# Estimating stream-flow reduction due to invasive alien plants: Are we getting it right?

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Alien vegetation, especially large invasive trees such as eucalyptus, pines and wattles, is known to reduce streamflow to less than that which would occur under naturally vegetated conditions. This is due to the additional biomass and greater rooting depth than natural vegetation, resulting in greater evapotranspiration. There are numerous models, methods and rules-of-thumb to estimate streamflow reduction due to invasive alien plants (IAPs) currently being applied within South Africa. However, these methods result in a very wide range of estimates of streamflow reduction. The result of this is that very often the impact of IAPs is over-estimated and, more importantly, the increase in yield due the removal of the IAPs is over-estimated. Since the removal of IAPs to increase the available water resource within water-stressed catchments is increasingly being considered as a possible water resources reconciliation option, it is important to make accurate estimates of this increase but crucial not to overestimate this increase since this will inadvertently lead to increased water-stress within the catchment in question. This paper describes a fundamental hydrological principle against which streamflow reduction due to IAPs can be tested. This test is then applied within a test catchment to several of the methods currently in use. A proposed way forward to estimating streamflow reduction due to IAPs is described and applied within the test catchment.

Keywords: Invasive alien vegetation, streamflow reduction, water resources

## Introduction

Alien vegetation, especially large invasive trees such as eucalyptus, pines and wattles, is known to reduce streamflow to less than that which would occur under naturally vegetated conditions. This is due to the additional biomass and greater rooting depth than indigenous species, resulting in greater evapotranspiration. In areas in which grassland dominates under natural conditions, the evergreen nature of trees is also an important factor since the trees continue to use water through winter while grasslands become dormant and use very little or no water during winter.

A considerable amount of research has been carried out in South Africa into streamflow reduction. This has for the most part been undertaken on commercial afforestation, but much of the research is also applicable to invasive alien vegetation. While this research has consistently shown that replacing indigenous grassland with large exotic trees results in a reduction in the natural streamflow, various models (and modellers) provide a wide range of estimates of the magnitude of this reduction.

A somewhat controversial water use licence application which entailed exchanging water freed up from the removal of IAPs in the upper reaches of the Olifants River catchment for use on a mine has been used as a case study and is reported on in this paper. The interesting aspect of this case study is the huge variation in estimates of streamflow reduction due to the removal of the alien vegetation. During the course of the Olifants Reconciliation Strategy study, commissioned by the Department of Water Affairs, this variation prompted the hypothesis that with such great variation in estimates, some of the estimates must be incorrect, for whatever reason. This led to a 'back-to-basics' look at streamflow reduction in order to ascertain if there is some hydrological parameter which limits the streamflow increase when IAPs are removed. This hydrological parameter is described in this paper and applied within the test catchment in the upper reaches of the Olifants River. The outcome of this analysis suggests that many of the methods applied to the mine

licence application overestimate the increase in runoff due to the removal of IAPs, some by a factor as much as three.

Streamflow increase due to the removal of IAPs in itself is not a particularly useful parameter for decision making relating to licence applications. The streamflow increase will result in an increase in yield, but the calculation of the increase in yield is not trivial since numerous factors play a role. Methods to convert streamflow increase to utilisable yield are discussed briefly in this paper.

## Techniques used to estimate streamflow reduction due invasive alien plants

There are numerous methods for estimating the streamflow reduction due to IAPs. These are summarised here briefly so as to provide context for the method used in the Olifants River catchment.

### Biomass Model

The Biomass model developed by Le Maitre (Le Maitre et al, 1996) estimates streamflow reduction from the knowledge of forestry water use linked to the biomass of the invasive plants relative to the biomass of the indigenous plants displaced by the IAPs. The model was developed from data collected as part of long-term studies which compared streamflow from natural fynbos catchments in the Western Cape with catchments afforested with pines. The biomass model is a simple view of vegetation water use and does not take the complexity of this process fully into account.

The advantage of this method is that it deals with three categories of IAPs, namely: tall shrubs, medium trees and tall trees, with an equation for each of these three categories. However, the model is based on data collected in only one region that is not representative of the whole country

### WRSM 2000

The WRSM 2000 Pitman model (Middleton and Bailey, 2008) uses the Biomass Model of Le Maitre (Le Maitre et al, 1996), but allows for both riparian and upland alien vegetation. However, it is not clear how WRSM2000 distinguishes between these two categories. A known shortcoming of WRSM 2000, with respect to IAPs, is that they are modelled as only having access to water from the quaternary catchment in which they are located, while in reality, IAPs located on the main stem of a river will have access to water from upstream catchments as well. This is a serious shortcoming which results in the under-estimation of the streamflow reduction attributable to riparian IAPs. This problem only becomes apparent in higher order rivers and is probably not significant in headwater catchments. A review of the streamflow reduction due to IAPs estimated using the WRSM 2000 model indicated that this model under-estimates SFR due to riparian IAPs, at least when compared to other estimates.

