



An Australian Government Initiative



Using Banded Tree-Agriculture Systems to meet surface water management targets – a design framework

**A report for the RIRDC/Land & Water Australia/FWPRDC/MDBC
Joint Venture Agroforestry Program**

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Foreword

The management of water in the agricultural landscape has always been paramount to rural prosperity in Australia. In recent times, the relative importance of agricultural productivity and other demands on this resource are being debated more widely. The fate of water, after it falls as rainfall, can play equally important roles in crop production, urban water supply, pollutant wash off or environmental flow. Catchment groups are increasingly being forced to manage land so that the best combinations of these roles are realised – and there is an increasing awareness that farms are part of this management.

The prospect of managing water in agricultural landscapes by manipulation of vegetation cover types has historically held some appeal. Over the last decade, at least, significant implementation and modelling of agroforestry systems has been directed to this end. For example, the JVAP design guideline “Trees, water and salt” addressed the use of trees in agricultural landscapes for the management of dryland salinity – a specific kind of water management.

This report addresses the potential for designing banded agricultural systems, comprising multiple vegetation types, for surface water management in agricultural landscapes. The study took place over an eighteen month period from January 2002 to June 2003 and has developed a model and preliminary design framework, which enables the investigation of hypothetical combinations of different vegetation types to address a wider range of surface water management objectives. These may range from minimising pollutant wash off to maximising water yield for water supplies or environmental flows, and any water management objective in between. In doing so, it provides a structured approach to exploring the design limits dictated by local conditions and plant water use characteristics.

This work is intended to facilitate simple desktop simulations that will help managers to rapidly identify designs that will not work and those that warrant further investigation. The design framework should not be applied where deep drainage or local shallow subsurface lateral flow represents a significant proportion of the water budget. Alongside this, there is a need for a spatially explicit and quantitative model that enables catchment managers to work backwards from catchment targets to provide a map of, for example, hypothetical runoff coefficients to meet targets. This would provide a structured method for focussing smaller scale agricultural system design frameworks such as the one developed in this study.

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This report, a new addition to RIRDC’s diverse range of over 1600 research publications, forms part of our Agroforestry and Farm Forestry R&D program, which aims to integrate sustainable and productive agroforestry within Australian farming systems.

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Peter O’Brien

Managing Director

Rural Industries Research and Development Corporation

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Symbols

Symbol	Meaning	Units
$1/\alpha$	average storm depth	mm
$1/\lambda$	average period between rainfall events	d
d, e	limits of integration of S_n	
c	normalising constant of $p(S_n)$	
D	drainage	mm
E_{max}	maximum evapotranspiration rate as a proportion of PET	
ET_{max}	maximum evapotranspiration rate	mm d ⁻¹
ET	evapotranspiration	mm
ij	specified probability density interval	
k_{sat}	soil saturated hydraulic conductivity	m d ⁻¹
I	infiltration	mm
N	number of observations	
L	shallow subsurface lateral flow	mm
n	soil porosity – the volumetric proportion between wilting point and saturation	
P	rainfall	mm
Pr	probability	
$p(S_n)$	probability distribution of S_n	
PET	potential evaporation	mm
Q_{in}	run-on	mm
Q_{out}	runoff	mm
s	slope	
S	soil water storage	mm
S^*	threshold relative soil water storage separating stressed and unstressed water use	
S_{max}	maximum soil water storage	mm
S_l	relative soil water storage identifying field capacity	
S_n	relative soil water storage, normalised with respect to S_{max}	
t	time	d
z	plant rooting depth	m
$1/\gamma$	averaged normalised (with respect to S_{max}) storm depth	
$\Gamma(a,x)$	Incomplete Gamma function	
η	average daily maximum evaporation rate normalised with respect to S_{max}	
30.27 S 144.90 E	latitude and longitude	decimal degrees
θ	S_{max}	d ⁻¹
$\rho(S_n)$	loss function – soil water loss as a function of S_n	mm d ⁻¹
ψ	soil matric suction	Pa

Executive summary

What the report is about

This report describes a preliminary study undertaken over an eighteen month period (from January 2002 to June 2003) to investigate the potential for designing banded agricultural systems, comprising multiple vegetation types (annual, perennial, shallow rooted, deep rooted), to managed surface water interception and flow. A conceptual model was developed and evaluated using data from previous studies of surface water movement in naturally banded vegetation. Five case studies based on real farms were run to simulate arrangement of crops and trees and to examine the effect on average annual runoff from hillslopes. The design framework presented, with its constituent water modelling, is intended to assist managers rapidly identify vegetation designs that are worthy of further investigation.

Who is the report targeted at?

This report will be useful to researchers and managers seeking better coordination of water capture, use and flow at the farm and catchment scale. The model, conceptual framework, and analysis of naturally banded vegetation will also be of use to those interested in using bands of vegetation for water and sediment interception.

Background:

Design philosophy

Production systems comprising multiple vegetation types offer a greater resilience within the highly variable Australian climates and provide the design scope to meet local water management targets. The design philosophy recognises that, at the hillslope scale, and within a catchment context, there are multiple demands placed on the rainfall that arrives at a hillslope. Local water capture and use may need to be maximised for reasons solely related to local production, or it may need to be reduced when downstream water supply or environmental flow requirements are simultaneously considered. In cases where quality surface water is considered to be a significant product from the hillslope, the amount of water leaving the hillslope may need to be maximised (e.g. water harvesting). In the case of a high erosion hazard or pollutant wash off, runoff from the hillslope may need to be minimised.

Deep-rooted perennial plant species (e.g. trees, lucerne), because of their greater water use potential, are typically considered to provide the greatest control over the amount of water leaving a hillslope. Historically, however, there has been little attention paid to the ability of deep-rooted perennials to capture excess water moving from upslope. As a starting point, we have simulated the redistribution of excess water, between bands of vegetation, in a manner that has been observed in naturally banded vegetation systems found in semiarid areas (Tongway *et al.*, 2001).

Aims/Objectives

1. To develop a preliminary design framework to assist the matching of vegetation species and their spatial arrangement to local soil and climate.
2. To investigate the potential for arranging banded vegetation systems on agricultural hillslopes to act as a source-sink sequence that can be designed to manage water yield for local requirements.

Methods

Design framework

Rather than modelling an 'optimum' solution for a hillslope, we have provided a framework within which 'first-cut' designs can be explored with regard to their potential for achieving a specified runoff target. The framework allows investigation of the effects of changing the vegetation type (annual, perennial, deep-rooted, shallow-rooted), their downslope order and relative proportions on a hillslope.

The intended use of the design framework is for rapid identification of design limits. That is, to identify what is likely to be physically possible, what likely tradeoffs will be required to achieve specified runoff targets, and what designs are worthy of greater attention.

Measured capture potential

We collected data from farm tree belts that suggest that the capture potential of such plantings, if stock is excluded, is significantly higher than adjacent pasture.

Water balance model

For purposes of simplicity, we have considered a “bucket” model where water inputs include rainfall and run-on, and water outputs include evapotranspiration (plant loss function) and runoff. Deep drainage and shallow subsurface lateral flow are not represented. Similarly, surface infiltration constraints are not considered, in this way, the ‘best bet’ conditions for water capture were represented. This should have a significant bearing on the use of the design framework; if a desired outcome cannot be achieved under ideal conditions, it is unlikely to be achieved in reality, and does not warrant a more sophisticated approach.

The design framework should not be applied where deep drainage or shallow subsurface lateral flow represents a significant proportion of the water budget.

If potential users of this design framework are unsure of local hydrology in this regard, we recommend that they seek expert opinion. As an initial guide, we refer them to Silberstein *et al.* (2002) and McKenzie *et al.* (2003).

Probabilistic approach

We have adapted a method for the probabilistic modelling of soil water storage at a point, to assist the matching of species to climate and soil water storage capacity. Advantages offered by this approach include some alternative conceptual approaches to the characterisation of climatic inputs, plant water use characteristics, soil water storage and an analytic solution. The probabilistic method also provides a ready mechanism for assessing the risk associated with plant, climate and site combinations.

Currently, this approach is not applicable to bands of vegetation where the individual bands are linked consecutively via overland flow. We suggest, however, that the development of an analytic solution for this application could provide a streamlined tool for preliminary designs for matching multiple vegetation systems to soils and climates.

We therefore append the probabilistic approach as we have applied it to a single plot and suggest there is merit in developing an analytical solution for multiple bands of vegetation that are hydrologically connected via runoff.

Numerical modelling

In the absence of an analytic method for the probabilistic modelling of banded vegetation systems, a numerical approach was used to construct a prototype model within Microsoft Excel, but retaining some of the characteristics of the probabilistic approach. Specifically, we have computed probability distributions of the daily outputs of soil water storage as a succinct method for characterising likely soil water storage scenarios.

The model underwent a basic evaluation using data from other studies of naturally banded vegetation systems, and was found to perform adequately for the purposes of this study.

Case studies

The numerical model was used to simulate vegetation scenarios at five case studies sites in catchments where there were issues of dryland salinity, pollutant wash off, gully erosion and off site water supply. Model scenarios were conducted to investigate the effects on runoff coefficient and soil water storage probability distributions of: 100% cover using different vegetation types (i.e. winter cereals, perennial pasture, trees); bands of different vegetation types. Where appropriate, the artificial runoff surfaces (e.g. wax treatment of soil; see Fink *et al.*, 1980) were included to enhance runoff where off site water supply was important. This strategy was also employed as a method of increasing the amount of water reaching the tree components, to increase tree growth in low rainfall areas. Plant growth was not represented but tree evapotranspiration was used as a rough indicator of potential growth differences in such cases.

Results

Simulations

The case studies simulated plant response and wetness (soil water store relative to field capacity) of the soil profile for combinations of annual and perennial vegetation at five sites with different rainfall. Combinations of vegetation were used to predict runoff. Landscape Function Analysis indicated that imposed vegetation bands can be designed to at least capture excess water via overland flow. In the catchment context, we raise the prospect of water farming, where landscapes become a mosaic of agriculture, forestry and water harvesting enterprises that meet consumptive and environmental water goals which providing a vital rural economy within rural catchments.

In the modelling process, we sought an appreciation of the sensitivity of the outcomes to climate, vegetation and soil parameters. Seasonality of the vegetation, root depth and plant use were the parameters most sensitive parameters with regard to soil water profile; future research should address the lack of real measured data for these parameters.

Design framework

The design framework we have developed, in its current form, can be widely and productively applied to answer some basic questions regarding the feasibility of vegetation designs for more sophisticated management of water on farms. Application should be restricted, however, to areas where shallow subsurface lateral flow and deep drainage do not constitute a significant proportion of the total water budget.

In each case, no particular design was recommended, rather, the scope for altering the runoff coefficient was demonstrated. Although a pivotal issue in the design of farming systems, water management is only one consideration. For real-world design problems, decisions regarding the most appropriate design would require consideration of many other factors affecting (probably) multiple stakeholders, both local and off site. Our case studies have highlighted the need for a tool that provides an objective and quantitative method for assisting the determination of a desired farm water management strategy in a catchment context. In a logical sense, we consider this to be a necessary precursor to hillslope scale designs.

A fundamental question?

These considerations highlight the question that must be answered prior to, or during, the design process: “How much water do I/we want to run off my/our hillslope?” Or, “What should the runoff coefficient be?” Initial consultations when designing this project indicated that surprisingly, this is not often directly considered during land management.

The answer, of course, will depend on many factors and there will be multiple solutions. We draw attention to the fact that, while it is a simple question, and basic to any subsequent efforts to change the hydrology of a hillslope by (say) tree planting, it is very difficult to answer. With some consideration, it is likely that land managers may be able to answer the question with regard to their own, local requirements for water management: plant production; salinity management; farm dam etc. It very rapidly becomes more difficult as off site requirements (urban water supply, environmental flows) need to be considered.

We therefore suggest that there is a need for a quantitative, and spatially explicit, tool to support consultative catchment management methods already widely used (for example, Ive and Cocks, 1999; see also www.cse.csiro.au/nsw_rangelands).

Application and knowledge gaps

The previous three paragraphs describe the most important issue relating the progression and application of the work of this scoping study in a catchment context. At the hillslope to farm scale, however, more ordinary knowledge gaps relating to plant water use restrict the application of this work.

These include, in order of importance:

1. Greater understanding of the potential of vegetation bands to capture and store excess water moving from upslope.
2. Simple characterisation of topographic influences with regard to 1.
3. Methods for rapidly estimating the rooting depth of vegetation types, especially trees.
4. Additional information on the evapotranspiration characteristics (plant loss functions) of key vegetation types.
5. Analytic solution to a probabilistic approach to the modelling of soil water storage of banded vegetation systems.

Links - water harvesting, pollutant management, commercial and environmental forestry

Although not addressed in detail by this project, we draw attention to the potential overlap between the designs of banded agricultural systems for water management and other studies involving water harvesting and pollutant management.

The arrangement of bands of vegetation across hillslopes to capture excess water is analogous to the use of filter strips (typically grasses) to trap suspended sediment. Variations on the techniques can also potentially, and beneficially, incorporate bands of trees. There is much scope, therefore, to combine the approach we have taken and some work undertaken by the Cooperative Research Centre for Catchment Hydrology to look at the dual benefits of capturing excess water and suspended sediment. This issue is of particular concern in coastal Queensland catchments where the suspended sediment washed from agricultural land to the river network is a serious pollutant of estuaries and the Great Barrier Reef.

Recommendations

This study has attempted to provide some structure to the notion of ‘redesigning farming systems’ with respect to environmental issues related to surface water management, which may have significant impact on our agricultural resource base. Recommendations arising from this exercise are as follows:

Knowledge gaps - catchment context

There is a need for a structured method for identifying, in a catchment context, hillslopes appropriate for potential redesign and with respect to specified water yield targets. We recommend a formal review and exploration of potential new methods for establishing such a method. The aim here is to provide a spatially explicit tool to assist catchment managers determine a range of solutions at the hillslope scale that will meet catchment scale targets.

Knowledge gaps – application and development of the design framework

With regard to improving the modelling capabilities for design problems such as these, we recommend a focus on experimentally addressing the knowledge gaps listed above for hillslope to farm-scale water management.

Links

We recommend an exploration of the scope for combining the design approach we have adopted for water management with analogous approaches adopted for measuring and modelling pollutant trapping (Ellis *et al.* 2006b; Leguedois *et al.*, submitted.) and water harvesting (Ellis *et al.* 2006a; Fink *et al.*, 1980; Richardson *et al.* 2004).

Introduction

Agricultural legacy

The replacement of natural Australian vegetation systems with European-style farming systems has led to significant and widespread hydrologic and ecological problems such as salinity, water logging and increased soil erosion. To a large extent, this has been due to European-style agricultural systems being poorly designed to cope with the southern Australian climates. These are typically characterised by a winter-dominated rainfall; rainfall events are very episodic and annual rainfall is highly variable between years.

Natural vegetation systems have evolved to survive unpredictable and often protracted drought periods of Australian climates, and to store the excess water that falls during winter, and use it over the drier summer months. Their key attributes in this regard are: perenniality, deep root systems and conservative water use. Some semiarid vegetation communities (e.g. mulga and mallee) have also evolved a spatial distribution of patches with different capacities to capture and store and use excess water (Nulsen *et al.*, 1986; Tongway *et al.*, 2001). This phenomenon has been described as a source-sink system (Noy-Meir, 1973) in which excess water (and other transportable resources) is internally redistributed within the system to increase overall water use efficiency. In these environments deep drainage below plant root zones is very small and overland flow is the principal mechanism for the movement of excess water between patches.

In contrast, crop and pasture plants are typically annual species, with shallow root zones and winter growing seasons, and therefore are less able to store excess water within the root zone, and use it when energy is not limiting (summer). Relative to most natural systems, agricultural systems have limited ability to capture and use excess water. This water leaves farms as overland flow or deep drainage, altering the local, or off-site hydrology, and can lead to salinity and water logging problems.

The inability of conventional European-style farming systems to mitigate these problems in southern Australia has been recognised and the need to redesign farming systems has been mooted (Walker *et al.*, 1999; Stirzaker *et al.*, 2000). In parallel to this, the reintroduction of woody perennials (mainly trees) into agricultural landscapes, via agroforestry systems, has attracted significant attention from both land managers and scientists over the last decade. In many cases, trees are arranged in belts, or bands, such as break-of-slope plantings and alley farm plantings, typically with the intent of altering the local hydrology and simultaneously providing other benefits such as wind protection, habitat and alternate primary products.

Reduction in perennial vegetation has also led to major changes to the magnitude and frequency of sediment and nutrient movement on hillslope and throughout stream networks (Prosser *et al.*, 2001). These changes have been characterised by massive expansion of gully networks in grazed and cropped landscapes and a major increase in turbidity and coarse sediment movement within most Australian streams. Reinstating perennial vegetation into hillslopes has a potential to mitigate these effects. However, in many environments, gullies now have stabilised and sediments within stream networks will persist for several decades.

Agroforestry design for salinity management

During the mid to late 1990s, a large effort was directed to providing the ‘best-bet’ design guidelines for placing trees on farms to mitigate salinity and to maximise productivity (Stirzaker *et al.*, 2002). Of particular relevance here is the chapter dealing with the placement of trees on hillslopes (Silberstein *et al.*, 2002). The authors undertook a large number of sophisticated water balance simulations to formulate rough design recipes to allow the arrangement of tree belts (belt width and spacing) on hillslopes such that excess water (deep drainage and overland flow) was minimised, and tree growth was maximised. This represented a state of the art look at the options for the use of trees to manage water on farms, with the specific objective of salinity control. This work has provided a starting point for our study and we have attempted to expand our brief in line with the current broader appreciation of the multiple demands on water in the landscape.

Farming water as an emerging enterprise

In forthcoming decades farming water is likely to emerge as a viable enterprise in the drier parts of the Australian landscape. Richardson *et al.* (2004) found that there are many working systems for enhancing runoff on hillslopes that can produce viable supplementary water supplies on farm and potentially to river network. While there are institutional barriers to the widespread use of such systems, the increasing value of stream flow may motivate further investigation of water farms as rural enterprises in Australia.

Water farms are likely to be complementary to agroforestry systems as they can be used to markedly increase stream flow where new tree crops have decreased it. Also, there is the potential to hybridise water farms and agroforestry systems. In such systems high levels of runoff from strips of treated land surface can be captured as run on to banded of trees or other crops. Such systems effectively increase the rainfall rate for an area of tree crops which could increase the viability of agroforestry in low rainfall areas. This concept is explored in some of the case studies undertaken in this report.

A broader design philosophy

In this scoping study, we have intended to build on the work of Silberstein *et al.* (2002) and to broaden the design philosophy and pose the question:

“Can we design a source-sink sequence to manage water yield from agricultural land?”
(Ellis *et al.*, 2003a).

We have taken a preliminary look at the potential for developing a design framework for the arrangement of different types of vegetation (crop, pasture, woody perennial) on farm hillslopes to meet a desired water yield (excess water). In doing so, we anticipate a possible future need of land managers to aim to meet hillslope water yield targets for a variety of objectives that will vary from case to case. The latter could represent a minimisation of water yield (e.g. to mitigate salinity) or it could represent the supply of a specified amount for environmental flows or water supply.

A more fundamental question?

In the process of developing a design framework for the hillslope scale, it has become apparent that, in a catchment context, there is a greater challenge of first determining an appropriate water yield target for individual hillslopes. The simple but key question which precedes this knowledge is “How much water do we want to leave the hillslope or subcatchment?” The answer depends on the number of valid uses, on and off site, for the rainfall that falls on the hillslope. It will depend entirely on the users who lay claim to that water (local landholder, downstream water user) and any negotiated apportioning of the resource. Addressing this issue is beyond the scope of this project and within the jurisdiction of catchment management groups.

A preliminary design framework

We describe in this report the development of a preliminary design framework for banded agricultural systems, assuming that the above issue can be addressed.

The principal intended use for our design framework is to permit rough evaluations of the effects of hypothetical arrangements of vegetation types in terms of water yield. In the process we seek to gain an appreciation of the sensitivity of the outcomes to climate, vegetation and soil parameters. If rough evaluations point to potential advantages of new designs, a more sophisticated approach may be warranted, such as that offered by McKenzie *et al.* (2003). The initial design process will also identify information gaps in, for example, water use characteristics (loss functions), soil physical properties and plant rooting depths. This will help focus any subsequent efforts to fill these gaps via experimental work.

Five case studies are presented, representing a range of climates and potential water management options. We offer our approach as a design framework only, rather than providing specific land management solutions. This is restricted, however, to areas where shallow subsurface lateral flow and deep drainage do not constitute a significant proportion of the total water budget. Every attempt is made to simplify the approach whilst retaining imperative design features and empirical processes.

Objectives

1. To develop a preliminary design framework to assist the matching of vegetation species and their spatial arrangement to local soil and climate.
2. To investigate the potential for arranging banded vegetation systems on agricultural hillslopes to act as a source-sink sequence that can be designed to manage water yield for local requirements.

Overview of methodology

Investigations were undertaken under the following headings:

1. Consultation.
2. Data collection.
3. Conceptual model/design framework and water balance model.
4. Model evaluation.
5. Case studies.

At the beginning of this study in January 2002, we undertook some consultation with land managers and scientists regarding the land and water management issues relevant to designing agricultural systems to manage surface water.

Preliminary data was then collected to determine the potential of farm tree belts to capture excess water moving from upslope via overland flow.

In light of the preliminary data, a conceptual and design framework was developed for the water use by vegetation bands and the subsequent cascade of excess water downslope from band to band. A spreadsheet model was then constructed to describe the water balance within each vegetation band and to predict runoff from individual bands and the entire hillslope.

The model was evaluated on a naturally banded vegetation site that was known to function (hydrologically) as described by the conceptual framework.

Following evaluation, the model was used to simulate runoff from hypothetical banded vegetation designs at five case study sites. In each case, three scenarios were tested and assessed with regard to their likely role in addressing local water management issues.

Consultation

A small component of this study was devoted to the discussion of the central ideas behind the project with land managers and scientists directly involved with resource management issues associated with excess water leaving farm hillslopes. These discussions included: a farm forestry group (Master Tree Growers; <http://www.mtg.unimelb.edu.au/>) and Landcare (<http://www.landcareaustralia.com.au/>) officers from Holbrook, New South Wales; individual farmers undertaking tree planting in the Holbrook, Yass and Gunning areas; scientists involved in the hydrologic modelling of Red Hill/Kylie's Run; and scientists undertaking monitoring, modelling and management of pollutant wash-off from the Burdekin.

Feedback from these groups was used to focus the simulations undertaken within the case studies and to develop the general approach toward the relevance and design of banded agricultural systems for management of excess water.

Typically, we posed the question "How much water do you want to run off your land?" While there was generally a good appreciation of the likely hydrologic connection between the sites in question, sites lower in the catchment and local hydrologically related problems, the posing of the question, in most cases, took participants by surprise.

We suggest that, while the question would appear to be the necessary starting point for any redesign of farming systems (in an effort to address hydrologically related problems), we are a very long way from being able to provide answers at a local scale that are appropriate within a catchment context.

Transfer of the new information from this study to user groups could be readily achieved via structured interaction with Landcare and catchment management groups. However, it is likely that the timing is premature without first providing guidelines for design targets at the hillslope scale, by consideration, in a catchment context, of the costs and benefits of doing so.

This issue is central to the redesign of farming systems, and to catchment management, and is addressed more fully in the Discussion section of this report.

Data collection

Deep-rooted perennial species (e.g. trees) in banded agricultural systems provide the greatest capacity to buffer against the loss of water that cannot be used by shallow-rooted species. This is due principally to the greater root zone storage capacity and the year-round water use characteristic of deep-rooted perennial species. This attribute is useless without a matching capability to capture overland flow from upslope and, without evidence of this, modelling studies such as this would be futile.

We therefore collected data to address the question “Are farm tree belts likely to capture excess water moving from upslope as overland flow?” as there is little work published on this in Australia. The initial limiting factor regarding capture of overland flow is the infiltration rate of water into the surface soil. This is often a complex process, varying with time, and is also dependent on initial soil water conditions and rainfall intensity, as well as specific soil surface characteristics such as biological or mechanically induced crusts and biologically or mechanically induced surface detention and storage; for example stubble retention and minimum tillage enhance surface detentional storage and infiltration. Many methods are available for physical measurement of this process (Angulo-Jaramillo *et al.*, 2000) for scales ranging from cm² to tens of m². All conventional methods are relatively laborious and/or time consuming and unsuitable for rapid surveys. We therefore employed a Landscape Function Analysis (LFA) technique (Tongway and Ludwig, 2000; Ludwig *et al.*, 2004), a method of scoring soil and vegetation characteristics, which gives an indirect, relative measurement of the infiltration characteristics of the surface soil. LFA transects were measured at three farm tree belt sites in the Jugiong and Upper Billabong Creek catchments. This method involves the scoring of attributes relating to mechanical protection (from raindrop impact), structural stability of the soil surface including: the proportion of perennial vegetation present; soil surface hardness; the presence or absence of a crust; soil texture; and degree of slaking. The infiltration index is calculated by weighting these scores relative to the role of each attribute in improving infiltration potential (Tongway, 1994).

