



A review of plantations as a water intercepting land use in South Australia

Ian P. Prosser and Glen R. Walker

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KEY FINDINGS

- Plantation forests use more water than agricultural land covers such as pasture, cereals and other crops. A direct consequence of the higher water use is lower runoff and recharge. The substantial extent of plantations in some regions together with the degree of runoff and recharge reduction is sufficient to justify the inclusion of plantations in water resource policy and management.
- The level of reduction of runoff and recharge depends on a number of factors but some general relationships hold that are useful for estimating the change. There is a wide range of evidence that runoff and recharge are typically reduced by approximately 80% relative to agricultural land covers. There are exceptions of both lower and a higher relative change to water use but to estimate local change is expensive and time-consuming.
- There is significant residual uncertainty when general rules are applied to estimate local water availability, environmental water requirements or plantation water use. This uncertainty is usually accommodated by using a precautionary approach to water allocations. There are places though where pressure on water resources is high and a precautionary approach may unnecessarily limit use of the resource. This variability in situations can be accommodated by taking a risk-based approach to water resource assessment.
- Where there is relatively low use of water there is a low risk of over use and generalised relationships can be used such as the 25% use limit and the 85% reduction in runoff under plantations.
- For areas where there is pressure on the resource, or where there are indicators of declining resource condition, then detailed studies should be undertaken to provide greater certainty in water planning. Detailed studies have been undertaken for the Lower South East and their use seems appropriate. Although it was not directly stated in the literature we reviewed, it is possible that pressure on water resources in the Mt Lofty Ranges is increasing. In that case the region would benefit from more detailed investigation of aspects such as the water requirements of wetlands, so that more detailed assessment approaches can be used.
- The wetland water balance assessment described for the Mt Lofty Ranges could provide a useful approach of intermediate complexity between the general rules and detailed local studies. Thought could be given to clarifying the approach because at present there is ambiguity between the general rules of a 25% use limit and use of a site specific wetland water requirement. In general, environmental water requirements seem to be the area of greatest uncertainty in water resource assessments and are worthy of future attention.
- The impact of plantations on water resources will typically be proportional to the extent of the resource that is covered by plantation. Areal extent will be the primary factor determining overall impact. The next most important factor is to consider places where plantation water use will be very high because of direct access to shallow groundwater. This is appropriately in the Lower South East. Other factors such as species type and the difference between gross and net plantation area are small and within the 20% uncertainty of even the best assessment methods.
- The scientific evidence supports the use of a 6 m trigger value for the depth to which trees extract groundwater in the South East region. At depths equal or less than this plantations will be directly using groundwater at a significant rates. There are measurements in the South East region which have quantified the use of groundwater. More generally, if use is not limited by salinity, it will be at the energy limit, or in other words the potential rate of evapotranspiration for the plantation.

- Plantations use increasing amounts of water as they grow from seedlings to a mature forest. For decadal or longer time planning of water resources, using an estimated maximum water use rate is consistent with a risk-based approach.
- The application of rules with respect to buffer strips seems to warrant some more thought. Criteria for buffer strips include water quality and ecological purposes and a width of 20 m can be justified on these grounds. There is a potential for higher water use of plantations within areas just outside the 20 m zone but at a sub-catchment or plantation scale there would be little difference in total water used. In upland areas, the possibility of trees within 50 m of streams or wetlands directly drawing down water tables as an additional impact is probably overstated. Thus the scientific support for 50 m wide buffers is probably weak. In areas of regional groundwater there are additional factors that need to be considered around supply of water to wetlands which cannot be dealt with by a simple buffer width.
- Similarly, restrictions on activities in drainage lines can be justified on grounds of reducing risks to erosion and water quality. Additional impacts on runoff generation relative to the overall areal extent of plantations are probably small and not justified. It is important to properly define drainage lines to give certainty of policy and ensure that restrictions are practical.
- Higher water use in plantations can have the benefit of reducing salt loads downstream. Often the tension between water resources and salinity management is not as great as first thought. High water yielding sub-catchments tend to yield fresh water and are favoured for plantations because of the consequent high forest productivity. Sub-catchments which yield salt tend to have low water yield and low forest productivity. Practical methods of hydrological characterisation can be used to identify the limited situations where there is a real need to consider the tradeoffs between salinity benefit and water resource dis-benefit.

1. BACKGROUND AND SCOPE

CSIRO was asked to provide an independent assessment and recommendations on scientific literature to assist the South Australian Government Water Resources and Forests Interdepartmental Committee (IDC) to agree on the appropriate methodologies used to account for the impacts of plantation forests on water resources in South Australia.

We have been provided with a compilation of over sixty scientific and technical papers which have been identified by the IDC Science Support Group as relevant to the topic. We have also been provided with an annotated bibliography on these papers, summarizing their scope, techniques and limitations. We were subsequently provided with additional papers thought to be relevant, and identified some further literature ourselves. There is considerable cross-referencing between papers and several are reviews of the topic. There are also papers which describe how the literature has been interpreted for use in South Australian water management. Others are commentaries on the proposed uses in South Australia.

We believe that to provide further summary and analysis of each paper separately would add little value beyond the existing summaries and reviews. It is also beyond the resources of the brief. Instead we offer an overall framework of how to address the problem. We fit the papers into that framework, showing how we believe they contribute best to overall understanding of the issues and to practical tools for assessing plantation consequences for water resources in South Australia. In some instances we justify where we dismiss particular papers as not being useful for practical management of the issue, or where we disagree with past interpretations. It is beyond the resources of our study to address all past interpretations explicitly.