### ACRU

The *ACRU* Model (Smithers and Schulze, 1995) has not been used specifically to model IAPs, but has been used extensively (Gush *et. al*, 2002; Jewitt *et. al*, 2009) to model streamflow reduction due to afforestation. The results of this research are largely applicable to IAPs which are not located in the riparian zone and consist of medium and tall trees. However, the forestry simulations assumed a fixed rotation period while IAPs reach maturity and could remain in place indefinitely resulting in higher streamflow reduction than afforestation. The Gush data therefore probably represents the lower limit of streamflow reduction due to IAPs.

### Models for estimating afforestation impacts (Scott-Smith, 1997)

A basket of models has been developed over time to estimate the impact of afforestation on water resources, and by extension the impact of IAPs. These models were based on research covering a number of different forestry species (primarily pines, eucalypts and wattles) and several experimental catchments,

but did not distinguish between upland (non-riparian) and riparian SFR since the entire catchments, including the riparian zones, were afforested in these experiments.

## Hydrological constraints to streamflow reduction

Consider a hypothetical catchment which is undeveloped and largely natural with a mean annual runoff (MAR) of X mm/annum. Should this catchment be entirely taken over by an alien invader such as Eucalyptus, the reduction in runoff would tend towards X. This is apparent from the so-called Scott curves (Scott et al, 1997) which show that after about 10 year the runoff from catchments planted with Eucalyptus almost entirely ceased. See **Figure 1**. Should these alien invaders then be removed and the catchment allowed to return to its natural state, the runoff can in turn be expected to return to its natural state with a MAR of X mm/annum. Any methodology that suggests that removal of alien vegetation results in a runoff (from that treated area) to be greater than X (the natural MAR), must therefore be incorrect. The only possible exceptions to this are that over the **short-term** while the natural vegetation is re-establishing itself there will be greater runoff than natural. Also, riparian IAPs have greater access to soil moisture than upland vegetation and hence selective removal of only riparian vegetation could result in greater increase in MAR over the treated area. Riparian IAPs therefore need to be modelled separately from upland IAPs.

It is also possible that the catchment does not return to natural but is developed with housing or an airport, for example. Under this scenario there will of course be increased runoff but this cannot and should not be linked to the removal of the IAPs.



Figure 1: Reduction in streamflow due to Eucalyptus (Scott & Smith, 1997)

# Application of the Streamflow Reduction Assessment Tool to the Estimation of SFR due to IAPs

While it was argued above that there is an upper limit to the streamflow reduction due to IAPs, this is not necessarily the best estimate of this streamflow reduction since generally it will be less than this upper limit. It is suggested that upland IAPs should have a streamflow reduction only slightly higher than commercial afforestation (i.e. usually in the range 50-100 mm/annum in forestry catchments, depending on rainfall, soil

depth and species). Therefore, using the streamflow reduction models that have been developed for forestry (Jewitt, 2009; Mallory and Hughes, 2011), would provide a better estimate of the upland streamflow reduction than simply applying the maximum possible streamflow reduction. The method proposed by Mallory and Hughes (2011) is to express the streamflow reduction as a dimensionless duration curve, an example of which is given in **Figure 2**. The advantage of this is that it allows the use of streamflow reduction relationships determined using the ACRU Model to be applied within models using different hydrology. This is important since most water resource models use monthly Pitman hydrology and not *ACRU* daily hydrology, and in many cases the differences between these hydrology datasets is large.

This method was developed for DWA's sub-directorate: Streamflow Reduction in 2006 and has been applied to numerous projects but has only now been formally document by Mallory and Hughes (2011). The method allows streamflow reduction for Pine, Wattle and Eucalyptus to be differentiated and knowledge of the invading species therefore improves estimates.



Figure 2: Streamflow reduction as a dimensionless duration curve

## Water use by riparian invasive alien plants

The methodology described above and in Mallory and Hughes (2011) does not allow for riparian IAPs. Vegetation within a riparian zone, whether alien or not, generally has access to more water than vegetation that is growing upslope, not only from the river but also from groundwater which contributes to the river baseflow through the riparian zone. If a river is perennial, the riparian vegetation is likely to take up as much water as it requires from the river, and will seldom be limited by soil moisture, as is the case with non-riparian vegetation. It must be borne in mind, however, that access to water is not the only limitation to vegetation growth, with potential evapo-transpiration being one of the other major limiting factors. Non-riparian (or

upland) IAPs generally rely on rainfall to sustain their growth, which in South Africa is usually a very limiting factor.

