Water use of grasslands, agroforestry systems and indigenous forests

CS Everson[1]*, PJ Dye[2], MB Gush[3] and TM Everson[4]

[1]*School of Bioresources Engineering and Environmental Hydrology, University of KwaZulu-Natal, Private Bag X01, Scottsville, Pietermaritzburg 3209, South Africa*
[2]*Ecological Engineering & Phytoremediation Programme, Restoration & Conservation Biology Research Group, School of Animal, Plant & Environmental Sciences (AP&ES), University of the Witwatersrand, Johannesburg, Private Bag 3, WITS 2050, South Africa*
[3]*CSIR Natural Resources & Environment, PO Box 320, Stellenbosch 7599, South Africa*
[4]*School of Biological and Conservation Sciences, University of KwaZulu-Natal, Private Bag X01, Scottsville, Pietermaritzburg 3209, South Africa*

Abstract

The biotic and abiotic components of ecosystems affect each other through complex interactions and processes. These dynamic interactions give ecosystems their distinct identities and provide ecosystem services critical to human survival (e.g. water, energy and nutrients). However, human activities (e.g. commercial forestry, agriculture) have placed increasing demands on specific ecosystem services. The effect of these activities on ecosystem processes has been the focus of numerous Water Research Commission (WRC) studies. Some of these have determined man's impact on plant-water use, biomass production (energy) and water use efficiency (biomass produced per unit of water transpired, termed productive green-water use). For example, measurements of evapotranspiration (ET_a) from different vegetation types showed that annual water use is strongly related to the proportion of the year in which a dense canopy of transpiring leaves is maintained. Thus, evergreen vegetation such as riparian fynbos and plantations of introduced tree species exhibit a relatively high annual ET_a, when compared to seasonal grasslands and deciduous trees that only maintain their transpiring canopy during summer. Quantification of the annual volumes of water used by these different vegetation types, under differing climatic and site conditions, has been possible through these studies. At a stand scale, measurements of the different components of evapotranspiration have allowed the partitioning of beneficial (transpiration) and non-beneficial (evaporation) fluxes. At a catchment scale measurements have quantified the proportional allocation of water to the different components of the water balance. Three case studies are presented to illustrate this. In a stand of *Jatropha curcas,* measurements of daily total evaporation rates during December to February (summer) on clear hot days ranged between 3 $mm \cdot d^{-1}$ to 4 $mm \cdot d^{-1}$. However, due to the deciduous nature of the species, water use was negligible (< 1 $mm \cdot d^{-1}$) during winter (May to August). At a catchment scale, studies in a montane grassland ecosystem of the KwaZulu-Natal Drakensberg showed that the partitioning of the main hydrological fluxes into streamflow and evaporation was dependent on the wetness of the hydrological year. In average to wet years (>1 200 mm precipitation) the hydrological flux was equally split between evaporation (650 mm) and runoff (550 mm), while in drier years evaporation became the dominating component of the water balance (752 mm vs. 356 mm, respectively). The data provided an important baseline for comparison with other impacted ecosystems (especially commercial forestry). Finally, results of a variety of studies on the growth and water use of indigenous trees growing in natural forest and plantation systems suggest that, compared to introduced tree species, indigenous species use substantially less water, show lower water use efficiency, and grow more slowly. Advantages to such indigenous systems potentially include lower management costs, higher product values, a wider range of non-wood products and a lower hydrological impact. Their usefulness may be greatest on sensitive sites (e.g. riparian zones, water-stressed catchments, land cleared of alien plants, land with a high erosion risk, degraded forest) where land use systems with a reduced environmental impact are required.

Keywords: evaporation, transpiration, grassland, indigenous trees, *Jatropha curcas*

Introduction

The biotic and abiotic components of ecosystems affect each other through complex interactions and processes. These dynamic interactions give ecosystems their distinct identities and provide ecosystem functions critical to human survival (e.g. energy, water and nutrients). Natural ecosystems are 'self-regulating' since they contain feedback mechanisms which function to maintain the components of the system in one or other of its equilibrium or stable states. Human activities (e.g. commercial forestry, agriculture and mining) have placed increasing demands on some ecosystem services, particularly those affected by the market economy. The effect of these activities on ecosystem functioning has been the focus of numerous WRC studies where the objectives have been to study man's impact on both water utilization and biomass production (water use efficiency). The results from these studies are critical for water-resource planning and management and policy implementation to provide for the growing demand for water and to reduce the degradation of water resources (Jewitt, 2002; Brauman et al., 2007). Any dryland-cultivation activity which uses more water than the natural vegetation has the potential to negatively affect ecosystem functioning, particularly in terms of water-related impacts. Under Section 36(2) of the National Water Act of South Africa (NWA, Act No. 36 of 1998) a streamflow reduction activity (SFRA) is defined as '... any activity … [that] ...

This paper was originally presented at the Water Research Commission 40-Year Celebration Conference, Kempton Park, 31 August - 1 September 2011.

* To whom all correspondence should be addressed.
☎ +27 (0)33 260-6093; fax: +27 (0)33 260-5818;
e-mail: eversonc@ukzn.ac.za

http://dx.doi.org/10.4314/wsa.v37i5.15
Available on website http://www.wrc.org.za
ISSN 0378-4738 (Print) = Water SA Vol. 37 No. 5 WRC 40-Year Celebration Special Edition 2011
ISSN 1816-7950 (On-line) = Water SA Vol. 37 No. 5 WRC 40-Year Celebration Special Edition 2011

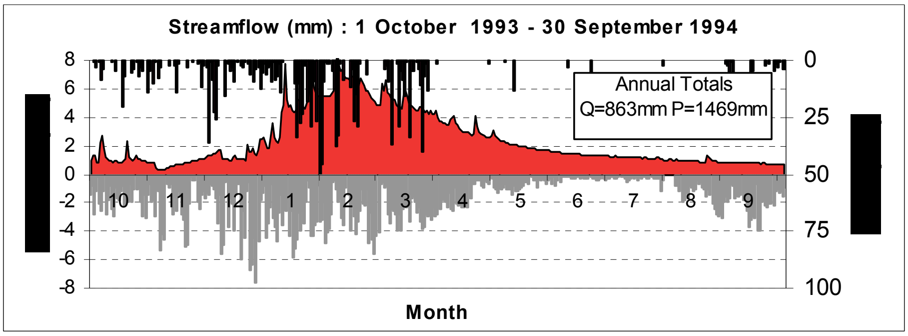

Figure 1
Daily streamflow (+ values), total evaporation (- values) and rainfall for the 1993-94 hydrological year at Cathedral Peak catchment VI

is likely to reduce the availability of water in a watercourse to the Reserve, to meet international obligations, or to other water users significantly.' Plantation forestry with introduced trees is (rightly or wrongly) currently the only declared SFRA in South Africa (Dye and Versfeld, 2007). There is an urgent need to assess the water use impacts of not only current, but also of any future land use changes involving the wide-scale cultivation of other crops.

