in terms of size are the bush/shrub (20,139 ha), grassland (11,495 ha), plantation (3719 ha), rainfed agriculture (3971 ha) and forest/woodland classes (1991 ha). Bush/shrub is the natural vegetation for a large part in the northern and eastern part of the basin where rainfall is moderate. Grassland is the natural vegetation in the south western part of the basin, on the high altitude plateau as shown in Figs. 2 and 3 where rainfall amount is favourable. The plantation class consists of commercial eucalyptus and pinus plantations and are situated mainly in the mountainous areas in South Africa and Swaziland, also known as the mist belt. Rainfed agriculture consists of small scale extensive agriculture, where maize is mainly cultivated for household consumption. The class forest/woodland is natural forest and is situated mainly on the eastern flanks of the mountainous areas in South Africa.

The irrigated area in the Incomati basin occupies 133,292 ha and is spread across three main zones: the area in Mozambique around the lower part of the Incomati river; the Komatipoort area in South Africa just before the border with Mozambique; and the area located in the mountains near the town of Hazyview in South Africa. Irrigated agriculture is an important land use class for water withdrawals in the Incomati basin, and it was therefore divided into different sub-classes: agriculture: irrigated, both sugarcane classes, all agriculture horticultural classes and the agricultural classes soya beans, wheat and vegetable/other. Their acreages are presented in Appendix A. The main irrigated crop in the Incomati is sugarcane (72,300 ha), which occurs mainly in the lower part of the Incomati in Mozambique and the Komatipoort area in South Africa. Other important irrigated crops are banana (7538 ha) which is mostly cultivated in the Hazyview area and citrus (11,306 ha) which is more spread out over the basin. The agricultural classes maize, planted pasture and fallow are assumed not to be irrigated although some fields of maize and planted pasture could have had supplemental irrigation.

2.2.2. Rainfall map

A number of different data sources where used for determining the spatial variability of rainfall across the Incomati basin. Local rainfall gauges and satellite measurements by the Tropical Rainfall Measurements Mission (TRMM) and Famine Early Warning System (FEWS) as well as a rainfall map from the Joint Inkomati Basin Study (JIBS) report were consulted and integrated. With these data sets available, two maps were produced: one map describing the rainfall over the investigated period between November 2011 and October 2012, and one for the long term average rainfall. First the process of rainfall determination from November 2011 to October 2012 will be described, followed by the estimation of the long term average rainfall.

The RainFall Estimates version 2.0 (RFE2.0) algorithm of FEWS uses a passive microwave (PM) sensor, infrared (IR) data from METEOSAT and daily rainfall data from the Global Telecommunication System (GTS) report (Dinku et al., 2007). The RFE rainfall data was first resampled by means of bilinear interpolation from 0.1° to 30 m. Next, the RFE data has been calibrated with 20 rainfall stations using the Geographical Difference Analysis (GDA) method presented by Cheema and Bastiaanssen (2012). New rainfall stations were installed in the mountainous areas during the study

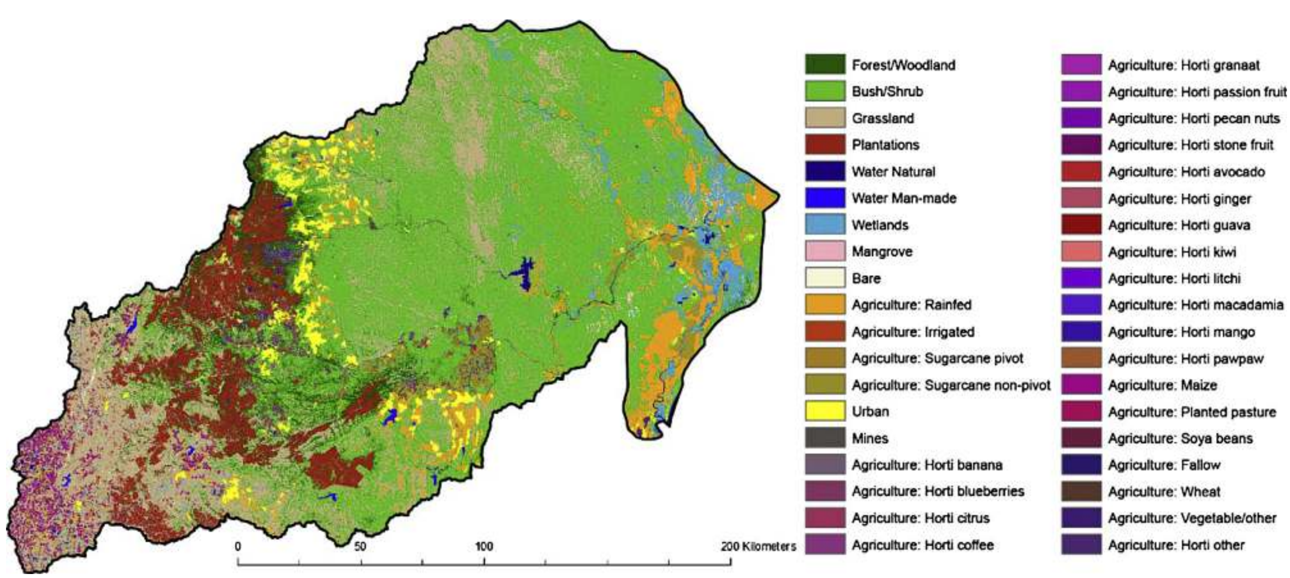

Fig. 3. Land use map of the Incomati basin (Jarmain et al., 2013).

period, hence part of the dataset includes measured rainfall from higher elevations. These areas with higher rainfall were previously poorly sampled. The calibrated rainfall map did, however, not resemble the correct total amount of rainfall in the basin. This was caused by the limited number of rain gauges and the systematic underestimation of rainfall by the RFE2.0 product (Dinku et al., 2007). While the absolute values of TRMM agreed better with the rain gauge values, TRMM alone could not be used, because of the coarse pixel resolution (0.25°).

The relative rainfall patterns of the RFE map was integrated with the absolute values of the TRMM map. The weighting was done by dividing the values of the calibrated RFE map by their map average value, followed by a multiplication of with the regional average of the TRMM map. The final product is the rainfall map (P_y) from November 2011 to October 2012 (see Fig. 4).

The long-term average rainfall map was obtained in a different manner. The rainfall map from the Joint Inkomati Basin Study (JIBS) report was integrated with the rainfall maps of Hellegers et al. (2012), who prepared maps for different rainfall years. The latter annual rainfall maps were based on TRMM maps, that were downscaled using the normalized difference vegetation index (NDVI) method published by Duan and Bastiaanssen (2013) and a digital elevation model (DEM). The JIBS map was produced with the data from 49 rainfall stations in Mozambique and 158 stations in Swaziland and South Africa. Using a simple linear average, the existing JIBS and Hellegers rainfall maps where combined into a single map of the long-term average rainfall, i.e., $P_{average}$ (see Fig. 4).

The P_y and $P_{average}$ map show the high and low rainfall areas in the basin to occur in the same zones. The high rainfall areas on the $P_{average}$ map tend to have a higher rainfall than on the P_y map and the area with low rainfall in the center tends to be lower on the $P_{average}$ map. The $P_{average}$ map for the long term average rainfall shows more spatial contrast than the P_y map, because it is based on local geographical features such as the DEM and NDVI. The patterns on the P_y map are mainly based on RFE data.

2.2.3. Evaporation map

The evaporation data used in this study were computed with the surface energy balance algorithm for land (SEBAL). SEBAL requires spatial information in the visible, near-infrared and thermal infrared along with spatially distributed weather data (Bastiaanssen et al., 1994; Teixeira et al., 2009). Weekly composite images of the Disaster Monitoring Constellation (DMC) were used to obtain the required multi-spectral data. With this information the albedo and the normalized difference vegetation index (NDVI) were calculated. Albedo and NDVI from DMC were combined with the land surface temperature product from MODIS and the solar radiation from MeteoSat Second Generation (MSG).

Daily averages values of air temperature, air humidity and wind speed were obtained from the available routine weather stations distributed in the catchment. This information was used to produce meteorological grids at daily and weekly basis using the MeteoLook algorithm (Voogt, 2006). This algorithm takes into account topography, distance to the sea and the state conditions of the land surface such as green vegetation cover and soil moisture, when interpolating point measurements acquired from the routine weather stations. Gridded data on air temperature, air humidity and wind speed are assimilated into the surface energy balance.

SEBAL computes net radiation (R_n), sensible heat flux (H) and soil heat flux (G) for every pixel. The net radiation Rn is computed from the incoming solar radiation, surface albedo, NDVI and surface temperature. G is estimated as a fraction of R_n. Surface temperature, surface roughness and wind speed are used to compute H. The latent heat flux (λE) is calculated as the residual component of the energy balance equation. The resulting bio-physical parameters from the satellite measurements and energy balance on satellite overpass days are used together with the routine weather data to compute reference, actual and potential evaporation for weekly time intervals using the Penman–Monteith equation. The accumulated evaporation values from November 2011 to October 2012 have been considered in the further analysis. The actual evaporation (E) estimated by SEBAL is a combination of interception, canopy evaporation, soil evaporation, and open water evaporation. The map of the actual evaporation is the total sum of the 52 weekly evaporation maps (see Fig. 5). Monthly values are not computed. The individual weekly E maps contained gaps caused by cloud cover. These gaps were filled with data from the same location using previous or next week pixel data. More detailed explanation of the working of SEBAL is given by Bastiaanssen et al. (1994, 1998, 2005), Allen et al. (2007) and Teixeira et al. (2009).