We also took supplementary soil and vegetation measurements from the mulga site at Louth (Tongway and Ludwig, 1990). These included: depth of soil wetting following a rainfall event, to aid understanding of the water redistribution processes; soil bulk density (for estimation of soil porosity) and rooting depth to enable a basic evaluation of the model at the site.

Capture potential of natural groves and farm tree belts

This section presents transects of infiltration index (Tongway and Ludwig, 2000; Ludwig *et al.*, 2004) from a banded mulga site, (Figure 1; Figure 2) used in the model evaluation and three farm tree belts (Figure 3 to Figure 8). The belts had been previously established on hillslopes to capture excess water from upslope.

The relationship between Infiltration Index and potential infiltration rate is non-linear; a small increase in Infiltration Index can indicate a large increase in potential infiltration rate (see Greene, 1992).

Natural mulga grove



Figure 1 Lake Mere site viewed obliquely from upslope.

Bare runoff zone in the foreground and grassy interception zone immediately in front of the mulga grove.

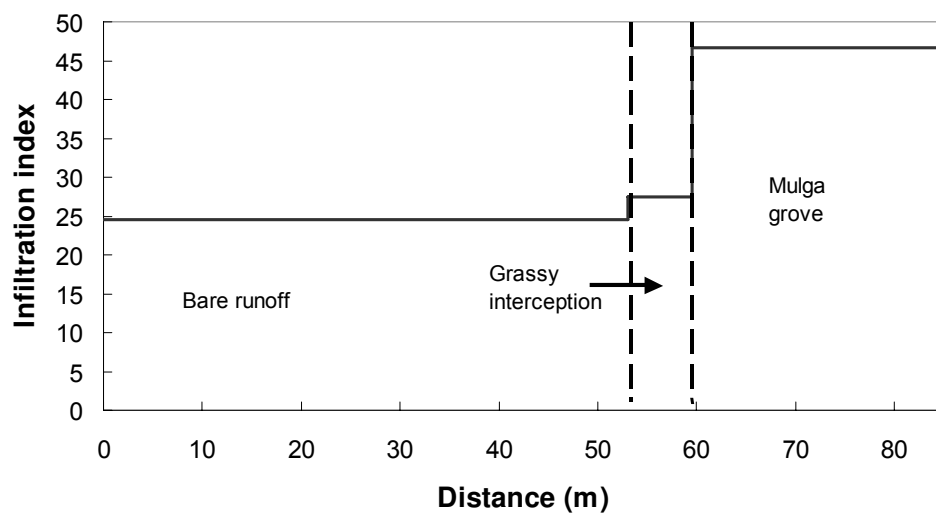


Figure 2 Transect of infiltration index (source: D. Tongway) measured across the three geomorphologic zones at the Lake Mere site, near Figure 1.

NB: The index values from Lake Mere (Figure 2) correspond with measured infiltration rates of 20, 32 and 245 mm h⁻¹ at supply potential of +10 mm (Greene, 1992). See also measured rainfall redistribution at the site, Appendix 1.

Farm tree belts



Figure 3 Tree belt at Wielora Shed Paddock (34.73° S, 148.65° E), near Binalong, NSW.

The belt was positioned to intercept flow from upslope (left), thought to be contributing to water logging and salinity downslope. The belt comprised a thick planting of relatively small eucalypt and acacia mixture (right), which were not managed for timber production. Some individuals, predominantly, acacias, were dying from water stress during a protracted drought.

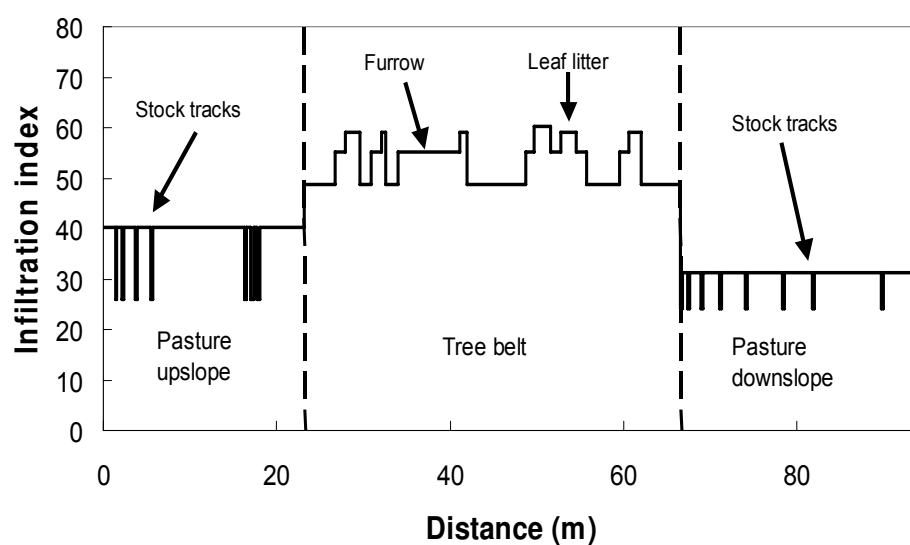


Figure 4 Infiltration index (Tongway, 1995) transect from a tree belt at Wielora Shed Paddock (Figure 3).

Stock tracks outside the belt gave the lowest values while leaf litter within the belt gave the highest values.



Figure 5 Tree belt at Wielora Dam Paddock (34.73° S, 148.65° E), near Binalong, NSW.

Photo left: Viewed from upslope looking towards the belt. Photo right: viewed from downslope, looking away from the belt. The belt is positioned to intercept flow from upslope thought to be contributing to waterlogging and salinity downslope. It included some eucalypts but was dominated by melaleuca species.

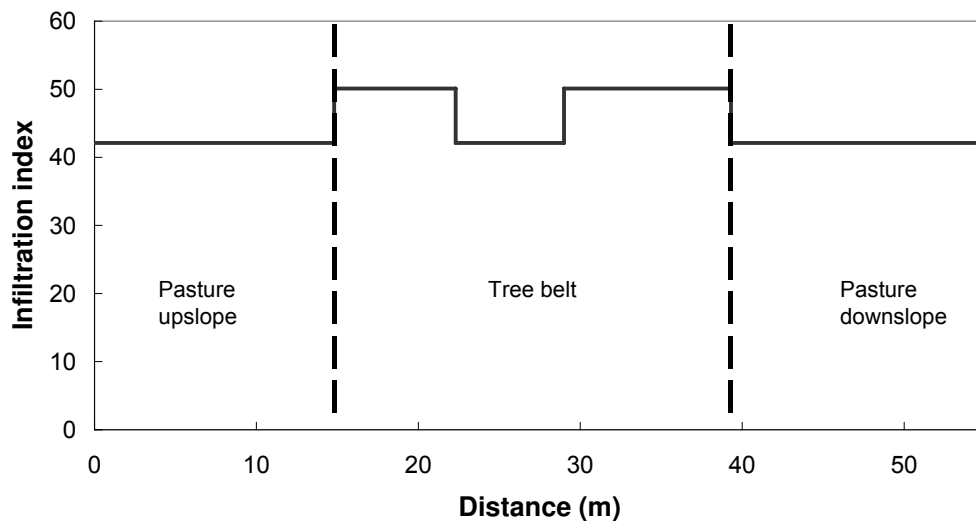


Figure 6 Infiltration index (Tongway, 1995) transect from the tree belt at Wielora Dam paddock.

The transect was deliberately chosen in the least healthy section of the belt, in a reportedly saline depression.



Figure 7 *E. saligna* and *A. melanoxylon* tree belt at Annandayle South (35.77° S, 147.35° E).

Viewed from the top of the hill (left) and looking lengthways into the belt (right). *A. melanoxylon* can be seen dying from water stress during the drought.

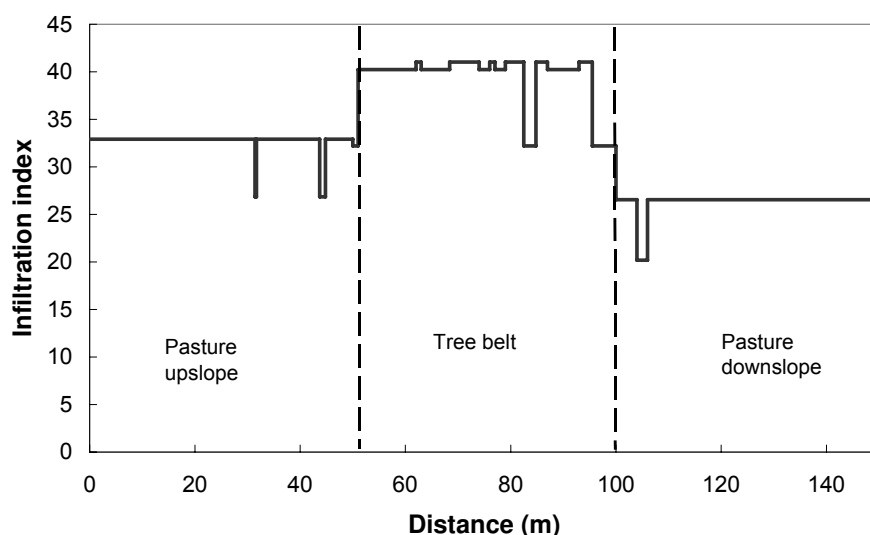


Figure 8 Transect of infiltration index (Tongway, 1995) across the farm tree belt at Annandayle South (Figure 7).

Bare soil on stock tracks (upslope) and cattle camp (downslope) gave the lowest values. Highest values were obtained from grass and leaf tree litter within the belt.

Interpretation of farm tree belt LFA transects

Generally, the LFA transects indicated a greater infiltration capacity with the farm tree belts compared to adjacent pasture areas immediately upslope and downslope. The differences were attributable to both soil and vegetation characteristics in all cases; the exclusion of livestock appeared to play a critical role with regard to maintaining vegetation cover and protecting the soil surface from consolidation due to rainfall impact and direct compaction from hoof traffic. This is illustrated clearly in Figure 4 and Figure 8, which included stock tracks in pasture areas. For statistical information regarding the data, see Appendix 3.

Conceptual model/design framework

Source-sink cascade

The semiarid mulga vegetation community at Lake Mere, near Louth, NSW (Tongway and Ludwig 1990; Figure 9) has been shown to function as a classic source-sink system (Noy-Meir, 1973). For our conceptual model, vegetation patches were conceived to be connected hydrologically by the cascade of excess water progressively downslope (Figure 10). In each case runoff from the upslope patch became run-on for the patch immediately downslope, and was combined with rainfall to provide the total water input for that patch. This phenomenon was verified during this project when soil water data was obtained from the site following a rainfall event that occurred after a long period of drought (see Appendix 1).

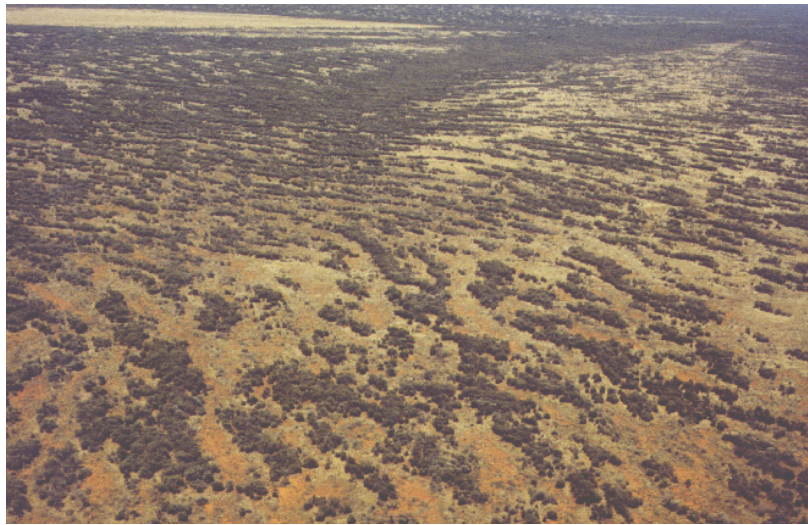


Figure 9 Oblique aerial view of naturally banded mulga landscape at 'Lake Mere', near Louth, NSW.

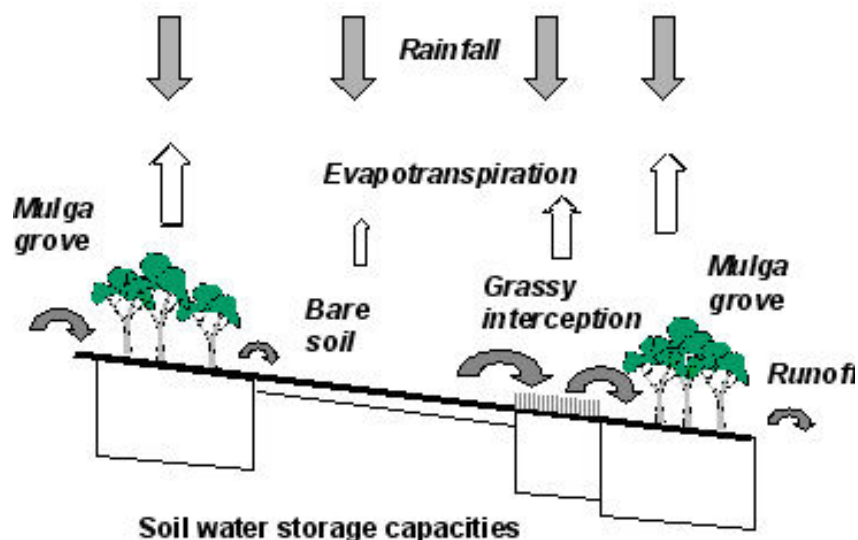


Figure 10 Conceptual model of the mulga vegetation system at Louth, NSW.

Indicates the main components of the water balance and the relative soil water storage capacities of each vegetation type. Excess water from each vegetation unit is assumed to move downslope as overland flow to the next vegetation unit in sequence.

An agricultural analogue of the natural system (for higher rainfall areas) could therefore comprise alternate bands of trees, winter cereal and lucerne, as an arbitrary example (Figure 11). Given that the vegetation types (in this case crops, trees) have different water storage capacities and water use characteristics (i.e. how fast water is used and when plants begin to reduce water use as the soil profile dries out), there is the potential to alter the relative widths of the vegetation types and therefore manipulate the overall runoff from the hillslope. Deep-rooted perennial plants (trees and lucerne), because they have the greatest soil water storage capacity and year-round water use are, therefore, likely to be the critical buffers that determine the overall excess water leaving the hillslope.

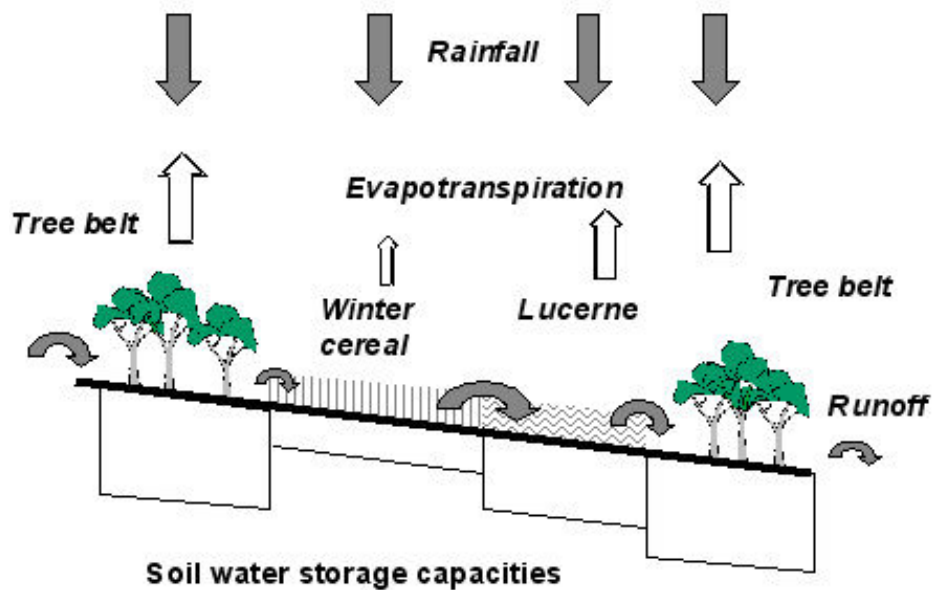


Figure 11 Agricultural analogue of a naturally banded vegetation system.

Excess water is assumed to cascade downhill as overland flow.

A spreadsheet model was written, using Microsoft Excel to describe the conceptual model of the cascade of excess water for a hillslope sequence of four 'cells', within each is represented three 'bands' of vegetation or, bare soil or artificial runoff surface (Figure 12). For a given climate, the design framework allows the user to alter the downslope band length, and the type of vegetation or surface within each band (by adjusting growing season, rooting depth and water use parameters). A simplified water balance is used to calculate the excess water from each band and the resulting runoff from the whole hillslope.

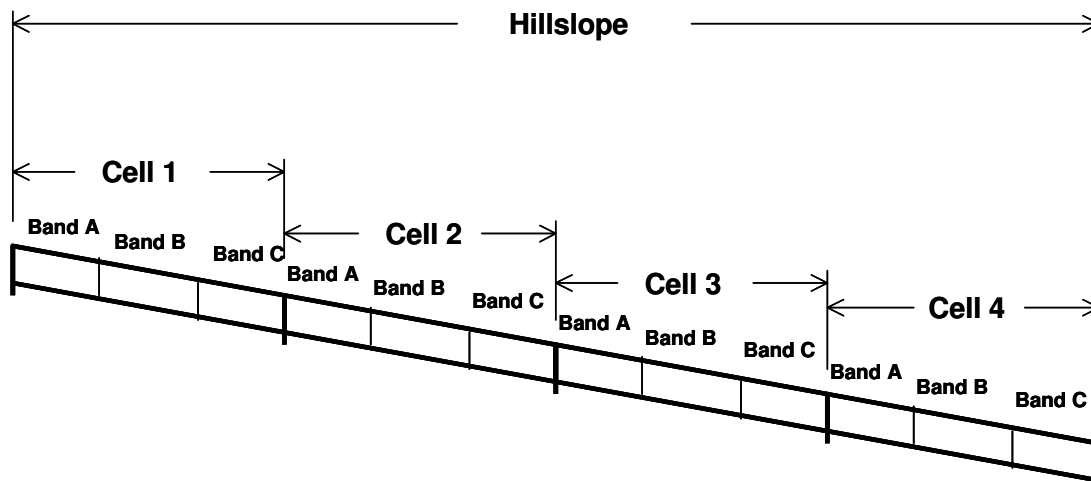


Figure 12 Hillslope structure used in the design framework.

This shows 4 cells, each comprising three bands A, B and C. The vegetation type and width of each band can be altered.

Water balance model

Fitting within the cascade conceptual model is a daily time step ‘bucket’ water balance model. This is driven by local daily rainfall and potential evaporation. The soil water storage capacities, and water use characteristics have the greatest influence on whether water is used by the plant, or is passed on as excess water to the next vegetation band downslope.

Assumptions

We recognise that, in reality, the movement of excess water from farm hillslopes is partitioned between deep drainage D and subsurface lateral flow L , as well as overland flow. The relative importance of each of these components, being dependent of soil characteristics and topography, is site-specific. For the purposes of this preliminary study, however, we have chosen to assume, as with the natural mulga and mallee systems, the main mechanism for the movement of excess water between vegetation patches is via overland flow. That is, deep drainage and subsurface lateral flow are assumed to be zero (Figure 14). This has greatly simplified the analysis and allows assessment of the potential best-case scenarios to achieve desired water yields.

We justify the omission of deep drainage on the basis of its representative proportion of the total water budget, rather than its possible contribution to dryland salinity or water logging. In most agricultural areas in Australia, deep drainage represents only a few percent of rainfall, except in deep, sandy soils (Petheram *et al.*, 2002).

The relative importance of lateral flow mechanisms (overland flow, shallow subsurface lateral flow) for water redistribution in agricultural landscapes is relatively poorly documented. During the development of the concepts described by Stirzaker *et al.* (2002), there was significant attention paid to shallow subsurface lateral flow as the most likely mechanism for ‘bringing water to the trees’ in the case of agroforestry designs. Silberstein *et al.* (2002) provided guidelines for estimating the likely significance of lateral flow from considerations of soil saturated hydraulic conductivity k_{sat} and surface slope s . The combinations of k_{sat} and s , which are likely to result in significant flow, are rare for much of Australian agricultural land. Opportunities for making use of this phenomenon are likely to be restricted to steeper catchments in eastern Australia and strongly duplex soils with sand A horizons in Western Australia (White *et al.*, 2002). Two recent studies (McKenzie *et al.*, 2003; Ticehurst, 2004) use modelling and experimentation to support this.

For design purposes, therefore, we consider D and L to be secondary considerations. Once a simplified water balance has been applied and if a more detailed investigation of a site and design appears to be warranted. A broad scale screening of landscape types with regard to the dominant water flow mechanisms for excess may be appropriate in any future investigations.

Similarly, infiltration characteristics of the soil surface have not been represented. Infiltration depth resulting from each rainfall event was calculated as the minimum of either the depth of the rainfall event or the available soil water storage. i.e. if the soil profile is not full (saturated) and a rainfall event occurs, infiltration will add directly to the soil water store and any excess will become runoff. While this representation is overly simplistic, we justify its use here on the basis of representing the best-case scenario for capture and management of overland flow for first-cut designs.

The extension of lateral roots of trees beyond the tree crown is not explicitly described in the model. It is assumed that each vegetation type occupies its designated band uniformly and does not extract water from outside the band. In reality, there is likely to be some overlapping of the root zones of trees and smaller species (Ellis *et al.*, 2005).

Water flows were not routed and were therefore assumed to occur instantaneously. Similarly, the growing patterns of crops and trees were not represented and were assumed to have reached some steady state.

Soil water storage capacity

Each vegetation band is represented as a separate bucket. In terms of plant water use, we have used the maximum soil water storage capacity S_{max} as a surrogate for plant available water capacity ($PAWC$). S_{max} is determined by plant rooting depth and is the product of plant rooting depth soil porosity. $PAWC$ represents the amount of water that can be stored in a soil between field capacity (1 bar) and permanent wilting point (15 bar). For our application, this level of detail was not considered necessary, but would become important where initial design explorations indicated a more sophisticated approach was warranted.

The soil water storage S at any time is the remainder of inputs (rainfall P and run-on Q_{in}) minus the outputs (evapotranspiration ET and runoff Q_{out}). Q_{out} will only occur when the soil profile is saturated (i.e. full; when $S = S_{max}$).

Evapotranspiration characteristics (loss functions)

Critical to the resilience of a natural vegetation in Australia in low to medium and highly variable rainfall areas, is the ET , or water use characteristic of each vegetation type or runoff surface. This was illustrated simply by Ritchie (1981) who distinguished between ‘stressed’ and ‘non-stressed’ water use domains. The combination of these two domains represents the plant ‘water use characteristic’ (Figure 13). For convenience, we will refer to the plant water use characteristic as the plant ‘loss function’ from here on. A more general version of this the ‘loss function’, as defined by Rodríguez-Iturbe *et al.* (1999), is described in Appendix 2.

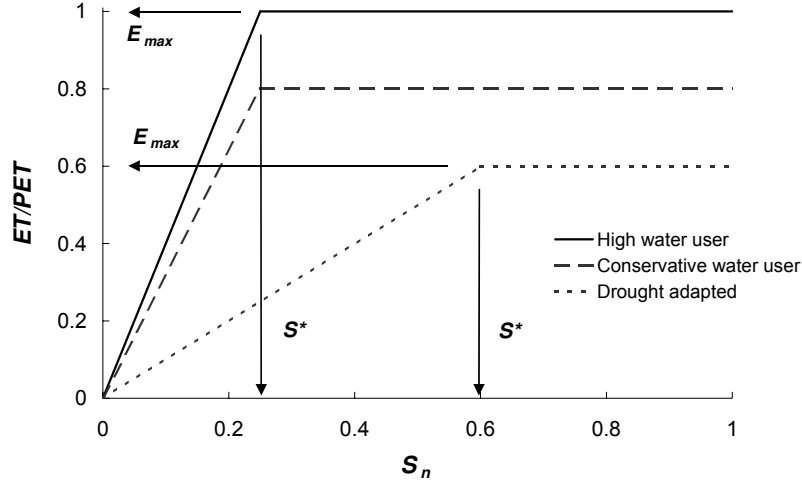


Figure 13 Example plant loss functions modified from Dunin *et al.* (2001).