The water use by riparian vegetation has been the topic of much research in South Africa, although much of this research has considered water use generally, and not streamflow reduction *per se*. The difference here is that streamflow reduction considers the <u>difference</u> in water use, that is, how much <u>more</u> water is being used by the IAPs, as opposed to the indigenous riparian vegetation. Considering that indigenous vegetation in riparian zones also use more water than upland vegetation, the impact of riparian IAPs on streamflow reduction can be over-stated (Dye and Jarmain, 2004).

South African forest hydrologists have for many years worked on the premise that riparian forestry has a streamflow reduction that is approximately twice that of upland vegetation (Roberts P, 2006). This was based on analyses of catchments that had been 100% afforested, with the riparian zone later cleared as a partial treatment (Smith and Bosch, 1989; Scott et al, 2000). The publication by Cullis *et al* (2007) assumed a factor of three, that is, that riparian IAPs reduce runoff by three times as much as upland vegetation. These multipliers came about from research carried out in viable forestry areas (areas of high rainfall) and are not necessarily applicable in lower rainfall areas. This is because water use by riparian vegetation is a function of the evapo-transpiration rate and access to water. Hence, IAPs along the banks of the Orange River will have a very high water use (high ET and access to water) while the streamflow reduction by upland IAPs in this same climatic region will be very low, simply because there is no runoff to reduce. Similarly, IAPs in Lesotho will have lower water usage due to the lower evapo-transpiration rate in this high-altitude region, while upland IAPs would have significant SFR due to the high rainfall, and hence high levels of available soil moisture in these catchments. The principle that is derived here is that riparian streamflow reduction can generally not be <u>directly</u> related to upland water use and upland streamflow reduction and must be considered as a separate entity with largely unrelated processes.

A review of available literature indicates that the upper limit to streamflow reduction due to riparian IAPs (in South Africa) appears to be in the order of 500 mm/annum. This would be in catchments where the indigenous vegetation is either partly deciduous, regularly burned grassland, and or has not been able to colonise the river wetlands and banks as successfully as the invader species. It must also be noted that this is a maximum estimate and that no stand of invasives is continuously at its peak evaporative stage. Invader trees tend, more than indigenous vegetation, to reach a period of peak vigour and then to become more and more moribund until some natural event (e.g. fire) renews the cycle. As is shown when modelling plantation water use, life-cycling of the vegetation significantly reduces overall water use. Based on the forestry rule-of-thumb that commercial forestry reduce runoff by about 100 mm/annum and that riparian forestry is double upland forestry (Roberts, 2006), a lower estimate of streamflow reduction due to IAPs of 200 mm/annum can be deduced.

# Water Resource Modelling to Determine the Impact of Streamflow Reduction on the Yields of the Dam

Streamflow reduction itself is not the main concern with IAPs but rather how this streamflow reduces the available water resource or yield. Since the streamflow reduction is a time series and not a single value, the impact of IAPs on system yield can only be determined through time-series simulation with the aid of a water resources model. Within the Water Resources Yield Model (WRYM) (DWAF, 2007), the user must provide the streamflow reduction as a unit runoff time series which needs to be calculated using a different model. The WRSM 2000 model can produce such a time series. WRYM does not however distinguish between upland and riparian vegetation so any scenarios relating to removal of only riparian or only upland vegetation requires the user to regenerate the streamflow reduction time series. This can be tedious and time consuming if several scenarios are required and/or the catchment is large.

The actual determination of the reduction in yield due to IAPs is also not trivial in complex catchments where the system yield is not well defined by a single dam. The determination of the impact is done by means of a 'before and after' comparative analysis with the difference in yield being accepted as the impact of the IAPs. Deciding on where to monitor the change in yield within a big system can be the biggest challenge since

IAPS are often widespread through the catchment and the impact on different users is seldom uniform within a catchment. The approach taken in the Olifants River catchment was to simplify the system down to the large dams where the impact is the largest and calculate the change in yield of these dams.

The modelling process adopted within the Water Resources Modelling Platform (WReMP) (Mallory et al, 2010), is to generate the streamflow reduction time series within the model at each time step using two processes. Upland IAPs are modelled using Gush duration curves (as described in Mallory and Hughes, 2011) while riparian vegetation is modelled as a river abstraction varying from month to month with evapotranspiration potential and water availability. Hence should river flow cease in a particular stretch of river over a particular time period due to upstream use then the impact of riparian vegetation over this time and river reach will be zero.