2. INTRODUCTION

The overall issue we address is the water resource consequences of plantation forestry. One of the principles being adopted to design appropriate policy and management of the issue is that it be based upon the best scientific evidence. Before outlining the science of forests and water, we describe some principles of how to use scientific evidence in practical policy and water management processes. These principles become important when the science is contested strongly, or where there is apparent contradictory evidence. The forests and water debate in South Australia, and more widely, have both of these elements.

The issue of plantations and water resources requires an understanding of several areas of hydrological knowledge. Forest vegetation cover influences several aspects of water balance in landscapes and we need to understand how it changes each aspect of the water balance, and what that means for landscape scale hydrology, which is the scale at which water is managed. The consequences vary from one landscape to another dependent on the predominant catchment runoff and groundwater processes in each landscape. Thus we briefly describe these processes and some of the differences in processes between landscapes.

The primary influence of forest vegetation is to increase evapotranspiration relative to that under pasture, crops and similar land covers, so we pay particular attention to evidence of those changes. Other factors, such as species type, forest age, and access to water influence the amount of evapotranspiration and these are described.

Proposed tools for assessing plantation impacts are reviewed for how well they represent the underlying processes, while being practical, consistent, and reflecting the uncertainty in local hydrology. One of the suggested policy options is to ensure adequate buffer width between plantations and streams, drainage lines and wetlands, so we review the hydrological and other basis for buffers.

Particular aspects of policy around plantation and water resources are considered for three regions of current concern: Mt Lofty Ranges, Lower South-East and Kangaroo Island.

We have also been asked to identify gaps in knowledge where further research is needed. We address this by first considering the level of knowledge against the significance of the decisions being made, identifying areas where decisions with significant consequences could be made with less risk if there was better knowledge.

3. PRINCIPLES OF USING SCIENTIFIC EVIDENCE IN POLICY AND MANAGEMENT

In areas of contested science and apparently contradictory evidence we need to have some sound and agreed principles for assessing the scientific evidence and resolving the conflicts. We use the following principles:

1. Multiple lines of evidence in support of a process or phenomena are much better than single lines of evidence. Evidence is stronger where the phenomena are consistent between a range of independent measurement techniques, or between field measurements, experiments, and modelling. Similarly, consistent observations from a range of circumstances provide evidence that the observations are not anomalous or particular to a single site.
2. Observations that are explained by theory or causal processes provide stronger evidence than unexplained observations.
3. Local information and relationships takes precedence over national or global information, but they should be explained in the broader context of those processes if there are significant differences.
4. Hydrological behaviour can change with scale, from point to hillslope to catchment. Knowledge at the same scale as that of the decisions being made is more appropriate than finer or coarser scaled knowledge. Typically, for water resources, decisions are made at the regional or catchment scale.
5. Application of the knowledge in policy and management should be consistent with the underlying observations, processes and theory. It should reflect, for example, the major components of the water balance in that landscape, or the major causes of variability from one place to another.
6. The assessment methods should be commensurate with the uncertainty of the local hydrology. There can be a temptation to advocate detailed assessment techniques that represent a particular process well, but these provide a false sense of accuracy if other important processes or sources of variability are not represented to the same level.
7. Wherever possible, assessments should integrate multiple processes into a single planning decision driven by the most important process. For example, groundwater, surface water, water quality and other environmental considerations can be integrated into a single planning decision in some cases.

The application of these principles and judgement of how to use the scientific evidence will need to be made by agency staff. The scientific literature itself rarely covers the application of the knowledge or how to apply techniques to particular circumstances.

4. FOREST WATER USE

The primary impact of plantations on water resources is that plantations and other forests transpire more water than pastures, crops and similar land covers (summarized as pasture land covers from here). As outlined below there are multiple lines of evidence for this and many studies have quantified the differences between forest and pasture evapotranspiration.

Increases in evapotranspiration must be accommodated by concomitant decreases to runoff, recharge, or water storage, to maintain water balance across the landscape. In upland catchments, soil water stores and local groundwater stores are relatively small, as is seepage or recharge to regional groundwater. Thus, over a decade or more, the increase in evapotranspiration is balanced by the same reduction to runoff (15). Often it is observations of reduced runoff that are used as evidence of increased evapotranspiration.

In regional groundwater systems, the increased evapotranspiration leads to reduced recharge or it is a result of trees accessing groundwater stores and thus increasing discharge of that groundwater. Both changes that reduce recharge and those that increase discharge can lead to lower groundwater levels and reductions in other discharges over time.

4.1. Controls on forest water use

Far from being a random process, the controls on transpiration (plant water use) are well-known. If one understands the controls on transpiration, it is possible to understand broad landscape variations in transpiration and evapotranspiration (ET) and hence the impacts of forest on other parts of the water balance such as run-off and recharge.

Firstly, evapotranspiration is limited by the amount of energy to drive the process. Secondly, it is also limited by the availability of water. These limits in turn can be related to climatic factors such as rainfall, temperature, radiation and humidity, sub-surface hydraulic and hydrological characteristics such as transmissivity, water table depth, up-gradient catchment area, physical and chemical impediments to root growth and also the salinity of potential water sources. Most of these are either mappable across large areas or can be determined as part of a site characterisation. Where there is ample water availability, such as where there is shallow and fresh groundwater, evapotranspiration is limited by energy. For most Australian situations evapotranspiration is limited by water availability.