2.3. A new method for determining withdrawals

In this paper withdrawals in more general sense are referred to as the water extracted from streams, rivers, lakes, reservoirs and

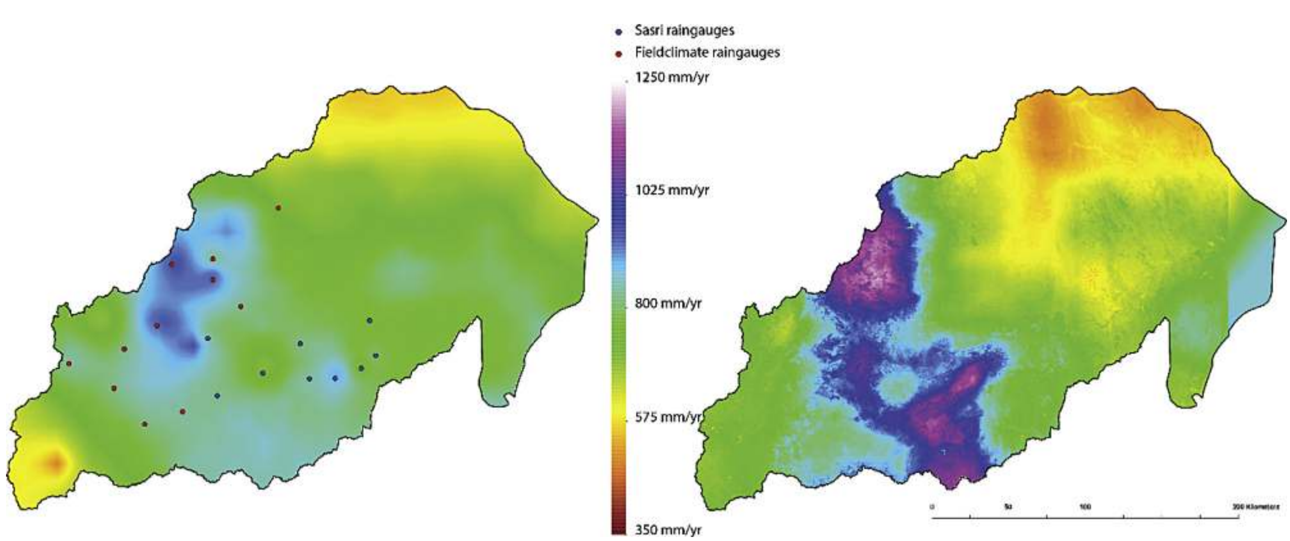

Fig. 4. Rainfall map for the period from 4 November 2011 to 31 October 2012 based on RFE, TRMM and local rain gauges P_y (left) and the long term average rainfall based on a map from JIBS and NDVI corrected TRMM $P_{average}$ (right).

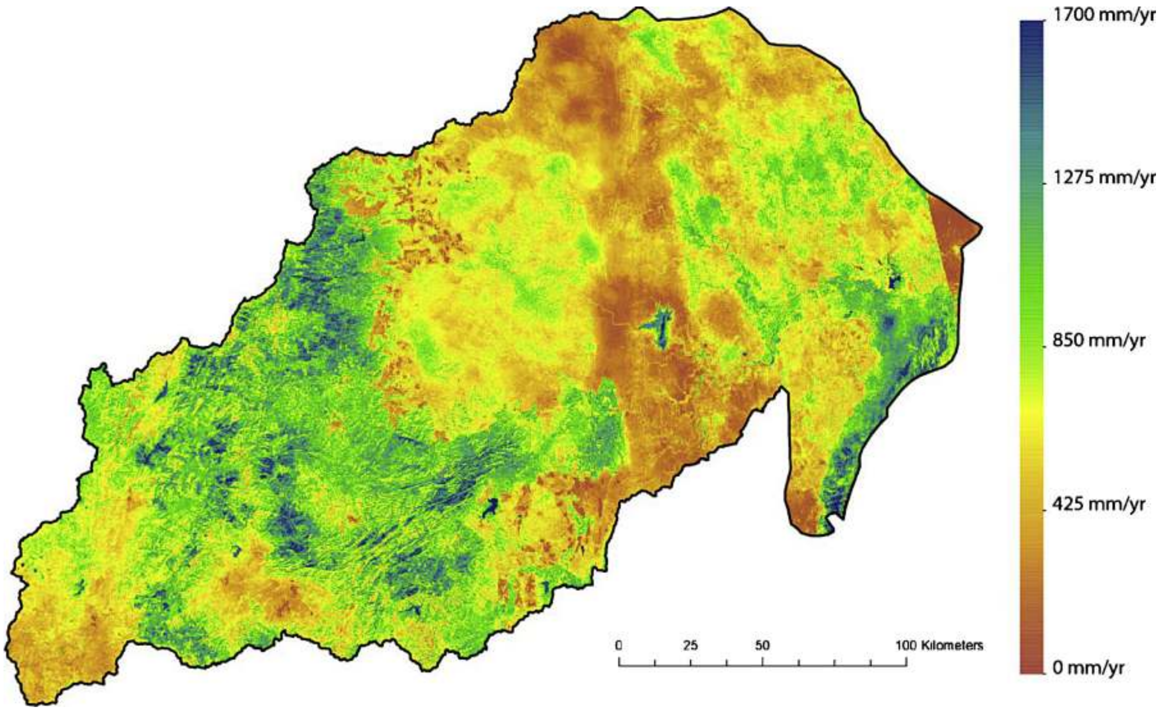

Fig. 5. Accumulated actual evaporation in the Incomati basin for the period from 3 November 2011 to 31 October 2012.

aquifers. Direct and indirect withdrawals supply extra water to the unsaturated zone – or at the surface when dealing with flood plains, wetlands and mangroves – in addition to natural rainfall. The higher soil moisture content increases land surface evaporation, basically because the biophysical resistances to evaporation (i.e., soil and canopy resistance) are lower. Higher soil water content enhances the actual evaporation rate, and this is referred to as incremental E. The total E is expressed as:

$$E = E_{\text{precipitation}} + E_{\text{incremental}} \quad (1)$$

where $E_{\text{precipitation}}$ is the volume of water evaporated from an area where withdrawals are excluded, and $E_{\text{incremental}}$ is the volume of water evaporated as the result of direct and indirect withdrawals. Withdrawals can occur naturally (e.g., inundation, seepage), by land use change (e.g., trees replace pastures), by construction of dams (e.g., reservoir evaporation) or weirs, gates and pumps that divert water (e.g., irrigated fruit orchards). Weiskel et al. (2007) characterized the direct human interaction with the hydrologic system as "anthropogenic hydrology".

The innovative character of this paper is that the E term in Eq. (1) is measured from satellites (see Fig. 5) and that a simple method is developed to estimate $E_{\text{precipitation}}$ from natural land use classes present on the same satellite image (see Fig. 3). The term $(E/P)_{\text{precipitation}}$ can be determined under the prevailing actual weather and soil conditions. The incremental E is the difference between the total E and $E_{\text{precipitation}}$:

$$E_{\text{incremental}} = E - \left(\frac{E}{P}\right)_{\text{precipitation}} \times P \quad (2)$$

$E_{\text{precipitation}}$ can be approximated from the pixel values of E for rainfed agro-ecosystems. The maximum value of the $(E/P)_{\text{precipitation}}$ fraction is in this study fixed at 0.85, because not all annual rainfall will infiltrate and be stored in the unsaturated zone and available for uptake by roots. There are a number of different methods to compute effective rainfall (e.g., Dastane, 1974; Patwardhan et al., 1990). The US Department of Agriculture has developed an empirical method to estimate the effective rainfall based on the soil moisture balance. This method was developed by analyzing the data of 22 stations in the US over a period of 50 years. In this method, effective rainfall is defined as the rainfall minus interception, deep percolation and runoff, being a good estimation of $E_{\text{precipitation}}$. The Budyko curve is an alternative method to infer $(E/P)_{\text{precipitation}}$ from climatological data (Budyko, 1974; Gerrits et al., 2009).

The $(E/P)_{\text{precipitation}}$ ratio was determined for all land use classes in the Incomati basin, except for urban, irrigated agriculture, wetlands, afforested and natural forest areas. The reason for excluding natural forests is their occurrences in small scattered patches in valleys and gorges where they are surrounded by grasslands (Geldenhuys, 1997). Inclusion of the natural forest will lead to steep step changes of $(E/P)_{\text{precipitation}}$. Since the map of $(E/P)_{\text{precipitation}}$ applies to specifically selected land use classes only, gaps arise in the basin wide $(E_{\text{precipitation}}/P)$ fraction map. These gaps were filled by spatial interpolation of the average $(E/P)_{\text{precipitation}}$ values from surrounding areas. The rainfall maps (P_y, P_{average}) are used together with the $(E/P)_{\text{precipitation}}$ fractions to estimate $E_{\text{precipitation}}$, which represents the evaporation from green water resources (Falkenmark and Rockstrom, 2006).