So, while work continues on improving our understanding of the water use of existing vegetation types in South Africa, attention has also been given to crops likely to be more extensively cultivated in future, especially where significant knowledge gaps in terms of water use exist. These knowledge gaps are of particular concern in a dry country such as South Africa, where total evaporation from vegetation accounts for the greatest loss of water from catchments. Accurate estimates of water use are fundamental to gaining a good understanding of the hydrological impacts of a specific plant species or vegetation type. Where large-scale changes in vegetation cover are proposed, this aspect becomes particularly important because the differences in total evaporation between the current and the proposed vegetation ultimately translate into changes in available streamflow from that catchment (Le Maitre et al., 2007a; Le Maitre et al., 2007b; Jewitt, 2006). Consequently, large-scale changes in land use could have significant hydrological implications if the water use of the introduced species were significantly different to that of the vegetation it would replace. To understand the effect of changing land use on water also requires knowledge of the natural 'baseline' vegetation where the concept of incremental water use has been developed in South Africa. In this paper we focus on 3 important land uses where detailed water use studies have been undertaken in WRC projects.

Grassland water use

The major catchment areas for South Africa's water resources are covered by natural grasslands which occupy approximately 29% (350 000 km^2) of the country (SANBI, 2011). These areas have a relatively cool climate, and have an annual rainfall of between 600 mm·yr^{-1} and 1 200 mm·yr^{-1}. These areas coincide with the afforestation zones for introduced commercial tree species, whose site requirements for growth are mostly limited by the availability of soil water. Given that the total area under introduced commercial tree species in South Africa in 2008 was 1.23 x 10^6 ha (mainly in the high-rainfall grassland catchment areas of Mpumalanga and KwaZulu-Natal) and combined with the continued and growing demand for timber (Godsmark, 2009), there can be no doubt that afforestation will have a further impact on the country's already scarce water supplies. Most of the research into predicting hydrological change due to afforestation has been to quantify the water use of the introduced tree species. Very little research has been directed at determining the water use of natural communities. To quantify the effects of afforestation and agriculture, it is necessary to have information on the evaporation losses from natural vegetation to provide a management baseline.

Traditionally, estimates of water use of vegetation in gauged catchments are made by determining the difference between precipitation and streamflow. However, these estimates are not precise enough to enable accurate predictions of water yield from hydrological models, and they ignore intra-annual variability. Since the water use (total evaporation) of mixed seasonal grasslands in high rainfall areas is largely energy-dependent, quantification of the surface-energy budget is the best approach for measuring the evaporation component of the catchment water balance. In addition, this approach allows for a better understanding of the hydrological processes involved. In the first of the WRC-funded studies highlighted in this paper (Everson et al., 1998), the Bowen ratio energy balance technique was used to measure the water use of a grassland catchment. This was the first long-term study (5 years) in South Africa in which all the components of the catchment water balance (rainfall, streamflow, evaporation and soil-water storage) were routinely measured simultaneously. The aim of this study was to identify and quantify the principal factors (meteorological, plant and soil) controlling the processes of water loss in montane grasslands. Total evaporation was measured using the Bowen ratio energy balance technique and compared to evaporation estimated from annual precipitation and discharge data (Fig. 1). Results showed that in normal years precipitation is equally split between evaporation and streamflow. In dry years evaporation is the dominant component of the water balance. The data were used to develop equations to calculate annual streamflow and evaporation from the ratio of precipitation to potential evaporation (Everson, 2000).

The average annual evaporation over the 5-year study period was 695 mm·yr^{-1}. Mean annual rainfall was 1 299 mm·yr^{-1} and therefore approximately 54% of the annual rainfall was evaporated back into the atmosphere and was not available for streamflow generation. The low variation in evaporation, irrespective of the high variability in rainfall, indicates that in the KwaZulu-Natal Drakensberg energy and not soil moisture is the main factor limiting evaporation. Low-rainfall years (<1 100 mm·yr^{-1}) were generally associated with high incoming radiation (> 6 150 MJ·m^{-2}) (Everson, 2000). The value of these baseline data lies in its usefulness in quantifying the effects of potential land use changes (e.g. afforestation or agriculture).

http://dx.doi.org/10.4314/wsa.v37i5.15
Available on website http://www.wrc.org.za

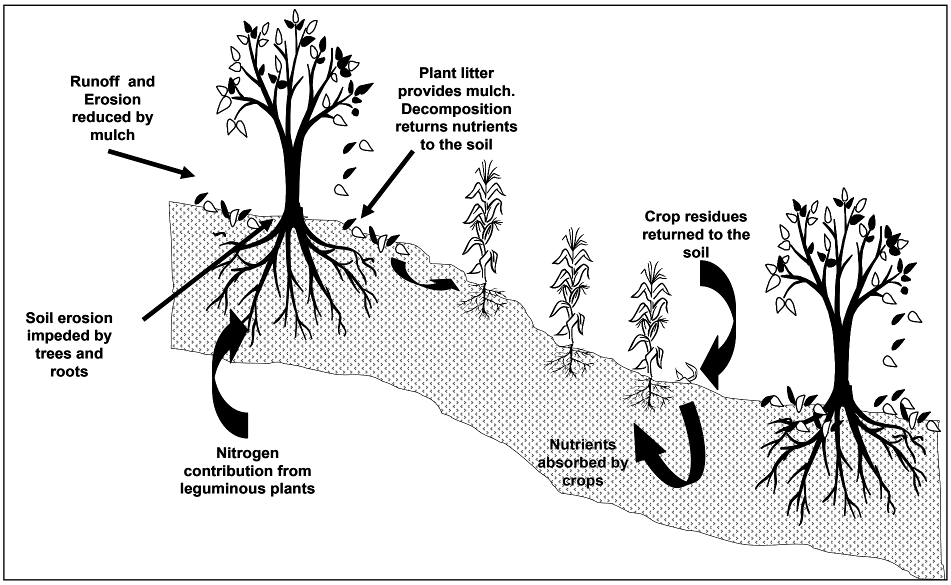

Figure 2
A schematic representation of the potential benefits of introducing an agroforestry system on ecosystem functioning