Finally, there are strong relationships between tree growth, leaf area and tree water use. Highly productive forests will use more water. Apart from water availability and accessibility, tree growth is affected by several factors such as soil fertility, root diseases, climate and soil depth. Most of the variation in water use of different evergreen species results from suitability of the site. The difference in water use between species with the same leaf area is relatively small when compared to differences in leaf area of different species.

Trees use more water than other plant types for a number of reasons. Trees are large plants with very large leaf areas that consequently transpire more water. The tree canopy intercepts more rain before it reaches the ground; trees often have deeper roots; use water over the whole year; and absorb more radiation directly.

4.2. Evidence from empirical catchment relationships and catchment studies

While controls may be well-understood, it is more difficult to quantify overall evapotranspiration and differences in ET from different land uses, especially at a scale relevant to water resource management. This is most easily done for gauged upland catchments, where nearly all of the water not lost by ET is measured by at a stream gauge. When forested catchments are compared with un-forested catchments, differences in

measured stream-flow can be used to compare evapotranspiration from different land uses. When done for a range of catchments, empirical relationships can be derived locally or globally. Zhang and others (31) analysed data from over 250 catchments in 28 countries from around the world. These catchments varied in size from 1 km² to over 100,000 km² and spanned a variety of climates including tropical, dry and warm temperate, while vegetation ranged from plantations to native woodlands, open forest, rainforest, eucalypts and pines to native and managed grassland and agricultural cropping.

These data reveal that, at least on an annual basis, the most important factors controlling evapotranspiration are annual rainfall, atmospheric demand and vegetation cover. The relationship between these factors can be described using the Zhang curves (31). Evapotranspiration is greater for forested catchments than for grassed catchments. Also, the ratio of the difference of ET to that of grassed catchments increases with decreasing rainfall, being 50% at 1000 mm rainfall.

There is scatter about these curves due to secondary factors such as rainfall seasonality soil depth, etc. The scatter becomes comparable to the difference at lower rainfalls (~600 mm). The shape of the Zhang curves is heavily influenced by high rainfall catchments (>1000 mm). It is not surprising that when applied to low rainfall catchments regionally, some modification is required to form 'local' Zhang curves. However, the difference in ET between forest and non-forest in the local Zhang curves appear to be similar to the global Zhang curves.

Finally, the scatter, combined with temporal variability of rainfall means that it may difficult to detect differences in ET when the difference in land use is small (e.g. less than 20% of the catchment area). This does not mean that the difference is negligible. It merely means that it is hard to see among the very high inter-annual variability in runoff (see below).

4.3. Evidence from land use change experiments

There have been several experiments of forest clearing or reforestation which have measured changes in runoff as a result of the change to land cover. These experiments are useful to test to see if the general differences between forested and grassed catchments described above are reproduced for land cover change in individual catchments.

The most thorough design for land use change experiments is to measure runoff before and after land use change and compare the runoff with a paired catchment of similar characteristics but where the vegetation cover is not changed. Then, other possible causes of change to runoff, such as climate variability can be dismissed. Vertessy (34) reports an Australian study of this type for a catchment with 850 mm mean annual rainfall. There was a 73% reduction in runoff, within 15% of that suggested by the general relationships and the reduction could be expected to increase as the forest grows. No change in runoff was recorded in the control catchment. Scott and Smith (62) report five paired catchment studies of afforestation in South Africa where relative decreases in water yield were between 80-100%. Brown et al. (63) show that such results from paired catchment studies are typical and support the general relationship explained above. A runoff reduction from reforestation of 70-100% is reported for a Mt Lofty Ranges catchment (12) where no similar reductions were observed in other gauged catchments. These local results are consistent with the general relationships discussed above.

There are exceptions to the large change in water use with deforestation or afforestation. Ruprecht and Schofield (64) is cited (46) as evidence for a much smaller change to runoff in two catchments of 800 mm rainfall. However, what is reported there is a 4% increase in runoff relative to rainfall as a result of forest clearing. No other studies report results this way. When this is recalculated as a percentage reduction in runoff from cleared to forested situations the difference is 90% lower runoff when the catchment was forested than when it was cleared.

Typically the land use change experiments are undertaken in small catchments where the most or all of the catchment is either cleared or reforested. The processes in small catchments are similar to those in larger upland catchments so there are no major scale issues and the results can be scaled simply by the areal extent of plantation. It has been claimed that there are systematic differences between plantations with buffers and full catchment clearing (11). The basis for this is probably overstated as the degree of higher water use within buffer zones has not been calculated, the reduction in through flow from forest upslope is neglected, and the areal extent of these zones is small.

We conclude that there is strong evidence for at least 80% reduction in mean annual runoff for plantations established on cleared land. The reduction could be as much as 100% in the driest catchments but less in the wettest sub-catchments.

4.4. Evidence from measurements of water use

The most thorough way to detect differences between ET of different land uses is through closing the water balance at the land surface and having separate measurements of different components. Historically, soil moisture meters, rainfall interception troughs and run-off plots have been used to infer the ET. Over the years, the development of soil water tracer techniques to estimate root zone drainage below different land use and soils has enabled estimation of recharge. Low cost sap flow detectors have allowed estimation of transpiration and eddy correlation and Bowen ratio techniques for estimation of ET above the tree canopies have become possible and plant tracer techniques have been used to distinguish sources of water.

