# Quantifying the economic water savings benefit of water hyacinth (*Eichhornia crassipes*) control in the Vaalharts Irrigation Scheme

**RS Arp[1]*, GCG Fraser[1] and MP Hill[2]**
[1]*Department of Economics and Economic History, Rhodes University, Grahamstown, 6140, South Africa*
[2]*Department of Zoology and Entomology, Rhodes University, Grahamstown, 6140, South Africa*

## ABSTRACT

Global freshwater resources are threatened by an ever-growing population and continued economic development, highlighting the need for sustainable water management. Sustainable management must include the control of any additional factors that may aggravate water scarcity, such as invasive alien plants. Water hyacinth (*Eichhornia crassipes*), one of the world's most destructive invasive plants, presents a direct threat to economically productive water resources. Through high levels of evapotranspiration, water hyacinth leads to substantial water losses that could otherwise be used more productively, thereby creating an externality on water-dependent industries, such as irrigation-fed agriculture. This study provides an economic valuation of the water-saving benefit of water hyacinth control, using Warrenton Weir on the Vaalharts Irrigation Scheme as a case study. A Residual Value Method was employed to estimate the average production value of irrigation water, based on water's relative proportion of total costs (TC), to serve as a proxy for the value of water lost via evapotranspiration by water hyacinth. Three evapotranspiration to evaporation ratios, derived from the literature, at three levels of invasion (100; 50 and 25% cover), were used to estimate the annual water loss at Warrenton Weir. The average production value of irrigation water was estimated to be R38.71/$m^3$, which translated into an annual benefit of between R54 million and R1.18 billion. These results highlight the need for invasive plant control, particularly in economically productive water resources. An alien plant control policy should prioritise invasions of this nature, as they present significant costs to the economy and threaten the sustainability of freshwater resources.

**Keywords:** sustainability, water resources, water hyacinth, water loss, externality, benefit, control

## INTRODUCTION

Water is an irreplaceable and indispensable natural resource, vital for life on earth, economic development and human well-being (Walter et al., 2011). Water demand for agriculture, and urban and industrial consumption continue to grow in the light of continued economic development, an ever-increasing global population and new demands for biofuel production (Walter et al., 2011; Saseendran et al., 2014 and Rosegrant et al., 2009). These anthropological pressures, coupled with ongoing climate change and ecosystem degradation, present a significant threat to the planet's freshwater resources, highlighting the importance of sustainable water management, at both global and local scales. The control of any additional factors that may reduce water quality, quantity or productivity must form part of broader water management programmes for effective sustainable management (De Fraiture et al., 2010).

One such additional factor is the threat presented by invasive alien species, particularly invasive alien plants (IAPs). The Millennium Ecosystem Assessment (MEA) identified invasive species as one of five of the most significant threats to the provision of ecosystem goods and services, including freshwater resources (MEA, 2005). According to Emerton and Howard (2008), invasive species can aggravate ecosystem degradation and water scarcity. Invasion by IAPs is a global phenomenon, which carries a host of environmental and socio-economic implications, particularly detrimental to water-stressed countries (Villamagna and Murphy, 2010; Van Wilgen et al., 2008; Hulme, 2009; Turpie, 2004; IUCN, 2000; Pejchar and Mooney, 2009).

South Africa is not immune to the IAP problem and is said to be one of the worst-affected countries in the world, with plant invasions costing R580 million annually in water-provisioning services (De Lange and Van Wilgen, 2010; Richardson and Van Wilgen, 2004). The impact of IAPs is especially concerning for water resource management, given South Africa's semi-arid climate and relative water scarcity. Compared to a global average annual rainfall of 860 mm, South Africa only receives an average of 450 mm, highlighting the fact that water is a limiting resource in South Africa (Cowling et al., 1997).

Water hyacinth (*Eichhornia crassipes*) is one of the most destructive aquatic weeds in the world and presents an indirect threat to economically productive water resources, such as irrigation water (Van Wilgen et al., 2008; Villamanga and Murphy, 2010). Through high levels of evapotranspiration and resulting water loss, water hyacinth may erode water and irrigation productivity, placing a negative externality on irrigation-fed agriculture. Despite contributing only 2.5% (R84.7 billion) to South Africa's primary production in 2014, agriculture is an important employer of labour and a significant consumer of the country's freshwater resources (RSA, 2015; Nieuwoudt et al., 2004). Irrigation water, specifically, contributes roughly 30% towards the country's total agricultural output and is directly impacted by the threat of IAPs such as water hyacinth (Nieuwoudt et al., 2004). Considering the economic importance of irrigation water, and its relative scarcity, the threat presented by water hyacinth needs to be controlled. To do so, an economic valuation of water hyacinth and its control is needed to justify the allocation of scarce funds and resources between competing control projects (Turpie, 2004). This paper provides such an economic valuation of the economic water-saving benefit of water hyacinth control, using the Vaalharts Irrigation Scheme, fed by Warrenton Weir on the Vaal River,

* To whom all correspondence should be addressed.
Tel: +27 82 560 5525; e-mail: arpyrsa@gmail.com
*Received 12 January 2016; accepted in revised form 24 November 2016*

http://dx.doi.org/10.4314/wsa.v43i1.09
Available on website http://www.wrc.org.za
ISSN 1816-7950 (Online) = Water SA Vol. 43 No. 1 January 2017

as a case study. Few studies have attempted to analyse or value the indirect impacts of invasive weeds, particularly water loss from water hyacinth. Thus, the aim of the study was to estimate the value of irrigation water in terms of agricultural production, which was used as a proxy for quantifying the economic water-saving benefit of water hyacinth control. This included estimating the net annual water loss from water hyacinth at three evapotranspiration to evaporation (ET:EW) ratios, within three invasion scenarios that reflect varying degrees of water hyacinth cover at Warrenton Weir.

## Water hyacinth (*Eichhornia crassipes*)

Since the early 20th century, water hyacinth has spread to all major water bodies across South Africa and follows a similar distribution to that of other IAPs (Hill, 2003). The weed carries a number of negative environmental and socio-economic impacts, from reducing dissolved oxygen and biodiversity in invaded water bodies, to obstructing transport routes and fishing ground accessibility. It forms large mats on the surface of water bodies, generally leading to increased water loss through evapotranspiration (ET) relative to 'normal', open-water evaporation (EW) (Villamanga and Murphy, 2010). Water hyacinth can therefore result in an unnecessary loss of water, which could otherwise be used in a more productive manner (Richardson and Van Wilgen, 2004; Van Wilgen et al., 2008; Villamagna and Murphy, 2010 and Singh and Gill, 1996).

There is, however, much debate surrounding the ET rate of water hyacinth relative to normal EW rates. Numerous authors (Table 1) suggest that the ET:EW ratio is larger than one, implying more water is lost from water hyacinth than 'normal' open-water evaporation. ET:EW ratios from various studies around the world have been summarised in Table 1.