For each vegetation type, or non-vegetated surface, we modified the approach of Richie (1981) to represent ET rate as a function of S_n , relative soil water storage, where S_n is S normalised relative to S_{max} . The features most relevant here are the maximum rate of ET and level of S_n below which the plant water use rate declines. That is, the level of S_n at which the plant switches from fast water use to slower water use, so that the water store is not completely emptied before the next rainfall event. We refer to this threshold as S^* . For drought tolerant plants (conservative water users) S^* has a larger value than more profligate water users such as annual species.

We express ET rate of a vegetation type as a proportion of potential evapotranspiration PET , or the atmospheric demand, which changes with daily weather conditions and follows a seasonal pattern (high in summer months and low in winter months). E_{max} represents the maximum ET rate (as a proportion of PET) for the plant under non-stressed conditions. The loss function we have used, therefore, is a plot of relative evapotranspiration rate ET/PET against relative soil water store S_n (Figure 13).

Strictly speaking, plants respond to soil matric suction Ψ , not S_n . The relationship between Ψ and S_n would be similar to that between Ψ and soil water content θ (McKenzie *et al.*, 2002), but will vary significantly with soil texture. The loss functions as represented in Figure 13, therefore, are specific to a particular soil texture. The measurement of Ψ represents a significant investment; therefore, typically, θ is much more easily related to ET . Methods are available for estimating Ψ from θ and soil texture (van Genuchten and Leij, 1997), however, this level of detail is not yet matched by our ability to characterise plant water use and would only be justified for studies more detailed than this one.

Bucket model

The water balance model is therefore a simple bucket representing each band (Figure 14) calculated on a daily time step. Water inputs were rainfall P and runoff from the vegetation band immediately upslope Q_{in} .

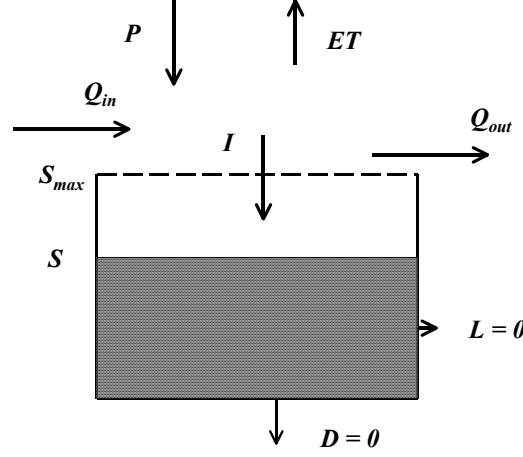


Figure 14 Simplified water balance of the root zone of a vegetation patch where the inputs are rainfall P and run-on from upslope Q_{in} . Outputs are ET and overland flow (runoff) Q_{out} . Deep drainage D and subsurface lateral flow L are assumed to be zero.

The amount of water that infiltrated the soil from the combined input of P and Q_{in} was determined by the available soil water store ($S_{max} - S$) at the time

$$I(t) = \min[(P(t) + Q_{in}(t)), (S_{max} - S(t-1))] \quad (1)$$

where $\min$ denotes the minimum value of the set, t denotes the time step, S_{max} is the maximum soil water storage and S is soil water storage.

S is then adjusted

$$S(t) = S(t-1) + I(t) - ET(t) \quad (2)$$

where $ET(t)$ is represented by a discontinuous function, modified from Ritchie (1981)

$$ET(t) = \begin{cases} PET(t) \frac{E_{max}}{S^*} S_n(t), & 0 \leq S_n(t) < S^* \\ PET(t) E_{max}, & S^* \leq S_n(t) < 1 \end{cases} \quad (3)$$

where PET is potential evaporation, E_{max} is the maximum ET rate (as a proportion of PET) of the plant when it is not experiencing water stress, S_n is S normalised with respect to S_{max} , and S^* is the threshold S_n between stressed and unstressed water use by the plant (see Figure 13).

Excess water (soil saturation excess) then becomes runoff Q_{out}

$$Q_{out}(t) = [P(t) + Q_{in}(t)] - I(t) \quad (4)$$

Q_{out} then becomes Q_{in} for the next band of vegetation.

Probabilistic modelling method

The method of Rodríguez-Iturbe *et al.* (1999) for the probabilistic modelling of soil water storage at a point offers some conceptually simple approaches for the matching of plant loss functions to climate and some basic soil conditions. The method has been further developed and tested (Laio *et al.*, 2001a, Porporato *et al.*, 2001, Laio *et al.*, 2001b) but has not yet been widely applied. For our purposes, the analytical solution offered by Rodríguez-Iturbe *et al.* (1999) is very attractive. However, the solution is limited to application at a single point and there is currently no solution that allows the hydrologic linking of multiple points on a hillslope as is required for banded systems. We have, however, drawn

on several aspects of the probabilistic method as they either offer an alternate view from conventional water balance modelling or a more expedient path to a design limit. We used an alternative formulation of the method to match trees species, to climate and soil conditions in order to achieve specified runoff targets. The methods of Rodriguez-Iturbe *et al.* (1999) and our application of it is described in Appendix 2.

Numerical modelling method

In the absence of an analytical solution to the probabilistic method (Rodriguez-Iturbe *et al.*, 1999) for multiple bands, we adopted a numerical method for the computation of Equations 1 to 4, above. This represented a discrete time-step analogue to the continuous solution of Rodriguez-Iturbe *et al.* (1999). The main model outputs were daily soil water storage and runoff for each vegetation band. We have presented soil water storage as time series and also as probability distributions as a more succinct indication of the likely soil water status.

As a prototype, the model has been constructed using Microsoft Excel and allows the simulation of a hillslope structure as described in Figure 12, and the ‘cascade’ of excess water downslope (Figure 11).

Input data and model parameters

Daily rainfall P (mm) and PET (mm) were imported from the SILO Patched Point Dataset (Jeffrey *et al.*, 2001) for the 10 year period 1 January 1989 to 31 December 1999 (a different time period was used for the model evaluation at Lake Mere to suit the local data set). The user specifies the total hillslope length, and this is automatically divided into 4 ‘cells’ of equal downslope length, although the ratio of cell downslope length to hillslope can be specified. There is facility to divide each cell into (a maximum of) 3 ‘bands’, of any specified downslope length, the total of which must sum to the cell downslope length.

Within each band, there is the facility to specify the vegetation or soil surface type, which is described by three characteristics:

1. Growing season. This represents the time period of a year during which the plant is transpiring: winter (1 May to 31 August), summer (1 November to 28 February) or perennial (all year).
2. The loss function (see Figure 13). This is determined by adjusting S^* and E_{max} .
3. Rooting depth z (mm), which, together with soil porosity n , determines S_{max} and, to minimise complexity, n was kept constant at 10%.

This represents a total of three parameters required to describe the characteristics of each band, once the seasonality of the vegetation or surface type was decided (bare soil or artificial runoff surfaces were represented as ‘perennial’). This was simplified further by the characterisation of loss functions into ‘high water use’, ‘conservative water use’ or ‘drought adapted’. The parameter values used for S^* , E_{max} and z are listed in Table 1.

Input parameter values used for the evaluation of the model at the Lake Mere site were obtained from measurements at the site or from studies at similar sites. We assigned the same loss function, as described by Dunin *et al.* (2001) for ‘agricultural communities’, to cereal crops, perennial pastures, lucerne, high water use trees and artificial runoff. This meant that the only difference between these vegetation types and runoff surface, as far as the model is concerned, is the amount of soil water storage, as determined by z and n . The loss function for ‘conservative water use’ trees was taken to be that of *Corymbia maculata* (previously *Eucalyptus maculata* – spotted gum) (Dunin *et al.*, 2001).

Off-season ET (i.e. ET during the non-growing season of winter or summer vegetation) was roughly approximated as a set 10% of PET for that period.

Rooting depths for the case studies were nominally set at 1 m for winter cereal and perennial pasture, 1.5 m for lucerne and 4 m for trees. These numbers were chosen as (conservative) default values and were not intended to accurately represent actual rooting depths at the case study sites. Similarly, the default soil porosity for case studies was chosen to be 10% and should also be considered to be conservative.

Rooting depth z of the bare soil and artificial runoff zones is an abstract concept with respect to reality (i.e. no roots); however, it has some physical meaning that it defines S_{max} for the zone. For the bare runoff zone at the Lake Mere model evaluation site (see Model Evaluation), z was set to match an observed S_{max} . For hypothetical artificial runoff surfaces used for water harvesting (e.g. wax), z was set such that the runoff coefficient matched published values for such surfaces (Fink *et al.*, 1980).

Table 1 Input parameter values for vegetation loss functions and soil characteristics for the model evaluation and case studies

Vegetation/crop	z (m)	Soil porosity (%)	S_{max} (mm)	S^*	E_{max}
Bare runoff	0.035 ^a	44.2 ^b	15	0.5 ^c	1.0 ^c
Grassy interception	0.7 ^b	42.3 ^b	207	0.9 ^c	1.0 ^c
Mulga grove	0.7 ^b	48.3 ^b	338	0.8 ^c	1.0 ^c
Artificial runoff	0.004 ^d	10 ^g	0.0004	0.25	1.0
Winter cereal	1.0 ^e	10 ^g	100	0.25 ^f	1.0 ^f
Perennial grass	1.0 ^e	10 ^g	100	0.25 ^f	1.0 ^f
Lucerne	1.5 ^e	10 ^g	150	0.25 ^f	1.0 ^f
High water use tree	4 ^e	10 ^g	400	0.25 ^f	1.0 ^f
Conservative water use tree	4 ^e	10 ^g	400	0.25 ^f	0.8 ^f

^a Adjusted to produce observed $S_{max} = 15$ mm (D. Tongway unpublished data, 1990).

^b Measured during this study.

^c Modified from Slatyer (1961).

^d Adjusted to match a runoff coefficient 0.95 for waxed soil (Fink *et al.*, 1980).

^e Default values. Users should endeavour to obtain local data if available.

^f From Dunin *et al.* (2001).

^g Default value. Users should endeavour to obtain local data if available.

Model outputs

Daily S and Q_{out} was calculated for all bands on the hillslope, where Q_{out} was expressed as a depth (mm) over the entire area upslope of the lower boundary of that band. Annual average water inputs ($P + Q_{in}$) and outputs (ET , Q_{out}) and runoff coefficient (P/Q_{out}) were calculated for each band.

As a method of summarising daily S_n , a probability density distributions [distributions of $p(S_n)$] are presented for the whole hillslope (in the case of 100% cover of the same vegetation type), or the band that provides the main control over runoff, typically the trees. The probability density distributions provide a visual representation of the distribution of S_n between 0 and 1 for the 10-year period. The curves shown should be regarded as approximate as they are smooth curves fitted to a distribution of discrete probability density where

$$p(S_n)_h = \frac{\#(S_n)_h / N}{h} \quad (5)$$

where $p(S_n)_h$ is the probability density over the interval h , $\#(S_n)_h$ represents the number of observations of S_n within h and N is the total number of observations of S_n (modified from Siminoff, 1996). For practical purposes, with regard to data presentation, the discretisation of the S_n was coarse, such that $h = 0.1$. As a indication of the probability that the soil will be ‘dry’ (S_n less than 20%) or ‘wet’ (S_n greater than 20%), $\Pr(S_n < 0.2)$ and $\Pr(S_n > 0.8)$, respectively, were calculated.

Model evaluation

Evaluation study site

Suitable data sets were not available set for complete evaluation of the model, however, preliminary evaluation was possible using published and unpublished data from naturally banded mulga study sites at Lake Mere (30.27° S, 144.90° E; Tongway and Ludwig, 1990; Greene, 1992, Ludwig and Tongway, 1999; Figure 9; Figure 15) and Alice Springs, NT (Slatyer, 1961). The naturally-banded systems were chosen for the evaluation as it was known that these landscapes functions as a source-sink (Noy-Mier, 1973) system at about the scale we propose for agricultural analogues (i.e. bands being metres, to tens of metres in downslope length). Comprehensive hydrologic studies of spatially heterogeneous systems in Australia, either natural or imposed, are very rare. At the time of this study, we were unaware of any data sets suitable for a detailed evaluation of our model.



Figure 15 Lake Mere mulga vegetation community showing the bare runoff zone (foreground), grassy interception (in front of, and immediately upslope from, the trees) and a mulga grove (trees). (The trees are approximately 6 m high. See also Figure 9.)

Lake Mere (Figure 15) was chosen as the evaluation site due mainly to its long history as an rangeland grazing study site, and the availability of local daily rainfall records; we used the 10 year period from 1 August 1986 to 31 July 1996. Daily *PET* was obtained from the Silo database for Cobar (The Meadows; 31.71° S, 145.28° E) approximately 100 km from Lake Mere. Input parameter values for Lake Mere are listed in Table 1.

The 3 geomorphologic zones were represented as the 3 bands in our conceptual model (Figure 12), using 120 m for the downslope length of each cell. The relative proportions of the bands within the cells was set as 60% bare runoff, 10% grassy interception, 30% mulga grove (Tongway and Ludwig, 1990). Loss functions for the 3 zones of system were taken from a study of a similar system near Alice Springs (Slatyer, 1961). Soil porosity was calculated from bulk density samples taken during this study using the membrane method described by McKenzie *et al.* (2002). Rooting depth in the grassy interception and the mulga groves was assumed equal to maximum soil depth measured in February 2003 during this study. We therefore adjusted z to set $S_{\max}$ to equal 15 mm, the nominal observed water storage capacity of the bare runoff zone (D. Tongway, unpublished data). This was the typical depth of rainfall observed to cause overland flow from the bare runoff zone.

Runoff from the Lake Mere site was not measured; therefore, the only observations available for model evaluation were the timing of inundation events. This response of the landscape represents an integration of the individual functions and interactions of the representative components.

Model evaluation results

This section shows the numerical model outputs for the Lake Mere site using the input parameter values listed in Table 1 for a total slope length of 480 m. The source of these values is described in the Methods section.

Model outputs are presented in several forms

1. Time series of daily S and Q (Figure 16) for each of the geomorphologic zones for the period 1 January 1989 to 31 December 1999, where S is stored soil water (mm) and Q is runoff (mm) calculated for the entire upslope contributing area.
2. Tabulated annual average water inputs, outputs and runoff coefficients (Table 2) for each band on the entire hillslope comprising 3 bands within each of 4 cells (Figure 12). Runoff is expressed as a depth Q_{out} for each band and as a depth Q (mm) for the whole upslope contributing area.
3. Probability density distributions [distribution of $p(S_n)$] for each of the geomorphologic zones (Figure 17). The soil profile dryness and wetness indicator values $\Pr(S_n < 0.2)$ and $\Pr(S_n > 0.8)$ values are presented in Table 8.

Because no time series measurements of S or Q are available from the Lake Mere site, evaluation of the performance of the model is approximate only and is limited to matching of modelled and observed runoff events from the mulga grove. This is indicative of total inundation of the site, and, although a relatively rare occurrence in this environment, total inundation was observed in April 1990 (D. Tongway, R. Greene unpublished data). The timing of inundation was matched by the model without any calibration (Figure 16); the magnitude of the runoff event was not considered.

Interpretation of model evaluation results

The time series of S and Q for the three zones (Figure 16) reflects the very small storage (Table 1) capacity of the bare runoff zone and hence runoff of excess water is frequent. The grassy interception has a greater storage capacity and therefore generates runoff less often. Similarly, the mulga grove has a relatively large storage capacity, but has a comparatively lower water input (Table 2), principally due to its order on the slope, but also because of the relative area proportions of the zones. The soil profile below the mulga grove is consequently full less often than the root zone of the grassy interception and is the final buffer against inundation of the landscape.

In the absence of a better evaluation data set, the matching of observed and modelled inundation in April 1991 (Figure 16) is taken as a reasonable indication that the model satisfactorily represented the redistribution of water at the Lake Mere site.

The $p(S_n)$ for each of the geomorphologic zones shown in Figure 17 indicates the three markedly different behaviours of the zones. The bare runoff zone is extremely ‘flashy’ and is typically dry. The grassy interception has a greater storage capacity and can buffer against the dry times to a certain extent and is therefore less likely to be dry. The mulga grove has the same storage capacity as the grassy interception but a more conservative loss function (see Table 1) and therefore exhibits greater likelihood that S_n will be around 0.1, but not completely ‘empty’. This is consistent with the drought-adapted nature of the mulga plant.

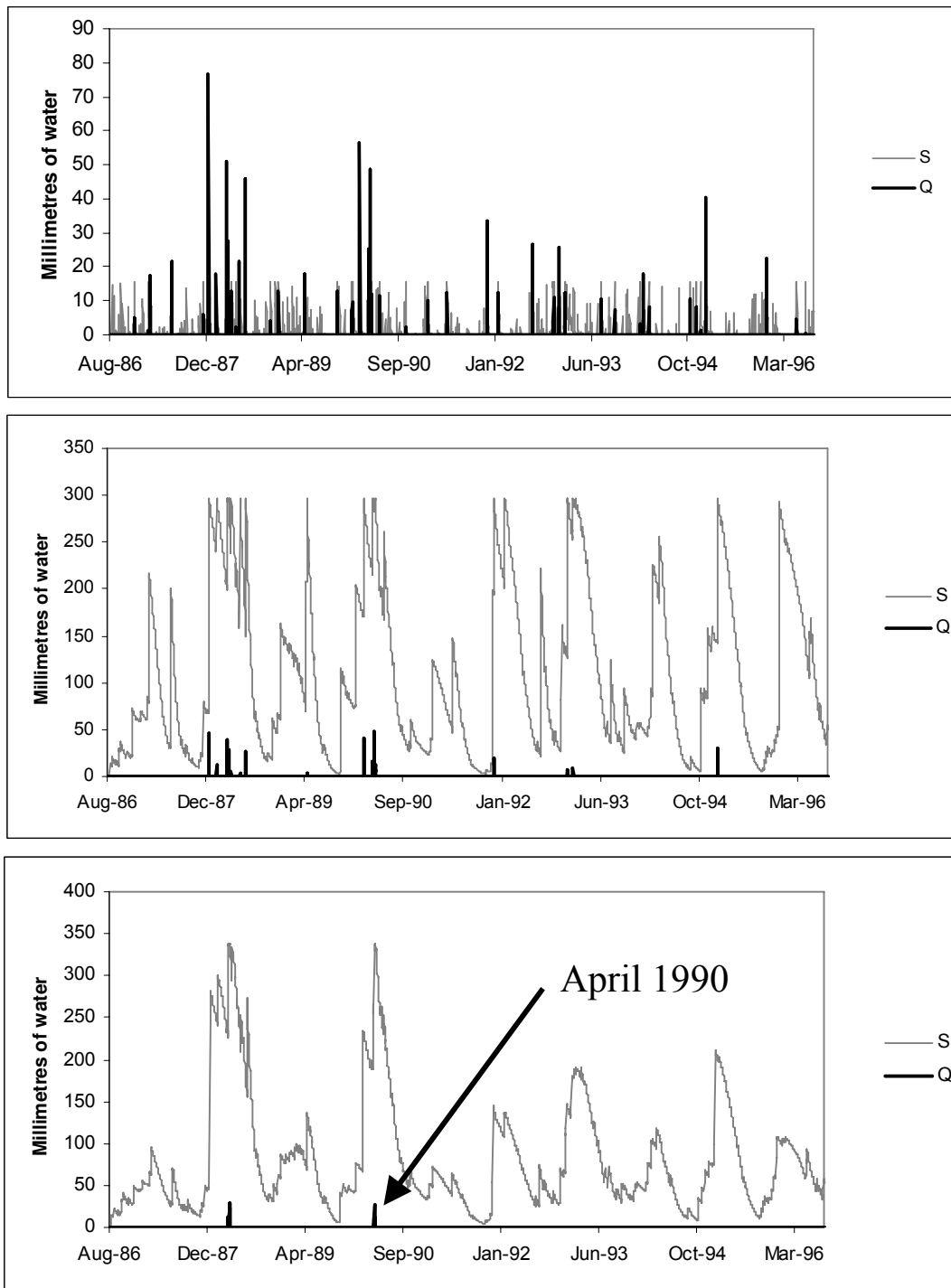


Figure 16 S (mm) and Q (mm) for the three geomorphologic zones at Lake Mere: bare runoff (top), grassy interception (centre), mulga grove (bottom).

Runoff event in April 1990 matches observed inundation of the landscape.

Table 2 Annual average water inputs, outputs and runoff coefficient for each of three bands within the four cells comprising the modelled hillslope at Lake Mere.

Runoff is expressed as a depth Q_{out} for each band and as a depth Q (mm) for the whole upslope contributing area.

Cell	Band	Cumulative slope distance (m)	$P+Q_{in}$ (mm)	Q_{out} (mm)	Q (mm)	ET	Runoff coefficient
1	Bare runoff	30	290	93	93	197	0.32
	Grassy interception	35	848	281	40	562	0.14
	Mulga grove	50	384	41	12	338	0.04
2	Bare runoff	80	310	113	43	197	0.15
	Grassy interception	85	970	403	24	562	0.08
	Mulga grove	100	424	81	12	338	0.04
3	Bare runoff	130	331	134	31	197	0.11
	Grassy interception	135	1092	525	19	562	0.07
	Mulga grove	150	465	122	12	338	0.04
4	Bare runoff	180	351	154	26	197	0.09
	Grassy interception	185	1214	647	17	562	0.06
	Mulga grove	200	506	162	12	338	0.04

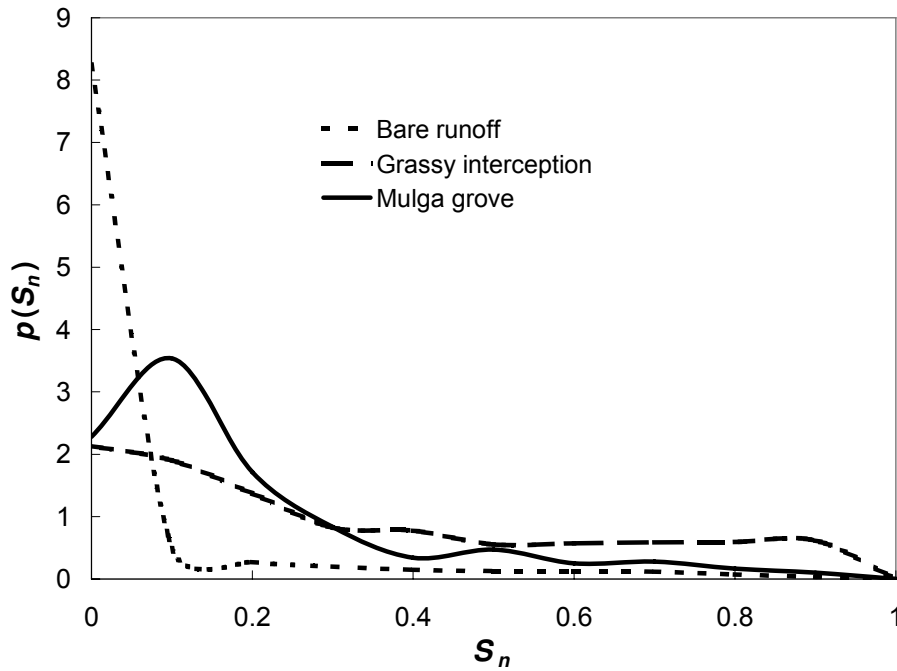


Figure 17 Distribution of $p(S_n)$ for the three geomorphologic zones at Lake Mere.

Case studies

Introduction

Five case study areas were chosen in which to simulate arrangements of crops and trees and to examine the effect on average annual runoff from hypothetical hillslopes 800 m in length. We undertook the case studies in catchments with differing resource management issues associated with excess water leaving agricultural land. These included: dryland salinity and water logging; pollutant wash-off; gully erosion; stream salinity; urban water supply.

For each case study, we have provided a brief description of the site, the principal perceived local water management issues and the vegetation scenarios simulated. Input parameters for each vegetation type are given in Table 1 in the previous section.

In each case, the combinations of vegetation type and proportions thereof, able to be simulated, are myriad, and since the design question (“How much runoff?”) could not be well defined, we undertook a more exploratory approach. Rather than aiming to determine the most suitable design for each site, we examined the response [in terms of runoff and $p(S_n)$] of the site to extreme options for vegetation of the hillslope (e.g. 100% winter cereals or 100% trees) before examining the effects of banding multiple species.