These techniques have enabled detailed analysis of processes, relating plant physiological processes, water fluxes and atmospheric drivers. For areas with deeper water tables, ET is limited by rainfall. The region of the Mallee, Upper South-East and Lower South-East represents the part of Australia best covered by recharge studies. A range of techniques have been used, comparisons are good and techniques range across scales. These studies consistently show recharge under trees to be much lower than under non-treed situations. The results are consistent with results elsewhere in Australia and overseas (66).

For areas of shallow water tables, trees are able to access water other than direct rainfall i.e. paleo-recharge or water that has moved laterally across the landscape. In principle, trees could use water at rates matching the atmospheric demand. This situation is seen in the Lower-East, where water balance studies would be one of the best studies in Australia. These high rates of groundwater use are not that common because the rate of water use by trees can be easily limited by the ability of the aquifer to transmit the required water, lack of up-gradient catchment area, salinity in the groundwater leading to osmotic controls on water use or the ability of the roots to reach the 'capillary fringe'.

4.5. Change in evapotranspiration through the forest growth cycle

Water use by plantations increases as they grow from seedlings to mature trees, and put on increasing leaf area. Greenwood and Cresswell (12) have reviewed evidence for the changes with forest age, showing that the changes with growth of a plantation in the Mt Lofty Ranges is consistent with the South African studies (62) where relationships of water use with plantation age were developed. This behaviour is also shown in the paired catchment studies of plantation establishment (63).

When a plantation is established there can be an initial increase in runoff relative to pasture covers because of predominantly bare soil (63). Runoff soon decreases in subsequent years relative to grassland due to growth of the trees. Burnt Out Creek is consistent with South African data on this, where the idea was developed.

The main question is how to accommodate into water policy the change in water use with plantation age. Some have claimed that average water use over time should be used because there will be a mix of stand ages in a plantation (15, 51). This may be true for large established plantations, but would not be true if a new development was established within the period of a rotation. A problem with a calculation based upon average conditions or planned times for harvesting is that it gives no flexibility for changes in circumstances and extension of rotation lengths.

Others have argued that maximum use should be used as tree growth is inevitable once the plantation is established and water resource planning is aimed at ensuring water security at times of maximum water use (12,17). It is worth observing that other uses of water, such as irrigation, farm dams and environmental entitlements do not use their maximum entitlement every year, with considerable variability in use from one year to another, below the maximum allowed. Thus the situation that use in many years may be below the level of entitlement required is not unique to plantations. The National Water Initiative encourages temporary trade of unused allocations to allow others to make use of the water. If a plantation is licensed for maximum use there will be years where actual use is below the entitlement volume and thus policy could consider whether trade can be allowed.

5. CATCHMENT HYDROLOGY AND ITS RELATIONSHIP TO FOREST WATER USE

We have argued above that the primary hydrological impact of forest cover relative to pasture cover is to increase evapotranspiration from the landscape. We have also argued that in upland catchments this has a direct and proportional impact on catchment runoff. There are, however, other changes to catchment hydrology that result from high forest water use. These enter the debate through considerations of whether the location of plantations within a catchment influences its impact on water resources or not. The main areas of concern here are:

- the impact of gross forest area versus net forest area; and
- whether there is a difference in water use between plantations developed on upper slopes versus footslopes.

The additional topic of buffer strip width is considered in a separate section below.

Some parts of plantation estates are not planted with trees. Thus the gross plantation area may be less than the net planted area. Unplanted areas may include roads, places that are too rocky or wet for plantations, remnant vegetation, places where machinery cannot get access, and buffers around streams. Some argue that it is only the planted area that should be taken into consideration in calculating water resource impacts (51). Others argue that calculations should be based upon the total area of the plantation including unplanted areas that are surrounded by trees (17).

It is true that only the planted area will experience a direct increase in evapotranspiration relative to pasture cover. However, in surface water catchments the fate of the water that is not evaporated from the unplanted areas needs to be considered. Rainfall on an unplanted area will result in direct surface runoff if the rainfall rate exceeds the infiltration rate of the surface. The runoff will move downslope with the topography and if the unplanted area is surrounded by plantation around it will enter the planted area. Road runoff is a good example. The infiltration rate will be high in the planted area so the runoff is likely to infiltrate. Alternatively, if rainfall infiltrates in the unplanted area but is in excess of the evaporation potential of the vegetation then it will either move downslope as throughflow or percolate down into groundwater systems. As outlined above the vast majority will move as throughflow in soil water or in shallow perched aquifers. That water will move downslope and will enter the planted area. Tree water use in most Australian environments is limited by

water availability so the extra water coming from the unplanted area will most likely be taken up by evapotranspiration in the planted area. It is only if the unplanted area feeds directly into a stream that it will not contribute to forest water use. Thus streamside buffers should not be considered as part of the plantation area.

There are also practical considerations to be made when deciding between gross and net forest area. We have observed that there is inherent uncertainty of approximately 20% in forest water use. Thus differences that are smaller than 20% are within the error of the calculations and there is little benefit in incorporating those into the analysis. There are also forest edge effects. Leaf area, and thus water use can be greater at the forest edge because of less shading from other trees. Thus if the unplanted area is small relative to the length of the edge then the water use difference will be vanishingly small.