Agroforestry water use

For fodder production

Agroforestry is a land use system where woody perennial trees are deliberately used on the same land-management unit as agricultural crops and/or animals (Lundgreen and Raintree, 1982). This land use system has the potential to provide dry-season forage and fuelwood for resource-poor farmers. Research on rural small-scale farmers in KwaZulu-Natal has revealed many challenges limiting the profitability of these farming enterprises. The challenges that these farmers face include a shortage of water, expensive fertilisers, and a lack of suitable crops.

While the potential benefits of agroforestry are well documented (Fig. 2), particular aspects of these systems need to be adapted to suit the areas where they are introduced. An agroforestry system that has potential in South Africa is the farming of livestock alongside trees and crops (silvopasture). These adaptations primarily involve the selection of the ideal combinations of trees, shrubs and crops that will benefit each other, the environment and the income of the small-scale farmers. WRC studies have shown that leguminous fodder trees (A*cacia karroo* and *Leucaena leucocephala*) are able to provide quality fodder with crude protein contents of 14.7% and 18.6%, respectively, compared to 3.5% crude protein of the natural veld. In addition, temperate pasture species, *Festuca arundinacea* (tall fescue) and *Dactylis glomerata* (cocksfoot) increased fodder production in winter by 64% when compared to the natural veld. The high total fodder production obtained from alley cropping (682.91 kg·ha^{-1}) compared to sole pasture cropping (142.60 kg·ha^{-1}) (pasture dry matter yields based on 4 weeks' harvest interval) was a further demonstration that growing pastures in combination with tree legumes may be an appropriate fodder-production technology for smallholder farmers in communal areas.

The diurnal trends in sap flow for *Acacia karroo* for December 2008 in these agroforestry systems indicated that maximum sap-flow rates were between 10 cm·h^{-1} and 15 cm·h^{-1} for mature *Acacia* trees and consistently higher (20 cm·h^{-1} to 30 cm·h^{-1}) for fast-growing young trees. The evergreen nature of the indigenous *Acacia* trees resulted in water use in all seasons. The introduced mulberry trees had maximum sap-flow rates of 10 cm·h^{-1} in July 2008 increasing to 25 cm·h^{-1} in October 2008, showing the reduced transpiration in winter due to the dry conditions and deciduous nature of the trees. By contrast *Gleditsia* had zero sap flow in July as it had shed all its leaves and maximum sap-flow rates in summer (December) of approximately 10 cm·h^{-1}. These data showed that mulberry had a higher water use than the *Gleditsia* trees. The fact that indigenous *Acacia* exhibited high sap-flow rates in all seasons was evidence that its annual water use was higher than that of the 2 introduced deciduous species (Everson, 2009).

For biofuel production in a silvopastoral agroforestry system

Jatropha curcas, a species from South America, elicited considerable interest in recent years as a potential income generator for small-scale farmers. The primary potential of *J. curcas* was that its seeds can be used to produce biofuel – the global demand for which is increasing dramatically as oil prices increase. A major problem with biofuel production is that it often requires large tracts of land, a resource that is becoming increasingly limited under global population increase (Parfit, 2004). However, *J. curcas* does not require arable land as it is able to grow in infertile, and moderately sodic and saline soils (Mohibbe Azam et al., 2005). It is also drought-resistant, thus able to grow in arid and semi-arid areas where it tolerates high temperatures and low soil moisture (Augustus et al., 2002). Because of these characteristics it has been used in land-reclamation and soil-erosion prevention (Openshaw, 2000). However, the extremely limited data available on its potential environmental impacts (specifically water use) necessitated further study. The water use and agronomic potential of *J. curcas* were the focus of 2 WRC studies, the first being an assessment of the water use and biophysical potential of *Jatropha curcas* (Holl et al., 2007), and the second focusing on agroforestry systems for improved food production through the efficient use of water (Everson et al., 2011).

In the first study, sap flow (transpiration) in 4-year-old and 12-year-old *Jatropha curcas* trees was measured continuously for a 17-month period at 2 sites in eastern South Africa. The heat-ratio method (Burgess et al., 2001) of the heat-pulse

http://dx.doi.org/10.4314/wsa.v37i5.15
Available on website http://www.wrc.org.za
ISSN 0378-4738 (Print) = Water SA Vol. 37 No. 5 WRC 40-Year Celebration Special Edition 2011
ISSN 1816-7950 (On-line) = Water SA Vol. 37 No. 5 WRC 40-Year Celebration Special Edition 2011

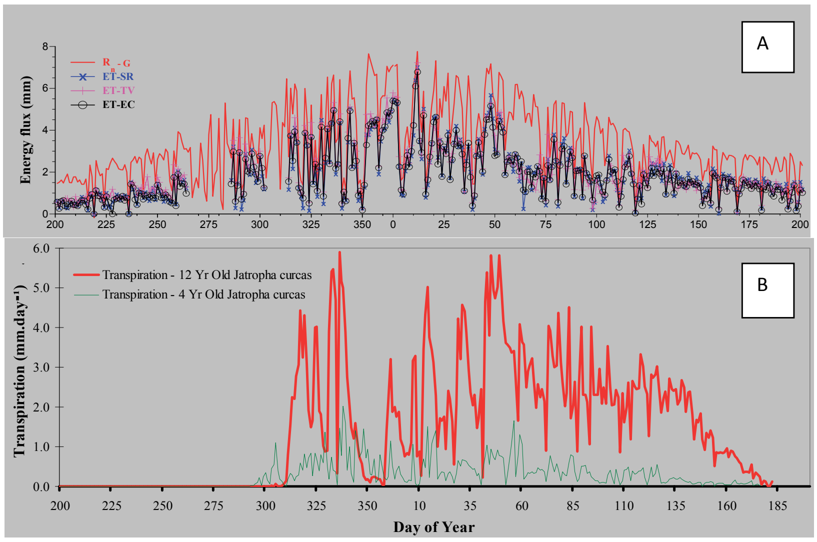

Figure 3
Diurnal variations in: (A) total evaporation (mm) above 3-year-old Jatropha curcas trees measured using the EC, SR and TV techniques, together with available energy (mm) from solar radiation (R_n – G) for a year (Mengistu, 2008; Abraha and Savage, 2008); and (B) transpiration (mm) in 4- and 12-year-old Jatropha curcas trees measured using the HPV technique (Gush, 2008)