For each case study site, results are presented as follows:

1. The $p(S_n)$ distributions as calculated from daily output from the numerical model. In each case $p(S_n)$ distributions for two extreme vegetation scenarios are presented, followed by combined $p(S_n)$ distributions for each band in the banded scenario.
2. A tabulated summary of average annual water inputs and outputs for each scenario is also presented. For banded scenarios, the runoff from the last band indicates the runoff from the whole hillslope.
3. The time series of S and Q for the three scenarios. A single chart is used for each of the uniform vegetation scenarios; three charts are used for the banded scenarios.
4. A summary of the all the site characteristics and model results are presented in Table 8. These include site specifications, modelled scenarios, average annual runoff coefficients and soil profile dryness and wetness indicator values $\Pr(S_n < 0.2)$ and $\Pr(S_n > 0.8)$.
5. A brief interpretation of the model outputs for the case study sites is given at the end of the Results section.

Annandayle South (35.77° S, 147.35° E)

Site description

The property Annandayle South is within the upper Billabong Creek Catchment, near Holbrook NSW. This is a focus catchment for the Heartlands Initiative (<http://www.per.clw.csiro.au/heartlands/index.html>), which is aimed at developing new systems of land use for multiple benefits, including management of dryland salinity and water logging. The general issue relating to the hydrology of the site, in a local context, excess water was accumulating at the bottom of the hillslope. The site comprised a 10 year-old farm tree belt (*E. saligna* and *Acacia melanoxydon*) originally planted across the hillslope to intercept perceived shallow subsurface lateral flow, which was thought to be causing water logging and dryland salinity on the lower slopes.

Another study (Ticehurst, 2004) running concurrently with this one, undertook detailed soil physical and hydrologic measurements at the site over two years. Preliminary results from the study suggest that the principal mechanism for the supply of excess water to the trees (from upslope) is by overland, rather than shallow subsurface flow (Figure 18).

There was, however, a 'deep' lateral flow path (6-7 m deep), too deep for the tree roots to access, and only became a connected flow path when the hillslope was saturated, which means that the trees have

plenty of shallow soil water to use. In this case, the trees are unlikely to draw from the deep lateral flow.

Shallow subsurface lateral flow only occurred locally (approximately 30-50 m horizontally from the trees) until the hillslope was saturated when the upper slope and lower slope hydrology became more connected.



Figure 18 Annandale South tree belt looking from the top of the hill (left) and inside the tree belt (right).

Although principally a grazing property, winter cereals are also grown in the area, and farm forestry is relatively popular. The scenarios investigated were

1. 100% winter cereal
2. 100% trees
3. 33% winter cereal, 33% perennial pasture, 33% high water use trees.

Soil water storage probability distributions $p(S_n)$

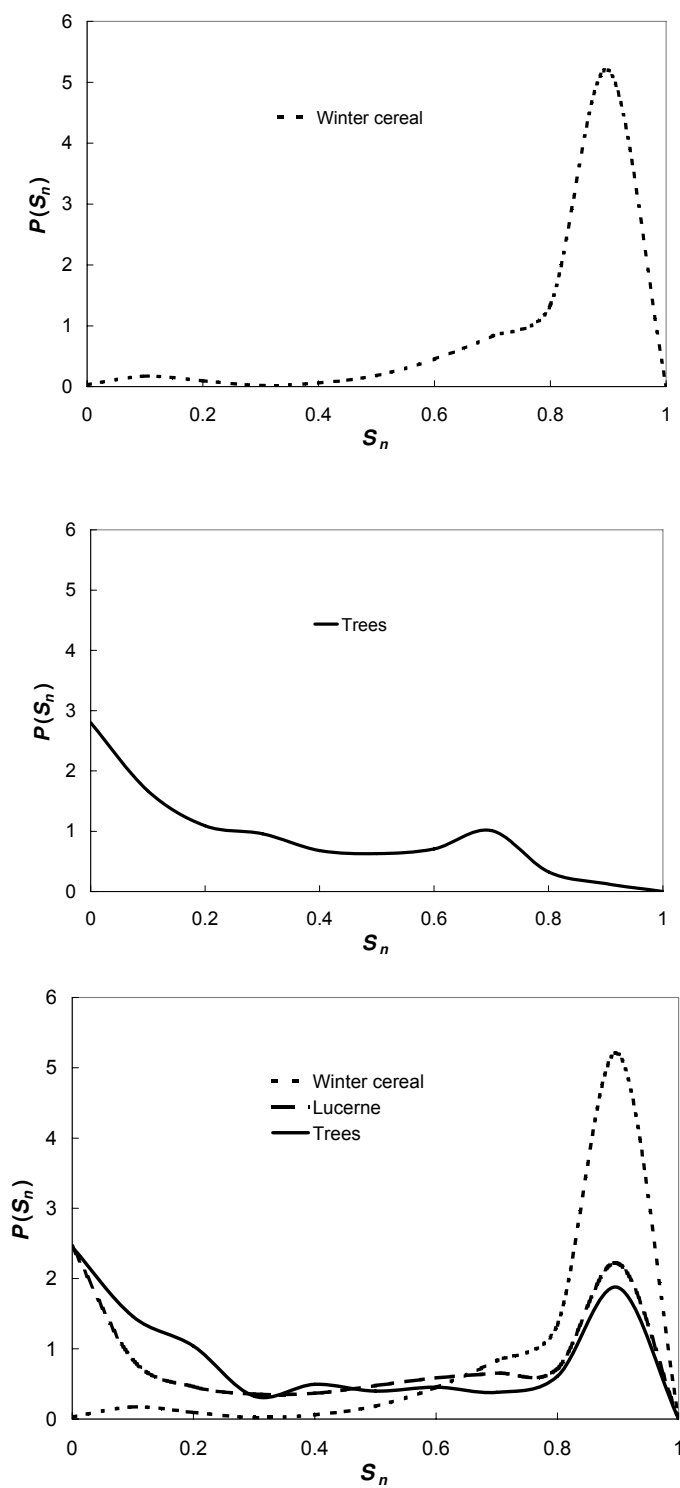


Figure 19 Distribution of $p(S_n)$ for Annandayle: 100% winter cereal (top); 100% high water use trees (centre); combined 33% winter cereal, 33% lucerne, 33% high water use trees (bottom).

Time series and annual average water balance

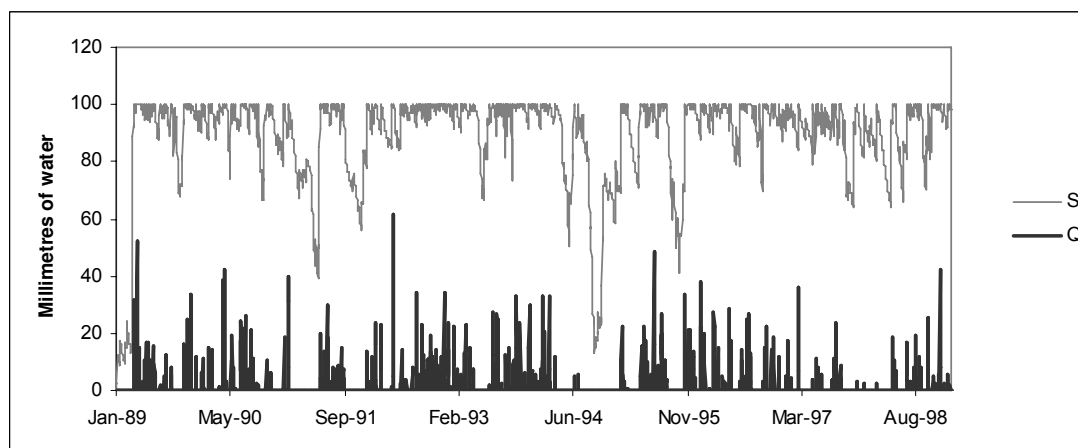


Figure 20 Time series of S and Q for Annandayle South 100% perennial pasture.

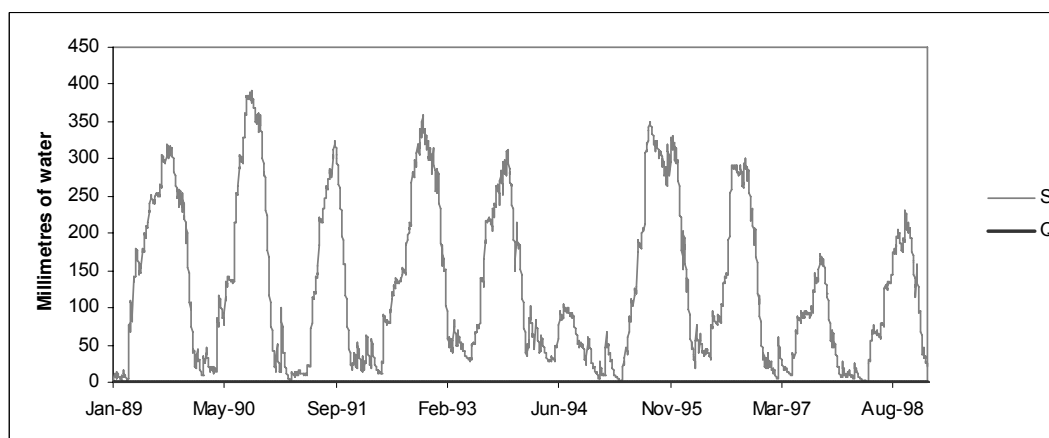


Figure 21 Time series of S and Q for Annandayle South 100% trees.

Table 3 Annandayle South - annual average water inputs, outputs and runoff coefficients for the entire hillslope of the banded scenario.

For a complete scenario description, see Table 8. Runoff is expressed as a depth Q_{out} for each band and as a depth Q (mm) for the whole upslope contributing area.

Cell	Band	Cumulative slope distance (m)	$P+Q_{in}$ (mm)	Q_{out} (mm)	Q (mm)	ET (mm)	Runoff coefficient
1	Winter cereal	67	770	437	437	324	0.57
	Lucerne	133	1207	409	204	798	0.27
	Trees	200	1179	322	107	851	0.14
2	Winter cereal	267	1092	759	190	324	0.25
	Lucerne	333	1529	730	146	798	0.19
	Trees	400	1501	643	107	851	0.14
3	Winter cereal	467	1414	1080	154	324	0.20
	Lucerne	533	1851	1052	132	798	0.17
	Trees	600	1822	965	107	851	0.14
4	Winter cereal	667	1735	1402	140	324	0.18
	Lucerne	733	2172	1374	125	798	0.16
	Trees	800	2144	1287	107	851	0.14

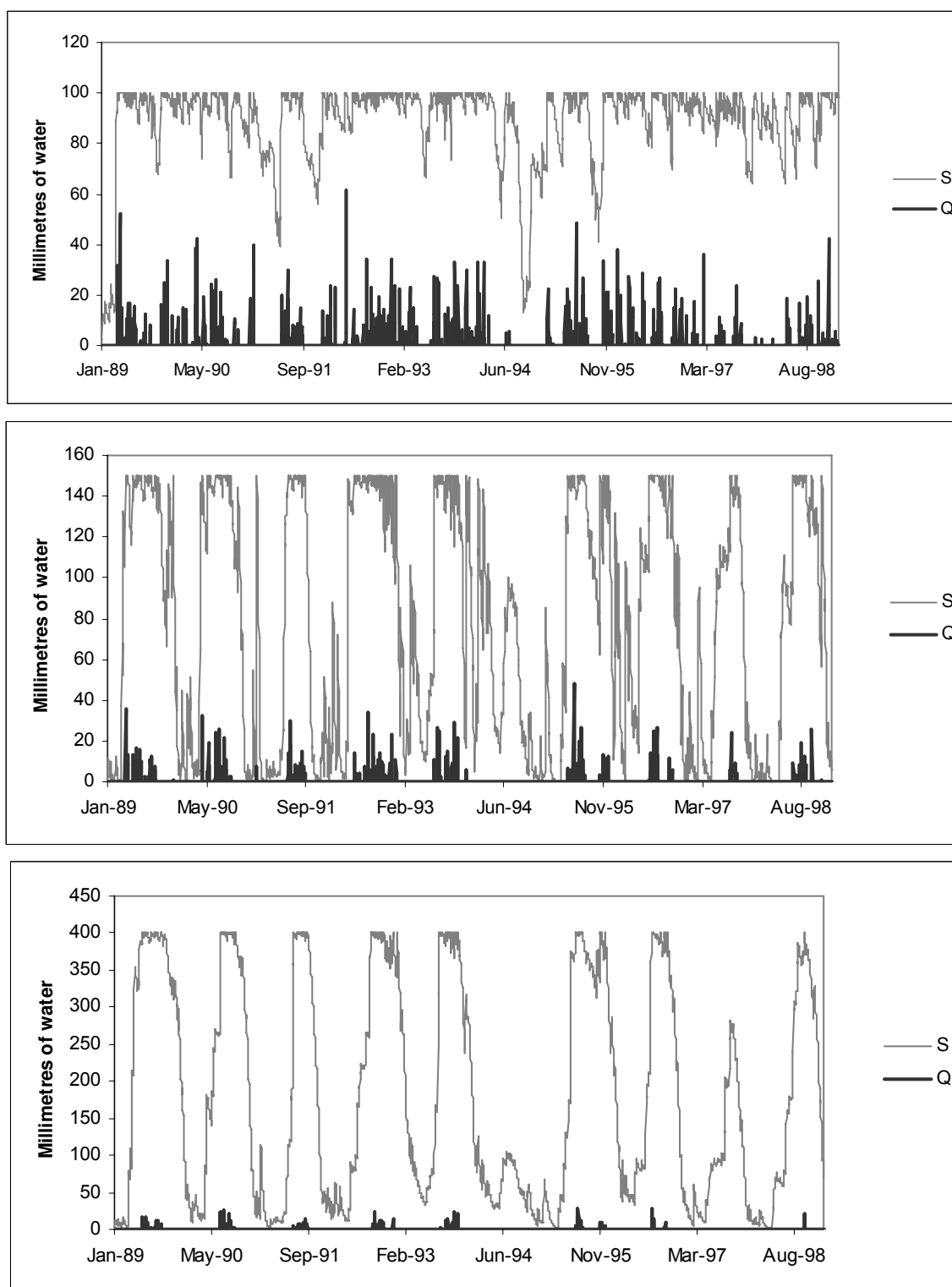


Figure 22 Time series of S and Q for Annandayle South: 33% winter cereal (top); 33% perennial pasture (centre); 33% trees (bottom).

Bluff Downs (19.60° S, 145.88° E)

Site description

Bluff Downs property is in the Burdekin catchment of far North Queensland, south of Cairns. The pollution of estuaries and the Great Barrier Reef by wash-off of suspended soil sediment and other pollutants from coastal catchments is currently the subject of significant attention (<http://www.pc.gov.au/study/gbr/finalreport/index.html>; <http://www.reef.crc.org.au/about/>; <http://www.gbrmpa.gov.au/>). Wash-off from cattle grazing areas in the Burdekin Catchment (tropical savannah) is thought to be a major contributor to this problem. In contrast to the catchments in southern Australia, the rainfall is strongly summer-dominant (monsoonal) and is highly episodic in nature (i.e. characterised by intense storms rather than more evenly distributed showers). Most of the pollutants are mobilised and delivered to estuaries during a small number of very large rainfall events. We therefore undertook simulations to investigate the effect that banded vegetation systems might have on buffering the largest rainfall events. An additional important function of banded vegetation systems in such situations (as it is in naturally banded systems) is the filtering role of the grassy bands, in particular. This process occurs from the slowing of overland flow due to greater flow resistance and the reduction of the suspended sediment load via deposition. We do not investigate this phenomenon within this study but draw attention to the strong links with other projects and models and methods designed specifically to investigate this issue (e.g. Ellis *et al.* 2006; Leguédais *et al.*, submitted).



Figure 23 A runoff and erosion site at Virginia Park station (19.75S 146 E), nearby to Bluff Downs.

Cattle grazing in the Burdekin catchment is thought to cause severe degradation of the vegetation and soil surface, greatly reducing the soil infiltration capacity (the rate at which water can infiltrate the soil surface), thereby increasing overland flow and soil erosion (Roth *et al.*, 2003; McIvor *et al.*, 1995; Prosser *et al.*, 2001). Vegetation and soil characteristics have been shown to improve dramatically in the absence of stock (McIvor *et al.*, 1995; Roth *et al.*, 2003) such that infiltration rates return to high values. Infiltration characteristics are not represented by the model therefore implicit within the scenarios tested is the assumption that infiltration rates were maximal. Modelled scenarios for Bluff Downs were:

1. 100% perennial pasture
2. 100% trees
3. 33% artificial runoff, 33% perennial pasture; 33% conservative water use trees

Rooting depth for the perennial grass was reduced from 1 m to 0.75 m such that the runoff coefficient of scenario 1 approached the measured value from the Virginia Park site (for three events only; R. Bartley, unpublished data, 2003). A water harvesting approach (i.e. runoff enhancement via soil surface treatment) was chosen to investigate the potential for increasing the effective rainfall supplied to the tree component.

Soil water storage probability distributions $p(S_n)$

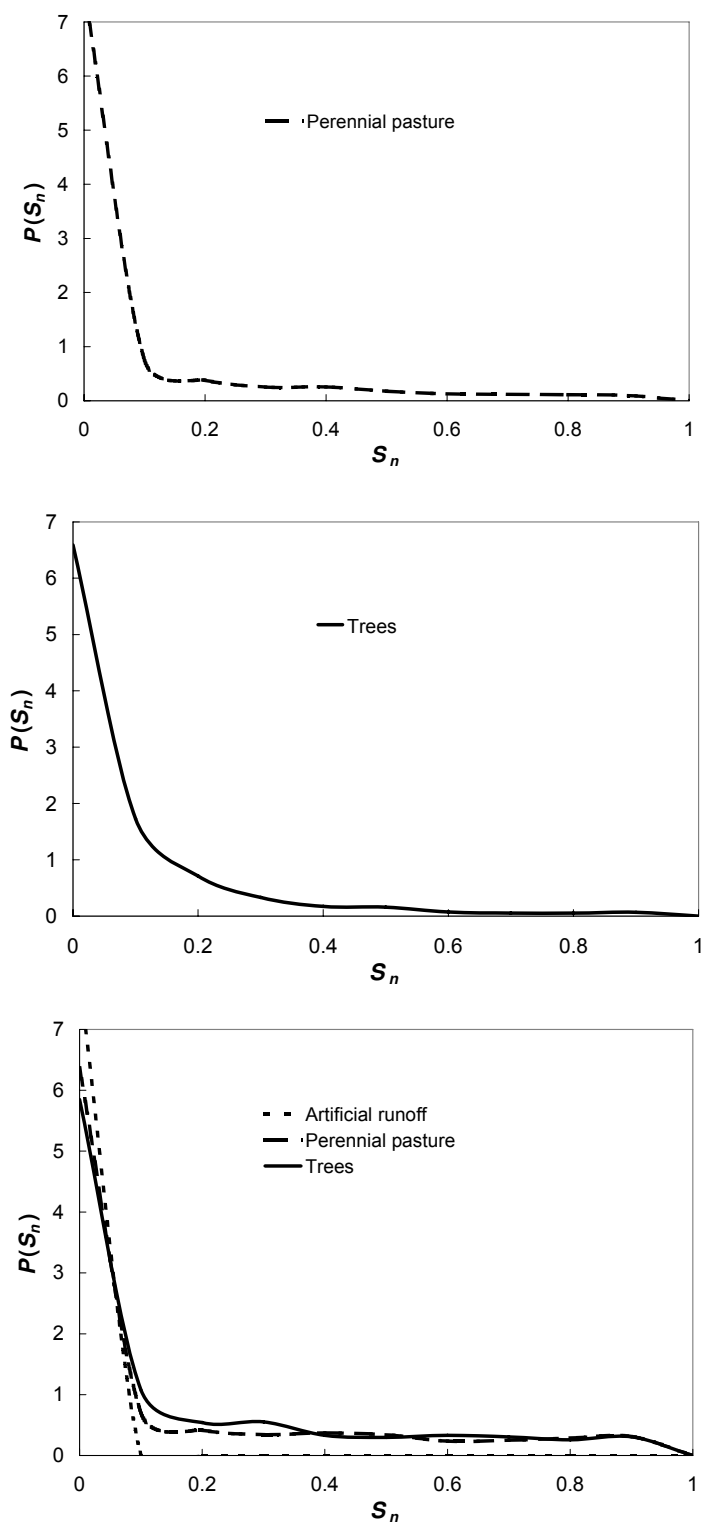


Figure 24 Distribution of $p(S_n)$ for Bluff Downs: 100% perennial pasture (top); 100% conservative water use trees (centre); combined 33% artificial runoff, 33% perennial grass, 33% conservative trees (bottom).

Time series and annual average water balance

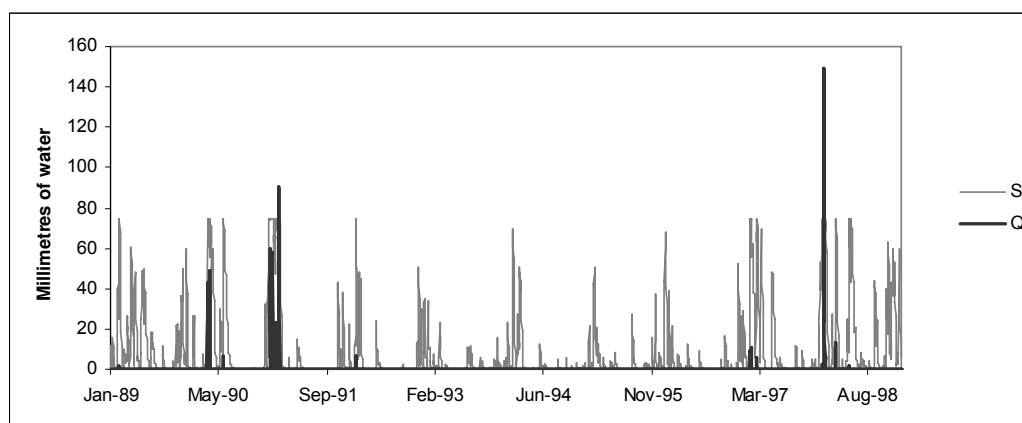


Figure 25 Time series of S and Q for Bluff Downs 100% perennial pasture.

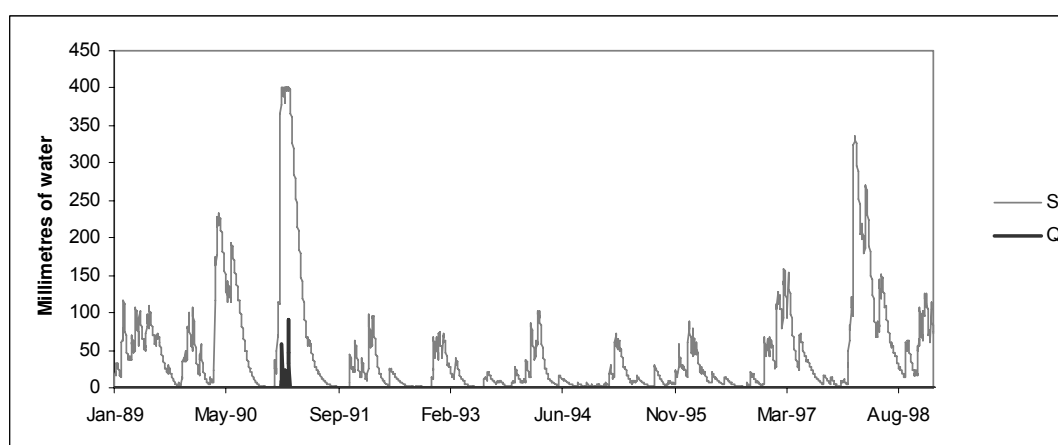


Figure 26 Time series of S and Q for Bluff Downs 100% trees.

Table 4 Bluff Downs - annual average water inputs, outputs and runoff coefficients for the entire hillslope of the banded scenario.

For a complete scenario description, see Table 8. Runoff is expressed as a depth Q_{out} for each band and as a depth Q (mm) for the whole upslope contributing area.