The incremental E from irrigated land is not the same volume as the volume of water that is withdrawn directly from the river, reservoir or aquifer. Conveyance losses from canals, pipes, soil surface, spray, deep percolations and tail end water occur and are not accounted for. Classical irrigation efficiency (Jensen, 1967) or consumed fraction (Perry et al., 2009; Reinders et al., 2013) describe the ratio between $E_{\text{incremental}}$ and volume of irrigation water withdrawn. Reinders et al. (2010) proposed a default system efficiency for South Africa (net to gross ratio) being 78% for traveling gun, 90% for center pivot, 93% for flood and 95% for drip. These figures apply to pristine conditions, and are therefore believed to be at the higher side. In this study the ratio between $E_{\text{incremental}}$ and withdrawals is assumed to be 0.75 for all irrigated land.

3. Results and discussions

3.1. Basin-wide results

The average actual evaporation E for the natural forest is 1091 mm/yr and for the forest plantations this is 1151 mm/yr. These numbers are normal for the forests in this area. Dye et al. (2008) mentions annual canopy evaporation rates of 1200 mm/yr for a site afforested with eucalyptus in the vicinity of Sabie. Albaught et al. (2013) stated that the evaporation from the forest plantation is in the range from 1100 to 1200 mm/yr. Dye and Olbrich (1993) measured transpiration of more than 1200 mm/yr from a eucalyptus tree in the Mpumalanga province. Dzikiti et al. (2013) compared stands of self-established invasive pinus on riparian and non-riparian sites. Evaporation from the riparian site was 1417 mm/yr compared to 1190 mm/yr from the non-riparian site. Evaporation was determined from the surface energy balance equation using sensible heat flux data from a Large Aperture Scintillometer (LAS). This range of field measurements (from 1100 to 1400 mm/yr) agree well with the average SEBAL-based ET values of the forest classes reported. Note that for every land use class, a large population of pixels with E values is available and that only the average values are discussed here.

The average annual E of irrigated sugarcane was found to be 1044 mm/yr in this remote sensing study, which is in agreement with values found in other studies. Bezuidenhout et al. (2006) for example found 1016 mm/yr for the Komatipoort area and 995 mm/yr for the Malelane area – both in the Incomati basin. Hellegers et al. (2010) also used SEBAL with low resolution MODIS images to determine the evaporation from sugarcane in the Incomati and they estimated an evaporation value of 1067 mm/yr with a standard deviation of 179 mm.

SEBAL-based estimates of evaporation from the natural classes grassland and bush/shrub is 633 mm/yr and 661 mm/yr respectively. Flux data from the Skukuza site located in the Kruger National Park (Scholes et al., 2001) with savanna shrub, showed annual evaporation rates of 645 mm/yr in 2005. Hence, the combination of validations of evaporation from different land classes provides sufficient evidence of the quality and confidence one can put in the evaporation map used.

Appendix A presents the results of the average long term rainfall ($P_{average}$), the rainfall of the investigated year (P_y), the E, and the differences $P-E$ for every land use class. A summary of the results is presented in Table 2. Appendix B provides a presentation by administrative boundaries. The rainfall in an average rainfall year (35.2 km^3/yr) exceeds the volume evaporated (33.5 km^3/yr) by 1766 Mm^3/yr, and this difference can be regarded as an approximation for the basin outflow. Carmo Vaz and van der Zaag (2003) stated that 50% of the virginal flow (i.e., the natural stream flow without any anthropogenic withdrawals) of 3587 Mm^3/yr is withdrawn, which suggests an actual longer term basin outflow of 1794 Mm^3/yr. This is only 1.5% different from the 1766 Mm^3/yr that we found, and therefore we have confidence in the overall water balance of the Incomati basin. (Fig. 6)

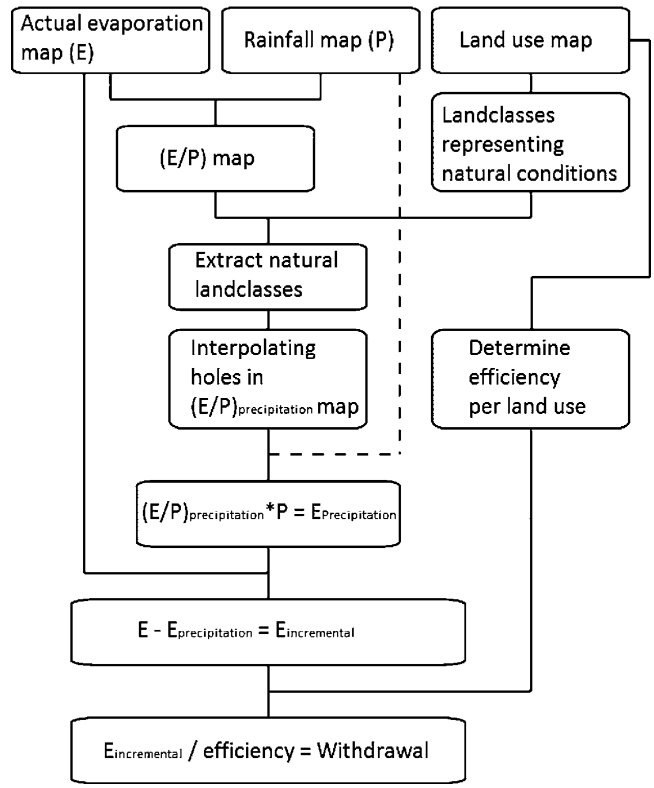

Fig. 6. Summary of the data analysis between input images and final pixel map of withdrawals.

Some land use classes produce water ($P_{average} > E$) and other land use classes consume water ($E > P_{average}$). The most important producers of water are bush/shrub, grassland, agriculture: rainfed and urban, see Appendix A. The most important water consumers in the area are the forest/woodland, plantations, Wetlands and agriculture: sugarcane non-pivot. Both forest classes are located in high rainfall areas, but apparently the E is even exceeding the high rainfall. These forests draw on groundwater with their deep rooting systems (Scott and Lesch, 1997) and by doing so intercept lateral flow that otherwise would feed a stream. The total rainfall

Table 2
Summary of rainfall (P_y and $P_{average}$), evaporation (E) and surplus water ($P-E$) by land use class across the entire Incomati basin.

Land class	Area (km^2)	$P_{average}$		P_y		E		$P_{average}-E$		P_y-E	
		(mm/yr)	(Mm^3/yr)	(mm/yr)	(Mm^3/yr)	(mm/yr)	(Mm^3/yr)	(mm/yr)	(Mm^3/yr)	(mm/yr)	(Mm^3/yr)
Forest/woodland	1991	934	1859	829	1650	1091	2172	−157	−313	−262	−521
Bush/shrub	20139	710	14293	749	15081	661	13316	49	977	88	1765
Grassland	11495	738	8480	744	8548	633	7272	105	1208	111	1276
Plantations	3719	994	3698	845	3143	1151	4281	−157	−583	−306	−1138
Open water	414	729	302	773	320	1098	454	−369	−153	−325	−134
Wetlands	1770	726	1285	724	1281	792	1402	−66	−117	−68	−121
Urban	1193	791	944	807	963	424	506	367	438	383	457
Rainfed agriculture	3971	744	2956	744	2956	627	2491	117	464	117	465
Sugarcane	723	789	571	785	568	1044	755	−255	−184	−260	−188
Irrigated agriculture (excluding sugarcane)	610	871	531	819	499	920	561	−49	−30	−102	−62
Other	438	753	330	749	328	620	272	133	58	129	57
Total	46463	759	35248	761	35338	721	33482	38	1766	40	1856