The ET rate of any hydrophyte is difficult to measure and is dependent on a number of variables, including climate, nutrient availability and plant growth rate (Crundwell, 1986). Allen et al. (1996) suggests that the ET:EW ratios reported in Table 1 may be somewhat larger than one would expect to find in reality. This is due to the 'clothesline' or 'boundary effect', where the small size of experimental ponds increases the surface area of peripheral foliage, thereby increasing evapotranspiration. In reality, evapotranspiration for large areas of water hyacinth coverage is expected to be lower in the absence of the clothesline effect (Allen et al., 1996).

Van Wyk and Van Wilgen (2002) used an average evapotranspiration rate of 5 mm/day to estimate the cost of water loss in the Hartbeespoort Dam. The annual water loss accruing to water hyacinth infestations in the dam was estimated to be about 37 million m$^3$, at a cost of R3.7 million (Van Wyk and Van Wilgen, 2002). Had the authors used different rates of evapotranspiration, such as the 21 mm/day suggested by Singh and Gill (1996), their cost estimates would have increased significantly. This highlights the complexity of economic valuations of water loss from water hyacinth and shows the importance of using a universally agreed upon ET rate for such evaluations. Alternatively, different scenarios, illustrating the variation in costs relative to variations in invasion density and evapotranspiration rates, should be presented.

Acknowledging the negative impacts of water hyacinth, specifically water loss, puts into perspective the necessity of controlling the weed. (Hill, 2003; Van Wyk and Van Wilgen, 2002). A number of control programmes have been used across South Africa, with varying degrees of success. In 1990, 200 adult weevils (*Neochetina eichhorniae*) were introduced into New Year's Dam in the Eastern Cape, which, at the time, was almost completely covered by the invasive weed (Fraser et al., 2016). This programme successfully saved 2 million m$^3$ of water at an estimated value of R8 million over a 22-year period. The cost effectiveness of the control programme at New Year's Dam was not economically viable at low ET:EW ratios; yet at higher ET:EW ratios the programme was economically justified (Fraser et al., 2016). However, had the marginal value of water been used instead of the supply cost of water, and other impacts from the weed included, such as effects on biodiversity (Midgley et al., 2006) and damage to infrastructure, the control programme would have been justified even at low ET:EW ratios (Fraser et al., 2016).

Warrenton Weir, which supplies the Vaalharts Irrigation system with water, is another example of a water body where water hyacinth infestations were successfully reduced. An integrated control method, using aerial spraying in conjunction with biocontrol, was implemented at the weir in 2001. Since then, the control programme has continued to be used with great success and the weed is limited to small populations along the edges of the weir (Coetzee, 2015 and Coetzee and Hill, 2012).

**TABLE 1**
**ET:EW ratios for water hyacinth**

| ET:EW ratios | Reference |
|---|---|
| 1.02 | Brenzny et al. (1973) |
| 1.02 | Singh and Gill (1996) |
| 1.3 | Rao (1988) |
| 1.31 | Snyder and Boyd (1987) |
| 1.36 | Brenzny et al. (1973) |
| 1.44 | Van de Weert and Kamerling (1974) |
| 1.48 | Van de Weert and Kamerling (1974) |
| 1.79 | Van de Weert and Kamerling (1974) |
| 1.96 | Rao (1988) |
| 2.3 | Reddy and Tucker (1983) |
| 2.52 | Snyder and Boyd (1987) |
| 2.6 | Dunigan (1973) |
| 2.73 | Lallana et al. (1987) |
| 2.9 | Reddy and Tucker (1983) |
| 3 | Benton et al. (1978) |
| 3.1 | Otis (1914) |
| 3.2 | Penfold and Earle (1948) |
| 3.7 | Timmer and Weldon (1967) |
| 5.3 | Rogers and Davis (1972) |
| 9.8 | Singh and Gill (1996) |

### Economic valuation

An important part of the economic analysis of invasive species is the valuation of their relative costs and benefits (Emerton and Howard, 2008; Turpie, 2004). Economic valuation is the process by which a monetary value is assigned to items that people care for, including both market and non-market goods and services (Hanemann, 2005). In doing so, economic valuation aims to determine individuals' preferences and their willingness to pay (WTP) for certain goods and services (Emerton and Howard, 2008). Valuation must therefore not be seen as the end, but rather a means to an end, providing better and more informed decision making (Emerton and Howard, 2008).

Economic valuation plays a crucial role in measuring the relative success of invasive species control programmes needed to justify continued funding for such programmes. This is especially important given the competition from other social development programmes and limited funds. According to Van Wilgen et al. (2004), the most commonly used approach to determining the feasibility of control programmes is benefit–cost analysis. This involves valuing and comparing the costs and benefits of different control programmes to ensure scarce resources are allocated efficiently among competing projects (Turpie, 2004; Emerton and Howard, 2008).

The benefits of water hyacinth control programmes are essentially 'avoided costs' of no control – in other words, the benefits gained from reducing water hyacinth populations (Hosking and Du Preez, 2004). There are numerous benefits of water hyacinth control, from increased biodiversity (Coetzee et al., 2014) to various 'water benefits', which include both improved water quality and water savings (Hosking and Du Preez, 2004). Water-saving benefits refer to the prevention of water loss through evapotranspiration. These water-saving benefits can be measured by estimating the value of the water lost from evapotranspiration – the focus of this paper. The use of the water in question will dictate both the valuation technique used (either market or non-market) and the value of the water (Tietenberg and Lewis, 2014 and Chowdhury, 2013). For example, the water saving benefits from water hyacinth control, established in a recreational dam or river, might simply be an increase in water available for the natural reserve or the increased use of the dam or river for recreational activities. This would require a non-market valuation technique to estimate the value of the water and thus the water saving benefit of control (Tietenberg and Lewis, 2014 and Chowdhury, 2013). If, however, water hyacinth was established in an irrigation dam, the water-saving benefit of control would be increased water supply for agricultural production. A market-valuation technique can be used within this context to estimate the production value of irrigation water to infer the water-saving benefit of water hyacinth control.

There are several economic valuation methods available to value both market and non-market goods and services that are affected by invasive species. However, the focus of this paper is to evaluate how water hyacinth impacts agricultural production, thus an 'effect on production' technique was required. Effect-on-production techniques are used to value ecosystem goods and services that form part of the production process for other marketed goods, such as valuing irrigation water that forms part of the crop production process (Emerton and Howard, 2008; Emerton and Bos, 2004).

## METHODS

### Site description

The Vaalharts Irrigation Scheme is the largest and most productive irrigation scheme in South Africa (RSA, 2008). It has a semi-arid climate with a mean annual precipitation of between 450 and 470 mm. The scheme is situated approximately 100 km north of Kimberley and sits on the border between the Northern Cape and North West Province (Fig. 1). The scheme supplies approx. 35 000 ha with irrigation water and produces about R2 billion in agricultural production every year (RSA, 2008; Erasmus. 2015).