The same principles apply to deciding if landscape position of the plantation is important. Most plantations blocks that are large relative to the size of individual hillslope segments so that they occupy a range of upslope and lower slope positions. Trees may be less productive on the upper slopes and thus use less water but the unused water will travel downslope and be taken up by higher tree water use by more productive trees downslope. Thus local topographic differences cancel out at the landscape or whole of plantation scale and need not be considered.

There are some unpublished results of Vertessy shown in review publications (11, 18) which suggest very large differences in water use between upslope and lower slope plantings. These results should be used with caution (45, 46) for two reasons. First, they are for small farm plantings aimed at addressing salinity. They consider the situation of planting a belt of trees across a predominantly grassed landscape, and whether the belt is more effectively positioned on the footslope rather than the upper slope. The higher water use for the footslope is because it is supplied with runoff and throughflow from the much larger area of low water using pasture upslope. This is quite different to a plantation where the majority of the landscape will be planted, with much less water coming from upslope and thus a much lower difference in water use with topographic position. The second reason for caution is that only one result is presented, from one set of circumstances, but as observed in (45) there are a range of circumstances. These were explored in the Vertessy study at CSIRO and in many circumstances there was little difference in water use with topographic position. If the transmissivity of the soil is low, excess water will evaporate before it has travelled to the foot of the slope and the differences in water use are much lower than shown. Also differences in water use are found for hillslope valleys but less so for planar slopes or spurs. Overall, we conclude that for plantations there is no need to consider topographic position as variations in water use will be small relative to the inherent uncertainties in resource assessment.

6. GROUNDWATER HYDROLOGY AND ITS RELATIONSHIP TO FOREST WATER USE

Groundwater hydrology is important for this review in at least two respects: the impact of forestry on the groundwater resource itself and the impact on salinity of the surface water resource. The groundwater processes may be important in the impacts of forestry in buffer strips.

The determination of groundwater allocation rules is outside of the scope of this report. Generally, groundwater allocation is a balance between consumptive and environmental demand. Again, the manner in which environmental requirements are handled is beyond the scope of this review.

Whatever the water allocation system for a groundwater system, a key factor in the quantity available for water allocation would be the total recharge. Recharge takes several forms: diffuse recharge: the amount of water moving to the groundwater system below the root zone of the land surface; point recharge: the amount of water moving to the groundwater system from surface water features such as rivers and lakes and irrigation recharge: the amount of water moving to the groundwater system from irrigation of agricultural crops either by surface or groundwater.

Plantation forestry will affect mainly diffuse recharge by the mechanisms described above. For areas of deeper water tables, the reduction in recharge will be approximately proportional to the area of plantation forestry relative to the area of recharge zone i.e if 30% of the recharge zone is planted to plantations, the reduction in diffuse recharge will be approximately 30%. For an unconfined system, the recharge zone may be all of the catchment. This proportional rule will be modified if the area of plantations on sandy soils or higher rainfall is disproportionate to the relative areas of these across the recharge zone. Nonetheless, it can be seen that a large area of plantations is required in order to have a significant impact, but if so, it is important to account for this.

As described above in areas of shallow water tables, ET may be limited by atmospheric demand rather than rainfall. This depends on the salinity of the groundwater, transmissivity of the aquifers and the ability of the roots to access the capillary fringe. The actual dependence of ET on water table depth is not clear as roots may be able to grow to some depths but rates of uptake may be low. As more data becomes available, this understanding will improve.

Because uptake of water is very high (100's of mm cf 10's of mm's for recharge), a small area of vegetation could offset a much larger area of recharge. For example, if 10% of the catchment was plantation forestry over shallow water tables which used 200 mm of groundwater and the rest of the catchment was 50 mm, the plantation forestry would use ~45% of the recharge despite being only 10% of the area. The remaining 55% is free to discharge to streams, groundwater-dependent ecosystems and/or the ocean. If groundwater irrigation also occurs in the catchment, the interactions can become complex with the irrigation not only reducing the discharge from the groundwater system, but also reducing the uptake by the plantation by causing water tables to fall.

Plantations can also reduce recharge to groundwater systems indirectly by reducing stream flow and hence point recharge. When studied in the MDBSY project, this effect was small due the area of plantations being small to the total upstream catchment area. This is more likely to be the case than not. It can also indirectly affect irrigation recharge through transfers of water to or from irrigation, thus increasing or decreasing the area of irrigation.

The impact of a groundwater extraction regime or a land use change across the catchment on the groundwater resource can be assessed through resource condition indicators. This may be water levels, groundwater salinity, impact on baseflow to streams or impact on groundwater-dependent ecosystems. For the Lower South East, falling water tables and

increasing groundwater salinity were used to identify hotspots. For a given scenario, the combination of impacts on these resource condition indicators could be used to provide a basis for the community to decide whether these impacts would be acceptable or not. The adverse impacts of any changes can be compared to the benefits. A groundwater model or some equivalent analysis may be required to assess these impacts. Some discharge from the groundwater system is required, if for nothing else, to avoid salt build. However, avoidance of adverse environmental impacts may increase the discharge.

In areas of higher groundwater salinity, the plantation impact on groundwater processes may lead to reduced salt loads to streams. Secondary (anthropogenic) salinity results from land use change causing increased recharge, which in turn, leads to increased discharge of saline water to the land surface, streams or oceans. Plantation forestry has the potential to reduce salinity. If the salinity benefit outweighs the disbenefit on water, then there is case under the NWI for the disbenefits to be neglected in water planning.