A typical input file for the WReMP alien vegetation modelling option is shown in **Table 1**. In order to model a different scenario it is only necessary to change the areas of IAPs or the potential streamflow reduction rate of riparian IAPs. Note that the table also indicates the quaternary catchment in which the IAPs are located. This is used as an index to source the correct Gush streamflow reduction curve and evapo-transpiration potential from a database.

A short-coming of this approach is that Gush streamflow reduction curves are not available for the whole country. They were only generated for catchments with a mean annual precipitation of greater than 600mm/annum. The application of this method is therefore currently limited to these wetter catchments, although generic streamflow reduction curves can be used in drier catchments, just at lower confidence.

Quaternary catchment	Catchment area (km <sup>2</sup> )	IAP area (km <sup>2</sup> )		Riparian SFR
		Upland	Riparian	(mm/annum)
B12D	362	3.37	0.17	300
B12E	436	7.84	0.39	300
B20D	480	1.87	0.08	300
B20F	504	0.92	0.40	300
B20G	522	0.88	0.48	300
B20H	563	2.84	0.55	300
B32B	614	5.14	0.92	300

Table 1: IAP data input table for WReMP

# Case study

A mine located downstream of the Loskop Dam, referred to as the Blue Ridge Mine, applied for a water use licence based on the removal of 2 500 ha of IAPs. The impact of removing these IAPs on streamflow was originally assessed by Marais in 2003. See **Table 2**.

Catchment	River	Total Area of Catchment (ha)	Area Invaded (ha)	Condensed Area (ha)
B20	Wilge	152 840	4 324	1 766
B20	Wilge	282 792	3 405	552
B12	Klein Olifants	239 086	318	87
B11	Upper Olifants	471 537	458	94
B32A	Olifants	Part of Catchment	292	174
		1 146 255	8 797	2 790

Table 2: Extent of invasions in the B20, B12 & B11 tertiary catchments

Marais suggested in his unpublished report to DWAF dated 2003 (Marais, 2003) that the estimated 2 790 ha is mostly riparian and removing 2 500 ha of this vegetation completely (with necessary follow up maintenance to prevent re-growth) will increase the runoff by approximately 13.36 million m<sup>3</sup>/annum based streamflow reduction estimates from the publication by Versfeld et al (1998). Expressing this in term of unit runoff results in an increase in runoff of 534 mm/annum, or 5 344 m<sup>3</sup>/ha.

Based on the above analysis, the Blue Ridge Mine paid for the removal of approximately 2 500 ha of alien vegetation and then in 2009 applied for a water use licence. The areas of alien vegetation actually removed are indicated in **Table 3**. What is immediately obvious is that only a small percentage of the area removed proved to be riparian, and this has a huge impact on the actual streamflow reduction. This emphasises the importance of detailed surveys of IAPs if trading for water use licences is envisaged.

Quaternary Catchment	Condensed Area (ha)	Riparian (ha)
B12D	337.1	17.44
B12E	784.1	39.0
B20D	187.4	7.5
B20F	91.6	39.7
B20G	87.8	48.4
B20H	284.1	55.2
B32B	513.9	91.9
Total	2 286.0	299.0

 Table 3: Areas of Alien Vegetation actually removed

In support of this licence application, Marais submitted calculations of streamflow reduction based on several different methods. These are summarised in **Table 4** so as to give an indication of the wide range of possible estimates derived from the different approaches.

### Table 4: Streamflow Reduction in the Olifants River Catchment

Mathad	SFR	SFR Total	SFR Riparian	SFR Upland
wethod	(million m <sup>3</sup> /annum)	mm/annum		
Le Maitre	5.5	214		
Gush	1.0	56		
Jewitt	1.7	97		
DWAF 1	1.6	90		
DWAF 2	1.1	60		
Dye and Jarmain	7.5	424		244
Cullis et al	1.1	115	300	100
Everson	2.2			
Gorgens & van Wilgen	5.4	274	548	

In order to separate out plausible methods from those that reduce the streamflow by more than is possible, the hydrological constraints were applied in each of these catchments. See **Table 5**.