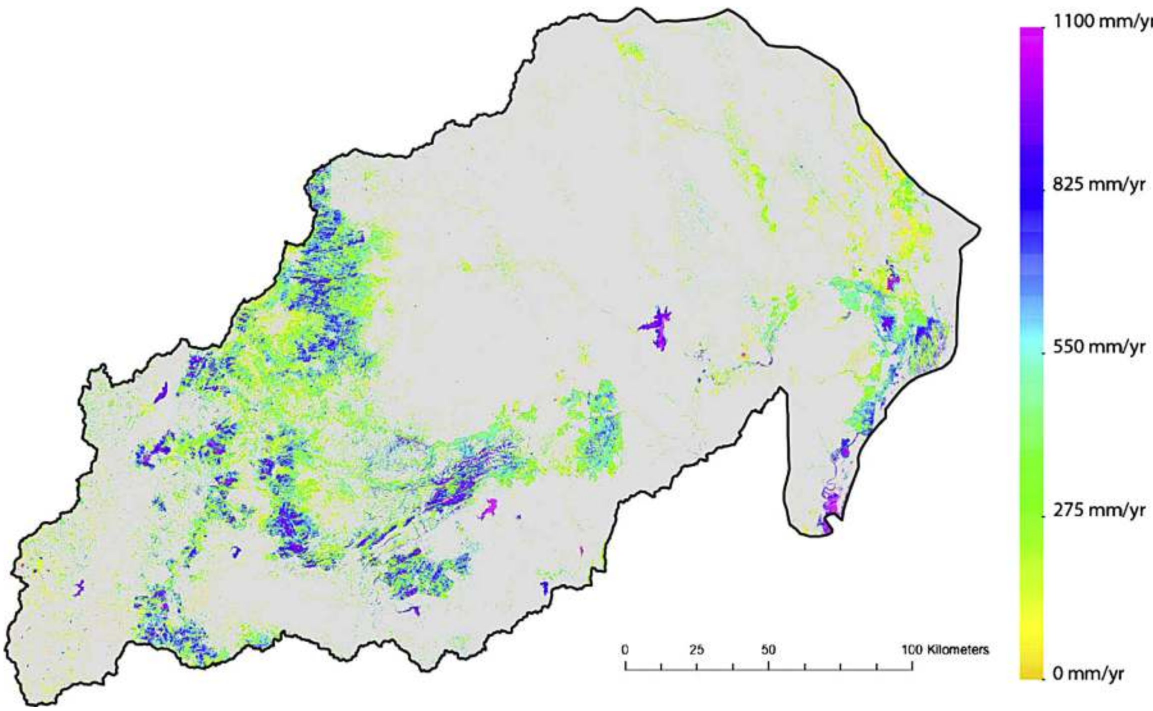

Fig. 7. Withdrawals for irrigated land, wetland, forests and plantations.

for the study period (P_y) is similar to the long term average rainfall $P_{average}$ (761 mm/yr against 759 mm/yr). During the year of study, the forest/woodland classes however received 105 mm/yr less rainfall and the plantations land use class received 149 mm/yr less rainfall study period compared to an average year. Inclusion of the longer term rainfall provides more representative insights of the behavior of withdrawals.

Incremental E occurs only if $E > E_{precipitation}$ and the distribution of $E_{incremental}$ for every pixel of 30 m is presented in Fig. 7. Despite the high rainfall, the highest $E_{incremental}$ values are in the forested areas. In the central part of the basin, the irrigation fields in the Komatipoort area and lake Corumana are clearly visible in Fig. 7. In the Mozambican part of the basin high $E_{incremental}$ mainly occurs in the wetlands and the sugarcane plantations on the banks of the Incomati river. The withdrawals in Swaziland occur between the Maguga reservoir in the Komati river and the Driekoppies reservoir in the Lomati river. Note that the inter-basin transfer volumes are not considered in the computations.

Table 3 provides an overview of the natural and the incremental evaporation rates. The classes with the highest incremental evaporation per unit of land are the mangroves (1086 mm/yr) (Appendix A), open water (516 mm/yr), sugarcane (402 mm/yr) and forest classes (392 and 433 mm/yr). The mangroves obviously receive large volumes of non-utilized flow from upstream areas, which meets the need for environmental conservation. The high open water evaporation is mainly from the reservoirs that have continuous inflow from the upstream catchment. The classes forest/woodland and plantations withdraw the biggest volume of water because they occupy relatively large areas of 1991 km^2 and 3719 km^2 respectively.

3.2. Direct withdrawals for irrigation

Fig. 8 shows the amount of water withdrawn for irrigation in the Komatipoort area. The areas with sugarcane generally have a larger irrigation depth than the other irrigated crops. According to our new remote sensing based withdrawal estimation procedure, the average irrigation application depth for sugarcane was 536 mm/yr with a range from 0 to 1200 mm/yr. Jarmain et al. (2012) measured the water balance on 10 fields of irrigated

Table 3
Summary of evaporation from rainfall and incremental evaporation from direct and indirect withdrawals across the entire Incomati basin. Irrigated agriculture and irrigation sugarcane represent the direct withdrawals.

Land class	Area (km^2)	E		$E_{precipitation}$		$E_{incremental}$	
		(mm/yr)	(Mm^3/yr)	(mm/yr)	(Mm^3/yr)	(mm/yr)	(Mm^3/yr)
Forest/woodland	1991	1091	2172	699	1391	392	781
Bush/shrub	20139	661	13316	661	13316	–	–
Grassland	11495	633	7272	633	7272	–	–
Plantations	3719	1151	4281	718	2671	433	1610
Open water	414	1098	454	582	241	516	213
Wetlands	1770	792	1402	577	1022	215	380
Urban	1193	424	506	667	796	–	–
Rainfed agriculture	3971	627	2491	627	2491	–	–
Irrigated sugarcane	723	1044	755	642	464	402	291
Irrigated agriculture (excluding sugarcane)	610	920	561	678	413	243	148
Other	438	620	272	619	271	–	–
Total	46463	721	33482	653	30348	67	3133

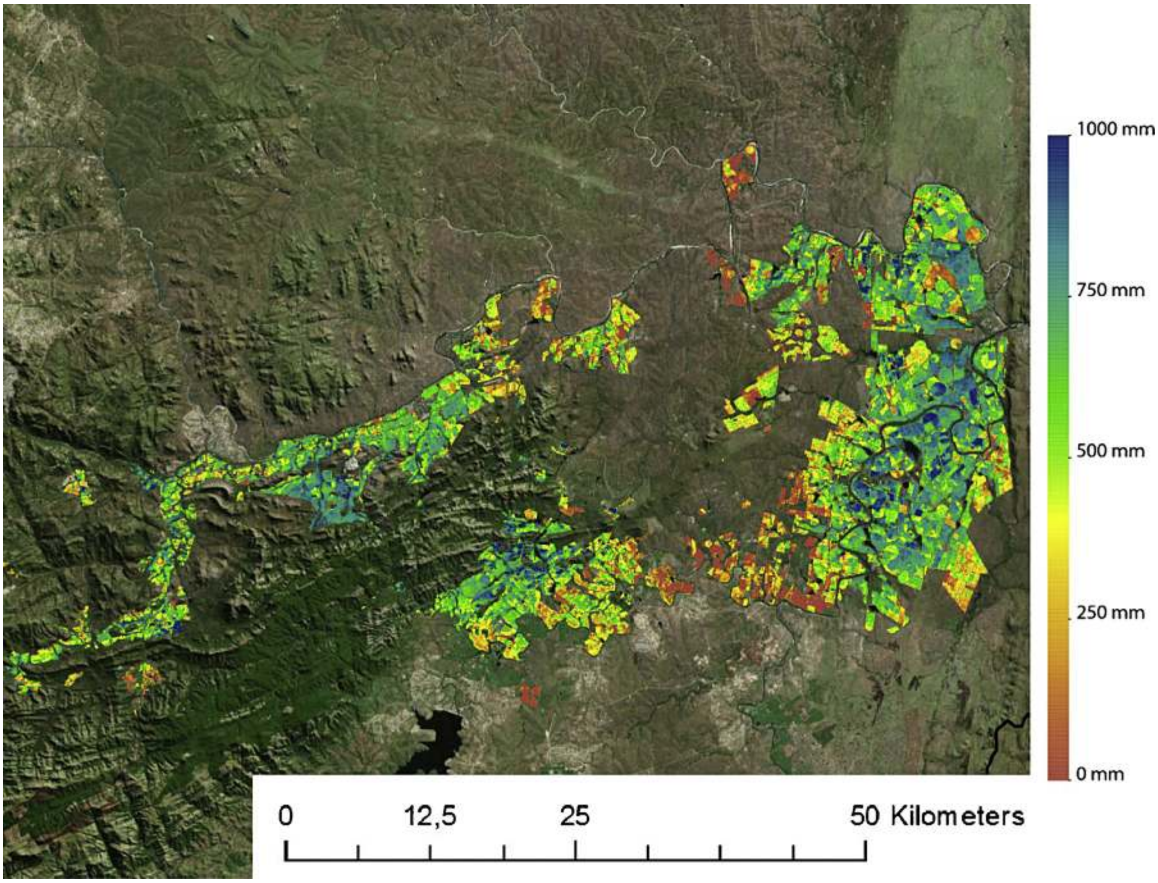

Fig. 8. Gross water withdrawal for the irrigated area around Komatipoort.

sugarcane farms in the Komatipoort region and found an average irrigation depth of 779 mm. For these same farms the irrigation depth according to remote sensing computations was 704 mm, hence a difference of less than 10%, that can be explained by the fixed irrigation efficiency of 75%. Note that different periods were considered, and that this is a qualitative check only. Jarmain et al. (2012) collected flow measurements at different points during the growing period, which is farm specific. Yet the results are encouraging, especially when one considers that also the evaporation estimations were in agreement with field observations. This increases the consistency of the entire spatial data set.

Banana and macadamia plantations are found in the Hazyview area. Although the evaporation from these plantations is about the same as from the sugarcane plantations the average irrigation depth is lower because the area of Hazyview receives more rainfall.