velocity (HPV) technique was utilised, together with measurements of meteorological variables and soil water. Sap-flow rates varied according to tree age, season, prevailing meteorological conditions, and soil moisture levels. During the warm and wet summer months (Dec to Feb), daily transpiration averaged 0.6 mm·d^{-1} and peaked at 2 mm·d^{-1} for the 4-year-old trees, while averaging 2 mm·d^{-1} and peaking at 5 mm·d^{-1} to 6 mm·d^{-1} for the 12-year-old trees (Fig. 3 A). Due to the deciduous nature of the species, water use at both sites was negligible during winter. The study concluded that the *J. curcas* trees studied were conservative in their water use, and were unlikely to transpire more water than indigenous vegetation types of the area (Gush, 2008).

In the second study, tree-grass interactions (water dynamics and plant productivity) within a *Jatropha curcas* / *Pennisetum clandestinum* (Kikuyu) silvopastoral experiment were investigated (Everson et al., 2007). Amongst a range of other measurements, monitoring of total evaporation from 3-year-old *J. curcas* trees using eddy covariance (EC), surface renewal (SR) and temperature variance (TV) techniques took place over a 12-month period (Mengistu, 2008; Abraha and Savage, 2008). Average daily *ET* ranged from <1 mm·d^{-1} in winter to approximately 3 mm·d^{-1} in summer (Fig. 3 B). Preliminary results from this study also suggest that the species uses relatively little water compared to other vegetation types.

These examples illustrate the importance of providing water use data on a previously unstudied vegetation type. Before this study, a modelling approach with its inherent uncertainties was the only alternative. Modelling (e.g. with the use of crop factors and the FAO56 approach) is still a requirement to extrapolate site-specific measurements to a wider scale but the availability of some observed data to ground the subsequent assumptions significantly reduces uncertainty (e.g. see Jongschaap et al., 2009).

Indigenous tree water use

The impacts on catchment water yields, where plantations of introduced tree species (eucalyptus, pine and wattle) have replaced seasonally dormant grasslands and fynbos, have been well documented in South Africa (Scott et al., 2000; Dye and Versfeld, 2007). As a result, restrictions on further afforestation have been implemented. The total national plantation area is unlikely to significantly expand, despite continued growth in demand for timber products. This situation has spurred increased interest in the utilisation of indigenous tree species and forests, in light of their perceived low water use, suspected higher water use efficiency, and sometimes high value of wood and other products such as traditional medicine and fruit. A WRC-funded investigation of the water use and utilisable biomass of various tree species and indigenous forests/plantations was conducted to evaluate the potential for new forms of forestry with reduced environmental impacts and more favourable ecosystem function (Dye et al., 2008).

Mixed species/mixed age indigenous forests

Estimates of water use and water use efficiency (WUE) for an entire forest (trees and undergrowth) were obtained for an evergreen mixed species/mixed age indigenous afrotemperate forest in the Southern Cape. Above-canopy total evaporation (*ET*) data were recorded using scintillometry and eddy covariance measurement systems, and compared to long-term growth data describing the increase in utilisable above-ground woody biomass. Results indicated a relatively high annual total evaporation (933 mm) in this region of relatively low potential evaporation, as a consequence of a high all-year green leaf area and an absence of drought stress. Stem-growth rates were low (4.2 m^3·ha^{-1}; Dye et al., 2008) compared to commercial even-aged plantations in the vicinity, reflecting the dominance of the few older, larger trees and suppression of many younger, smaller trees. Despite this low water use efficiency, an economic analysis patterned on the harvesting scheme implemented in the area (Seydack, 1995) showed that the profitability of such indigenous forests was similar to many commercial forest plantations, as a result of higher product value and lower management costs (Wise et al., 2011).

Indigenous tree plantations

Measurements of both total evaporation and sap flow in a plantation of even-aged *Afrocarpus (Podocarpus) falcatus* (Outeniqua yellowwood) in Magoebaskloof, Limpopo, showed that the trees used less than half of the available soil water originating from rainfall. The water use of the understorey vegetation was estimated to account for 66% of the total evaporation recorded in this indigenous tree system during the summer growing season. This result highlights the important role that

http://dx.doi.org/10.4314/wsa.v37i5.15
Available on website http://www.wrc.org.za
ISSN 0378-4738 (Print) = Water SA Vol. 37 No. 5 WRC 40-Year Celebration Special Edition 2011
ISSN 1816-7950 (On-line) = Water SA Vol. 37 No. 5 WRC 40-Year Celebration Special Edition 2011

stand management can play in minimising the total evaporation from low-density stands of slow-growing indigenous species with sub-optimal leaf-area index. A further important insight was the low sap-flow rate characteristic of *A. falcatus*, demonstrating the potential for selecting indigenous species with a low impact on catchment water yields.

Single trees

A number of single-tree studies of growth and sap flow have allowed comparisons of water use efficiency among a range of indigenous and introduced commercial tree species. Hourly transpiration in sample trees was recorded continuously over a full year, and compared to stem growth and height increments recorded at the start and end of the measurement period. Tree age was variable, but mostly between 3 years and 6 years. While the water use efficiency of introduced commercial tree species was shown to be variable, reflecting differences in species, age and site, it was nevertheless clear that the comparable productive green water use efficiency of the 6 species of indigenous trees was relatively low (Gush and Dye, 2009). The results for the indigenous species need to be confirmed in high-density stands, but suggest that while water use efficiency is lower than for introduced commercial tree species, this is also associated with relatively low water use in indigenous tree species (Fig. 4).