There is a wide range of crops grown within the scheme and their relative distribution for 2015 is depicted in Fig. 2. Eight major crops were selected for the study, which represent 98% of the cultivated area (Erasmus, 2015). It must be noted that representation was based on cultivated area rather than gross farm income. Smaller crops such as grapes, citrus, olives

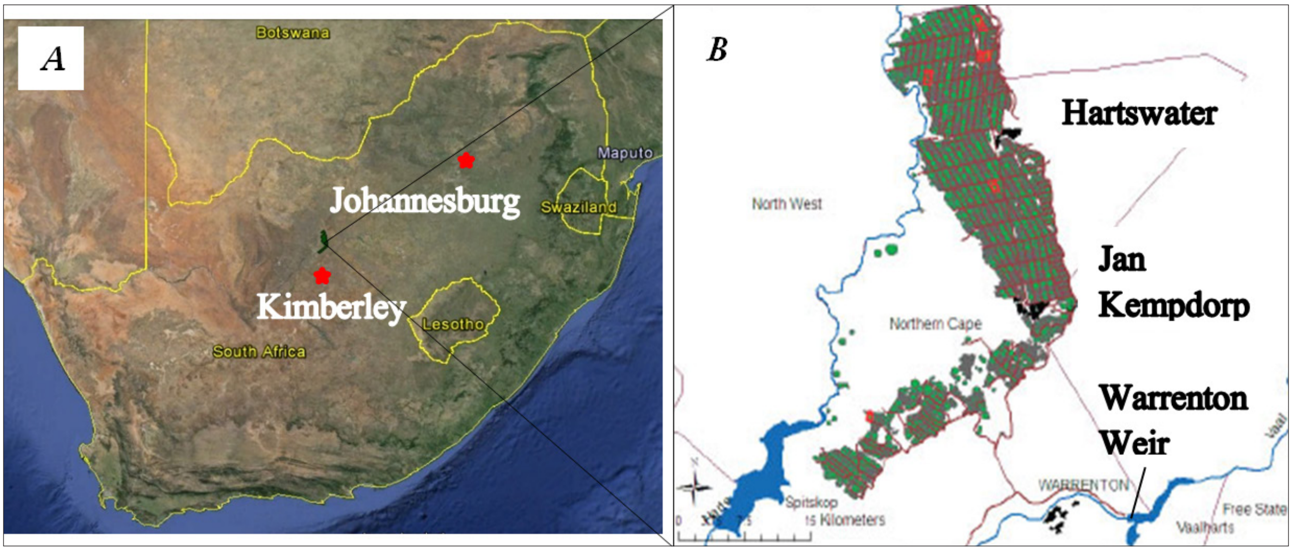


***Figure 1***

*A: Map illustrating the location of the VHIS in South Africa (27°47'58" E; 24°47'24"E) (Arp, 2015).*
*B: Map of the Vaalharts Irrigation Scheme (Adapted from Van Rensburg et al., 2011).*

http://dx.doi.org/10.4314/wsa.v43i1.09
Available on website http://www.wrc.org.za
ISSN 1816-7950 (Online) = Water SA Vol. 43 No. 1 January 2017

and various vegetable crops were included as 'other' within Fig. 2 and accounted for less than 2% of the cultivated area (Erasmus, 2015).

Warrenton Weir, just south of the scheme, diverts water from the Vaal River to the scheme and has a surface area of roughly 900 ha, with a storage capacity of approximately 45 million $m^3$ (Van Vuuren, 2012; Coetzee, 2015). The majority of the water released from the weir is used for agriculture and environmental flow, while the remainder is supplied to small towns in the area (Harbron, 2015). Warrenton Weir, as discussed previously, has been a successful site for long-term water hyacinth monitoring and control, making it a suitable study site for this research (Coetzee et al., 2011).

### Data collection

Primary crop production data was sourced from three agricultural co-operatives, which represented crop water requirements, production yields, prices and various input costs that farmers would generally expect to receive each year. These data were used to estimate the production value of irrigation water for each of the major crops listed in the previous section. Irrigation data were based on extensive research conducted by each of the co-operatives and are based on the water requirements for each crop in an average rainfall year. It was evident from farmer interviews and discussions that farmers are extremely dependent on agricultural co-operatives for assistance in a number of areas. For this reason, data collected from the co-operatives were assumed to be a good representation of crop input and output data for the Vaalharts region. There was no reason to doubt the reliability of data gathered from agricultural co-operatives, as the co-operatives' relative success is dependent on their farmers' success and thus they must work in the best interests of their clients/farmers.

Secondary data on water hyacinth ET:EW ratios were collected from a number of different sources in the literature (Table 1). The average annual evaporation rate for the Vaalharts region was sourced from Midgley et al. (1994), which provided average annual evaporation rates for different regions across South Africa.

### Estimating the average production value of irrigation water

The Residual Value Method (RVM) was used to estimate the average value of irrigation water for each of the eight crops listed previously. These eight crops account for 98% of the total cultivated area under irrigation and, therefore, provided a suitable representation of revenue and cost structures farmers face within the scheme. The RVM described here was based on the following assumptions: (Hussain et al., 2009; Berbel et al., 2011, Lange et al., 2006; Speelman et al., 2008).

- Farmers were assumed to be profit maximizers and the competitive equilibrium, therefore, set price equal to the return at the margin (MC = P).
- Adapted primary data obtained from agricultural co-operatives was assumed to be representative of the costs and returns to production experienced by farmers. This assumption was based on the apparent dependency of farmers on the co-operatives.
- The price associated with a particular variable was assumed to be its marginal productivity, or opportunity cost, such that the total value of output is divided into portions equal to each inputs' contribution to production.
- All markets were assumed to be competitive, except for water.
- The average production value of water was estimated as its contribution to the total value of production, based on its proportion of total costs.

The total value of production was assumed to be equal to the opportunity costs of all inputs, such that:

$$TVP = \Sigma P_i Q_i + P_w Q_w \quad (1)$$

where:

$TVP$ = total value of production/ha
$P_i$ = price/ha of all non-water inputs
$Q_i$ = quantity/ha of all non-water inputs
$P_w$ = average value of water/ha
$Q_w$ = the volume of water applied/ha