3.3. Indirect withdrawals by forested areas

The forest area is split into two categories: natural forest (199,065 ha) called the forest/woodland class and commercial forest plantations (371,931 ha) or the plantation class. The spatial variability of indirect withdrawals to forested areas is presented in Fig. 9. The natural forests generally have a lower incremental evaporation ($E_{\text{incremental}}$ = 391 mm/yr) than the afforested areas ($E_{\text{incremental}}$ = 433 mm/yr). The tapping of deep soil water reserves is confirmed by Clulow et al. (2011) in a study of the long term impact of Acacia trees on the stream flow and the groundwater resources in Kwazulu-Natal. In their study the observed groundwater level dropped by one meter between the dry season of 2007 and 2008 although 2008 was a wetter year with 819 mm of rainfall compared to 689 mm of rainfall in 2007. Deep roots can withdraw water either direct from groundwater or by suction and capillary rise. Due to deep unsaturated zones, trees can store water carried over from above-average rainfall years.

3.4. Stream flow reduction by afforestation

The classical definition in South Africa of reduction of runoff is expressed as a difference from the virgin conditions and not a difference from rainfed *E* as discussed in the previous section. The remote sensing estimates of the evaporation due to rainfall is 718 mm/yr, and all extra evaporation above this threshold value is attributed to indirect withdrawals. If the virgin conditions have a lower natural evaporation than 718 mm/yr, then the estimated stream flow reduction activity should increase further.

The influence of afforestation on stream flow reduction from the catchments can be determined by paired catchment studies (e.g. Bosch and Hewlett, 1982; Smith and Scott, 1992; Brown et al., 2005), or by measuring evaporation, and consequent runoff reduction, using direct energy balance and other techniques (Savage et al., 2004), which are mostly complex, expensive, long term, and only provides localized catchment information. According to Bosch and Hewlett (1982) pinus and eucalyptus forest types reduce water yield of a catchment by about 40 mm per 10% of land use change. This is a maximum reduction of 400 mm if 100% of the natural vegetation is replaced by forests. The incremental *E* of Table 3 (that is not based on land use changes but on non-rainfed *E*) suggest an average value of 392 mm and 433 mm for natural and plantations respectively, being in harmony with the findings of Bosch and Hewlett (1982).

Scott et al. (2000) in a re-analysis of the South African catchment afforestation experimental data found that the peak

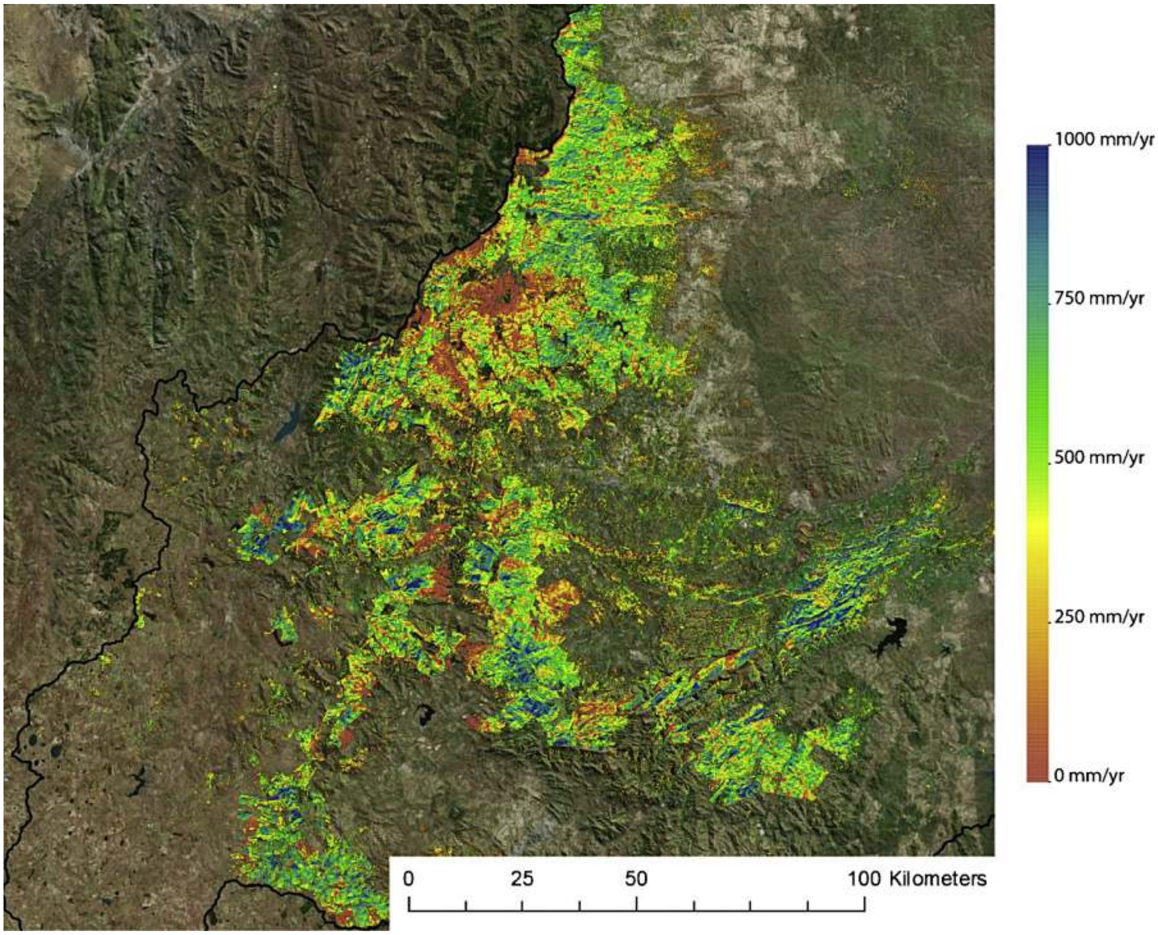

Fig. 9. Indirect water withdrawal due to root water uptake by natural forest and plantations in the Drakensberg mountainous range.

reduction as a mean over 5 years ranged from 17 to 67 mm per 10% for pinus plantations and from 37 to 41 mm per 10% for eucalyptus plantations. The average runoff reduction per 10% of forest plantation of 43.3 mm, being in the same order of magnitude as the previously mentioned studies. The range is however widely variable and depends on the catchment chosen, the underlying geology, groundwater conditions and age of the plantations.

Undertaking experimental studies on a perfectly representative catchment in the quantification of stream flow reduction is a challenge, and a bias is easily obtained. Gush et al. (2002) report a stream flow reduction varying between 120 and 370 mm per 100% afforested catchment. Scott and Lesch (1997) studied the stream flow response to afforestation of grassland in Mokobulaan, Mpumalanga, with Eucalyptus and Pinus and subsequent clear-felling. They mention a complete drying up of the 236 mm stream flow nine years after planting the entire catchment with eucalyptus. Similarly, a complete drying up of the 217 mm stream flow twelve years after planting the entire catchment with pinus was found.

Scott et al. (1998) determined the runoff reduction due to afforestation to be substantially lower (98.6 mm/yr). This was determined by empirical models based on Scott and Smith (1997). Different spatial data sources (rainfall, specie type, rotation length and surface runoff) were used as input for the model to determine the flow reduction for the whole of South Africa. While their estimates of stream flow reduction are systematically lower than the average values, the results of Scott et al. (1998) were used by the Department of Water Affairs and Forestry of South Africa as the official number for water accounting. This has, however, significant consequences for monitoring lawful water use, and international agreements on water allocation. The Tripartite Interim Agreement (TIA) adopted nevertheless unit values for stream flow reduction of 100 mm/yr for Mozambique, 130 mm/yr for South Africa and 142 mm/yr for Swaziland using the Pitman rainfall–runoff model (JIBS, 2001).

Satellite measurements provide a spatial picture of evaporation changes with land use and hydrological conditions. The range of indirect withdrawals must thus be highly variable, and various experimental studies report on values between 98.6 and 670 mm/yr for a 100% afforested catchment. These values match well with the range derived from satellite images as portrayed in Fig. 9.