In order to distinguish the trade-offs, it is important to understand the spatial context of each of these. Higher rainfall areas usually have good quality water at high availability and plantation forestry productivity high. The water resource disbenefit would outweigh the salinity benefit. Areas of low rainfall are often associated with lower quality water and with low water availability, but also low productivity for forests. The salinity benefit would outweigh the water resource disbenefit but these areas may be less attractive for forestry because of the productivity disbenefits. There may be some grey areas in between because of the terrain and the geology leads to a win-win situation.

Most of the previous paragraphs deal with whole-of-catchment or whole-of groundwater system processes. Groundwater management may need to be intensified in some local areas of the groundwater system. For example, a large area of plantation could cause a reversal in groundwater flow due to groundwater uptake, leading to salinisation of the resource in that area. This could occur even if the overall groundwater balance appears to be sound. For example, in an aquifer of variable salinity, groundwater extraction and forest groundwater uptake would be focussed in areas of good quality water while recharge could be occurring for down-gradient poorer quality groundwater. This situation occurs in some of the larger NSW alluvial aquifers.

A large plantation close to an ecological asset may impact on that asset. The draw-down around a plantation depends on the transmissivity of the aquifer. Suppose a forest uses a certain amount of groundwater. The groundwater flow to match this demand leads to changes in gradients around the plantations. Low transmissivity aquifers will require steeper hydraulic gradients to deliver the water and this leads to larger draw-downs of the water table and decreased extent. The ecological asset could be affected by this asset. Another way of viewing this is to consider the capture zone of water for the ecological asset and the reduction in total water going to the asset caused by the plantation.

While processes are common across groundwater systems, the large variation in the characteristics, rainfall, land uses means that results or management methods may differ between groundwater systems.

7. PRACTICAL METHODS FOR ASSESSING IMPACTS OF FORESTS ON WATER RESOURCES

There is a tension between wanting consistency across regions and focussing effort where the risks are higher. One way of achieving this is to use a framework similar to that used in WA for groundwater. In that, the groundwater systems are divided on the basis of groundwater use being 0-30% of extraction limit, 30-70%, 70-100% and over 100%. The level of assessment required for those categories are different with much greater effort being focussed on high-risk situations. The more intensive assessment should reduce uncertainty, giving greater confidence that the groundwater system can cope with the level of groundwater use. It should be noted that as groundwater extraction increases, components of the water balance change. For example, increased extraction can lead to increased stream recharge. High levels of use will require a good monitoring network both temporally and spatially. The same logic could be applied to surface water catchments. The level of use may be more legitimately replaced by risk with values being applied to assets. There is no reason why this could not be applied to sub-components of catchments or groundwater systems where hotspots may exist or there is a very important asset.

The areas of higher priority for forestry should also be able to be determined on the basis of land and climatic suitability, markets and logistics of the industry. These relative priority areas when overlain with levels of risk, one can obtain a priority for assessing impacts of forestry. A high-risk water resource with high potential for plantations represents a big need for detailed assessment. A lower priority in a high risk water resource or a high potential in a low-risk water resource system may lead to medium level of detail in the assessment while low priority in low risk water resources means a more superficial system may apply. The last category probably covers most of the state.

Also, there is a need to consider different conceptualisations. There is no reason to expect the same method would apply to high rainfall areas in the Mt Lofty, Kangaroo Island and the Lower South-East. Hence, one needs to distinguish different parts of the landscape. It would be feasible to define a conceptual framework not dissimilar to the groundwater flow system approach used for salinity. This should allow sensible transfer of methods and rules from areas of similar landscape and rainfall characteristics. However, if this was a formal system, when combined with priority and risk, it would lead to an overly complex system.

The uncertainty associated with the water use of intercepting activities needs to be recognised. While water entitlements do not need to be used, water use can be measured or estimated, perhaps with greater accuracy than that of intercepting activities. On the other hand, the longevity of forest rotations means that there is a constancy compared to the vagaries of the water trade for the lifetime of the rotation. Somehow or other, the different water use of the plantations need to modify the water availability of the catchment or the water use. It would then be feasible to apply water sharing plan rules consistent with all land uses.

At the lowest level of priority/risk, the rules need to be simple and relatively independent of landscape types. Rules based on the area of the plantation relative to that of the water generating area or some weighted average dependent on soils and rainfall. Such a system should recognise the water use of plantations across the broader part of the catchment and higher water use areas, where water tables are shallow and/or near riparian zones affected by sub-surface water movement from up-catchment. It may be feasible to have simple rules for salinity benefits using groundwater flow system data and a model such as BC2C or rules embedded in it.

At the other end of the spectrum, there would be expected to be a more detailed conceptual model tailored to the catchment, detailed field measurements and application of models such as MODFLOW or catchment models.

In between, there can be several approaches, including transferring results and methods from similar catchments and use of site characterisation and mapped data.

Zhang and Walker (67) have documented most of the available methods for estimation of recharge and discharge. These include soil tracer, groundwater tracer, surface water balance, lysimeters, soil measurement, plot-scale model, piezometric and groundwater modelling methods. At the simpler end is the use of models, and some soil and groundwater tracer methods, especially those using chloride.