Preliminary studies of water use and growth based on a limited range of indigenous forests, plantations and single trees have convincingly demonstrated the potential for new forms of forestry based on indigenous species that may supplement commercial forests where environmental concerns exist. Compared to introduced tree species, indications are that indigenous species use substantially less water, show a lower water use efficiency, and grow more slowly. However, advantages to such indigenous systems potentially include lower management costs, higher product values, a wider range of non-wood products and a lower hydrological impact which is often not accounted for in economic assessments. Possible applications of these results include the establishment of indigenous trees on sensitive sites (riparian zones, water-stressed catchments, land cleared of alien plants, land with a high erosion risk, degraded forest) to improve land management, protect biodiversity, help sustain catchment water yields and bring additional income to land-owners.

Looking back

Water use concerns, primarily associated with the rapid expansion of the commercial forestry industry, led to the initiation of catchment hydrological research in South Africa in 1935. This resulted in the establishment of a number of hydrological research stations in the high-rainfall regions of the country, and initiated the era of paired catchment experiments. Long-term paired-catchment trials aimed at assessing the impacts on streamflow associated with land use changes (primarily afforestation with introduced plantation tree species) were conducted over a period of approximately 50 years (Scott et al., 2000). This period was initially characterised by data-capture efforts, with little focus on wider-scale and more strategic aspects such as integrated water resource management. However, once sufficiently long data sets had been accumulated, detailed analyses were subsequently carried out, resulting in the development of a number of tools, such as the CSIR curves (Scott and Smith, 1997), to estimate the impacts of afforestation on streamflow at larger scales. Research during

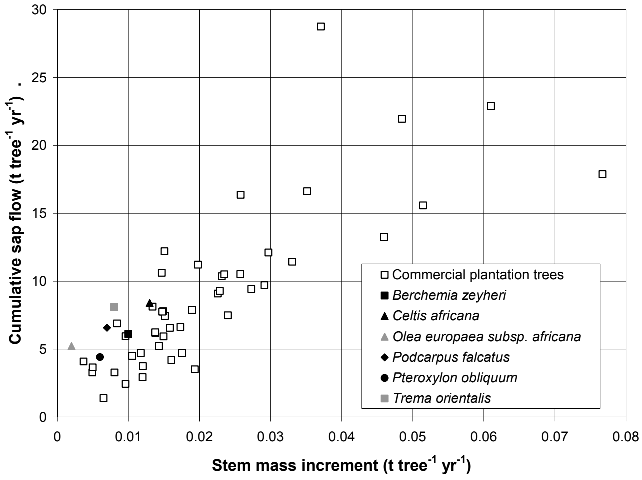

Figure 4
A comparison between 1-year stem mass increment and 1-year total sap flow, for introduced commercial plantation trees (Olbrich et al., 1996; Dye et al., 2001) and selected South African indigenous trees (Gush and Dye, 2009)

this period was still based on a catchment water-balance approach, where streamflow changes associated with particular treatments to the catchment were the primary interest, as opposed to an understanding of the individual hydrological processes causing those streamflow changes. This prompted Bosch and Von Gadow (1990) to caution that catchment experimental results should be utilised for broad-scale decision-making only, and that decisions at a finer scale required more detailed understanding of aspects such as seasonal effects and variation in ET. Scott et al. (1999) concluded that streamflow response was an integration of all hydrological processes in the catchment, and that individual processes were therefore likely to remain inadequately explained in paired catchment comparisons. Consequently, in the late 1980s/early 1990s, direct measurements of various hydrological processes started to receive more attention. At the same time, greater recognition emerged of the significance of evaporative losses from land surfaces in South Africa, and a need arose to assess these losses (Dye and Bosch, 2000). Researchers recognised the importance of understanding entire catchment hydrological processes and the impact of land use on all these processes, specifically the link between streamflow and evaporative losses from surfaces. Consequently, by the mid-1990s micrometeorological methods such as the Bowen ratio energy balance and eddy covariance techniques were increasingly applied to estimate evaporative losses from land surfaces. Advances in technology (computers, etc.) required to process the vast amounts of data generated by these techniques, as well as the availability of specialist expertise, facilitated the estimation of total evaporation in this way. It was also around this time that the concepts of 'blue' and 'green' water were first introduced (Falkenmark et al., 1999). 'Green' water represents transpiration (beneficial) and evaporation (non-beneficial) losses from surfaces, while 'blue' water represents streamflow and groundwater recharge. Within the same decade, the National Water Act (Act No. 36 of 1998) was promulgated, which required that 'water resources be managed, protected and used (developed, conserved and controlled) in an equitable way which is beneficial to the public'. This effectively enacted the need to understand transpiration (plant water use) and evaporative losses from different land uses, especially since it was proposed that water be managed at a