Cell	Band	Cumulative slope distance (m)	$P+Q_{in}$ (mm)	Q_{out} (mm)	Q (mm)	ET (mm)	Runoff coefficient
1	Artificial runoff	67	573	544	544	29	0.95
	Perennial pasture	133	1116	394	197	719	0.34
	Trees	200	966	287	96	654	0.17
2	Artificial runoff	267	859	831	208	29	0.36
	Perennial pasture	333	1403	680	136	719	0.24
	Trees	400	1253	574	96	654	0.17
3	Artificial runoff	467	1146	1118	160	29	0.28
	Perennial pasture	533	1690	967	121	719	0.21
	Trees	600	1540	861	96	654	0.17
4	Artificial runoff	667	1433	1404	140	29	0.25
	Perennial pasture	733	1977	1254	114	719	0.20
	Trees	800	1827	1147	96	654	0.17

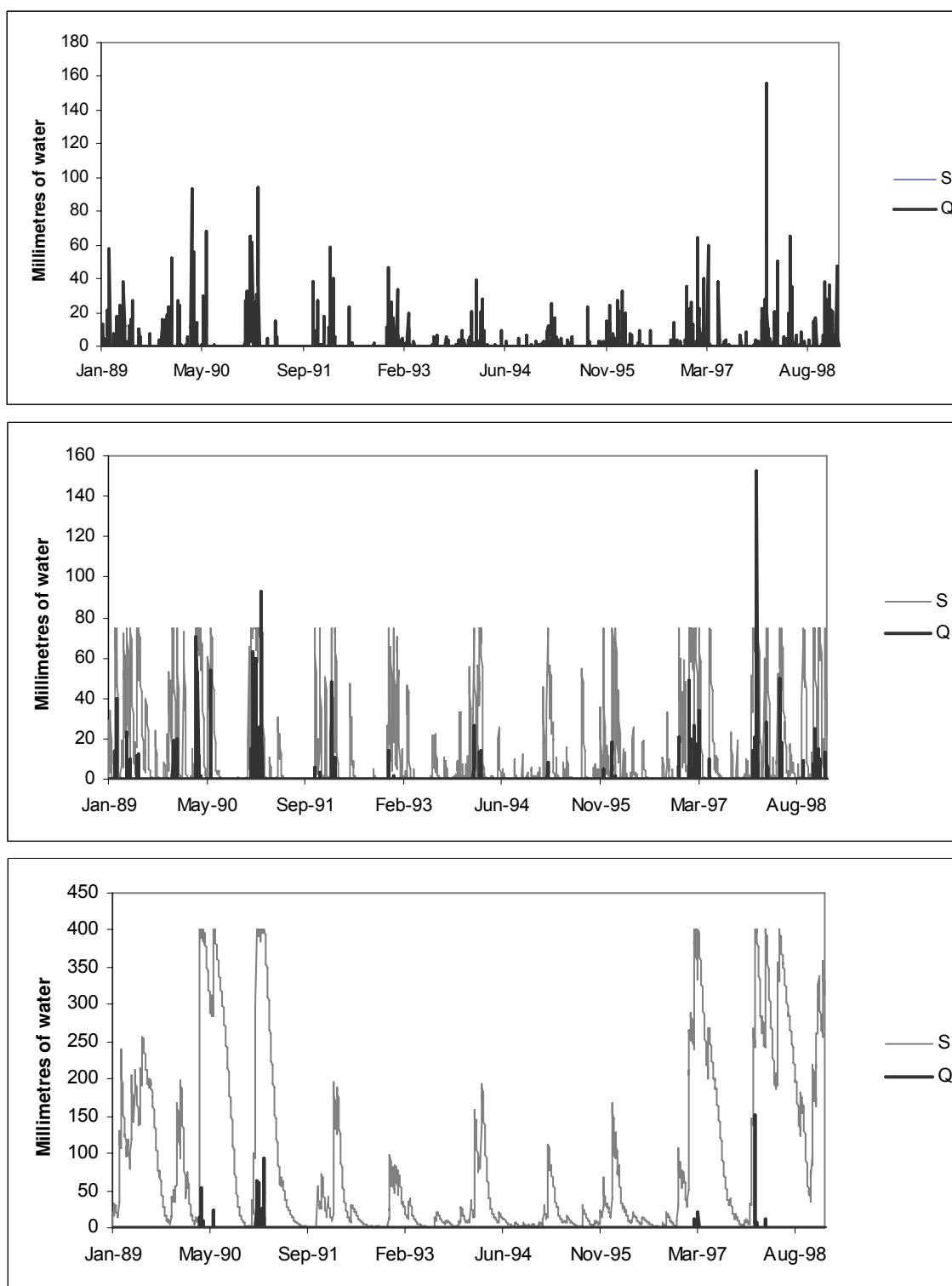


Figure 27 Time series of S and Q for Bluff Downs: 33% artificial runoff (top); 33% perennial pasture (centre); 33% conservative trees (bottom).

Bogolara (35.00° S, 148.60° E)

Site description

The site at Bogolara is in a sheep grazing area in the Murrumbidgee Catchment near Bookham, NSW. It was chosen as a case study site (funded by Land and Water Australia, Wool Innovation, and CSIRO Land and Water; contact Gary Caitcheon – gary.caitcheon@csiro.au) to demonstrate remedial action on gully erosion (Figure 28). It is believed that the erosion is a result of significant overland flow leaving the hillslope (due to poor infiltration capacity following grazing-induced soil surface degradation) combined with dispersive clay subsoil (Figure 29). Perennial grass and tree plantings are being considered as a method of capturing and using more water on the hillslope to reduce overland flow. We therefore modelled the following scenarios

1. 100% perennial pasture.
2. 100% trees.
3. 66% perennial pasture and 33% high water use trees.

The Land Water and Wool project has funded the recent installation of flow gauges at the site, which will provide data for a more rigorous testing of potential new scenarios in the future.



Figure 28 Severe gully erosion at the Bogolara site (Photo D. Tongway).



Figure 29 Micro terracing (photo left) of the grazed pasture surface at Bogolara following rainfall indicating significant overland flow (from right to left). Dispersive subsoil (photo right) causing collapse of the A horizon at the head of an active gully (Photos D. Tongway).

Soil water storage probability distributions $p(S_n)$

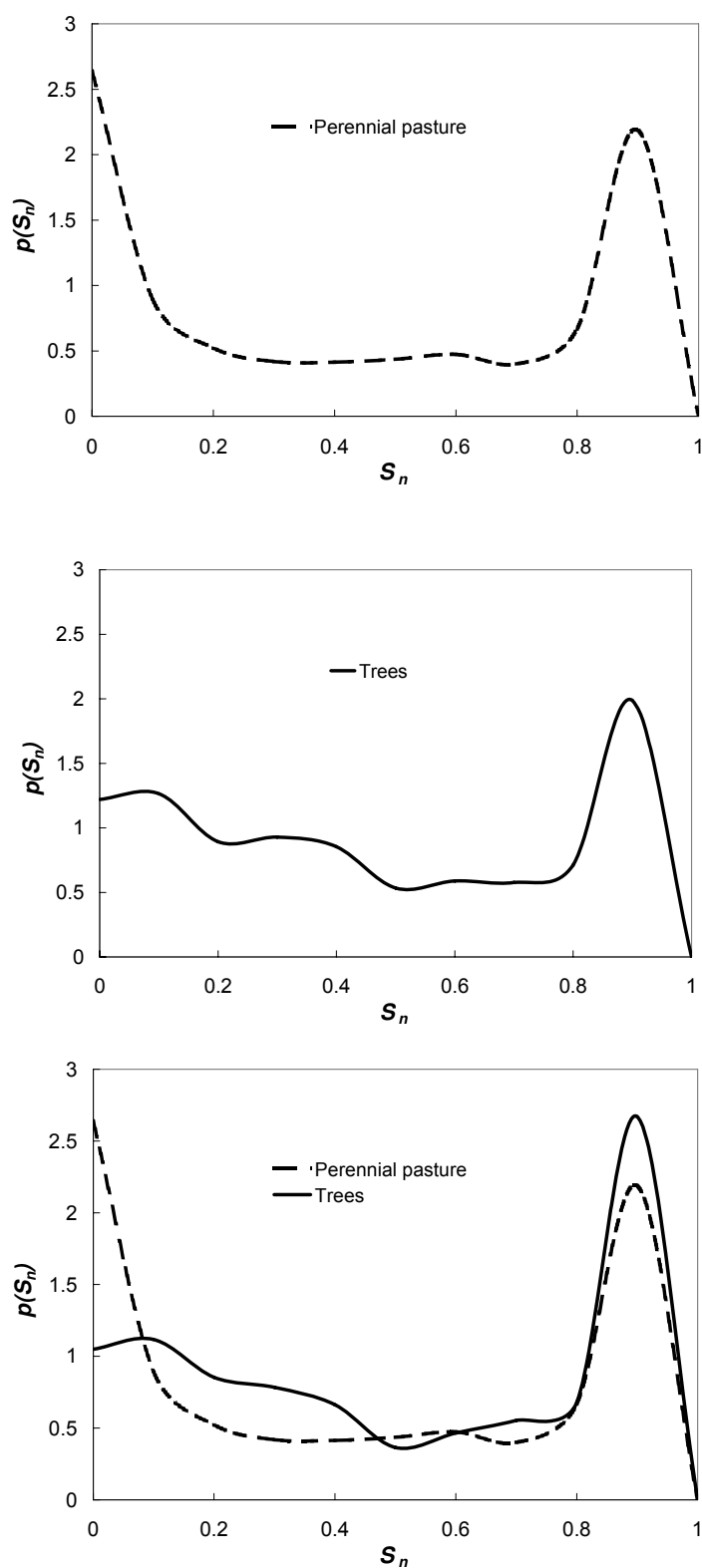


Figure 30 Distribution of $p(S_n)$ for Bogalara for three scenarios: 100% perennial pasture (top); 100% high water use trees (centre); combined 66% perennial grass, 33% high water use trees (bottom).

Time series and annual average water balance

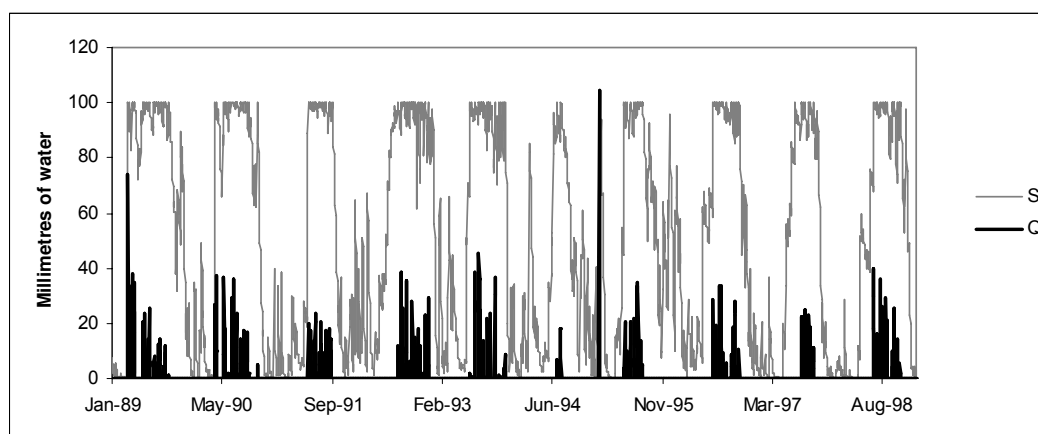


Figure 31 Time series of S and Q for Bogolara 100% perennial pasture.

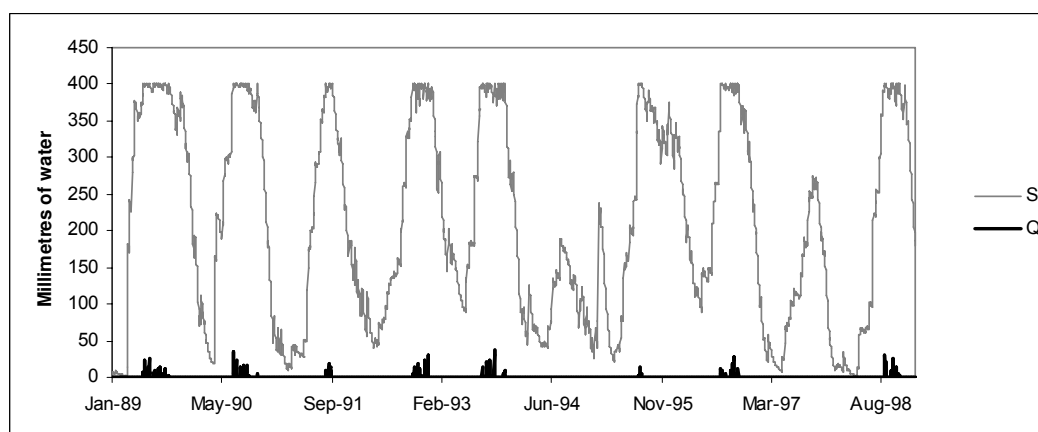


Figure 32 Time series of S and Q for Bogolara 100% trees.

Table 5 Bogolara - annual average water inputs, outputs and runoff coefficients for the entire hillslope of the banded scenario.

For a complete scenario description, see Table 8. Runoff is expressed as a depth Q_{out} for each band and as a depth Q (mm) for the whole upslope contributing area.

Cell	Band	Cumulative slope distance (m)	$P+Q_{in}$ (mm)	Q_{out} (mm)	Q (mm)	ET (mm)	Runoff coefficient
1	Perennial pasture	67	990	361	361	629	0.36
	Perennial pasture	133	1351	722	361	629	0.36
	Trees	200	1712	811	270	884	0.27
2	Perennial pasture	267	1801	1171	293	629	0.30
	Perennial pasture	333	2161	1532	306	629	0.31
	Trees	400	2522	1621	270	884	0.27
3	Perennial pasture	467	2611	1982	283	629	0.29
	Perennial pasture	533	2972	2343	293	629	0.30
	Trees	600	3333	2432	270	884	0.27
4	Perennial pasture	667	3422	2793	279	629	0.28
	Perennial pasture	733	3783	3154	287	629	0.29
	Trees	800	4144	3243	270	884	0.27

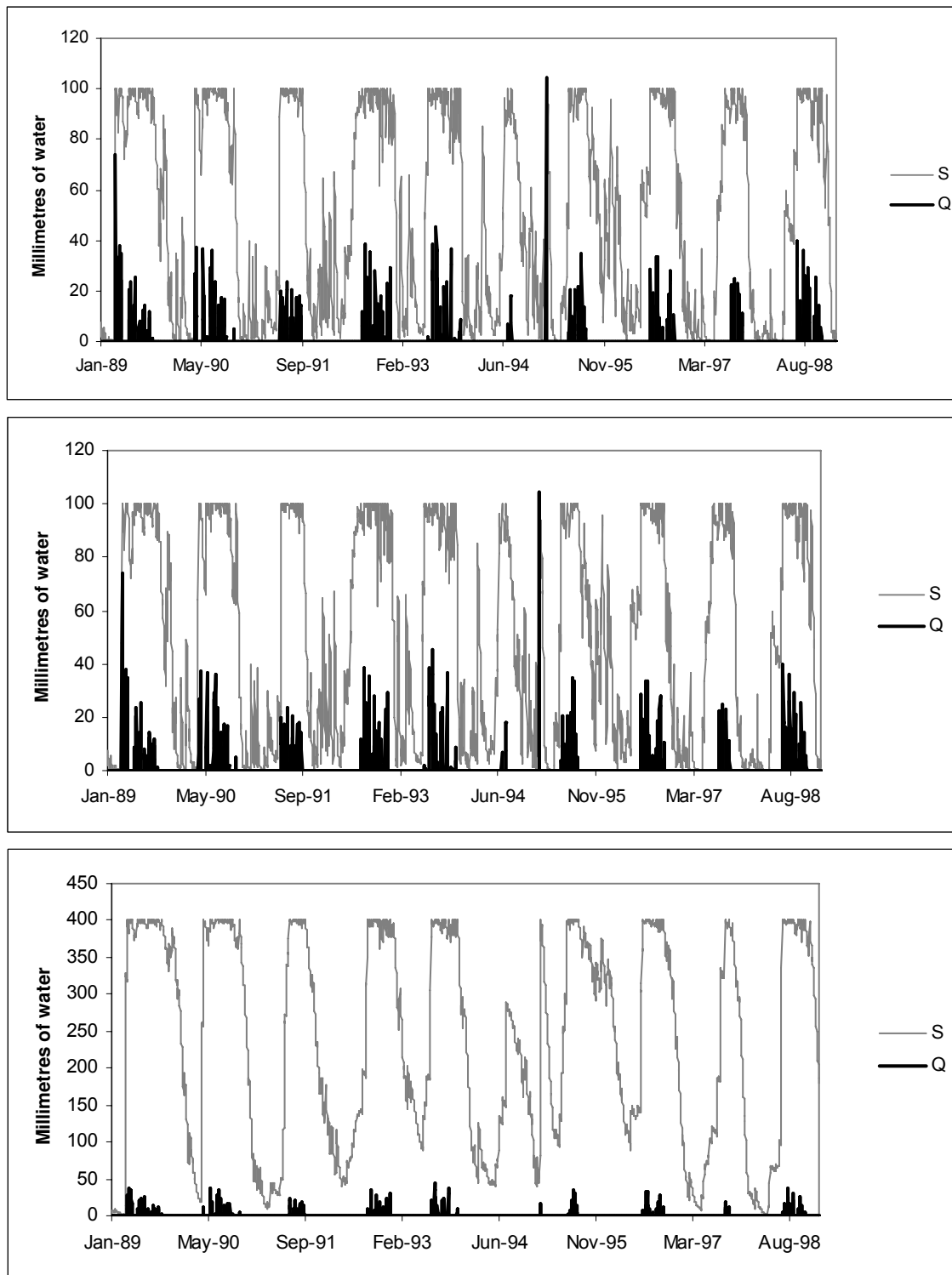


Figure 33 Time series of S and Q for Bogolara: 66% perennial pasture (top and centre); 33% high water use trees (bottom).

Tumut (37.12° S 148.35° E)

Site description

Tumut was chosen as a case study site because of studies associated with nearby Red Hill and Kiley's Run catchments (Major, 1998; Hickel, 2001). These are small adjacent catchments located 23 km northeast of Tumut at 590-835m a.s.l. in the upper Murrumbidgee. Local average annual rainfall is 876 mm and both catchments were initially grazed pastoral land before Red Hill was planted with *Pinus radiata* in 1988/89. Climate data for Tumut was used in this study, which showed had an average of 825 mm over the modelled period 1989 to 1999.

Following the plantation establishment, runoff conditions in Red Hill have responded sharply from perennial to intermittent streamflow during the 1994 drought. Today, Red Hill yields no flow for most of the year but the yield from Kiley's Run remains relatively unchanged (Major, 1998; Hickel, 2001).

There has been recent debate in the Australian catchment community concerning the tradeoffs between new plantations and the available stream flow downstream. Vertessy *et al.* (2003) present the current state of knowledge of afforestation and streamflow at catchment scale. New plantations in higher rainfall zones have a major influence on the streamflow with reductions of streamflow being of the order of 2 ML per year per hectare of plantation planted on land that was previously used for grazing or cropping. In lower rainfall zones (<800 mm yr⁻¹) the magnitude of these reductions are considerably less. The net environmental benefits of new plantations for rivers must also include consideration of the movement of salts to streams and in some instances the occurrence of dryland salinity. Vertessy *et al.* (2003) suggest that reducing dilution flows with lower salt concentrations flowing from high rainfall zones is a cost of establishing new plantations in such catchments. Recent analysis of Dowling *et al.* (2004) reinforces this conclusion and demonstrates that in low rainfall areas with specific combinations of hydrogeology and salt availability that new plantations will have the result of reducing stream salinity (concentration) at the end of valleys. This analysis is vital in the spatial targeting of forestry and agroforestry systems for the intention of establishing public benefits.

Given this concern regarding the potential adverse effects of forestation of upland catchments on stream salinity due to reduced flows, we used our model to compare simulated scenarios of partial forestation.



Figure 34 Red Hill (left) and Kiley's Run (right) adjacent catchments.

Scenarios tested were:

1. 100% perennial pasture
2. 100% trees
3. 66% perennial grass, 33% high water use trees.

Soil water storage probability distributions $p(S_n)$

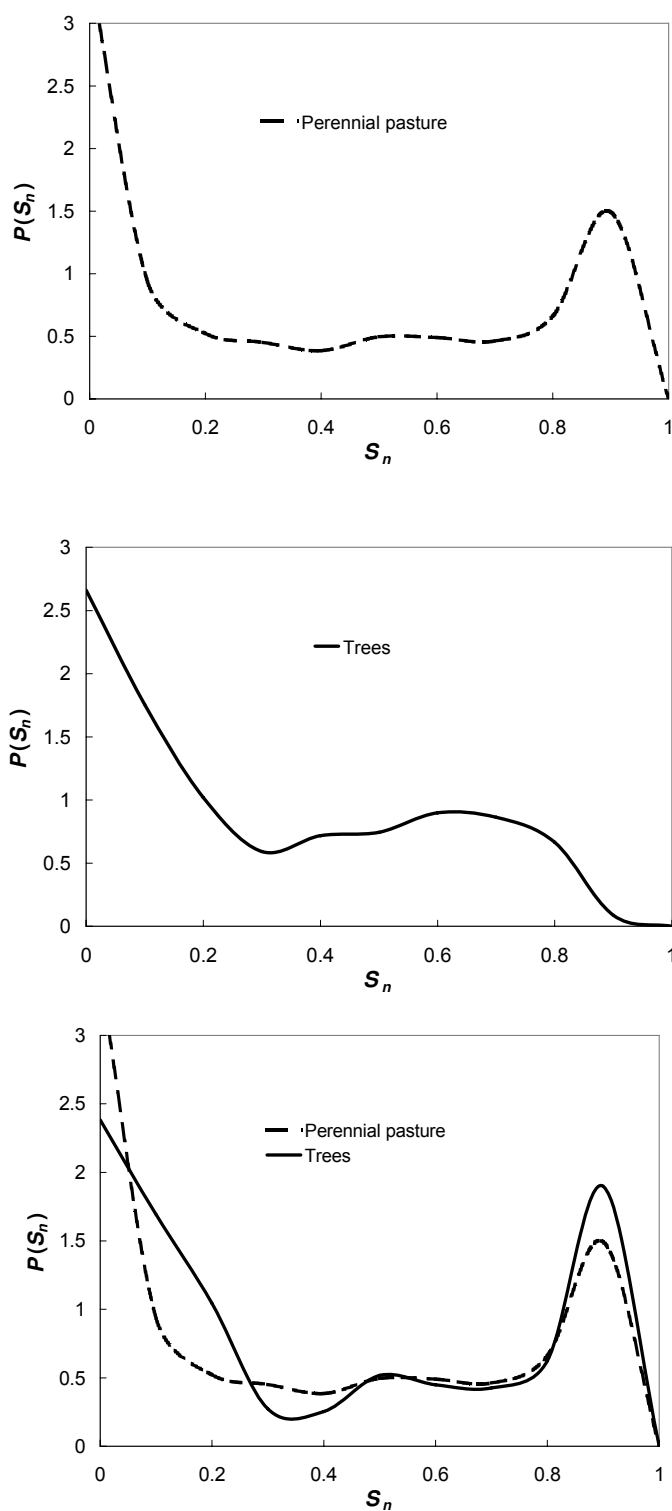


Figure 35 Distribution of $p(S_n)$ for Tumut for three scenarios: 100% perennial pasture (top); 100% high water use trees (centre); combined 66% perennial grass, 33% high water use trees (bottom).

Time series and annual average water balance

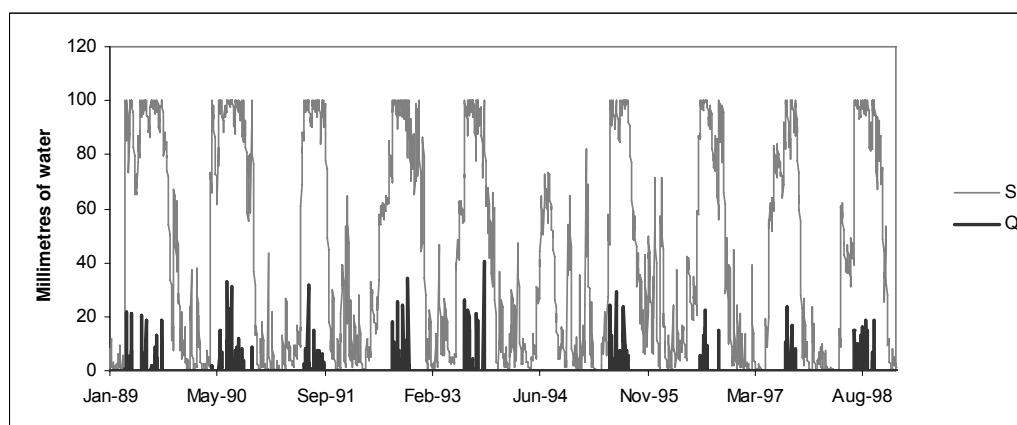


Figure 36 Time series of S and Q for Tumut 100% perennial pasture.