3.5. Indirect withdrawals by water bodies and wetlands

The indirect withdrawals by wetlands have a natural character and are related to floods and rising shallow water table areas due to leaking rivers and groundwater seepage zones. The mangrove class is very small and only situated near the mouth of the Incomati river. The man-made water class consists of the reservoirs in the area. The natural water class consists of the river system, some natural lakes and lake Corumana which is in reality a man-made reservoir. The wetland class is mainly situated in Mozambique and is a combination of true wetlands being saturated the entire year, and floodplains that are wet for a limited period. The results shown in Fig. 10 demonstrate that the majority of the wetlands have a lower evaporation rate than open water. Mohamed et al. (2011) concluded that this is bio-physically feasible, provided that water

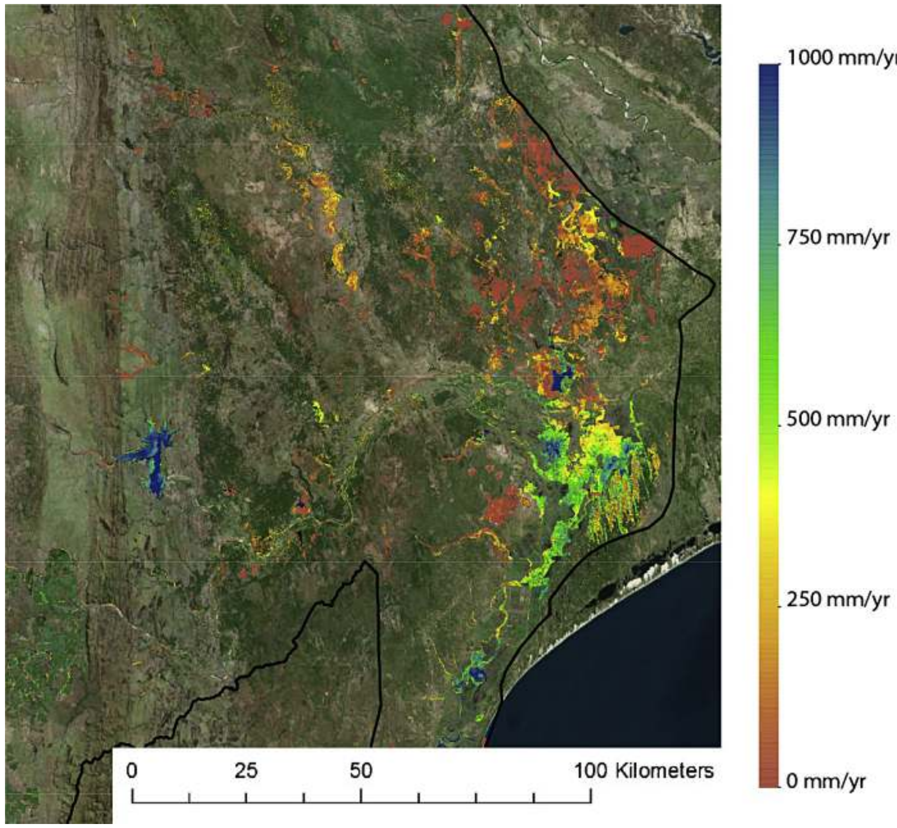

Fig. 10. Incremental evaporation from wetlands and open water due to floods and shallow water table areas.

table fluctuations and moisture availability are limiting factors for the evaporation process during certain periods of the year.

4. Water allocations

Table 4 links the results of the remote sensing analyses with the figures used for the TIA for each country. The TIA figures show that the remote sensing estimate of the withdrawals (1796 Mm^3/yr) are 4% less than permitted by the allocations defined by TIA for these water user classes (1873 Mm^3/yr). First priority and reserved flow are excluded in this comparison (see Table 1). It is apparent that the allocations for different water use sectors and countries are not adhered to. The fact that the total irrigation and runoff reduction figures are in line with the agreement, can be attributed to the fact that the water resources are almost fully allocated; there are simply not much utilizable flows, and the cap on water withdrawals has been reached.

The main discrepancy between remote sensing and the TIA figures is for groundwater uptake and subsequent runoff reduction. The TIA values are determined by the Pitman monthly runoff model (Pitman, 1973), and this is rather different from the remote sensing results for Swaziland and South Africa. The Pitman runoff values also differ from work done by several researchers (e.g. Bosch and Hewlett, 1982; Scott et al., 2000). Table 4 shows that the water withdrawals for South Africa calculated by remote sensing is 1132 Mm^3/yr in an average rainfall year and 1478 Mm^3/yr for a below average rainfall year. This is a factor 2–3 larger than the 475 Mm^3/yr, calculated with the Pitman model. It should be recalled that our calculations are based on the assumption that the evaporation due to rainfall on the forest plantations is 718 mm/yr and that all extra evaporation is attributed to water withdrawals and hence runoff reduction.

In cases where plantations replace a certain form of natural land use, the stream flow reduction might even be higher: natural forests have an average rainfed evaporation of 699 mm/yr, and grass ($E_{precipitation}$ = 633 mm/yr) and shrubland ($E_{precipitation}$ = 661 mm/yr) are also lower. These values of natural evaporation are lower than the rainfed evaporation of plantations. We therefore

Table 4
Withdrawals, using remote sensing compared against the volumes determined in the trilateral agreement.

	Tripartite Interim Agreement (TIA)			Gross withdrawals calculated with remote sensing (based on rainfall from the period 3 Nov 2011 and 31 Oct 2012)			Gross withdrawals calculated with remote sensing (based on long term average rainfall map)		
	Irrigation (Mm^3/yr)	Runoff reduction (Mm^3/yr)	Total (Mm^3/yr)	Irrigation (Mm^3/yr)	Runoff reduction (Mm^3/yr)	Total (Mm^3/yr)	Irrigation (Mm^3/yr)	Runoff reduction (Mm^3/yr)	Total (Mm^3/yr)
Mozambique	280	25	305	173	0	173	179	0	179
South Africa	786	475	1261	426	1478	1904	372	1132	1504
Swaziland	261[a]	46	307	4	170	174	4	109	113
Incomati basin	1327	546	1873	603	1649	2252	555	1241	1796

[a] This value includes an inter-basin transfer to the Umbeluzi basin of approx. 136 Mm^3/yr; this latter amount is not accounted for in this paper since the evaporation resulting from its use occurs outside the Incomati basin.

Table 5
Allocated irrigation volumes in three South African irrigation boards compared with the maximum possible crop water consumption (E_{pot}).

Irrigation board	Allocated irrigation depth (mm)	Rainfall		Allocated + rainfall		E_{actual} (mm/yr)	E_{pot} (mm/yr)	$E_{precipitation}$ (mm/yr)	$E_{incremental}$ /allocation [–]
		$P_{average}$ (mm/yr)	P_y (mm/yr)	Longer term (mm/yr)	Short term (mm/yr)				
Komati irrigation board	850	783	778	1633	1628	1076	1330	654	0.5
Lomati irrigation board	995	845	843	1840	1838	959	1227	717	0.24
Crocodile IB upper	800	830	800	1630	1600				
Crocodile IB lower	1300	830	800	2130	2100				
Crocodile irrigation board	1105	830	800	1935	1630	997	1251	652	0.31

believe, that our long term estimates of 1132 and 1478 Mm^3/yr for surface runoff reduction are even at the conservative side.

The irrigation volumes in the TIA are based on an agreed irrigation depth (mm/yr), see Table 5. The allocated irrigation depths provided by the crocodile irrigation board for the upper and lower parts of the catchment were different. The weighted average from these two sources of information was calculated based on the irrigated surface area provided by the irrigation board. This allocated irrigation depth is compared with the potential evaporation (E_{pot}) computed from SEBAL for all pixels flagged as irrigated land. E_{pot} is the physical upper limit of crop evaporation according to the prevailing atmospheric and land surface conditions, and in the situation of unlimited soil moisture content.

The total gross crop water supply is the sum of the allocated irrigation depth and the gross rainfall. The total value varies between 1630 and 2130 mm/yr and appears generally to be significantly higher than what is physically possible by E_{pot} (959–1330 mm/yr). This simple comparison demonstrates that a large portion of the irrigation water allocated can impossibly be consumed by irrigated crops. The allocation is thus based on significant non-consumed water fractions (Perry, 2007), that unnecessarily raises the total water resources allocated for the irrigation sector. The right hand column of Table 5 shows the consumed fractions, and they vary between 0.24 and 0.50. This confirms the large discrepancy between water allocated and water actually abstracted for irrigation. In the future, irrigation water allocations should be based on E_{pot}–$E_{precipitation}$ values and an average consumed fraction of 0.75, following Reinders et al. (2010).

5. Limitations

Land use classification procedures are not free from errors. Karimi and Bastiaanssen (2014) reviewed 56 peer reviewed papers on calibrated land use classifications, and concluded that the overall accuracy on average is 85% with a standard deviation of 7%. One of the areas where the land use map presented in Fig. 3 contains certainly errors is in the eastern part of Swaziland at the border with South Africa. The withdrawal for irrigation for Swaziland is only 4 Mm^3/yr (Table 4); this is far too low compared to the inter-basin transfer of 136 Mm^3/yr. The explanation is apparent when satellite and aerial images, land use maps, and evaporation maps are examined. There are areas where the satellite and aerial images show fields that by a visual inspection are assumed to be irrigated and not classified as such, but are mostly classified as bush/shrub.

The spatial distribution of rainfall and evaporation plays an important role in this study. Getting an accurate spatial distribution is not straightforward because the spatial rainfall products RFE and TRMM have a coarse resolution of 0.1° and 0.25° respectively. Data from rain gauges is only available for a limited number of points and these points are not always representative for a large area due to the significant variability. Reliable spatial rainfall maps are essential for good results. Although errors can be involved locally, we believe that the average rainfall amounts are reasonable. Similarly, evaporation maps play an important role in this study. Evaporation was calculated with SEBAL, and proven, through many international studies, to be accurate (e.g., Bastiaanssen et al., 2005). SEBAL-based evaporation results for the Incomati basin with values ranging from 600 to 1200 mm/yr seems to agree with flux tower measurements. Yet rainfall and evaporation values are determined from spectral measurements, that always contain a certain error.