### Table 5: Applying the hydrological constraints to streamflow reduction due to IAPs

	Catchment Area	Mean Annual Runoff		Area of upland IAPs	Maximum possible streamflow reduction
Catchment	(km²)	million m <sup>3</sup> /annum	mm/annum	(ha)	(million m <sup>3</sup> /annum)
B12D	362	19.88	54.92	337.1	0.19
B12E	436	21.89	50.21	784.1	0.39
B20D	480	22.39	46.65	187.4	0.09
B20F	504	16.67	33.08	91.6	0.03
B20G	522	22.87	43.81	87.8	0.04
B20H	563	22.85	40.59	284.1	0.12
B32B	614	26.20	42.66	513.9	0.22
Total	3 481	152.75	43.88	2 286.0	1.07

In the above table, the assumption is made that the long-term reduction in runoff cannot exceed the natural MAR from the catchment. As example calculation is given below for clarity.

## Sample calculation

Catchment: B12E

Natural MAR: 50.2 mm/annum

Area of IAPs: 784.1 ha

Maximum possible streamflow reduction:  $(50.2 \times 784.1)/100000 = 0.39$  million m<sup>3</sup>/annum

The upper limit to streamflow reduction due to riparian vegetation is more uncertain and debatable but from the various methods applied by Marais in his analysis of the Blue Ridge mine calculation the maximum appears to be about 500 mm/annum. Applying this rule in **Table 6** results in a maximum possible streamflow reduction due to riparian IAPs of about 1 million m<sup>3</sup>/annum.

Table 6: Upper	r Limit of SFR	due to Riparian	Vegetation
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Quaternary catchment	Riparian vegetation (ha)	Assumed SFR (mm)	Maximum SFR (million m <sup>3</sup> /annum)
B12D	17.44	500	0.09
B12E	39.0	500	0.20
B20D	7.5	500	0.04
B20F	39.7	500	0.20
B20G	48.4	500	0.24
B20H	55.2	500	0.28
Total			1.04

Combining the above two maximum streamflow reductions results in a maximum possible streamflow reduction of 2.1 million m<sup>3</sup>/annum. Based on this, only the methods referred to by Marias as Gush, DWAF1, DWAF2, Cullis and Jewitt are plausible. Jewitt is not a method or a model *per se* but a national average for forestry. The methods DWAF1 and DWAF2 were the calculations carried out by the Department of Water Affairs when assessing the licence application. DWAF used the Gush duration curves (Gush et, 2002) to carry out these calculations.

Applying the methodology used in the WReMP model and assuming a unit streamflow reduction due to riparian vegetation of 300 mm/annum (as described in this paper) results in the following streamflow reduction estimates:

Quaternary Catchment	Streamflow reduction due to (million m <sup>3</sup> /annum)			
	Upland IAPS (ha)	Riparian IAPs	Total	
B12D	0.11	0.05	0.16	
B12E	0.26	0.12	0.38	
B20D	0.05	0.02	0.07	
B20F	0.02	0.12	0.14	
B20G	0.02	0.14	0.16	
B20H	0.06	0.17	0.23	
B32B	0.17	0.28	0.45	
Total	0.69	0.90	1.59	

Table 7:	Streamflow	reduction	calculated by	<b>WReMP</b>
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## Conclusions

There are several different methods and models to estimate streamflow reduction due to IAPs. However, these methods result in a very wide range of estimated streamflow reduction. This poses a very serious risk that the streamflow, and hence available yield, gained by removing IAPs will be overestimated and water allocated to those removing IAPS which does not actually exist. This will result in catchments becoming even more stressed than they already are.

A simple hydrological test is described in this paper against which models and methods can be tested. The principle behind this test is that removing IAPs cannot put back more water than occurred under natural conditions, at least in the long-term. Several of the models and methods applied within a test catchment failed this basic hydrological test. It is not clear why this is the case but possibly it is due to these models being used out of context and beyond the hydrological scope within which they were developed. It is also possible that some models are calculating total water use by vegetation and not streamflow reduction, *per se*.

A common result from most of the methods used is that the streamflow reduction due to riparian IAP is much higher than from upland plants. This is to be expected due to the increased access to water that vegetation has in this zone. However, the methodologies applied within the riparian zone are a lot less certain that in the case of upland IAP. More robust models are therefore required to estimate streamflow reduction in the riparian zone.

The method developed by the University of KwaZulu-Natal (Jewitt et al, 2010) and applied widely to estimate streamflow reduction due to commercial forestry (Mallory and Hughes, 2011) has been adapted to estimate streamflow reduction due to IAPs. This method is based on sound hydrological principles and therefore passes the hydrological constraints test. The method allows for both upland and riparian IAPs and through linking with a database of quaternary hydrological parameters operates seamlessly within a yield modelling environment. Scenario modelling is possible through the Water Resources Modelling Platform by changing the area of IAPs (upland and/or riparian) or the riparian water use rate. It is never necessary to revert back to a hydrology model to test scenarios.

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