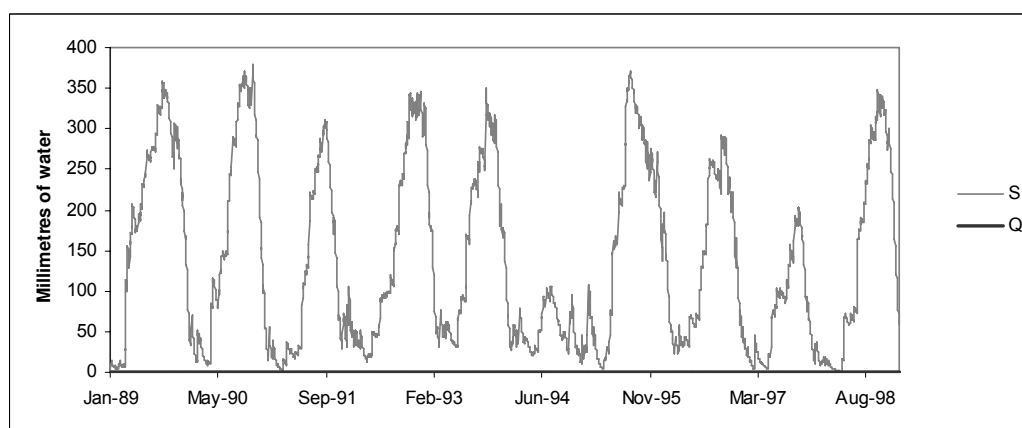


Figure 37 Time series of S and Q for Tumut 100% trees.

Table 6 Tumut annual average water inputs, outputs and runoff coefficients for the entire hillslope of the banded scenario.

For a complete scenario description, see Table 8. Runoff is expressed as a depth Q_{out} for each band and as a depth Q (mm) for the whole upslope contributing area.

Cell	Band	Cumulative slope distance (m)	$P+Q_{in}$ (mm)	Q_{out} (mm)	Q (mm)	ET (mm)	Runoff coefficient
1	Perennial pasture	66	825	181	181	644	0.22
	Perennial pasture	133	1007	363	181	644	0.22
	Trees	200	1188	302	101	877	0.12
2	Perennial pasture	266	1127	483	121	644	0.15
	Perennial pasture	333	1308	664	133	644	0.16
	Trees	400	1490	603	101	877	0.12
3	Perennial pasture	466	1429	785	112	644	0.14
	Perennial pasture	533	1610	966	121	644	0.15
	Trees	600	1791	905	101	877	0.12
4	Perennial pasture	666	1730	1086	109	644	0.13
	Perennial pasture	733	1912	1268	115	644	0.14
	Trees	800	2093	1207	101	877	0.12

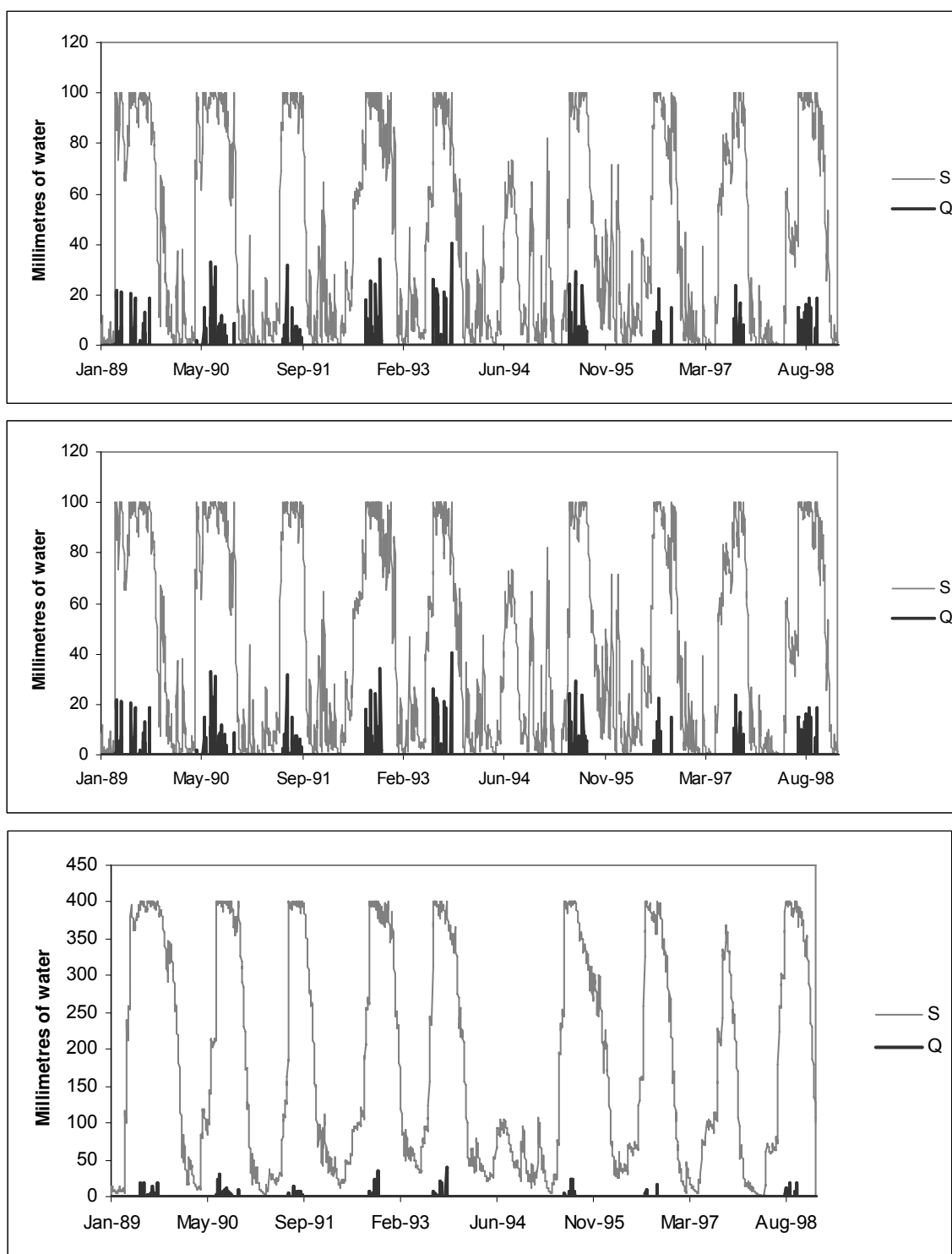


Figure 38 Time series of S and Q for Tumut: 66% perennial pasture (top and centre); 33% high water use trees (bottom).

Yass (34.83° S148.91° E)

Site description

The rural town of Yass, as well as nearby towns of Bowning and Binalong rely on water drawn from the Yass Dam on the Yass River (http://yass.local-e.nsw.gov.au/roads/03/1027982894_23328.html), which is surrounded predominantly by sheep grazing properties (Figure 39). During the recent protracted drought, the town water supply diminished to an unusable level.



Figure 39 Landscape typical of the pastoral properties in Yass water supply catchment.

The potential for enhancing surface runoff via artificial soil surface treatment was therefore included in the modelled scenarios. These were:

1. 100% perennial pasture
2. 100% trees
3. 33% artificial runoff, 33% perennial pasture, 33% high water use trees.

Soil water storage probability distributions $p(S_n)$

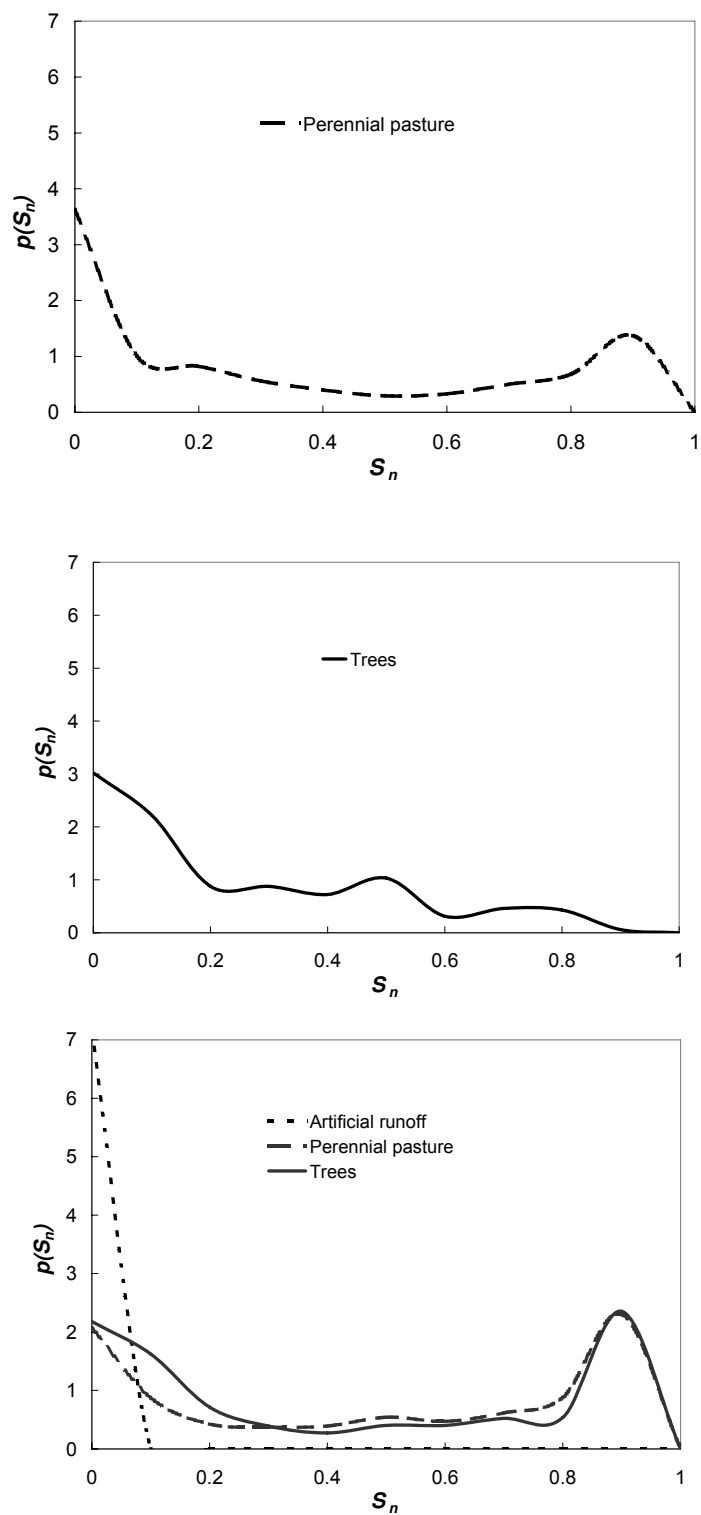


Figure 40 Distribution of $p(S_n)$ for Yass: 100% perennial pasture (top); 100% high water use trees (centre); combined 33% artificial runoff, 33% perennial pasture, 33% high water use trees (bottom).

Time series and annual average water balance

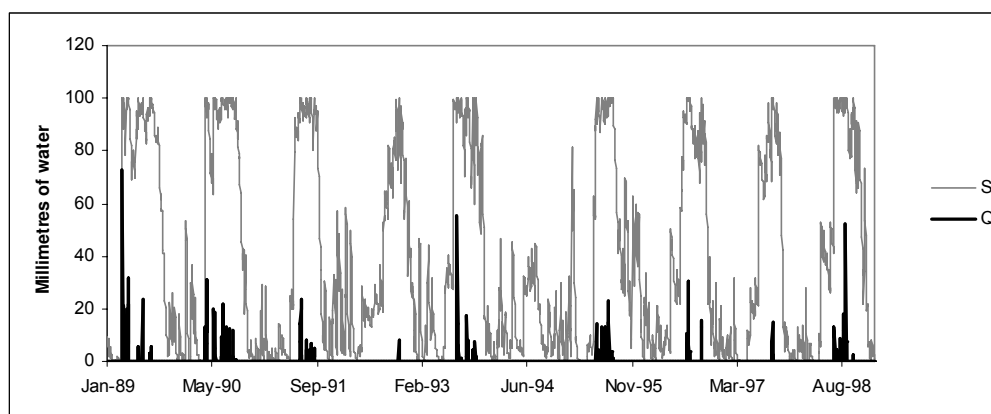


Figure 41 Time series of S and Q for Yass 100% perennial pasture.

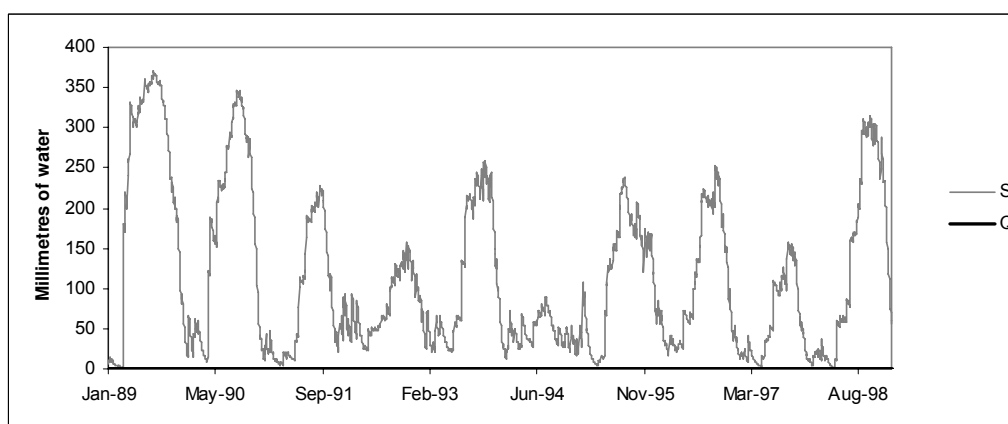


Figure 42 Time series of S and Q for Yass 100% trees.

Table 7 Yass - annual average water inputs, outputs and runoff coefficients for the entire hillslope of the banded scenario.

For a complete scenario description, see Table 8. Runoff is expressed as a depth Q_{out} for each band and as a depth Q (mm) for the whole upslope contributing area.

Cell	Band	Cumulative slope distance (m)	$P+Q_{in}$ (mm)	Q (mm)	Q_{hin} (mm)	ET (mm)	Runoff coefficient
1	Artificial runoff	67	724	685	685	40	0.95
	Perennial pasture	133	1409	577	288	832	0.40
	Trees	200	1301	404	135	883	0.19
2	Perennial pasture	267	1128	1088	272	40	0.38
	Perennial pasture	333	1812	981	196	831	0.27
	Trees	400	1705	807	135	883	0.19
3	Perennial pasture	467	1532	1491	213	40	0.29
	Perennial pasture	533	2216	1384	173	831	0.24
	Trees	600	2109	1211	135	883	0.19
4	Perennial pasture	667	1935	1895	189	40	0.26
	Perennial pasture	733	2619	1788	163	831	0.22
	Trees	800	2512	1615	135	883	0.19

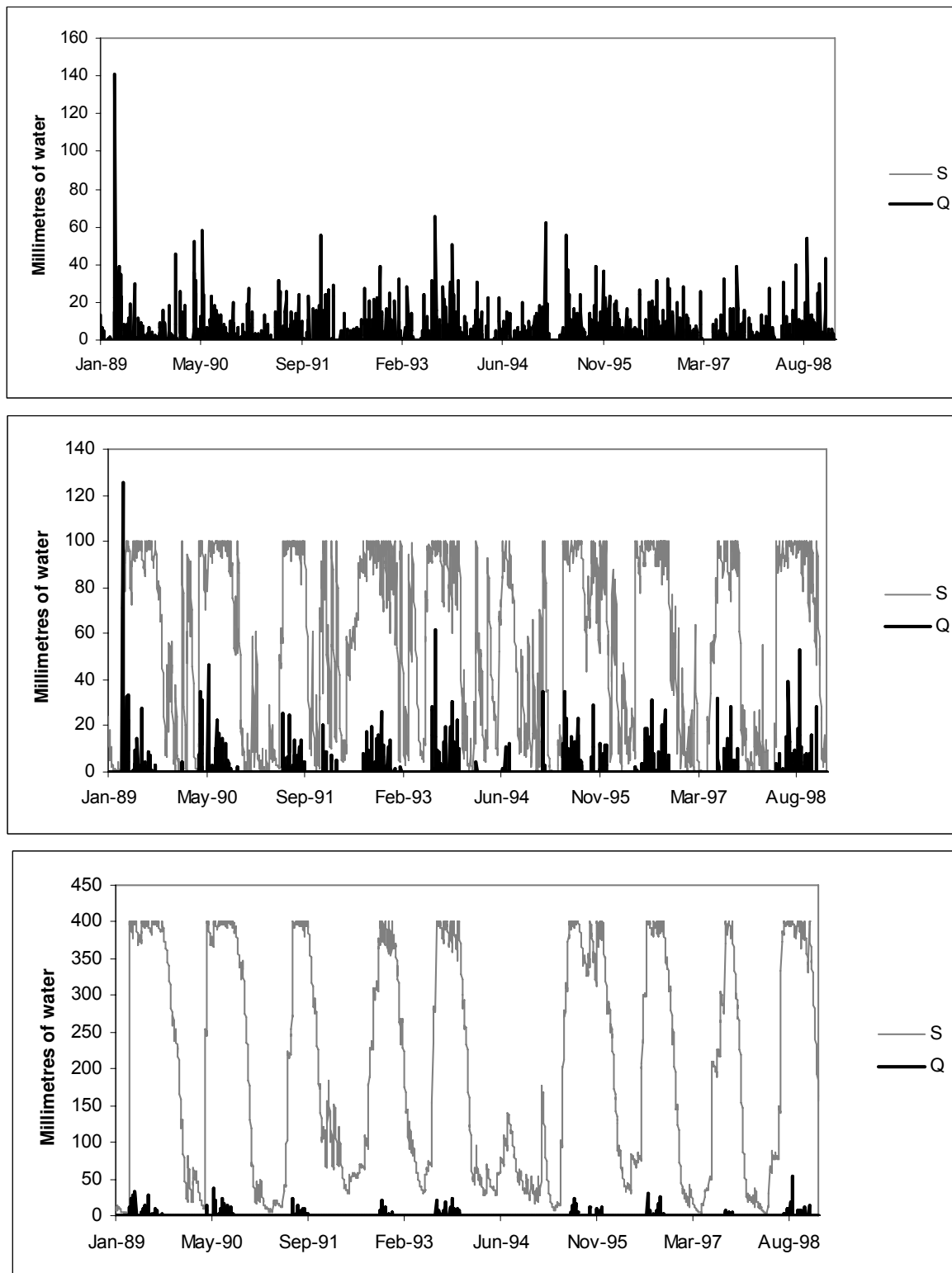


Figure 43 Time series of S and Q for Yass: 33% artificial runoff (top); 33% perennial pasture (centre); 33% trees (bottom).

Table 8 Site characteristics, scenario specifications and resulting average annual runoff coefficients and $p(S)$ properties.

Site	Meteorological station	Lat Long (decimal degrees)	P (mm)	ET (mm)	Scenario	Runoff coefficient	$\Pr(S_n < 0.2)$	$\Pr(S_n < 0.2)$
Lake Mere	P from Lake Mere ET from Cobar (The Meadows)	30.27 S 144.90 E 31.71 S 145.28 E	290	2290	Natural – 60% bare runoff, 10% grassy interception, 30 % mulga grove	0.04	0.55	0.02
Annandayle South	Annandayle South	35.77 S 147.35 E	770	1365	100% perennial pasture 100% high water use trees 33% winter cereal, 33% lucerne, 33% high water use trees	0.57 0.00 0.14	0.02 0.36 0.32	0.59 0.03 0.22
Bluff Downs	Bluff Downs	19.60 S 145.88 E	570	2087	100% perennial pasture 100% conservative trees 33% artificial runoff, 33% perennial pasture, 33% low high water use trees	0.16 (0.23*) 0.07 0.17	0.64 0.66 0.44	0.09 0.09 0.15
Bogalara	Burrinjuck Dam	35.00 S 148.60 E	990	1076	100% perennial pasture 100% high water use trees 66% perennial pasture, 33% high water use trees	0.36 0.12 0.27	0.25 0.23 0.21	0.25 0.23 0.30
Red Hill	Tumut	37.12 S 148.35 E	825	1338	100% perennial pasture 100% high water use trees 66% perennial pasture, 33% high water use trees	0.22 (0.25*) 0.00 (0.05*) 0.12	0.29 0.36 0.34	0.18 0.04 0.22
Yass	Yass Composite	34.83 S 148.91 E	724	1272	100% perennial pasture 100% high water use trees 33% wax runoff, 33% perennial pasture, 33% high water use trees	0.16 0.00 0.20	0.32 0.42 0.31	0.17 0.03 0.26

Note: The $p(S_n)$ values (last two columns) for the banded scenarios refer to the tree bands only, as they control runoff from the whole hillslope; * indicates measured value.

Summary notes on case study results

Brief notes regarding the simulated results for each site are given below.

Annandayle South

The combination of a winter-dominant rainfall and a winter cereal at this site would typically result in a 'wet' soil profile (Figure 19). High water use trees are likely to dry the profile and produce minimal runoff (Table 8). The banded scenario of cereal, lucerne and trees significantly reduces the 'wet' peak (Figure 19). It is possible that trees suffered drought stress during 1995 (Figure 21; Figure 22).

Bluff Downs

This is typically a dry and 'flashy' catchment. Increasing the root zone storage with trees slightly increases soil wetness (Figure 24). A banded scenario incorporating an artificial runoff zone provides a greater water supply to the trees, possibly avoiding drought conditions for that component (Figure 26; Figure 27) and results in a similar runoff coefficient to 100% pasture (Table 8).

Bogalara

Results from this site show a strongly bimodal $p(S_n)$ under pasture, indicating that the soil is likely to dry or wet. The trees appear to buffer against the very dry times but, the soil profile is most likely to be wet (Figure 30). A banded scenario of 66% perennial pasture and 33% trees does not reduce the runoff coefficient enormously (Table 8).

Tumut

As with Bogalara, $p(S_n)$ is strongly bimodal under pasture (Figure 35). However, trees buffer against wet times and Table 8 shows that trees reduce the runoff coefficient to a low value as is confirmed from measurements at the site. A banded scenario of 66% pasture and 33% trees also produces a strongly bimodal $p(S_n)$. It is possible that, in this configuration, trees can be grown in this environment and downstream water supply could be maintained (Table 8). It is possible the pure tree stand would have been drought stressed in 1995 and the trees in the banded scenario would not have been as severely affected (Figure 37; Figure 38).

Yass

The Yass site showed a slightly bimodal $p(S_n)$ (Figure 40) and a relatively modest runoff coefficient for 100% pasture, compared with the higher rainfall areas (Table 8). To increase the runoff coefficient, a banded system was modelled comprising 33% artificial surface to increase the water supply to the trees and to provide enhanced runoff for an urban water supply. This arrangement appeared to offer greater drought protection to the trees (Figure 42; Figure 43).

Discussion

Introduction

This was an exploratory scoping study undertaken with the following objectives

1. To develop a preliminary design framework to assist the matching of vegetation species and their spatial arrangement to local soil and climate.
2. To investigate the potential for arranging banded vegetation systems on agricultural hillslopes to act as a source-sink sequence that can be designed to manage water yield for local requirements.

We have accomplished objective 1) and produced a simple design framework that will facilitate objective 2). With regard to objective 2), it appears there is ample potential for the development of banded agricultural systems to manage water yield. It is clear, however, that the reasons for wanting to achieve this, as well as the main accompanying design objectives, are dependent on decisions that need to be made in a context wider than the hillslope under consideration. Below (see Catchment Context), we provide a suggested approach to this impasse by addressing some fundamental questions regarding water management at the catchment scale. To place this in perspective, we briefly revisit some of the background and concepts that inspired the study and discuss their legitimacy. The model evaluation is then discussed briefly and case study results are broadly assessed as outputs from the design framework.

Previous work – what's new?

The JVAP publication 'Trees, Water and Salt' (Stirzaker *et al.*, 2002) provided state-of-the-art, best bet strategies for planting trees for agroforestry production and to mitigate dryland salinity. The general design philosophy was to 'dry up the landscape' and 'maximise tree production from a minimum area'. Here we have attempted to broaden the domain of the design process to allow exploration of the placement of vegetation on hillslopes to permit a wider choice of water management options. These can include maximising or minimising water yield, and any magnitude of influence in between. Emphasis on this change in design philosophy is in recognition of the reality that there is a wider range of desirable outcomes than solely salinity management, and the 'desirable outcome', is very much context dependent.