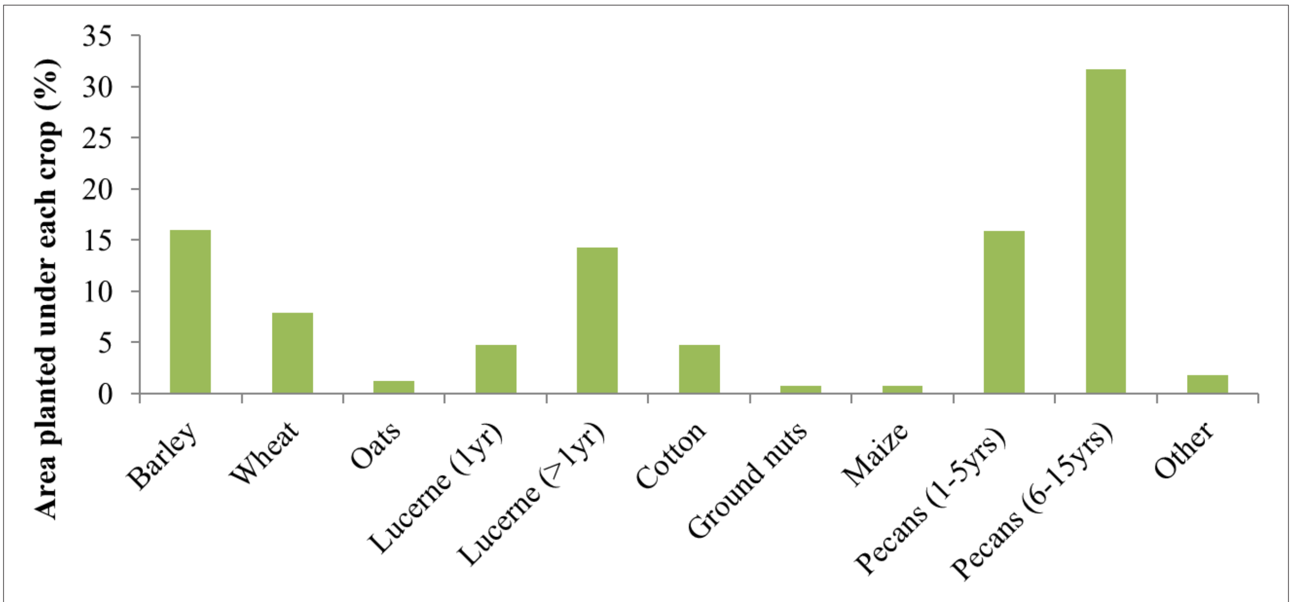


***Figure 2***
*Relative crop distribution of the Vaalharts Irrigation Scheme for 2015 as a percentage of the total cultivated area (Adapted from Erasmus, 2015)*

Data obtained from agricultural co-operatives provided both prices and quantities per hectare for all inputs into the production process for each of the eight major crops. Crop-specific input data (such as fertilizer, seed, fuel, etc.) was first aggregated, before estimating the average value of water for that particular crop. Labour, however, was omitted from the calculations since farmers only employ 1 labourer/25 ha for pre-harvest work and therefore labour costs did not have a significant influence on average water values.

A crop budget, expressed as Eq. 2, was developed for each crop type. Lucerne and pecan nuts were divided into two age groups such that lucerne crops in their first year were labelled 'Lucerne (1st year)' and lucerne crops in their second or third year were labelled 'Lucerne (> 1 year)'. Immature pecan nuts were labelled 'Pecans (1 – 5 years)' and mature pecan nuts were labelled 'Pecans (6 – 15 years)'. This was done to account for variations in input costs, such as seed and fertilizer, and output, which vary according to the age of the crop. For example, immature pecan nut trees do not produce output until their fourth or fifth year, after which output grows rapidly with each additional year (Erasmus, 2015).

The opportunity cost (OC) of non-water inputs was assumed to be given by their prices. Thus, the price, or average value, of water was calculated as water's contribution to TVP based on its proportion of TC. The estimated average value of water is given by:

$$AV_w = ((TC_w / TC)^* \, TVP) / Q_w \qquad (2)$$

where:

$AV_w$ = average value of water
$TC_w$ = total cost of water
$TC$ = total costs
$TVP$ = total value of output
$Q_w$ = quantity of water used in production

The crops' water values were then aggregated based on the relative distribution of each crop. This aggregated water value was then used in the final calculations to estimate the value of water lost through evapotranspiration and, therefore, to estimate the water-saving benefit of water hyacinth control.

### Quantifying the benefit of control

To account for the discrepancies in the ET:EW ratios presented in the literature and to reflect variations in climate and nutrient availability, three EW:ET ratios were developed. The 25th, 50th and 75th percentiles of ET:EW ratios selected from the literature were chosen to reflect conservative, moderate and extreme ET/EW ratios and are presented in Table 2.

Midgley et al. (1994) provided evaporation data needed to calculate the average annual open-water evaporation rate for Warrenton Weir. The mean annual evaporation rate (MAE) (mm) for the Vaalharts region was first multiplied by monthly evaporation percentages to obtain mean monthly evaporation rates (mm). Each of these monthly rates were then multiplied by the corresponding month's pan factor for open-water evaporation to obtain an average monthly open-water evaporation rate (mm) for the region. These were then summed to provide a mean annual open-water evaporation rate, which was then multiplied by the area of Warrenton Weir to provide an annual water loss volume for 'normal open-water evaporation'. This normal open-water evaporation rate for Warrenton Weir was then

**TABLE 2**
**Conservative, moderate and extreme ET:EW ratios selected for estimating water loss from water hyacinth**

| | Conservative | Moderate | Extreme |
|---|---|---|---|
| Selected ET:EW ratio percentiles | 25th | 50th | 75th |
| corresponding ET:EW ratios | 1.38 | 2.41 | 3.08 |

multiplied by each of the three ET:EW ratios, to provide three 'gross' water loss volumes resulting from evapotranspiration by water hyacinth.

Three scenarios were then developed to reflect varying degrees of water hyacinth cover at Warrenton Weir, at 100, 50 and 25% cover. The area covered by water hyacinth, in each of the three scenarios, was then multiplied by the three evapotranspiration rates to provide nine estimates of the 'gross' mean annual water loss from water hyacinth. Finally, to estimate the OC of water hyacinth, in terms of water loss, the mean annual evaporation rate (mm) was subtracted from each of the nine 'gross' average annual water loss volumes to provide nine 'net' average annual water loss volumes that occur through evapotranspiration by water hyacinth.

Finally, the nine 'net' average annual water loss values, estimated above, were multiplied by the average value of the irrigation water to estimate the cost of water loss from water hyacinth as follows:

$$WSBC_{ij} = (AV_w) \cdot ET_{ij} \qquad (3)$$

where:

$WSBC_i$ = the water-saving benefit of control for the $i^{th}$ scenario and $j^{th}$ ET/EW ratio
$AV_w$ = the average value of water for the Vaalharts
$ETij$ = the total evapotranspiration of the $i$th scenario and $j$th ET/EW ratio

This estimated cost of water loss, resulting from water hyacinth, was then used as a proxy value for the benefit of its control.

## RESULTS

The average water values (R/m³) for each of the eight main crops are illustrated in Fig. 3. Mature pecans had the highest average water value of R83/m³, while immature pecans had the lowest average water value at R1/m³. This was due to the fact that immature pecans do not produce output until their fifth year and thus do not generate an income.

The average value of irrigation water for the Vaalharts Irrigation Scheme as a whole was estimated to be R38.71/m³. This amount was based on the weighted average value of water for each crop.