The determined impact from forests on stream flow reduction is on the high side compared to the TIA, although research undertaken by national science foundations support the remote sensing estimates. The soil type, rainfall distribution in time, surface runoff, and other factors influence the effective rainfall, i.e., the amount of rainfall that is infiltrated into the soil matrix and subsequently converted into evaporation. Additional research is needed to refine the computations of $E_{precipitation}$, on areas where withdrawals occur, although we feel that the current approach provides reasonable results. The results are sensitive for the consumed fractions imposed, and they need to be realistic. A constant value of 0.75 for all irrigation systems has been applied, while in reality micro-irrigation has higher efficiencies.

While the innovative solution on withdrawal estimation from satellite measurements yields estimates of incremental E, the TIA is based on a different type of incremental E: The incremental E due to changes of the evaporation between the natural land use class and the forest plantations. Because the forests are planted on the most suitable sides with the highest rainfall it can be that on these areas naturally some different vegetation grew that consumed a higher portion of the rainfall than the surrounding indigenous vegetation.

6. Conclusions

In many parts of the world the pressure on the water resources is growing. It becomes more important to know where, when and what the size of water withdrawals are. While flow meters are needed to verify lawful water use, they will give incomplete insights in direct and certainly for indirect water withdrawals. A new method was therefore developed based on satellite measurements which provides the spatial distribution of direct and indirect withdrawals.

The method described in this paper aims at partitioning the actual evaporation into a part induced by the rainfall ($E_{precipitation}$) and a part that is induced by water withdrawals ($E_{incremental}$). The total volume of withdrawn water for an average year is in agreement with the TIA. The breakdown of total withdrawals is however rather different from the TIA specifications. Runoff reduction through afforestation is a factor 2–3 larger than the amounts specified in the TIA. This could be a result of possible under estimation of the rainfall in the mountainous areas or different estimates of the land use conditions prior to the introduction of the plantations. It is estimated that the longer term evaporation from rainfall in these catchments is 718 mm/yr and this is largely the result of the $(E/P)_{precipitation}$ ratio and the absolute rainfall P values. The rainfed evaporation from grassland and bushland varies between 630 and 700 mm/yr, and if this is representative for the ancient land use prior to afforestation, our estimate is at the conservative side. Literature studies both confirm and refute the values of runoff reductions for plantations, but the wider ranges detected by the new remote sensing method does agree with the wider range found during paired catchment studies. The evaporation rates could be verified successfully with flux towers.

The calculated irrigation withdrawal is less than specified in the TIA. This can be attributed to the extreme low consumed fractions associated to the allocation of irrigation water. Irrigation water allocations should be based on potential evaporation and net rainfall.

To meet the volumes agreed upon in the TIA South Africa needs to reduce its withdrawals. The indirect withdrawals from afforestation are the largest. Therefore reducing the area of afforestation is an option to be considered. Although the volume of irrigation does not exceed the volumes in the TIA, reducing the size of irrigated area can also be an option to reduce the amount of water withdrawn. It is a choice between timber and food. Both actions will have a significant socio-economic impact on the basin.

This paper has demonstrated that remotely sensed data on land use, rainfall and evaporation can be used to determine spatially distributed water withdrawals with a grid of 30 m × 30 m. No single flow measurement has been used. The computational procedure outlined is universal and can be applied to all land use classes and for ungauged river basins. Consistent and transparent satellite measurements can be very helpful to get an unbiased picture of water withdrawals in transboundary basins, and can feed into water accounting systems (Karimi et al., 2013). It facilitates the development of a transparent monitoring system based on independently gathered measurements that all parties trusts.

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Appendix A.

Overview of rainfall, evaporation per land use class (Tables A1 and A2).

Appendix B.

Summary of rainfall and evaporation per country (Tables B1–B6)

Table A1
Complete overview of rainfall, evaporation and surplus per class.

Land class	Area (km^2)	$P_{average}$		P_y		Evaporation		$P_{average} - E$		$P_y - E$	
		(mm/yr)	(Mm^3/yr)	(mm/yr)	(Mm^3/yr)	(mm/yr)	(Mm^3/yr)	(mm/yr)	(Mm^3/yr)	(mm/yr)	(Mm^3/yr)
Forest/woodland	1991	934	1859	829	1650	1091	2172	−157	−313	−262	−521
Bush/shrub	20139	710	14293	749	15081	661	13316	49	977	88	1765
Grassland	11495	738	8480	744	8548	633	7272	105	1208	111	1276
Plantations	3719	994	3698	845	3143	1151	4281	−157	−583	−306	−1138
Water natural	270	692	187	765	206	991	267	−299	−81	−226	−61
Water man-made	144	798	115	789	114	1300	187	−502	−72	−511	−73
Wetlands	1766	726	1283	723	1278	790	1396	−64	−114	−67	−118
Mangrove	4	682	3	834	3	1477	6	−794	−3	−643	−3
Bare	365	748	273	757	277	628	229	120	44	129	47
Agriculture: rainfed	3132	743	2328	760	2379	631	1978	112	351	128	402
Agriculture: irrigated	50	897	44	834	41	961	48	−63	−3	−126	−6
Agriculture: sugarcane pivot	120	779	93	782	94	1075	129	−296	−35	−293	−35
Agriculture: sugarcane non-pivot	604	791	478	785	474	1038	627	−247	−149	−253	−153
Urban	1193	791	944	807	963	424	506	367	438	383	457
Mines	32	785	25	723	23	614	19	171	5	109	3
Agriculture: horti banana	75	904	68	818	62	1053	79	−149	−11	−234	−18
Agriculture: horti blueberries	0.25	704	0.17	759	0.19	962	0.24	−258	−0.06	−203	−0.05
Agriculture: horti citrus	113	863	98	828	94	955	108	−92	−10	−127	−14
Agriculture: horti coffee	0.38	1029	0.39	857	0.33	977	0.37	51	0.02	−120	−0.05
Agriculture: horti granaat	0.8	786	0.6	805	0.7	771	0.6	15	0.01	34	0.03
Agriculture: horti passion fruit	0.01	913	0.01	891	0.01	924	0.01	−11	0	−33	0
Agriculture: horti pecan nuts	15	901	14	869	13	974	15	−72	−1	−105	−2
Agriculture: horti stone fruit	0.12	780	0.09	791	0.09	850	0.1	−70	−0.01	−59	−0.01
Agriculture: horti avocado	40	917	37	857	35	1005	40	−87	−4	−148	−6
Agriculture: horti ginger	0.06	1050	0.06	879	0.05	878	0.05	171	0.01	1	0
Agriculture: horti guava	1.4	993	1.4	906	1.2	869	1.2	124	0.2	37	0.1
Agriculture: horti kiwi	0.23	984	0.23	867	0.2	812	0.19	172	0.04	55	0.01
Agriculture: horti litchi	17	933	16	858	15	1036	18	−103	−2	−178	−3
Agriculture: horti macadamia	58	970	57	865	51	1105	65	−135	−8	−239	−14
Agriculture: horti mango	20	888	18	827	17	988	20	−100	−2	−161	−3
Agriculture: horti pawpaw	35	821	29	774	27	1019	36	−197	−7	−244	−9
Agriculture: maize	404	732	295	661	267	615	248	117	47	46	19
Agriculture: planted pasture	436	762	332	711	310	610	266	152	66	101	44
Agriculture: soya beans	46	721	33	655	30	641	29	80	4	14	1
Agriculture: fallow	41	766	32	693	29	547	23	219	9	146	6
Agriculture: wheat	4	701	3	740	3	696	3	5	0.02	44	0.19
Agriculture: vegetable/other	80	885	71	837	67	765	61	120	10	72	6
Agriculture: horti other	52	794	41	820	42	701	36	92	5	119	6
Total	46463	759	35248	761	35338	721	33482	38	1766	40	1856

Table A2
Complete overview of evaporation and incremental evaporation per land use class.