There is nothing necessarily new in the idea of banded agricultural systems. Land managers have been using vegetation and soil surface management to modify water yield from hillslopes for millennia. What we have attempted to do is to provide a quantitative environment within which to easily explore options and design limits at the hillslope scale. This approach is complementary to similar qualitative approaches at larger scales for whole farm and catchment planning (Ive and Cocks, 1999), and quantitative approaches at the farm scale (McKenzie *et al.*, 2003).

Concepts and assumptions

Sources and sinks

A central premise to our approach is recognising that, to a large degree, natural Australian landscapes at the hillslope scale, comprise source-sink sequences (Noy-Meir, 1973), and suggest that similar processes can be promoted on agricultural hillslopes by imposing patchiness. In our case, patchiness necessarily takes the form of bands aligned across the hillslope, parallel to topographic contours. Some arid and semiarid natural systems exhibit this geometry (Tongway *et al.*, 2001) and the cascade of excess occurs very much how we have described it in our model, downslope, perpendicular to the tree belts. However, the limits to being able to mimic this behaviour on agricultural hillslopes are virtually unknown and would depend on soil type, soil heterogeneity, topography and excess water flow paths. It is likely that there would exist thresholds of slope and terrain beyond which the geometry of bands that operate as a source-sink sequence would not suit many agricultural practices. That is, they would likely be too narrow and contorted. It is also possible, in such situations, that there could be a more appropriate geometry that would exhibit source-sink processes. Issues such as this would need to be

included in any future work undertaken to screen for landscapes that would be suitable for the imposition of banded or otherwise patchy systems.

Infiltration processes, deep drainage and lateral flow mechanisms

We have structured our design framework using two major assumptions: 1) the major mechanism for the redistribution of excess water is overland flow; and 2) there are no soil surface processes restricting or enhancing infiltration.

While 1) is certainly valid for the semiarid vegetation systems we have modelled our design framework on, it will not be valid for all agricultural landscapes. We suggest, however, that the proportion of Australian agricultural land where significant shallow subsurface lateral flow occurs would be relatively small (Silberstein *et al.* 2002; McKenzie *et al.*, 2003; Ticehurst, 2004). A notable exception here is a large amount of agricultural land in Western Australia with strongly duplex soils and a sandy A horizon (White *et al.*, 2002).

We justify the omission of deep drainage on the basis of its representative proportion of the total water budget, rather than its possible contribution to dryland salinity or waterlogging. In most agricultural areas in Australia, deep drainage represents only a few percent of rainfall, except in deep, sandy soils (Petheram *et al.*, 2002).

With regard to 2), this most certainly does not hold for most agricultural soil surfaces, but is approaching the truth where livestock are excluded and where significant perennial vegetation cover is maintained; i.e. it can be manipulated. We justify the use of 2) in this study for first-cut designs of banded vegetation systems, where erring on the side of over-simplification will represent ideal conditions for water capture and therefore control of water yield. When using our design framework to consider alternative arrangements of vegetation types, it is typical to find other, relatively immutable, physical constraints to the attainment of water yield targets such as rooting depth and plant loss functions.

With regard to both simplifying assumptions, we suggest that greater model complexity may be justifiably added if subsequent design iterations are required, and if suitable data is available to represent infiltration processes.

Bands of agricultural vegetation - will they act as sinks?

Or, can bands of agricultural vegetation capture, store and use excess water? The answer, or answers, to this question have significant bearing on the prospect for designing banded systems to manage water on agricultural hillslopes. Despite significant agroforestry tree plantings being undertaken in Australia over the last decade, often with a view to changing local hydrology, there is a dearth of information regarding whether or not tree belts will actually capture, store and use excess water. McJannet *et al.* (2000) undertook detailed hydrologic and water use measurements at a break of slope tree belt site. They concluded that the trees were not supplied with subsurface flow and those workers had difficulty quantifying the amount of water supplied to the trees via overland flow. White *et al.* (2002) estimate the water use, in excess of rainfall, of a tree belt in Western Australian that receives shallow subsurface flow over prolonged periods. The capacity for storing excess water in the root zone for later use was not reported. Ticehurst (2004) undertook hydrologic measurements on break of slope tree belt in New South Wales, which indicated that the tree belt was likely to capture and store overland flow events, but that subsurface flows were likely to be small. Tree water use was not measured at this site.

In the absence of conclusive answers, and without undertaking the required hydrologic measurements (which would necessarily constitute a substantial experiment), we employed the Landscape Function Analysis (LFA; Tongway, 1994) technique to obtain an indication of the capture capability of farm tree belts. This has provided encouraging evidence that imposed vegetation bands (as distinct from natural ones) can be designed to at least capture excess water via overland flow. It would appear, however, that an essential condition for this to occur is that livestock be excluded from these areas, except for occasional grazing. Since LFA provides assessment of the ground surface only, the relative magnitude of the capture potential is not clear. We would expect, therefore, that via the exclusion of

livestock and the promotion of perennial vegetation cover (including grasses), the capture potential of bands of agricultural vegetation could be managed to be significantly larger than crop or pasture surfaces. Since the work for this report was undertaken, Ellis *et al.* (2006a) undertook a rainfall simulation experiment on an ungrazed tree belt at Boorowa, NSW, showing that the tree belt did, in fact capture significant proportions of runoff events from upslope. The experiment also highlighted, however, the need to include some infiltration control on the maximum infiltration within the belt.

In the catchment context

How much water? Where in the catchment?

The question that is necessarily a precursor to these simulations is “how much water (what proportion of average annual rainfall) do you want to leave your hillslope?” The answer would depend on whether the objective is to mitigate salinity and waterlogging, or to guarantee flow for water supply or environmental reasons, or any intermediate management motives. We believe that, although the answer to this question is paramount to the design of agricultural systems to achieve such objectives, the question is generally beyond the current scope of land management planning. Our experience with individual farmers, farmer groups and catchment managers is that, although thinking is sufficiently advanced to recognise the role of individual hillslopes/farms in the water yield catchments, understanding the roles is not well advanced. Catchments are spatially, environmentally and socially complex. There are a number of decision support systems (DSS) available to help catchment managers, which can play important roles in a consultative catchment management process. These DSSs generally manifest as ‘what-if?’ scenario testers that enable stakeholders to test the sensitivity of catchment outputs to changes in land use or land management. There are, however, no structured quantitative tools that enable working backwards from catchment targets to provide a map of, for instance, hypothetical runoff coefficients that will meet the targets. A necessary condition of valid solutions is that mass balance is maintained.

We suggest that the development of a spatially explicit model that can perform this operation would be a useful tool that could be used in conjunction with consultative catchment management methods. This would provide a structured method for focussing smaller scale agricultural system design frameworks such as the one we have developed in this study.

Water farming/harvesting

The reestablishment of perennial vegetation in the Australian rural landscape has many environmental benefits that are well-documented. There is also an environmental cost of reduced stream flow (Vertessy *et al.*, 2003). This particular cost has had considerable weighting in recent debates as a result of the over- or full allocation of available water resources, and in response to recent regional droughts and the emerging value of water as a tradable commodity.

Water farming offers a positive approach to the above tradeoffs where landscapes become mosaics of agricultural, forestry and water harvesting enterprises that meet consumptive and environmental water goals while providing a vital rural economy within rural catchments. We anticipate that water farming will first be conducted on a small scale to supply on-farm intensive land uses such as viticulture and will then expand to meet the demands of catchment scale water markets.

Model evaluation

The model evaluation we have undertaken at Lake Mere is precursory, due mainly to the lack of data available for testing such a spatially heterogeneous model. However, we believe it to be sufficient for the purposes of this preliminary study and are confident that our simple representation of water infiltration, storage and use has captured the salient hydrologic characteristics of the semiarid landscape. The ability of the model to represent the behaviour of analogous agricultural landscapes, however, cannot be assessed without collection of appropriate field data. In the first instance, large-scale rainfall simulation experiments on farm tree belts or other vegetation bands are likely to provide useful evaluation data sets.

The simple modelling approach we have adopted is likely to be susceptible to errors associated with the simplifying assumptions used. This approach, however, is suitable for first-cut designs and for

identifying limits. Where initial modelling suggests potential for designing an improved vegetation system to meet water yield (and other) targets, there is justification for employing a more sophisticated water balance model within the design framework. This would necessarily have to represent shallow subsurface lateral flow and deep drainage. If a more holistic investigation is warranted, plant growth and livestock models could be incorporated. This level of simulation, however, requires significant knowledge of animal, plant and below ground parameters. It also enters the realm where significant errors may arise from the complexity of the many processes and interactions represented.

Case study results and interpretation

In the absence of meaningful water yield targets for the case study sites, we explored the sensitivity of the sites to significant changes in vegetation types, as well as a relatively arbitrary banded design, loosely intended to address a potential local water management issue. These are covered in the site descriptions in the methods section.

We expressed the results of the simulations as changes in runoff coefficient and probability distributions of soil water storage $p(S_n)$. Time series of Q and S are provided where information is required regarding specific seasons or events. Detailed interpretation of the results is somewhat futile in the absence of specific objectives for the new designs. These would necessarily have been derived following consideration of the multiple issues (e.g. local productivity, pollutant wash off, salinity management, environmental flows). However, the $p(S_n)$ outputs provide a concise visual summary of the likely limits of feasible designs.

The probability distributions of soil water storage $p(S_n)$ gives an indication of the likely relative soil water storage S_n for each scenario. To obtain a measure of the probability of S_n being within a chosen interval, $p(S_n)$ is integrated over that interval (see Equation 8, Appendix 2). Probabilities of the relatively arbitrary ‘dry’ and ‘wet’ intervals ($\Pr(S_n < 0.2)$ and $\Pr(S_n > 0.8)$) for each scenario at each site are provided in Table 8. The $p(S_n)$ representation also provides a rough measure of likely plant stress, although we currently lack sufficient knowledge of specific plant-soil-water relations for it to be usefully accurate. Porporato *et al.* (2001), when extending the work of Rodriguez-Iturbe *et al.* (1999), present a dynamic plant stress index, which is much more descriptive. There may be uses for such indices in more sophisticated matching of vegetation types to climates and soils (see Appendix 2), however, it is likely that significant experimental data would be required for this to be realised. Similarly, the $p(S_n)$ representation allows a crude risk analysis of designs, but this is still reliant on substantial, species-specific information regarding plant water stress.

For each case study we simulated two extreme conditions of vegetation cover (e.g. winter cereal; trees) and one banded arrangement nominally directed towards addressing the main local water or pollutant management issue we indicated with each site description (see Methods section). The design framework allows the designation of any combination of representation of different vegetation types in a three-banded system. For simplicity, and for lack of more specific design objectives, we used 33% cover of each vegetation type in a 3 - band system. Where we used only 2 types they were represented as 66% and 33%, typically with trees having the lesser amount. This rough analysis makes it clear that the proportions of the landscape typically devoted to tree planting in rural areas (< 10%) are unlikely to make large differences to hydrology at the hillslope scale.

This is highly relevant to the whole question regarding the redesign of land use systems, in particular the use of trees to significantly change the local hydrology on farms. Often the opportunity cost of agroforestry (via lost crop or pasture production) restricts the desirable proportion of tree coverage to small values, therefore achieving little in the way of hydrologic control. The impetus to make more significant changes to the distribution of different vegetation types on farms may be greater in areas where the value of changes to the water yield rivals the value of local production.

Tree productivity – agroforestry for low rainfall areas?

Banded arrangements comprising < 100% trees effectively enhance the water supply to trees in much the same way as the mulga system at Lake Mere has evolved to do. As demonstrated in the Bluff Downs and Yass case studies, artificial runoff surfaces can be used to emphasise this effect. We suggest that there may be potential application for this phenomenon to promote agroforestry in low rainfall areas. Our design framework does not represent plant growth, however, to investigate possible relative growth differences between 100% tree cover scenarios and trees in banded scenarios, we have tabulated tree *ET* as a surrogate for a growth index.

Table 9 shows the banded scenarios at Bluff Downs and Yass (comprising artificial runoff surfaces) increased tree *ET* by 24% in both cases. Although not a rigorous analysis, this gives an indication of the potential for increasing the viability of agroforestry in low rainfall areas. The latter would, however, represent a trade-off with other aspects of the enterprise.

Table 9 Comparison of tree *ET* between scenarios of 100% tree cover and 33% banded tree cover.

For complete scenario description, see Table 8.

Case study site	Average annual rainfall (mm)	Tree <i>ET</i> (mm)	
		100% trees	33% trees banded with other vegetation
Lake Mere	290	n/a	338
Annandayle South	770	768	851
Bluff Downs*	570	526	654
Bogolar	990	851	884
Red Hill	825	820	887
Yass	724	719	883

*Conservative water use trees used in both scenarios.

Maximum soil water storage S_{max}

Our definition of S_{max} as the product of root depth z and soil porosity n is a very crude approximation, although it is appropriate for the level of application in this study. As observed by Milly (1994), this concept ignores many of the details of water flow in soil. In addition, any variations in the soil profile and plant water extraction patterns are not accounted for. Milly (1994) points out, however, the application of more sophisticated theories of water movement in natural field conditions would be unlikely to reduce the errors associated with estimating S_{max} .

Obtaining accurate estimates of z and n on their own is a significant task. For practical purposes, n can be successfully estimated within a realistic range. However, estimating z remains a significant challenge. Typically, with regard to water balance simulations, z was the most sensitive parameter after seasonality of the vegetation (we note that n is equally sensitive but has a smaller relative range than z). Ironically, rooting depth is also the parameter least well represented by experimental data. This is readily explained by gaining an appreciation of the intractable nature of detecting plant roots *in situ* (Smit *et al.*, 2000). Indirect measurements of functional rooting depth via soil moisture monitoring are less complex but require protracted monitoring. For our preliminary modelling purposes, we provided some rough estimates of likely rooting depths of the vegetation types. Where a more accurate simulation is justified, site and species-specific rooting depth data may be required and would typically be obtained by destructive sampling methods. Often cost or logistics preclude such investigations, but recent advances in electrical root mapping technique may provide a more timely solution in the near future (Ellis *et al.*, 2003b).

Loss functions

The third most sensitive parameter is the plant loss function, or water use characteristic. For the model evaluation and case studies, we used loss functions derived from field experiments on a small number of species (Slatyer, 1961; Dunin *et al.*, 2001). Despite relatively few measured loss functions being available, for preliminary design purposes there is sufficient knowledge of likely extreme values to enable identification of likely physical limits. There is, however, little knowledge regarding the seasonal dependence of loss functions, particularly with respect to crops and pastures. The loss functions we used were derived from physical measurements of water use with respect to soil water storage, typically from a lysimeter or similarly monitored water use experiment. Salvucci (2001), however, derived and tested a method for determining loss functions using a time series of soil water storage and precipitation measurements. The wider applicability of this method is unknown but if sufficiently robust, it could greatly reduce the expense required to determine loss functions and hence facilitate a swifter and wider application of the design methods we have presented.

Probabilistic and numerical modelling approaches

We initially adopted the probabilistic approach of Rodriguez-Iturbe *et al.* (1999) as it has several features that are attractive for a design framework. These include: a stochastic approach to the characterisation of rainfall inputs and soil water storage outputs; an analytic solution; a conceptually useful approach to describing water use characteristics using loss functions; and a focus on soil water storage which has inspired a fresh look at aspects relating to matching plants to locations. It should be noted, however, at the heart of the probabilistic approach is a simple bucket model, which offers relatively unsophisticated descriptions of water balance, but which is appropriate for the level of investigations we describe in this study.

Appendix 2 describes our adaptation of the method of Rodriguez-Iturbe *et al.* (1999) for matching species to achieve desired outcomes in specified locations and we believe it has significant application for preliminary planning. Ideally, we would have extended this approach to our analysis of banded systems, however, there is currently no analytic solution of the form of Rodriguez-Iturbe (1999) for bands of vegetation that are hydrologically linked. The scope for developing such a solution is currently under investigation.

In its absence, we adopted a numerical approach but used the same statistical representation of the soil water storage by post-processing of the model outputs. This produced a discrete distribution of $p(S_n)$ rather than the continuous distribution provided by the method of Rodriguez-Iturbe *et al.* (1999). Because of the coarse discretisation used in these calculations, the $p(S_n)$ outputs presented are approximate only. The numerical approach avoided the problem of seasonal characterisation of rainfall distributions using a marked Poisson process. On the other hand, it is likely that the methods of Potter *et al.* (2003) will allow a stochastic representation of seasonality that could be incorporated in future studies.

Limitations

Within the design framework described in this report, we have used a very simple water balance model. As discussed above under ‘Infiltration processes, deep drainage and lateral flow mechanisms’

The design framework should not be applied where deep drainage or shallow subsurface lateral flow represents a significant proportion of the water budget.

If potential users of this design framework are unsure of local hydrology in this regard, we recommend that they seek expert opinion. As an initial guide, we refer them to Silberstein *et al.* (2002) and McKenzie *et al.* (2003).

The lack of representation of surface infiltration processes is also limits the valid application of our design framework for the purposes of accurate simulation of hillslope hydrology. For initial design purposes, however, it is not a serious limitation as provides the 'best case scenario' with respect to water capture. If potentially desirable designs were selected using the framework described in this report, more detailed testing should then be undertaken using more sophisticated water balance model, within the same design framework.

Recommendations

This study has attempted to provide some structure to the notion of ‘redesigning farming systems’ in the face of environmental issues related to water management, and which can have significant impact on our agricultural resource base. Recommendations arising from this exercise are as follows

Knowledge gaps - catchment context

We recommend a formal review and exploration of potential new methods for establishing a structured approach for identifying, in a catchment context, hillslopes appropriate for potential redesign and appropriate water yield targets. The aim here is to provide a spatially explicit tool to assist catchment managers determine a range of solutions at the hillslope scale that will meet catchment scale targets.

Knowledge gaps – application and development

For the purposes of defining the physical limits to designs aimed at meeting water management targets, the framework we have developed is adequate. Where initial designs warrant further investigation, we recommend that the following knowledge gaps be addressed. We have listed these in order of priority:

1. Greater understanding of the potential of vegetation bands to capture and store excess water moving from upslope.
2. Simple characterisation of topographic influences with regard to 1.
3. Methods for rapidly estimating the rooting depth of vegetation types, especially trees.
4. Additional information on the evapotranspiration characteristics (plant loss functions) of key vegetation types.
5. Analytic solution to a probabilistic approach to the modelling of soil water storage of banded vegetation systems.

Links

We recommend an exploration of the scope for combining the design approach we have adopted for water management with analogous approaches adopted for pollutant management (Ellis *et al.* 2006) and water harvesting (Ellis *et al.*, 2006a; Richardson *et al.*, 2004).

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Appendix 1

Lake Mere banded mulga system

This section presents soil water measurements taken in February 2003 at Lake Mere following approximately 60 mm rainfall over several days, at the end of 33 months of drought. Figure 44 shows a wetting front transect across the three geomorphologic zones.

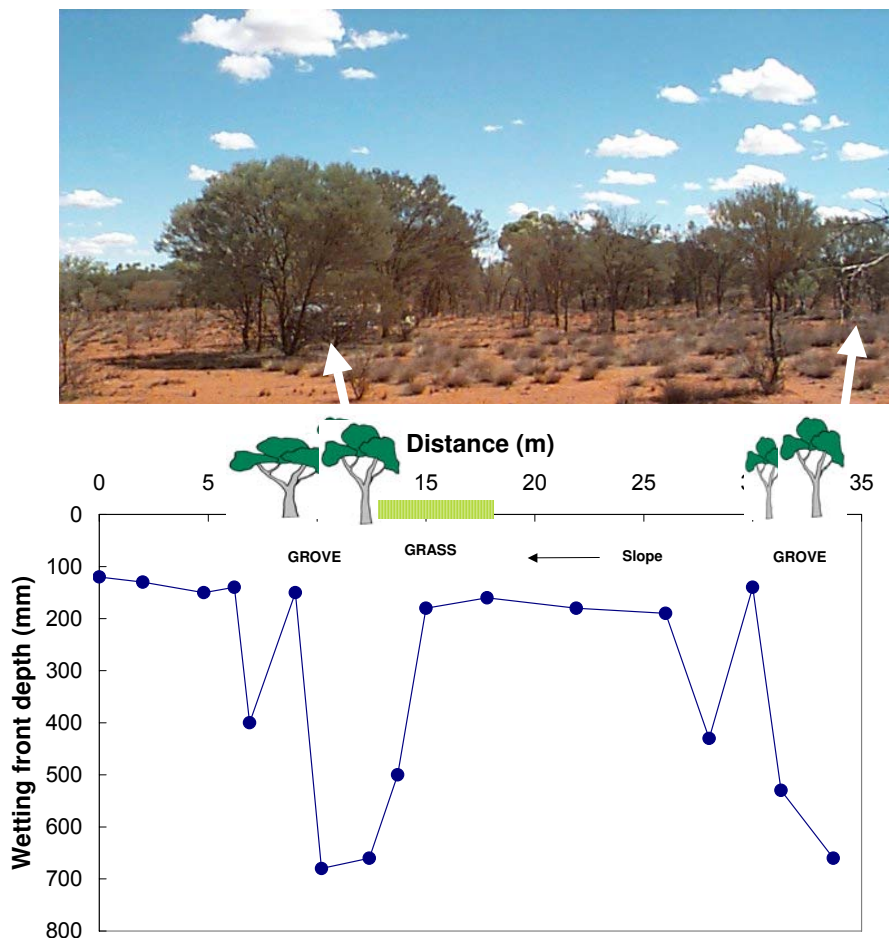


Figure 44 Photograph showing relative position of mulga groves at Lake Mere and the wetting front observed in the soil profile below each of the geomorphologic zones.

The natural tendency for rainfall to be redistributed within the system is obvious following such events. Figure 45 gives profiles of volumetric soil water content measured at the site. The sampling depth in the mulga grove was limited by sheet calcrete which marked the base of the soil profile; the sampling depth in the other zones was limited by soil hardness due to extremely dry conditions below.

Table 10 shows that nearly 9 times as much water entered the mulga root zone compared to the bare runoff. The principle mechanism for lateral water redistribution was by overland flow.

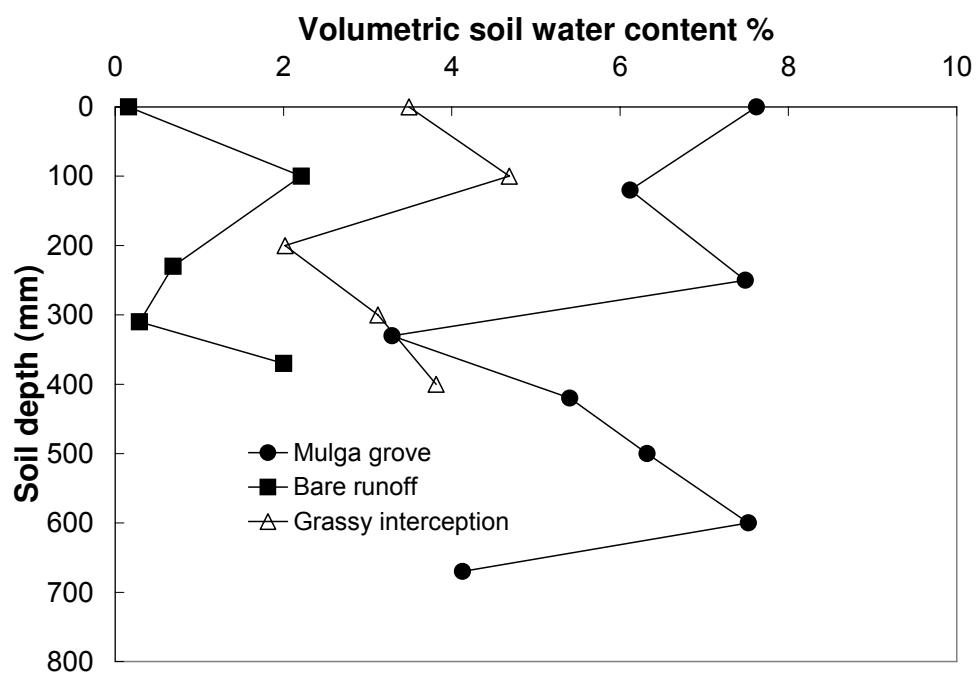


Figure 45 Volumetric water content profiles measured in each of the geomorphologic zones at Lake Mere in February 2003.

Table 10 Total water stored in the three geomorphologic zones at Lake Mere following approximately 60 mm rainfall, February 2003.

Profile	Total soil water (mm)
Bare runoff	5
Grassy interception	15
Mulga grove	44

Appendix 2

Probabilistic modelling method

Introduction

This section describes briefly the design framework and the probabilistic method proposed for:

- matching tree species to local climate and soil type and subsequently
- designing agroforestry systems for low rainfall areas.