In upland catchments an initial step is to determine overall water availability through an assessment of the amount of runoff. For gauged catchments this is typically done with a calibrated rainfall-runoff model that reproduces as closely as possible the observed runoff. Many catchments or sub-catchments are ungauged, however, demanding a practical method to predict runoff across a landscape.

Predicting runoff in local catchments is inherently uncertain. There are many factors which determine the runoff of a local catchment. These might include local rainfall gradients, localised storms, different types of rainfall, variations in vegetation cover and soil properties, aspect and other topographic affects. Thus, as illustrated in Figure 8 of (8), catchment runoff even for a particular mean annual rainfall may vary by 70 to 100%. Within a single catchment there can also be variability of runoff from year to year of up to 100% unexplained by differences in year to year rainfall, as illustrated by Figure 12 in (8). Water resource assessment can deal with the uncertainty by making water allocations using the best information available and incorporating the risks of uncertainty into the decisions. Proposed methods do need to be critically evaluated though for whether they incorporate the uncertainty and do not give a false sense of accuracy by focusing on a single factor, for example, while neglecting other sources of variability from one place to another. The sophistication of the methods needs to reflect the underlying uncertainty of the results.

The most well established method of predicting runoff in ungauged catchments is to extrapolate calibrated rainfall-runoff models from calibrated gauged catchments. This method is used in water planning models across Australia. The South Australian WaterCRESS model is used in this way, to our understanding. The main skill is in "regionalization", which is the method used to choose the appropriate parameters for an ungauged catchment. That might be by choosing the closest calibrated catchment or the one with the most similar characteristics.

When considering the topic of forest water use, more general methods have been used to characterize total runoff. Because the runoff curves from Zhang and others (see 8, 18, 25, 34, 63) show mean annual runoff for pasture land and for forested land it is tempting to use these curves to calculate the current local catchment runoff. This is typically done by using the local mean annual rainfall and the proportional cover of pasture and forest. This is much less accurate than a calibrated rainfall runoff model, particularly for lower rainfall areas. Particular regions may differ systematically from the global relationships. This has been shown to be case for Australia and for South Australia (8). In that case a relationship can be constructed for South Australia using South Australian data (e.g. Figure 8 in (8)). The State relationship could be used as a general rule across the State, but local calibration of a rainfall runoff model will still be more accurate where that is justified by availability of data and the importance of the decision.

For calculating the reduction in runoff as a result of plantations the global literature suggests that absolute changes vary a lot (8, 62, 63) but that the percentage decrease in runoff varies much less, although there is a general pattern of higher percentage decrease with lower mean annual rainfall (15, 18, 25, 34, 63). In this case the one set of local data from South Australia (12) give a similar result to the global percentage changes. This is well approximated by a uniformly applied rule of 85% reduction in runoff over plantation areas. Variability in results suggests that across South Australia runoff may be reduced by 70-100%

but there is very little ability to predict where in that range any particular local catchment falls or whether the mean reduction is slightly higher or lower than 85%.

There are more detailed predictive models of runoff which take a process-based view of local hydrology, incorporating the environmental factors which drive those processes. One that has been suggested for assessment of plantation water use (see 11) is the Topog model and associated topographic scaling rules presented by Aryal and others. There are two limitations to using Topog or similar topographically based models for plantation water assessment. First, while they are very good at incorporating the effect of topography on runoff processes, and to some extent vegetation cover, for accurate predictions of water yield they also need information on soil transmissivity. Soil transmissivity is the ability of soils to conduct water, scaled up from site hydraulic conductivity to the landscape scale. There is very little data on soil hydraulic conductivity in most catchments, and it can vary by several orders of magnitude. There are no methods to scale-up hydraulic conductivity to landscape soil transmissivity. Thus soil transmissivity is usually used as a fitted parameter in Topog to produce observed runoff. In ungauged catchments this reduces it to effectively the same level of complexity and performance as a calibrated rainfall-runoff model. The second limitation with Topog is that there is much work required to set-up and run for individual catchments and it is too cumbersome for large regions. For application to forest water assessment the considerable extra effort is not warranted as it will not produce matching improvements in accuracy. Topog is best suited to problems of process response in small catchments, not routine hydrological assessment across large areas.

8. BUFFERS AROUND STREAMS AND WETLANDS

A buffer strip width of 50 m has been advocated in South Australia on grounds of high water use (13, 17). It is suggested in surface water catchments that trees not be planted within 50 m of streams or wetlands because of direct use of the water in the streams and wetlands and because of drawdown of local groundwater which feeds the streams. The hydrological basis for this may not be strong and would benefit from more analysis.

As outlined in Section 5 above the difference in water sue between upslope and footslope positions next to streams is probably overestimated. The contribution of flow to the stream will already be reduced by the upslope plantation, reducing the extent and water level of saturated areas or local perched groundwater tables. This effect appears to have been neglected in the analysis. The additional water use in the last 50 m of slope may not be much higher than already considered in the overall areal extent of the plantation.

Trees growing within 50 m of streams and wetlands may directly extract water from the stream or wetland. Whether that effect extends as far as 50 m is questionable and the vast majority of use may be within the first 10 to 20 m of the trunk of the tree. Also the water balance of the stream or wetland needs to be considered. If the catchment area of the stream or wetland was several square kilometres or more the direct water use by trees adjacent to the stream will be small compared to the volumes of water passing through from upstream and thus can be neglected in a stream or wetland water balance.