To account for variations in nutrient availability and climate, three ET:EW ratios were identified from the literature at the 25th; 50th and 75th percentiles, representing conservative, moderate and extreme ratios. A conservative ET:EW ratio, computed as the 25th percentile, was 1.38, while a moderate and extreme ET:EW ratio, computed as the 50th and 75th percentile, was 2.41 and 3.08, respectively. The mean annual evaporation rate for the Vaalharts region was 1 950 mm (Midgley et al., 1990). The mean annual open-water evaporation rate for the region, after adjusting the

http://dx.doi.org/10.4314/wsa.v43i1.09
Available on website http://www.wrc.org.za
ISSN 1816-7950 (Online) = Water SA Vol. 43 No. 1 January 2017

mean annual evaporation rate for pan factors, was 1 637.66 mm. Warrenton Weir is approximately 900 ha, therefore, the average annual water loss, via normal open-water evaporation, for the weir was estimated to be 14.7 million m³.

Under 100% cover (indicated in light red in Fig. 4), gross water loss ranges from 20.3 million m³ to 45.3 million m³, depending on the ET:EW ratio. Between 10 million m³ and 22. million m³ of water are estimated to be lost under 50% cover (indicated in light blue), and under 25% cover (light green) the gross water loss was between approx. 5 million m³ and 11.3 million m³.

After accounting for normal open-water evaporation, the maximum net water loss from water hyacinth ranged from 5.6 million m³ to 30.6 million m³ under 100 % cover (depicted in dark red in Fig. 4). With only half the weir covered, net water loss ranged between 2.8 million m³ and 15.3 million m³ (dark blue). The minimum net water loss was estimated to be between 1.4 million m³ and 7.6 million m³ at 25% cover (dark green).

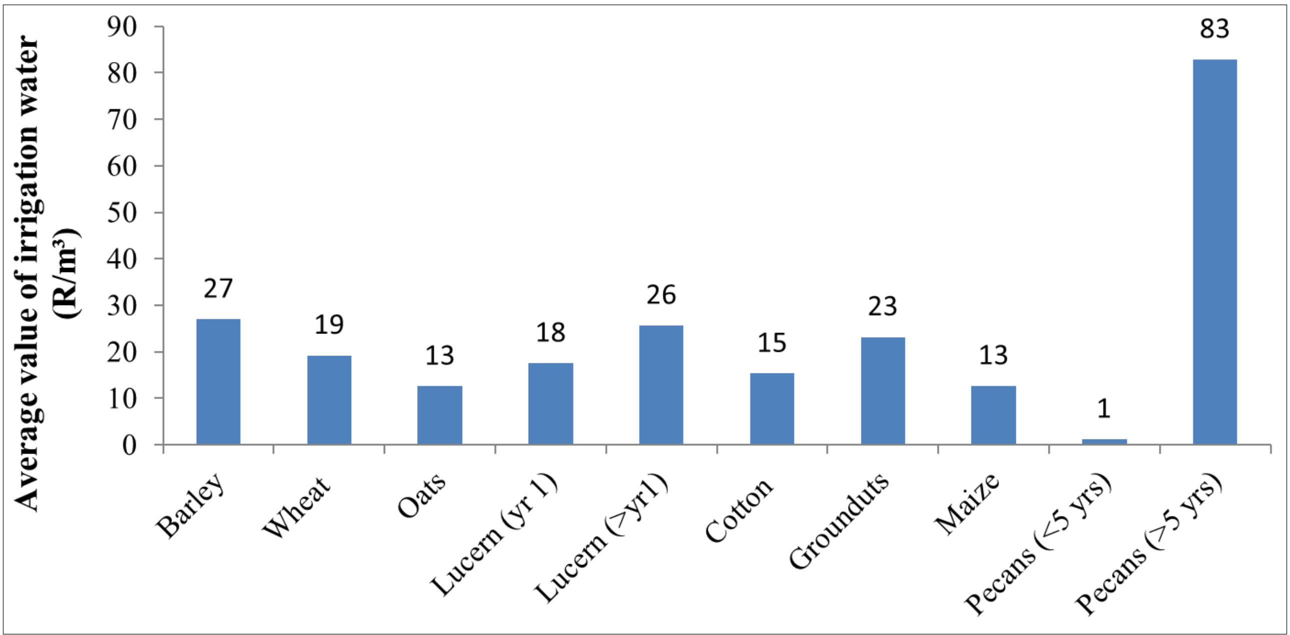


***Figure 3***

*The average value of irrigation water (R/m3) for each of the major crops in the Vaalharts Irrigation Scheme*

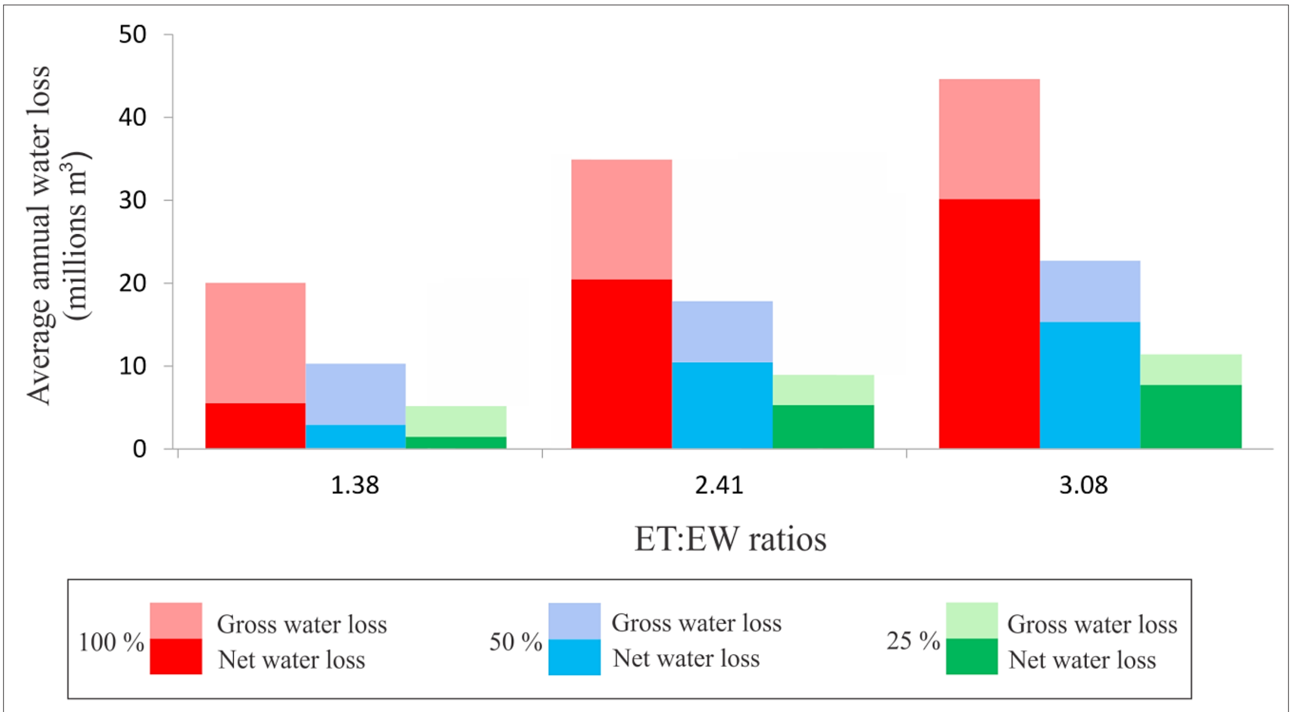


***Figure 4***

*Average annual 'gross' and average annual 'net' water loss (millions m3) from evapotranspiration by water hyacinth for 100; 50 and 25% cover of Warrenton Weir, at three ET:EW ratios*