This information was also presented in Ellis *et al.* (2002).

We provide here a summary of the method of Rodriguez-Iturbe *et al.* (1999) for the probabilistic modelling of soil water storage at a point. It offers some conceptually simple approaches for the matching of plant loss functions to climate and some basic soil conditions. The method has been further developed and tested (Laio *et al.*, 2001a, Porporato *et al.*, 2001, Laio *et al.*, 2001b) but has not yet been widely applied. The approach is also limited to application at a single point and there is currently no solution that allows the hydrologic linking of multiple points on a hillslope as is required for banded systems. However, we have drawn on several aspects of the probabilistic method as they either offer an alternate view from conventional water balance modelling or a more expedient path to a design limit. These are useful attributes within a design framework and include:

- a stochastic representation of water input (rainfall)
- a single ‘loss function’ to describe all the water outputs (evapotranspiration and drainage)
- an analytic solution for the probability distribution of soil water storage

The main premise of the probabilistic approach is that characterisations of the rainfall as a random, stochastic process can be combined with deterministic soil water ‘loss functions’ in order to derive analytical soil moisture probability density functions.

Rodriguez-Iturbe *et al.* (1999) employed the same ‘bucket’ approach to the water balance as we have described in the Methodology section. Maximum soil water storage is defined as plant rooting depth z multiplied by soil porosity n . Rainfall was described as a marked Poisson process requiring two parameters; average storm depth $1/\alpha$ and average number of days between rain events $1/\lambda$.

This approach assumes no change in the characteristics of the temporal rainfall distribution or ET within the time period considered. That is, where rainfall distributions are strongly seasonal, different $1/\alpha$ and $1/\lambda$ and average ET must be used for each season.

Alternatively, where these parameters are assumed to change *continuously* throughout the year, Monte Carlo simulations of the process may be employed (Milly, 1994; Potter *et al.*, 2003). However, this procedure limits the usefulness of the modelling approach due to the lack of analytical solutions.

Rodriguez-Iturbe *et al.* (1999) used a loss function $\rho(S_n)$ of water output where S_n is relative soil water storage, the amount of water stored in the profile relative to maximum soil water storage S_{max} (Figure 46). use of relative soil water storage S_n requires normalization of the average storm depth and maximum/potential ET parameters so that

$$\gamma = \alpha S_{max} \quad (5)$$

and

$$\eta = \frac{ET_{max}}{S_{max}} \quad (6)$$

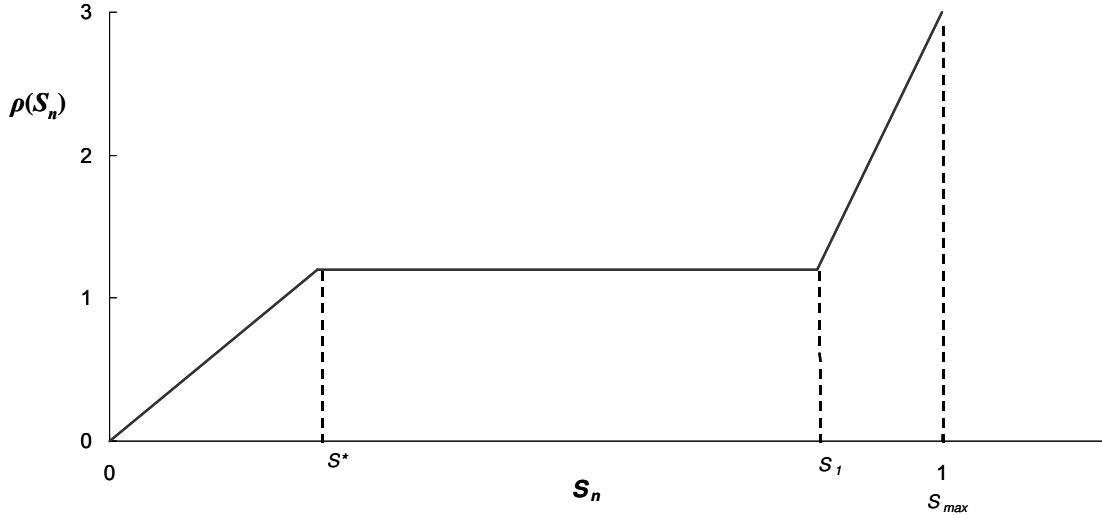


Figure 46 Sketch of the form of a loss function, modified from Rodriguez-Iturbe *et al.* (1999).

When the profile is full (i.e. when $S_n = S_{max}$), S_n is equal to 1. When the profile is half full (i.e. when $S_n = 0.5S_{max}$), S_n is equal to 0.5, etc.

The loss function describes evapotranspiration ($0 < S_n < 1$) and drainage ($S_l < S_n < 1$) as rates (mm d^{-1} ; Figure 46), where S^* and S_l are the threshold between ‘stressed’ and ‘unstressed’ water use by the plant, and the threshold between no drainage and drainage, respectively.

Rodríguez-Iturbe *et al.* (1999) provided another expression for the infiltration of rainfall into the soil (the minimum of rainfall depth and available soil water storage) also accounting for interception losses from plant foliage, although the assumptions implicit in the expression are likely not to apply generally. The resulting expression for the probability density function $p(S_n)$, where p represents probability density, allows a coarse assessment of the probability of soil profile to be ‘wet’ or ‘dry’ or with certain specified limits.

Ellis *et al.* (2002) assumed that drainage was not present in the soil water dynamics, so the loss function of Rodriguez-Iturbe *et al.* (1999) reduced to evapotranspiration only

$$\rho(S_n) = \begin{cases} \frac{\eta}{S^*} S_n, & 0 < S_n \leq S^* \\ \eta, & S^* \leq S_n \leq 1 \end{cases} \quad (7)$$

where S_{max} now represents S_l (Figure 46) and η is the average daily evaporation rate normalised with respect to S_{max} . Substitution of this form of the loss function into equation (4.5) from Rodriguez *et al.* (1999) yields the soil moisture probability density function $p(S_n)$ under the assumption of no drainage losses

$$p(S_n) = \begin{cases} \frac{c}{\eta} \left(\frac{S_n}{S^*} \right)^{(\lambda S^* / \eta) - 1} e^{-\gamma S_n}, & 0 < S_n \leq S^* \\ \frac{c}{\eta} \exp\left(-\frac{\lambda S^*}{\eta}\right) \exp(S_n (\lambda / \eta - \gamma)), & S^* \leq S_n \leq 1 \end{cases} \quad (8)$$

where c is a constant that normalises $p(S_n)$ so that the integral is equal to 1. This can be found to be equal to

$$c = \frac{\eta(\gamma S^*)^{\lambda S^*/\eta}(\gamma\eta - \lambda)}{S^*(\gamma\eta - \lambda)\Gamma(\lambda S^*/\eta, \gamma S^*) + \eta(\gamma S^*)^{\lambda S^*/\eta} [e^{-\gamma S^*} - e^{\lambda(1-S^*)/\eta - \gamma}]} \quad (9)$$

and $\Gamma(a, x) = \int_0^x t^{a-1} e^{-t} dt$ is the incomplete Gamma function.

An example of the form of $p(S_n)$ is given in Figure 47.

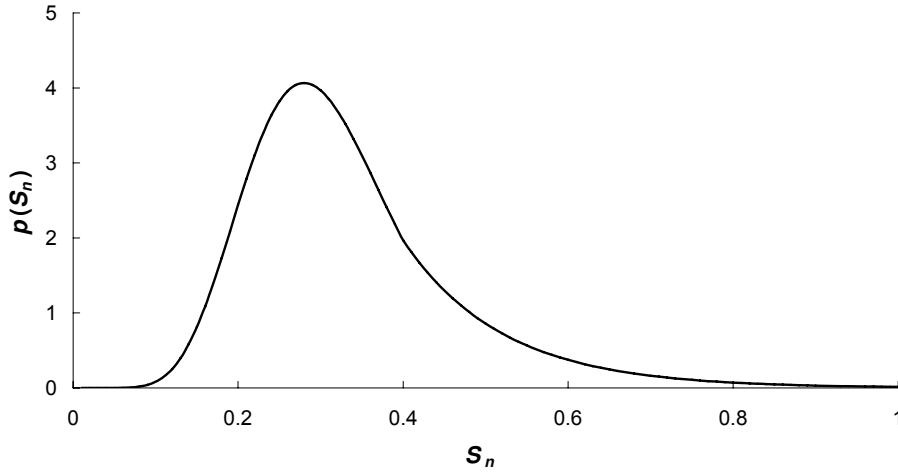


Figure 47 Example of probability density function $p(S_n)$ using $1/\alpha = 5 \text{ mm}^{-1}$ and $1/\lambda = 5 \text{ d}^{-1}$, $E_{max} = 1.3 \text{ mm d}^{-1}$, $S^* = 0.4$ and $S_{max} = 180 \text{ mm}$.

Given that the probability of the S_n being between two values d and e is

$$\Pr(d < S_n < e) = \int_d^e p(S_n) dS_n \quad (10)$$

then, for the example shown in Figure 47, there is a much greater probability that S_n will be less than 0.5 than greater than 0.5. That is, for the combination of climate, soil water storage capacity and loss function, the soil profile is more likely to be dry rather than wet. We use these properties of $p(S_n)$ to help characterise the results of our numerical modelling of the water balance (see results section).

Using the probabilistic approach for hillslope design

We explored the potential for using the probabilistic approach to match vegetation with climate and soil characteristics to achieve a hydrologic target for a hillslope. For simplicity, we considered only a simplified version of reality where deep drainage and subsurface lateral flow of water is zero and therefore the loss functions comprised only the evaporative components.

As a hypothetical design problem, we examined the suitability of two tree species *Corymbia maculata* – previously *Eucalyptus maculata* - (conservative water user) and *Eucalyptus dumosa* (drought adapted species) planted at Molonglo (35.46S, 149.42E; 720 mm annual average rainfall) to provide an expected annual water yield of 100 mm and 0 mm. The loss functions for each of these species are shown in Figure 13 in the Methods section, expressed in terms of *PET*.

To address the hypothetical design question for Molonglo, we solved the equations of Rodriguez-Iturbe *et al.* (1999) for expected annual runoff, with respect to maximum soil water storage S_{max} . Using $1/\alpha = 4.7 \text{ mm}^{-1}$ and $1/\lambda = 8.9 \text{ d}^{-1}$ derived from Molonglo daily rainfall data, and measured loss functions (evaporative only) of the species *C. maculata* and *E. dumosa* (Dunin *et al.*, 2001).

The expected value of daily evapotranspiration can be determined by solving

$$\frac{E(ET)}{S_{max}} = \int_0^1 \rho(S_n) p(S_n) dS_n \quad (11)$$

which was found to be equal to

$$\frac{E(ET)}{S_{max}} = \frac{c\Gamma(1 + \lambda S^* / \eta, \gamma S^*)}{\gamma(\gamma S^*)^{\lambda S^* / \eta}} + \frac{c\eta}{(\gamma\eta - \lambda)} \left[e^{-\gamma S^*} - e^{\lambda(1-S^*) / \eta - \gamma} \right]. \quad (12)$$

The normalised expected daily rainfall is equal to $\frac{E(P)}{S_{max}} = \frac{\lambda}{\gamma}$, so the expected daily runoff $E(Q)$ is equal to the difference of these two, that is

$$E(Q) = S_{max} \left\{ \frac{\lambda}{\gamma} - \frac{c\Gamma(1 + \lambda S^* / \eta, \gamma S^*)}{\gamma(\gamma S^*)^{\lambda S^* / \eta}} - \frac{c\eta}{(\gamma\eta - \lambda)} \left[e^{-\gamma S^*} - e^{\lambda(1-S^*) / \eta - \gamma} \right] \right\}. \quad (13)$$

Figure 48 shows the form of expected annual runoff for the example of the two tree species considered for the Molonglo case.

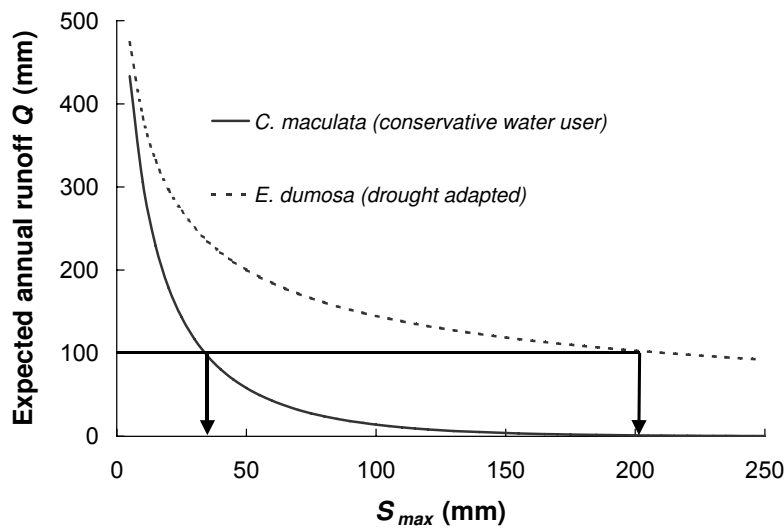


Figure 48 Expected annual runoff for two tree species considered for meeting runoff targets in the Molonglo catchment.

This allows the preliminary assessment of the suitability of the two tree species to meet specified water yield targets in the Molonglo catchment. Consider 2 different hypothetical annual water yield targets:

1. Zero
2. 100 mm

As a preliminary screening method in the absence of values of S_{max} (S_{max} for the site is likely to vary between 100 and 250 mm) in the catchment, this gives an indication of the suitability of each species for meeting the water yield targets. In the first case, it is obvious that *E. dumosa* cannot achieve the zero runoff target, but *C. maculata* is more likely to achieve this if S_{max} is between 150 and 200 mm. For the target of 100 mm runoff, *E. dumosa* and *C. maculata* could achieve this if S_{max} were equal to 30 mm and 200 mm, respectively. Again, *E. dumosa* is unlikely to be a suitable species.

If we specify a value for S_{max} , inspection of $p(S_n)$ allows comparison of the likely soil water status in the root zones of the two species under these conditions (Figure 49). As indicated from the calculations of $E(Q)$ with respect to S_{max} , (Figure 48), Figure 49 suggests that for $S_{max} = 250$ mm (an extreme value) the root zone of *C. maculata* is more likely to be ‘dry’ while the root zone of *E. dumosa* is likely to be wet and possibly waterlogged.

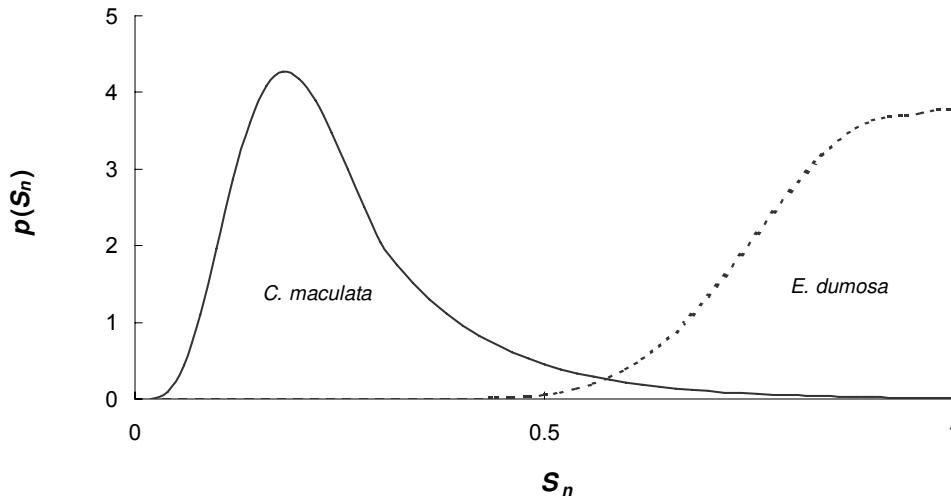


Figure 49 $p(S_n)$ for the two tree species considered for the Molonglo example, where S_{max} was set to 250 mm.

This example, to a certain extent, confirms the obvious. That is, a drought-adapted species is unlikely to be suitable for manipulating the water balance in a relatively high rainfall area. However, the analytic solution for $E(Q)$ with respect to S_{max} is novel, and we suggest it is suitable for preliminary matching of rainfall, soil and plant water use characteristics. At present, an analytic solution is available only for a single point (or plot). We anticipate that the development of an analytic solution for multiple plots on a hillslope, linked hydrologically via the cascade of excess water, as overland flow (see Figure 11 and Figure 12), is possible. This would be a very useful tool for preliminary matching and design for banded or other spatially heterogeneous vegetation systems.

Appendix 3

LFA infiltration index (Tongway, 1995) data for the mulga vegetation community and the 3 farm tree belts

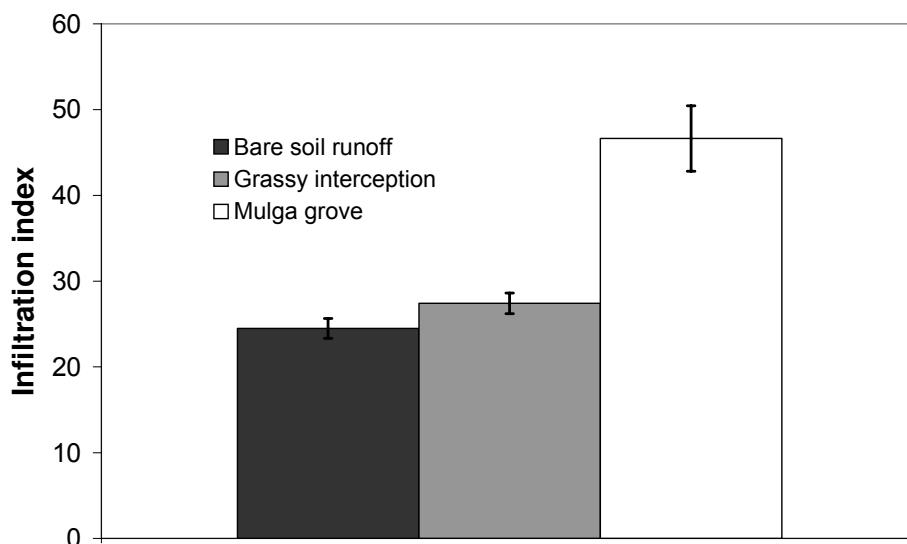


Figure 50 Infiltration index values (Tongway and Ludwig, 2000; Ludwig *et al.*, 2004) for the ground surface units used in the transect of the farm tree belt at Lake Mere.

These values correspond with measured infiltration rates of 20, 32 and 245 mm hr⁻¹, respectively (Greene, 1992).

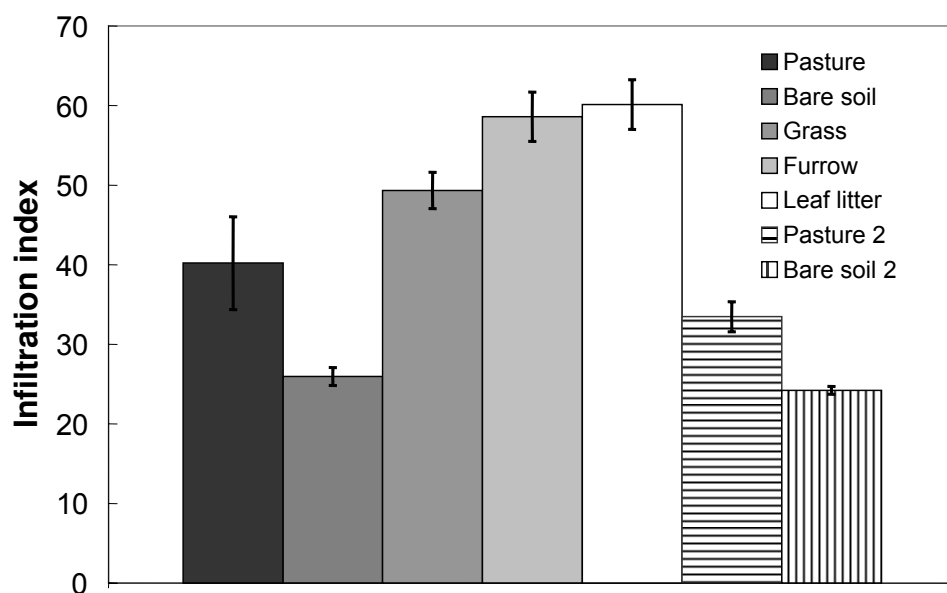


Figure 51 Infiltration index values (Tongway and Ludwig, 2000; Ludwig *et al.*, 2004) for the ground surface units used in the transect of the farm tree belt at Wielora shed paddock

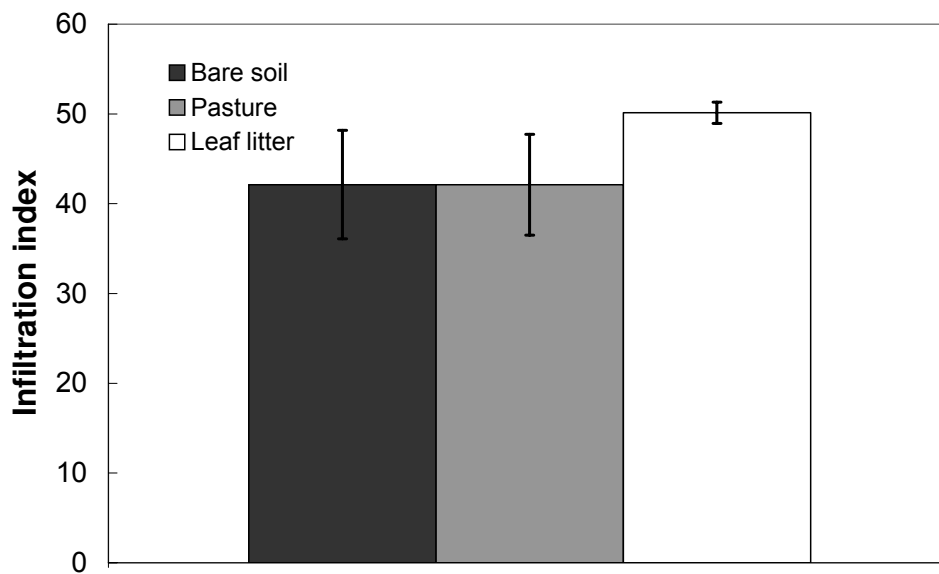


Figure 52 Infiltration index values (Tongway and Ludwig, 2000; Ludwig *et al.*, 2004) for the ground surface units used in the transect of the farm tree belt at Wielora dam paddock

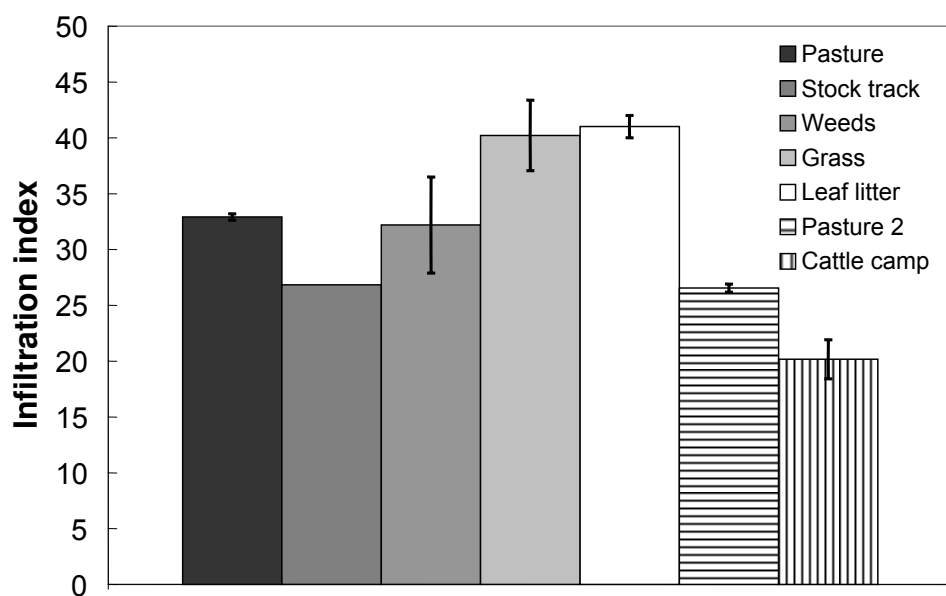


Figure 53 Infiltration index values (Tongway and Ludwig, 2000; Ludwig *et al.*, 2004) for the ground surface units used in the transect of the farm tree belt at Annandayle South.