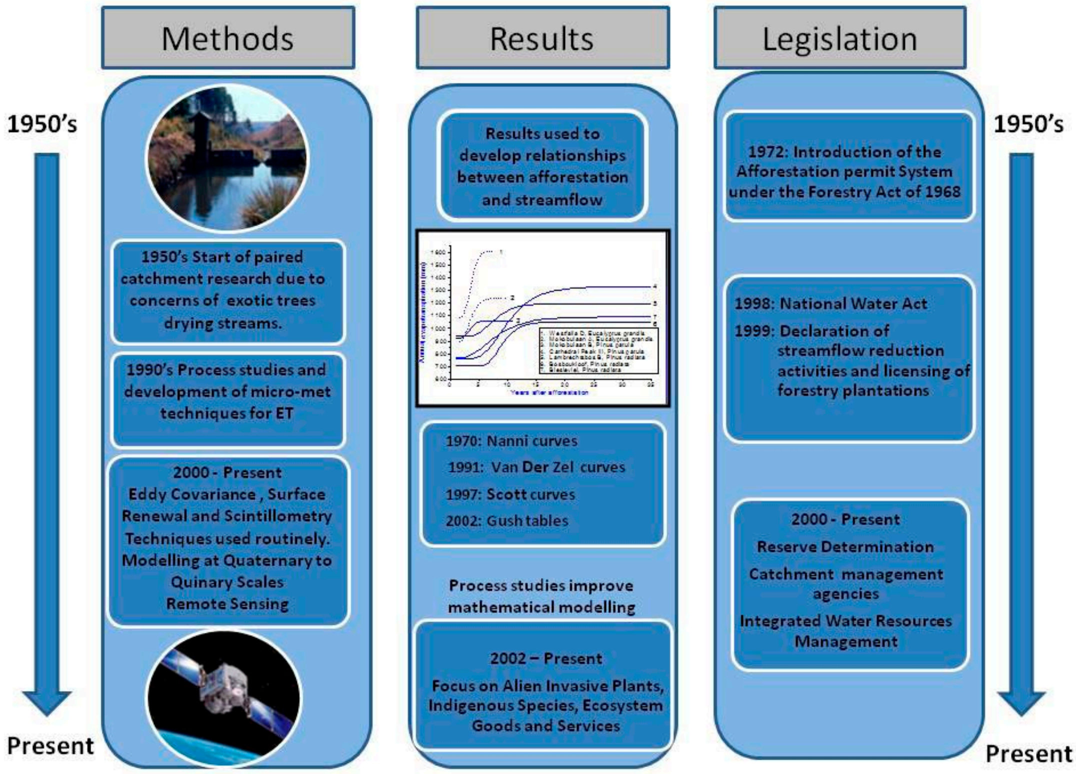

Figure 5
Schematic representation of key elements associated with estimating the impacts of land use change on water resources

catchment level. At the same time a need for greater integration of land, water and ecological resources was identified, for catchment management to be effectively implemented (*National Water* Resource *Strategy (*NWRS) – DWAF, 2004). The implementation of integrated water resource management (IWRM) is not without its own challenges (Biswas, 2004), particularly the availability of adequate data and information to facilitate decision-making. In this respect, a limitation in the quantification of green water losses for IWRM was the fact that most techniques only quantified the losses provided by 'point' estimates of total evaporation. This exacerbated the problem of extrapolating these losses to larger scales. However, with the introduction to South Africa in early 2000 of more spatially representative measurement techniques such as scintillometry (Savage et al., 2010), as well as remote sensing-based evaporation estimation techniques (Jarmain et al., 2009), assessment and verification of the impacts of land use on water resources over wider spatial scales became achievable (Fig. 5). This created opportunities for spatially distributed data on evaporation losses to be integrated with streamflow and rainfall data, thereby facilitating IWRM.

Looking forward

The environmental challenges facing future researchers and water resource managers are represented by the 'rim' of the wheel illustrated in Fig. 6. In order to meet these challenges, it is essential that the 'hub' of the wheel functions effectively, with a smooth interface ('the cogs') between good governance, research funding and capacity-building which are ultimately all inter-dependent (Fig. 6). Increasing population pressures on land and water resources in South Africa are set to continue into the future as growing demand for products and resources exceeds the capacity of present land use systems. An improvement in efficiency of land use systems is required to maximise the use of scarce water resources in particular, to increase productivity and minimise resource degradation. A detailed understanding of the impacts of land-management practices on watershed services (streamflow, sediment yield and water quality) and the study of their ecosystem processes is necessary to quantify resource utilisation and attain maximum efficiencies. Studies on a wider range of sites are required to obtain a greater level of precision in estimating the hydrological impacts of land use systems at a catchment scale. Such information is required to permit improved decision-making on optimal land use. South Africa encompasses a wide range of climate, soil conditions, and land use practices, and the large variety of permutations ensure that much remains to be investigated. Improvements in evaporation-measurement systems are required to make such assessments less costly, less intensive, and more practical for wider deployment. Future work is likely to see a greater emphasis on the use of remote-sensing techniques to improve the measurement of spatial evaporation at catchment scale. Validation studies at ground level will remain crucial to prove the accuracy of new techniques.

Global climate change is a challenge faced by all the countries of the world and it is generally recognised that water is one of the primary resources which will be impacted in an already water-scarce country such as South Africa (Fig. 6). Clearly the challenges faced by the South African water sector will be compounded by the uncertainties and risks associated with the increasing periodicity of droughts and floods.

Bioenergy in all its different forms is seen as a future solution to the reduction of greenhouse gas emissions in South Africa. Biofuels and biogas are options that are being researched and proposed by the South African Government through identification of optimal growing areas that will not conflict with food production and water supply (Fig. 6). This will require spatial mapping using technologies such as remote

http://dx.doi.org/10.4314/wsa.v37i5.15
Available on website http://www.wrc.org.za
ISSN 0378-4738 (Print) = Water SA Vol. 37 No. 5 WRC 40-Year Celebration Special Edition 2011
ISSN 1816-7950 (On-line) = Water SA Vol. 37 No. 5 WRC 40-Year Celebration Special Edition 2011

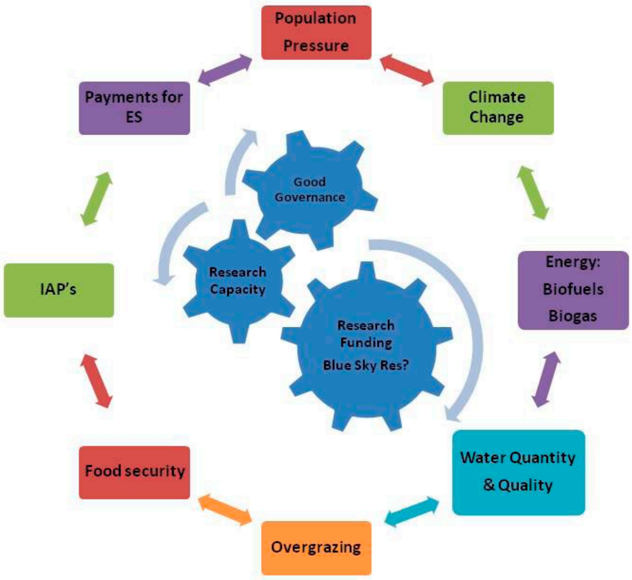

Figure 6
Challenges facing the management of land and water resources in South Africa for the next 40 years

sensing, extensive knowledge of crop water use and the application of hydrological modelling to predict the impacts of planting biofuels on water resources. In the case of biogas, the need for integrative crop, livestock and energy solutions will be necessary to alleviate poverty of resource-poor farmers. Research on the potential of agroforestry systems as a possible solution needs to be a priority in the future. Agroforestry can also reduce the impacts of overgrazing (Fig. 6) by providing alternative fodder for livestock and promoting food security by provision of fruit and nuts.