The net OC of water hyacinth in each of the three scenarios is tabulated below, using a proxy value for irrigation water of R38.71/m$^3$. The net average annual OC of water loss ranges between R216 million and R1.18 billion under 100% cover, depending on the ET:EW ratio. Under 50% cover, the average annual OC of water hyacinth ranges between R108 million and R591 million. An OC of between R54 million and R295 million was estimated at 25% water hyacinth cover. The average net water loss per m$^2$ of water hyacinth cover was estimated to be 0.62 m$^3$; 2.3 m$^3$ and 3.4 m$^3$ at each of the three ET:EW ratios. This equated to an average annual net OC of R24; R89 and R132/m$^2$ of water hyacinth cover, respectively.

**TABLE 3**
**Annual net opportunity cost (R/m$^3$) of water loss from evapotranspiration by water hyacinth at Warrenton Weir**

| ET:EW ratio | Annual net opportunity cost of water loss (R/m$^3$) | | |
|---|---|---|---|
| | Water hyacinth cover | | |
| | 100% | 50% | 25% |
| 1.38 | 216 642 600 | 108 321 300 | 54 160 650 |
| 2.41 | 804 224 700 | 402 112 350 | 201 056 175 |
| 3.08 | 1 183 523 400 | 591 761 700 | 295 880 850 |

## DISCUSSION AND CONCLUSION

This paper presents an economic valuation of water hyacinth control in the Vaalharts Irrigation Scheme, focusing specifically on the water-saving benefits of control. The average production value of irrigation water was estimated to be approximately R38.71/m$^3$, indicating substantial benefits of water hyacinth control. By comparison, biological control of the weed in a less productive water source, such as New Year's Dam in the Eastern Cape, was justified at a conservative water value of R0.26/m$^3$ (Fraser et al., 2015). This suggests that control at Warrenton Weir will also be justified, given the high value of irrigation water.

Table 3 summarised the annual net OC of water hyacinth at three invasion scenarios (100; 50 and 25% cover), using three different ET:EW ratios (1.38; 2.41 and 3.08). This net OC of water loss is the water-saving benefit of water hyacinth control, which ranged from as much as R1.18 billion to about R54 million. It is important to note that the results reported in the previous section are based on the particular crop distribution and associated prices of 2015. With annual changes in price, and the associated changes in crop distribution, the production value of water (and hence the benefit of control) will fluctuate. This is due to the dependency of the valuation method on market prices and various assumptions. The reader must also be aware that another disadvantage with the RVM is that it computes the average value of water, which generally provides inflated and unrealistic results (Hanemann, 2005). Thus, the results reported in this paper must be understood within the limitations of the valuation method used.

In the worst-case scenario, using an ET:EW ratio of about 3 and at 100% cover, the benefit of control was valued at just over R1.18 billion. However, due to the various limitations associated with the valuation method, and the fact that the average value of water tends to be inflated, this value may not be a true reflection of the benefit of control. Such a high ET:EW ratio is also an unrealistic figure to use when calculating water loss from the weed. According to Allen et al. (1996), a 'boundary' effect produces higher ET rates than would actually occur in reality (Allen et al., 1996). On this basis, it is suggested that benefits calculated using ET:EW ratios of 3 or 2.4 are inflated and unrealistic. Therefore, using a more conservative, or what Allen et al. (1996 p. 9) might call, 'a more realistic' ET:EW ratio, the benefits of control become smaller. Depending on the extent of invasion, water hyacinth created a negative externality on the Vaalharts Irrigation Scheme that ranged between R216 million (at 100% cover) and R54 million (at 25% cover) using an ET:EW ratio of about 1.4. Therefore, water hyacinth has the potential to reduce agricultural productivity by 11% under full invasion of Warrenton Weir; by 5% if half the weir is invaded and by 3% if water hyacinth covers a quarter of the weir. This suggests that control programmes, which reduced water hyacinth coverage to almost 0%, generated an annual benefit of R216 million. Therefore, for every square metre of water hyacinth cleared, the return is approximately R24. Once again, this is specific to 2015 and may fluctuate depending on a number of influential factors, including prices, inflation, crop distributions, climate and nutrient availability.

Critics would argue that such high benefits are meaningless without comparing them to the associated costs of control, by means of a full cost–benefit analysis. Unfortunately, due to a lack of cost data for control programmes at Warrenton Weir, a full cost–benefit analysis could not be conducted as part of this research. However, it is possible to formulate an idea of the typical annual costs that such a control programme might face. These would include direct cost, such as annual surveys, herbicidal applications and travel costs, as well as indirect costs, such as developing control agents (Hill, 2015). Hill (2015) suggests that the control programme at Warrenton Weir carries an annual cost of about R1.6 million.

A conservative benefit value of R54 million is substantially larger than a typical annual cost of R1.6 million, thereby justifying water hyacinth control at Warrenton Weir. Even if the benefit value was reduced by a factor of 4, making it R13.5 million, it is still substantially larger than the costs of control. Therefore, even at a conservative benefit value, reduced by a factor of 4, water hyacinth control is still justified, albeit not proven by means of a full cost–benefit analysis.

Regardless of the inability to confidently prove the cost effectiveness of water hyacinth control at Warrenton Weir, the water-saving benefits speak for themselves. If agricultural water losses, from one irrigation system, are valued at R54 million per annum, one can only imagine the value of water loss from the agricultural sector as a whole. Water losses from invasions within other sectors, such as manufacturing, mining and industry activities, would presumably generate substantially larger economic losses per unit of water than that of agriculture. However, whether this is true in absolute terms is uncertain and may provide a window for further research.

The methods used within this research can easily be adapted for quantifying the benefits of various other control programmes and species. Economic valuations of this kind afford important insight into how scarce resources and funds can be allocated more effectively, thus providing another step towards improved water management and IAP control.

The results of this paper indicate the need for alien plant control programmes, especially in economically productive water systems. This is not only in an attempt to reduce unnecessary water loss, but also to reduce the economic impact of various invasive plants. IAP control policy should, therefore, prioritise those invaded systems that support important economic activity, such as agriculture, mining and industry.

## ACKNOWLEDGEMENTS

Special thanks to the National Research Foundation (NRF); the Environmental and Natural Resource Economics Focus Area (ENREFA), as part of the Department of Economics and Economic History at Rhodes University and to the DEA:NRM: WFW Programme. Funding for this work was provided by the South African Research Chairs Initiative of the Department of Science and Technology and the National Research Foundation of South Africa. Any opinion, finding, conclusion or recommendation expressed in this material is that of the authors and the NRF does not accept any liability in this regard.