Land class	Area (km^2)	E		$E_{preciptation}$		$E_{incremental}$	
		(mm/yr)	(Mm^3/yr)	(mm/yr)	(Mm^3/yr)	(mm/yr)	(Mm^3/yr)
Forest/woodland	1991	1091	2172	699	1391	392	781
Bushshrub	20139	661	13316	661	13316	–	–
Grassland	11495	633	7272	633	7272	–	–
Plantations	3719	1151	4281	718	2671	433	1610
Water natural	270	991	267	538	145	453	122
Water man-made	144	1300	187	666	96	634	91
Wetlands	1766	790	1396	578	1021	213	376
Mangrove	4	1477	6	390	2	1086	4
Bare	365	628	229	628	229	–	–
Agriculture: rainfed	3132	631	1978	631	1978	–	–
Agriculture: irrigated	50	961	48	703	35	258	13
Agriculture: sugarcane pivot	120	1075	129	627	75	448	54
Agriculture: sugarcane non-pivot	604	1038	627	645	389	393	237
Urban	1193	424	506	667	796	−243	−290
Mines	32	614	19	610	19	4	0.1
Agriculture: horti banana	75	1053	79	688	52	365	28
Agriculture: horti blueberries	0.25	962	0.24	645	0.16	316	0.08
Agriculture: horti citrus	113	955	108	696	79	260	29
Agriculture: horti coffee	0.38	977	0.37	729	0.28	249	0.09
Agriculture: horti granaat	0.8	771	0.6	660	0.5	111	0.1
Agriculture: horti passion fruit	0.01	924	0.01	757	0.01	166	0.001
Agriculture: horti pecan nuts	15	974	15	738	11	236	4
Agriculture: horti stone fruit	0.12	850	0.1	673	0.08	178	0.02
Agriculture: horti avocado	40	1005	40	728	29	277	11
Agriculture: horti ginger	0.06	878	0.05	747	0.04	131	0.01
Agriculture: horti guava	1.4	869	1.2	770	1.1	99	0.1
Agriculture: horti kiwi	0.23	812	0.19	737	0.17	75	0.02
Agriculture: horti litchi	17	1036	18	728	12	308	5
Agriculture: Horti macadamia	58	1105	65	736	43	369	22
Agriculture: horti mango	20	988	20	676	14	312	6
Agriculture: horti pawpaw	35	1019	36	638	23	381	13
Agriculture: maize	404	615	248	615	248	–	–
Agriculture: planted pasture	436	610	266	610	266	–	–
Agriculture: soya beans	46	641	29	553	25	87	4
Agriculture: fallow	41	547	23	547	23	–	–
Agriculture: wheat	4	696	3	629	3	67	0.3
Agriculture: vegetable/other	80	765	61	707	56	58	5
Agriculture: horti other	52	701	36	553	28	148	8
Total	46463	721	33482	653	30348	67	3133

Table B1
Summary of rainfall, evaporation and surplus by land use class for South Africa.

Land class	Area (km^2)	$P_{average}$		P_y		Evaporation		$P_{average} - E$		$P_y - E$	
		(mm/yr)	(Mm^3/yr)	(mm/yr)	(Mm^3/yr)	(mm/yr)	(Mm^3/yr)	(mm/yr)	(Mm^3/yr)	(mm/yr)	(Mm^3/yr)
Forest/woodland	1884	936	1763	831	1565	1087	2049	−152	−286	−257	−483
Bush/shrub	9542	729	6960	770	7347	690	6587	39	372	80	759
Grassland	8988	740	6651	745	6697	656	5896	84	754	89	801
Plantations	3390	986	3342	845	2865	1143	3876	−157	−533	−298	−1011
Open water	212	766	162	760	161	1063	225	−297	−63	-304	−64
Wetlands	321	780	250	733	235	794	255	−14	−4	−60	−19
Urban	1094	798	873	811	887	421	461	377	413	390	427
Sugarcane	425	818	348	789	335	1036	440	−218	−93	−247	−105
Rainfed agriculture	1834	761	1396	737	1351	599	1098	162	298	138	253
Irrigated agriculture	581	878	510	818	475	939	545	−61	−36	−121	−70
other	324	778	252	759	246	653	212	124	40	106	34
Total	28596	787	22508	775	22166	757	21645	30	863	18	521

Table B2
Summary of rainfall, evaporation and surplus by land use class for Mozambique.

Land class	Area (km^2)	$P_{average}$		P_y		Evaporation		$P_{average} - E$		$P_y - E$	
		(mm/yr)	(Mm^3/yr)	(mm/yr)	(Mm^3/yr)	(mm/yr)	(Mm^3/yr)	(mm/yr)	(Mm^3/yr)	(mm/yr)	(Mm^3/yr)
Forest/woodland	46	726	34	755	35	1084	50	−358	−17	−329	−15
Bush/shrub	9286	656	6087	715	6637	598	5555	57	532	117	1082
Grassland	1778	644	1146	698	1241	498	885	147	261	200	356
Plantations	–	–	–	–	–	–	–	–	–	–	–
Open water	184	675	124	782	144	1099	203	−424	−78	−316	−58
Wetlands	1450	714	1035	722	1046	792	1148	−78	−112	−70	−102
Urban	98	712	70	767	75	458	45	254	25	309	30
Sugarcane	298	748	223	779	232	1057	315	−308	−92	−278	−83
Rainfed agriculture	2020	723	1461	746	1508	663	1339	60	122	83	168
Irrigated agriculture	18	688	13	826	15	286	5	403	7	540	10
Other	113	679	77	719	81	521	59	158	18	198	22
Total	15292	672	10269	720	11014	628	9603	44	666	92	1411

Table B3
Summary of rainfall, evaporation and surplus by land use class for Swaziland.

Land class	Area (km^2)	$P_{average}$		P_y		Evaporation		$P_{average} - E$		$P_y - E$	
		(mm/yr)	(Mm^3/yr)	(mm/yr)	(Mm^3/yr)	(mm/yr)	(Mm^3/yr)	(mm/yr)	(Mm^3/yr)	(mm/yr)	(Mm^3/yr)
Forest/woodland	60	1026	62	832	50	1207	72	−181	−11	−375	−22
Bush/shrub	1312	950	1247	837	1098	895	1174	56	73	−58	−76
Grassland	729	938	683	838	610	673	491	264	193	165	120
Plantations	329	1082	356	845	278	1232	405	−151	−50	−388	−127
Open water	17	853	15	840	15	1519	26	−666	−12	−679	−12
Wetlands	0.01	880	0.01	833	0.01	780	0.01	100	0.001	53	0.001
Urban	0.6	923	0.6	817	0.5	672	0.4	251	0.2	145	0.1
Sugarcane	–	–	–	–	–	–	–	–	–	–	–
Rainfed agriculture	117	841	98	832	97	460	54	381	44	372	43
Irrigated agriculture	10	830	9	827	9	986	10	−156	−2	−159	−2
Other	1.2	950	1.2	841	1	713	0.9	238	0.3	128	0.2
Total	2576	959	2471	838	2158	867	2234	92	237	−30	−76

Table B4
Summary of evaporation both incremental and through precipitation for South Africa.

Land class	Area (km^2)	E		$E_{precipitation}$		$E_{incremental}$	
		(mm/yr)	(Mm^3/yr)	(mm/yr)	(Mm^3/yr)	(mm/yr)	(Mm^3/yr)
Forest/woodland	1884	1087	2049	703	1325	384	724
Bush/shrub	9542	690	6587	690	6587	–	–
Grassland	8988	656	5896	656	5896	–	–
Plantations	3390	1143	3876	718	2434	425	1441
Open water	212	1063	225	634	134	429	91
Wetlands	321	794	255	613	197	180	58
Urban	1094	421	461	679	743	−258	−282
Rainfed agriculture	1834	599	1098	599	1098	–	–
Sugarcane	425	1036	440	653	277	383	163
Irrigated agriculture	581	939	545	689	400	250	145
Other	324	653	212	653	212	–	–
Total	28596	757	21645	675	19305	82	2340

Table B5
Summary of evaporation both incremental and through precipitation for Mozambique.

Land class	Area (km^2)	E		$E_{precipitation}$		$E_{incremental}$	
		(mm/yr)	(Mm^3/yr)	(mm/yr)	(Mm^3/yr)	(mm/yr)	(Mm^3/yr)
Forest/woodland	46	1084	50	504	23	580	27
Bush/shrub	9286	598	5555	598	5555	–	–
Grassland	1778	498	885	498	885	–	–
Plantations	–	–	–	–	–	–	–
Open water	184	1099	203	510	94	588	108
Wetlands	1450	792	1148	569	825	222	322
Urban	98	458	45	537	53	−79	−8
Rainfed agriculture	2020	663	1339	663	1339	–	–
Sugarcane	298	1057	315	627	187	430	128
Irrigated agriculture	18	286	5	299	5	−14	−0.2
Other	113	521	59	521	59	–	–
Total	15292	628	9603	590	9026	38	578

Table B6
Summary of evaporation both incremental and through precipitation for Swaziland.

Land class	Area (km^2)	E		$E_{precipitation}$		$E_{incremental}$	
		(mm/yr)	(Mm^3/yr)	(mm/yr)	(Mm^3/yr)	(mm/yr)	(Mm^3/yr)
Forest/woodland	60	1207	72	707	42	500	30
Bush/shrub	1312	895	1174	895	1174	–	–
Grassland	729	673	491	673	491	–	–
Plantations	329	1232	405	718	236	514	169
Open water	17	1519	26	714	12	805	14
Wetlands	0.01	780	0.01	655	0.01	125	0.002
Urban	0.6	672	0.4	691	0.4	−19	−0.01
Rainfed agriculture	117	460	54	460	54	–	–
Sugarcane	–	–	–	–	–	–	–
Irrigated agriculture	10	986	10	699	7	287	3
Other	1.2	713	0.9	687	0.8	–	–
Total	2576	867	2234	783	2018	84	216

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