South Africa is faced with unique challenges in the prevention of water pollution. The extent of this problem is compounded by the mining industry (acid mine drainage); agriculture (non-point source pollution); non-compliance of municipal wastewater treatment plants combined with increasing abstraction; rapidly increasing population growth; urbanisation and increased water abstractions. As a result, a 'water-quality crisis' of unprecedented proportions in South Africa's history is facing the country (Fig. 6). This will only be solved through strong legislative mechanisms, political will, good governance and research. From a plant water use perspective further research on the use of trees with the potential to use excess water in mining areas, waste-disposal sites and in riparian buffer strips is required to ameliorate the impacts of high pollution loads.

Morris (2011) noted that the global importance of the ecosystem services provided by rangelands (e.g. water and nutrient cycling, fodder and energy production, erosion control, carbon sequestration, biological diversity) has not yet been fully recognised. In addition, the links between the different components of multifunctional rangelands have received little research attention. Since livestock production is already an important component of many smallholder farming systems, farmers need to develop innovative ways to capitalise on the use of low-cost natural resources to increase production and food security (Fig 6). Research also needs to address ways to overcome the potentially negative impacts (e.g. erosion and loss of biodiversity) of unsustainable grazing and fire regimes on the quality and quantity of watershed services.

The large-scale invasion of previously pristine catchments by invasive alien plants (IAPs) has been shown to reduce streamflow more than that which would occur under naturally vegetated conditions. This is attributed to the faster growing rates (additional biomass) and water use efficiency attributed to alien species. The Working for Water Programme (Turpie et al., 2008) is a good example of an innovative solution to returning rivers to their natural flow regimes through the removal of invasive alien plants, thus increasing the runoff from the catchment and, to a lesser extent generally, the yield of the dams. However, there are still many unanswered questions on the best management practices to restore and rehabilitate these degraded catchments after removal of invasive alien plants (Fig. 6). Amongst other things, there is a need for further work on the impacts of IAPs on groundwater, as well as the water use efficiency of different replacement land use/vegetation types, taking into account the impact of their selection and management on the quality and quantity of watershed services.

South Africa's innovative job-creation programme for the removal of invasive alien plants embedded in the Working for Water (WfW) Programme has formed the ground-breaking basis for the initiative on 'Rewards for Ecosystem Services'. The pilot project, whereby rural communities were paid for rehabilitating degraded catchment areas, was originally funded by DWA, but since April 2011 the WfW Programme has been administered by DEA. This innovation needs further research on potential indicators for 'Rewards for Ecosystem Services' (e.g. water quality, water quantity, runoff and basal cover). In addition, the capacity of communities to monitor the impacts of rehabilitation on water resources needs to be included in future research projects.

From the preceding list of challenges it is clear that scientists in South Africa are faced with a multitude of interconnected challenges which will ultimately depend on the 'cogs' of good research (including blue sky research and access to funding), capacity-building and good governance at all government levels. These will have a positive impact on water resource planning and management for the effective implementation of the National Water Act (1998).

References

ABRAHA MG and SAVAGE MJ (2008) Seasonal Water Use Assessment of *Jatropha curcas*. Unpublished report, University of KwaZulu-Natal, Pietermaritzburg, South Africa.

AUGUSTUS GDPS, JAYUBALAN M and SEILER GJ (2002) Evaluation and bioinduction of energy components of *Jatropha curcas*. *Biomass Bioenerg.* **23** 161-164.

BISWAS AK (2004) Integrated water resources management: A reassessment. *Water Int.* **29** (5) 248-256.

BOSCH JM and VON GADOW K (1990) Regulating afforestation for water conservation in South Africa. *S. Afr. For. J.* **153** 41-54.

BRAUMAN KA, DAILY GC, DUARTE TK and MOONEY HA (2007) The nature and value of ecosystem services: An overview highlighting hydrologic services. *Ann. Rev. Environ. Resour.* **32** (1) 67-98.

BURGESS SSO, ADAMS MA, TURNER NC, BEVERLY CR, ONG CK, KHAN AAH and BLEB TM (2001) An improved heat pulse method to measure low and reserve rates of sap flow in woody plants. *Tree Physiol.* **21** 589-598.

DWAF (DEPARTMENT OF WATER AFFAIRS AND FORESTRY (DWAF) (2004) National Water Resource Strategy (1st edn.). September 2004. Department of Water Affairs and Forestry, Pretoria, South Africa.

DYE PJ and BOSCH JM. (2000) Water, wetlands and catchments In: Owen DL (ed.) *South African Forestry Handbook*. South African Institute of Forestry. 567-573.