## REFERENCES


ALLEN JR LH, SINCLAIR TR and BENNETT JM (1996) Evapotranspiration of vegetation of Florida: perpetuated misconceptions versus mechanistic processes. *Soil Crop Sci. Soc. Florida* **56** 18–20.

BENTON AR, JAMES WP and ROUSE JW (1978) Evapotranspiration from water hyacinth (*Eichhomia Crassipes* (Mart.) Solms) in Texas Reservoirs *J. Am. Water Resour. Assoc.* **14** (4) 919–930. https://doi.org/10.1111/j.1752-1688.1978.tb05588.x

BERBEL J, MESA-JURADO MA and PISTON JM (2011) Value of irrigation water in Guadalquivir Basin (Spain) by residual value method. *Water Resour. Manage.* **25** 1565–1579. https://doi.org/10.1007/s11269-010-9761-2

BREZNY O, MEHTA I and SHARMA RK (1973) Studies on evapotranspiration of some aquatic weeds. *Weed Sci.* **21** (3) 197–204.

CHOWDHURY NT (2013) Marginal product of irrigation expenses in Bangladesh. *Water Resour. Econ.* **4** 38–51. https://doi.org/10.1016/j.wre.2013.11.002

COETZEE F (2015) Personal communication, 31 March 2015. Mr. Floors Coetzee, Junior Scheme Manager, Vaalharts Water Association, Northern Cape, South Africa 8550. https://doi.org/10.4001/003.019.0202

COETZEE JA, HILL MP, BYRNE MJ and BOWNES A (2011) A review of the biological control programmes on *Eichhornia crassipes* (C. Mart.) Solms (Pontederiaceae), *Salvinia molesta* D.S.Mitch. (Salviniaceae), *Pistia stratiotes* L. (Araceae), *Myriophyllum aquaticum* (Vell.) Verdc. (Haloragaceae) and *Azolla filiculoides* Lam. (Azollaceae) in South Africa. *Afr. Entomol.* **19** (2) 451–468. https://doi.org/10.4001/003.019.0202

COETZEE JA and HILL MP (2012) The role of eutrophication in the biological control of water hyacinth, *Eichhornia crassipes*, in South Africa. *BioControl* **57** (2) 247–261. https://doi.org/10.1007/s10526-011-9426-y

COETZEE JA, JONES RW and HILL MP (2014) Water hyacinth, *Eichhornia crassipes* (Pontederiaceae), reduces benthic macroinvertebrate diversity in a protected subtropical lake in South Africa. *Biodiv. Conserv.* **23** 1319–1330. https://doi.org/10.1007/s10531-014-0667-9

COWLING RM, RICHARDSON DM and PIERCE SM (1997) *The Vegetation of South Africa.* Cambridge University Press, Cambridge.

CRUNDWELL ME (1986) A review of hydrophyte evapotranspiration. Horizon Documentation. URL: http://horizon.documentation.ird.fr/exl-doc/pleins_textes/ cahiers/hydrob-trop/25121.pdf. (Accessed 11 May 2014).

DE FRAITURE C, MOLDEN D and WICHELNS D (2010) Investing in water for food, ecosystems, and livelihoods: An overview of the comprehensive assessment of water management in agriculture. *Agric. Water Manage.* **97** (4) 495–501. https://doi.org/10.1016/j.agwat.2009.08.015

DE LANGE WJ and VAN WILGEN BW (2010) An economic assessment of the contribution of biological control to the management of invasive alien plants and to the protection of ecosystem services in South Africa. *Biol. Invasions* **12** 4113–4124. https://doi.org/10.1007/s10530-010-9811-y

DUNIGAN EP (1973) Nitrogen and phosphorus uptake and evapotranspiration losses by water hyacinths. In: Report of Projects for 1973. Department of Agronomy, Louisiana State University, Baton Rouge, LA.

EMERTON L and BOS E (2004) *Value: Counting Ecosystems as an Economic Part of Water Infrastructure.* IUCN, Gland and Cambridge. https://doi.org/10.2305/IUCN.CH.2004.WANI.3.en

EMERTON L and HOWARD G (2008) *A Toolkit for the Economic Analysis of Invasive Species.* Global Invasive Species Programme, Nairobi.

ERASMUS B (2015) Personal communication, 18 August 2015. Mr Barry Erasmus, Agriculturalist: Projects. Hartswater: South African Breweries. Northern Cape, South Africa 8570.

FRASER G, HILL MP and MARTIN J (2016) Economic evaluation of water loss saving due to the biological control of water hyacinth at New Year's Dam, Eastern Cape province, South Africa. *Afr. J. Aquat. Sci.* http://dx.doi.org/10.2989/16085914.2016.1151765

HANEMANN M (2005) The value of water. University of California, Berkeley. URL: http://www.ctec.ufal.br/professor/vap/Valueofwater.pdf. (Accessed 10 April 2014).

HARBRON K (2015) Personal communication, 7 September 2015. Mr Kobus Harbron, Scheme Manager, Vaal-Harts Water Association, Jan Kempdorp. Northern Cape, South Africa, 8550.

HILL M (2015) Personal communication, 20 October 2015. Professor Martin Hill, Head of Entomology, Department of Zoology and Entomology, Rhodes University. Eastern Cape, South Africa 6140.

HILL MP (2003) The impact and control of alien aquatic vegetation in South African aquatic ecosystems. *Afr. J. Aquat. Sci.* **28** (1) 19–24. https://doi.org/10.2989/16085914.2003.9626595

HOSKING SG and DU PREEZ M (2004) The valuation of water for conservation projects in South Africa. *Dev. South. Afr.* **21** (2) 385–398. https://doi.org/10.1080/0376835042000219604

HULME PE (2009) Trade, transport and trouble: managing invasive species pathways in an era of globalization. *J. Appl. Ecol.* **46** (1) 10–18. https://doi.org/10.1111/j.1365-2664.2008.01600.x

HUSSAIN I, SIAL MH, HUSSAIN Z and AKRAM W (2009) Economic value of irrigation water: evidence from a Punjab canal. *Lahore J. Econ.* **14** (1) 69–84.

IUCN (International Union for the Conservation of Nature) (2000) *Guidelines for the Prevention of Biodiversity Loss Caused by Alien Invasive Species.* IUCN, Gland.

LALLANA VH, SABATTINI R A and LALLANA MDC (1987) Evapotranspiration from *Eichhornia crassipes*, *Pistia stratiotes*, *Salvini A herzogii* and *Azolla caroliniana* during summer in Argentina. *J. Aquat. Plant Manage.* **25** 48–50.