DYE PJ and VERSFELD D (2007) Managing the hydrological impacts of South African plantation forests: An overview. *For. Ecol. Manage.* **251** 121-158.
DYE PJ, GUSH MB, EVERSON CS, JARMAIN C, CLULOW A, MENGISTU M, GELDENHUYS CJ, WISE R, SCHOLES RJ, ARCHIBALD S and SAVAGE MJ (2008) Water Use in Relation to Biomass of Indigenous Tree Species in Woodland, Forest and/or Plantation Conditions. WRC Report No. 1462/1/08. Water Research Commission, Pretoria, South Africa.
DYE PJ, VILAKAZI P, GUSH MB, NDLELA R and ROYAPPEN M (2001) Investigation of the Feasibility of Using Trunk Growth Increments to Estimate Water Use of *Eucalyptus grandis* and *Pinus patula* Plantations. WRC Report No. 809/1/01. Water Research Commission, Pretoria, South Africa.
EVERSON CS (2000) The water balance of a first order catchment in the montane grasslands of Natal. *J. Hydrol.* **24** 110-123.
EVERSON CS, MOLEFE GL and EVERSON TM (1998) Monitoring and Modelling Components of the Water Balance in a Grassland Catchment in a Summer Rainfall Area of South Africa. WRC Report No. 493. Water Research Commission, Pretoria, South Africa.
EVERSON CS, ANDERSSON C, EVERSON TM and GHEHEZI S (2007) Growth and water use of a *Jatropha*/Kikuyu silvopastoral system for the production of biofuel and fodder. *Proc. International Committee on Irrigation and Drainage (ICID), 2nd African Regional Conference*, 6 November 2007, Johannesburg, South Africa.
EVERSON CS (2009) The effect of the introduction of agroforestry species on the soil moisture regime of traditional cropping systems in rural areas. Phase II: on farm trials of alternative agroforestry systems. Annual Progress Report for WRC Project No. K5/1351, 5 March 2009. Water Research Commission, Pretoria, South Africa.
EVERSON C, GHEHEZI S, EVERSON TM and ANNANDALE J (2011) Agroforestry systems for improved food production through the efficient use of water. Final report for WRC Project No. K5/1480, presented at WRC Reference Group Meeting, 16 November 2011. Water Research Commission, Pretoria, South Africa.
FALKENMARK M, ANDERSSON L, CASTENSSON R and SUNDBLAD K (1999) *Water – A Reflection of Land Use. Options for Counteracting Land and Water Mismanagement*. Swedish Natural Science Research Council, Stockholm, Sweden.
GODSMARK R (2009) The South African Forestry and Forest Products Industry: 2008. Annual Report: Forestry South Africa. URL: http://www.forestry.co.za/website_industry_data/#.
GUSH MB (2008) Measurement of water use by *Jatropha curcas* L. using the heat pulse velocity technique. *Water SA* **34** (5) 579-583.
GUSH MB and DYE PJ (2009) Water use efficiency within a selection of indigenous and exotic tree species in South Africa as determined using sap flow and biomass measurements. *Acta Hort.* **846** 323-330. http://www.actahort.org/books/846/846_37.htm.
HOLL MA, GUSH MB, HALLOWES J and VERSFELD DB (2007) *Jatropha curcas* in South Africa: An Assessment of its Water Use and Bio-Physical Potential. WRC Report No. 1497/1/07. Water Research Commission, Pretoria, South Africa.
JARMAIN C, MENGITSU M, JEWITT GPW, KONGO V and BASTIAANSSEN W (2009) A Methodology for Near-Real Time Spatial Estimation of Evaporation. WRC Report No.1751/1/09, Water Research Commission, Pretoria, South Africa.
JEWITT G (2002) Can integrated water resources management sustain the provision of ecosystem goods and services? *Phys. Chem. Earth* **27** 887-895.
JEWITT G (2006) Integrating blue and green water flows for water resources management and planning. *Phys. Chem. Earth*, Parts A/B/C **31**(15-16) 753-762.
JONGSCHAAP REE, BLESGRAAF RAR, BOGAARD TA, VAN LOOA EN and SAVENIJE HHG (2009) The water footprint of bioenergy from *Jatropha curcas* L. *Proc. National Academy of Sciences of the United States of America* **106** (35) 92.
LE MAITRE DC, O'FARRELL PJ and REYERS B (2007a) Ecosystems services in South Africa: a research theme that can engage environmental, economic and social scientists in the development of sustainability science? *S. Afr. J. Sci.* **103** 367-376.
LE MAITRE DC, MILTON SJ, JARMAIN C, COLVIN CA, SAAYMAN I and VLOK JH (2007b) Landscape-scale hydrology of the Little Karoo: linking ecosystems, ecosystem services and water resources. *Front. Ecol. Environ.* **5** 261-270
LUNDGREEN B and RAINTREE JB (1982) Sustained agroforestry. In: Nestel B (ed). *Agricultural Research for Development: Potentials and challenges in Asia.* ISNAR, The Hague. 37-49.
MENGISTU MG (2008) Heat and Energy Exchange above Different Surfaces using Surface Renewal. Ph.D. Thesis. University of KwaZulu-Natal, Pietermaritzburg, South Africa. 151 pp.
MOHIBBE AZAM M, WARIS A and NAHAR NM (2005) Prospects and potential of fatty acid methyl esters of some non-traditional seed oils for use as biodiesel in India. *Biomass Bioenerg.* **29** 293-302.
MORRIS CD (2011) Rangeland management for sustainable conservation of natural resources. In: Lemaire G, Hodgson J & Chabbi A (eds.) *Grassland Productivity and Ecosystem Services*. CABI Publishing, Wallingford, UK.
OLBRICH B, OLBRICH K, DYE PJ and SOKO S (1996) A Year-Long Comparison of Water Use Efficiency of Stressed and Non-Stressed *E. grandis* and *P. patula*: Findings and Management Recommendations. CSIR report FOR-DEA 958. CSIR, Pretoria, South Africa.
OPENSHAW K (2000) A review of *Jatropha curcas*: an oil plant of unfulfilled promise. *Biomass Bioenerg.* **19** 1-15.
PARFIT M (2005) Future Power: Where will the world get its next energy fix? *National Geographic* **208** 2-31.
SANBI (2011) *The Grasslands Programme*. URL: http://www.sanbi.org/index.php? Option = com_content & view = article&id =291&Itemid=115 (Accessed 5 July, 2011).
SAVAGE MJ, ODHIAMBO GO, MENGISTU MG, EVERSON CS and JARMAIN C (2010) Measurement of grassland evaporation using a surface-layer scintillometer. *Water SA* **36** (1) 1-8.
SCOTT DF (1999) Managing riparian zone vegetation to sustain streamflow: Results of paired catchment experiments in South Africa. *Can. J. For. Res.* **29** 1149-1157.
SCOTT DF AND SMITH RE (1997) Preliminary empirical models to predict reductions in annual and low flows resulting from afforestation. *Water SA* **23** 135-140.
SCOTT DF, LE MAITRE DC and VAN WYK E (1999) The effects of forestry on low-flows: further studies on low-flow in wet and dry cycles and in relation to catchments of increasing size. CSIR Contract Report No. ENV/S-C 99059. CSIR, Pretoria, South Africa.
SCOTT DF, PRINSLOO FW, MOSES G, MEHLOMAKULU M and SIMMERS ADA (2000) A Re-analysis of the South African Catchment Afforestation Experimental Data. WRC Report No. 810/1/00. Water Research Commission, Pretoria, South Africa.
SEYDACK AHW (1995) An unconventional approach to timber yield regulation for multi-aged, multi-species forests (1): Fundamental considerations. *For. Ecol. Manage.* **77** 139-153.
TURPIE JK, MARAIS C and BLIGNAUT JN (2008) The working for water programme: Evolution of a payments for ecosystem services mechanism that addresses both poverty and ecosystem service delivery in South Africa. *Ecol. Econ.* **65** 788-798.
WISE RM, DYE PJ and GUSH MB (2011) A comparison of the biophysical and economic water use efficiencies of indigenous and introduced forests in South Africa. *For. Ecol. Manage.* **262** 906-915.