LANGE GM (2006) Case studies of water valuation in Namibia's commercial farming areas. In: Lange GM and Hassam R (eds). *The Economics of Water Management in Southern Africa: An Environmental Accounting Approach.* Edward Elgar Publishing, Chelthenham. 237–255. https://doi.org/10.4337/9781847203021.00017

MIDGLEY DC, PITMAN WV and MIDDLETON BJ (1994) Surface water resources of South Africa 1990. Volume II, Appendices. WRC Report No 298/2.1/94. Water Research Commission, Pretoia.

MIDGLEY JM, HILL MP and VILLET MH (2006) The effect of water hyacinth, *Eichhornia crassipes* (Martius) Solms-Laubach (Pontederiaceae), on benthic biodiversity in two impoundments on the New Year's River, South Africa. *Afr. J. Aquat. Sci.* **31** (1) 25–30. https://doi.org/10.2989/16085910609503868

MILLENNIUM ECOSYSTEM ASSESSMENT (2005) *Ecosystems and human well-being: synthesis.* Island Press, Washington, DC.

NIEUWOUDT WL, BACKEBERG GR and DU PLESSIS HM (2004) The value of water in the South African economy: some implications. *Agrekon* **43** (2) 162–183. https://doi.org/10.1080/03031853.2004.9523643

OTIS CH (1914) The transpiration of immersed water plants: its measurement and its relationships. *Bot. Gaz.* **58** 457–494. https://doi.org/10.1086/331451

PEJCHAR L and MOONEY HA (2009) Invasive species, ecosystem services and human well-being. *Trends Ecol. Evol.* **24** (9) 497–504. https://doi.org/10.1016/j.tree.2009.03.016

PENFOLD WT and EARLE TT (1948) The biology of water hyacinth. *Ecol. Monogr.* **18** 447–472. https://doi.org/10.2307/1948585

RAO AS (1988) Evapotranspiration rates of *Eichhornia crassipes* (Mart.) Solms, *Salvinia molesta* DS Mitchell and *Nymphaea lotus* (L.) Willd. Linn. in a humid tropical climate. *Aquat. Bot.* **30** (3) 215–222. https://doi.org/10.1016/0304-3770(88)90052-6

REDDY KR and TUCKER JC (1983) Productivity and nutrient uptake of water hyacinth, *Eichhornia crassipes* I. Effect of nitrogen source. *Econ. Bot.* **37** (2) 237–247. https://doi.org/10.1007/BF02858790
RSA (REPUBLIC OF SOUTH AFRICA) (2008) Revitalisation of the Vaal-Harts/Taung Irrigation Scheme. Agriculture Engineering Services, Pretoria.
RSA (REPUBLIC OF SOUTH AFRICA) (2015) Abstract of Agricultural Statistics. Department of Agriculture, Forestry and Fisheries, Pretoria.
RICHARDSON DM and VAN WILGEN BW (2004) Invasive alien plants in South Africa: How well do we understand the ecological impacts? *S. Afr. J. Sci.* **100** (1) 45–52.
ROGERS HH and DAVIS DE (1972) Nutrient removal by water hyacinth. *Weed Sci.* **21** (5) 423–428.
ROSEGRANT MW, RINGLER C AND ZHU T (2009) Water for agriculture: maintaining food security under growing scarcity. *Ann. Rev. Environ. Resour.* **34** 205–222. https://doi.org/10.1146/annurev.environ.030308.090351
SASEENDRAN SA, AHUJA LR, MA L, TROUT TJ, MCMASTER GS, NIELSEN DC, HAM JM, ANDALES AA, HALVORSON AD, CHAVEZ JL and FANG QX (2014) Developing and normalizing average corn crop water production functions across years and locations using a system model. *Agric. Water Manage.* **157** 65–77. https://doi.org/10.1016/j.agwat.2014.09.002
SINGH S and GILL MS (1996) Evapo-transpiration loss of water hyacinth (*Eichhornia crassipes*) and chemical control of weed. *Ind. J. Agric. Sci.* **66** (8) 487–489.
SNYDER RL and BOYD CE (1987) Evapotranspiration by *Eichhornia crassipes* (Mart.) Solms and *Typha latifolia* L. *Aquat. Bot.* **27** (3) 217–227. https://doi.org/10.1016/0304-3770(87)90042-8
SPEELMAN S, FAROLFI S, PERRET S, D'HAESE L and D'HAESE M (2008) Irrigation water value at small-scale schemes: evidence from the North West Province, South Africa. *Water Resour. Dev.* **24** (4) 621–633. https://doi.org/10.1080/07900620802224536
TIETENBERG T and LEWIS L (2014) *Environmental and Natural Resource Economics* (9th edn.). Pearson, Cape Town.
TIMMER CE and WELDON LW (1976) Evapotranspiration and pollution of water by water hyacinth. *Hyacinth Control J.* **6** 34–37.
TURPIE J (2004) The role of resource economics in the control of invasive alien plants in South Africa. *S. Afr. J. Sci.* **100** (1) 87–93.
VAN DER WEERT R and KAMERLING G E (1974) Evapotranspiration of water hyacinth (*Eichhornia crassipes*). *J. Hydrol.* **22** (3) 201–212. https://doi.org/10.1016/0022-1694(74)90075-4
VAN RENSBURG LD, DE CLERCQ WP, BARNARD JH and DU PREEZ CC (2011) Salinity guidelines for irrigation: case studies from Water Research Commission projects along the lower Vaal, Riet, Berg and Breede rivers. *Water SA* **37** (5) 739–749. https://doi.org/10.4314/wsa.v37i5.11
VAN VUUREN L (2012) Water savings: persistence pays off at Vaalharts: Commercial Irrigation. *The Water Wheel* **11** (1) 20–23.
VAN WILGEN BW, DE WIT MP, ANDERSON HJ, LE MAITRE DC, KOTZE IM, NDALA S and RAPHOLO MB (2004) Costs and benefits of biological control of invasive alien plants: case studies from South Africa: working for water. *S. Afr. J. Sci.* **100** (2) 113–122.
VAN WILGEN BW, REYERS B, LE MAITRE DC, RICHARDSON DM and SCHONEGEVEL L (2008) A biome-scale assessment of the impact of invasive alien plants on ecosystem services in South Africa. *J. Environ. Manage.* **89** (4) 336–349. https://doi.org/10.1016/j.jenvman.2007.06.015
VAN WYK E and VAN WILGEN BW (2002) The cost of water hyacinth control in South Africa: a case study of three options. *Afr. J. Aquat. Sci.* **27** 141–149. https://doi.org/10.2989/16085914.2002.9626585
VILLAMAGNA AM and MURPHY BR (2010) Ecological and socio-economic impacts of invasive water hyacinth (*Eichhornia* crassipes): a review. *Freshwater Biol.* **55** (2) 282–298. https://doi.org/10.1111/j.1365-2427.2009.02294.x
WALTER T, KROOS J and TSEGAI D (2011) Options for improving water use efficiency under worsening scarcity: evidence from the middle Olifants sub-basin in South Africa. *Water SA* **37** (3) 357–370. https://doi.org/10.4314/wsa.v37i3.68487