A study by Vertessy has been cited (17) to show that groundwater levels can be drawn down within 40 m of the edge of a plantation. The Vertessy study was in a flat plain landscape with low soil transmissivity. In catchments that are not flat the topography will be the primary influence on groundwater level with large differences in elevation across the landscape, and steep hydraulic gradients. This gives far less opportunity for local drawdown. Also where soil transmissivity is high, typical of upland catchments the extent of drawdown will be much lower. Thus the particular circumstances need to be taken into account but in general in catchment situations drawdown of water levels will not extend to 50 m.

There are a number of water quality, erosion control and ecological reasons for having plantation buffers of the order of 20 m (65). A 20 m buffer would have some small additional hydrological benefit relative to no buffer. Extending the buffer width to 50 m would seem to have little questionable hydrological benefit in most upland catchment circumstances so should be rethought as a general rule if it is argued purely on hydrological grounds.

The question of buffers has been raised in the Lower SE. A criterion has been used based on aquifer diffusivity and time.

$$X = \text{sqrt}(Tt / S)$$

Where: X is the distance of ground water drawdown around a plantation; t is the time of the plantation rotation; T is the transmissivity; and S is the specific yield. Using t = 11 years, T = 2500 m²/day; S = 0.1, the zone of influence is up to 10 km.

In reality, this assumes some impact expands without limit and ignores recharge. In reality, the impact will approach a limit where recharge within the impact zone balances the water use by plantation. As a rough guide, if the groundwater use of the plantation is assumed to be 200 mm/day; surrounding recharge 50 mm/day, the area of the plantation is 10,000 ha, the area needed to balance the water use of the plantation is 40,000 ha and would represent a zone of about 14 km around the plantation. This value is then relatively insensitive to the aquifer diffusivity and time since plantation occurred. Conceptually, the zone of influence grows until equilibrium is reached, albeit somewhat slower than formula above. The gradient at the edge of the plantation in the example is about 1 in 1000, so that drawdown may be relatively small, even though extent is large. As transmissivity decreases, drawdown at the edge of plantation increases, but extent of drawdown decreases.

This approach is used to avoid interference of adjacent production bores, where bore might penetrate deeply into the aquifer. However, ET from both the plantation and the groundwater-dependent ecosystem (GDE) is depth sensitive. As water tables fall, ET decreases. Wetlands that are groundwater-dependent must be in an area of shallow water tables. This means (a) that upgradient recharge must be sufficiently large for the aquifer to be full, given transmissivity and gradient and (b) other vegetation in the area is likely to be using groundwater including agriculture. If a large area of plantation were to decrease recharge sufficiently upgradient, the water tables begin to fall in the region of the wetland, irrespective of the proximity of the plantation to the wetland. However, before it reaches this threshold, the effect would be to decrease groundwater ET. This was found to be the case in the modelling of Padthaway (54).

In considering all of the above, the impact of a plantation on a wetland depends on:

- 1) the separation,
- 2) area of plantation
- 3) upgradient area,
- 4) water requirements of wetland, and
- 5) hydrogeological characteristics.

The examples show that extent of drawdown can be large. Whether this is important depends on the type of GDE and value of the GDE. Because of the complex interactions, it is difficult to define simple rules. If the situation were to be transferred to the Eastern Mt Lofty, the hydrogeological characteristics would be completely different.

The suggested approach is as follows:

A For areas where total plantations are not expected to affect groundwater recharge upgradient of an important wetland by more than 30%, say, whether by rainfall interception or direct groundwater use, simple buffer rules are developed. This will require both modelling to develop pragmatic rules and some hydrogeologic characteristics for different landscapes.

B Both monitoring and field investigations be required for higher levels of development.

C For developments exceeding 70%, say, of a catchment, all of the above plus a calibrated groundwater model will be required.

9. REVIEW OF THE USE OF SCIENCE IN KEY REGIONS

9.1. Mt Lofty Ranges

The main concerns over plantations in the Mt Lofty Ranges appear to be limiting local use of water resources to allow passing flows for downstream uses. The main downstream use of concern seems to be nationally and internationally significant wetlands. The review presented here is of the assessment method described in DWLBC Technical Notes 12 and 13 (17, 13). That method has been critiqued in (11, 47, and 51).

One of the main principles of the assessment method is that only 25% of the total water resources in a catchment can be used. This is called the sustainable use limit. This limit appears to apply at all scales: catchment, sub-catchment and property (see (13), page 23) to ensure that use is not monopolised in any one place and water is allowed to pass to downstream users. The choice of 25% comes from earlier work on the impacts of farm dams on downstream water resources in both South Australia and Victoria. Evaluation of the 25% rule was beyond the scope of our review but at face value it appears sound as a precautionary rule in areas where there has been no further assessment of environmental and other water uses downstream.

The implication of limiting use to 25% at all scales is that the responsibility is shared equally across all properties in the catchment. The scale of application is a decision of how to implement policy and scientific evidence of hydrology has little to contribute to the decision. It is essentially a decision about water sharing rules. The following observations can be made though. The scale at which the policy applies matters for development opportunities at the property scale. For example, a contrasting policy would be to apply the rule at the catchment scale and not restrict development on any property until the 25% use was achieved for the catchment, after which no further development is allowed. Then early developers would reap the full benefit and undeveloped properties would bear the full responsibility for meeting the limit, unless trade was allowed.

Sharing the burden evenly across all properties means future development potential for some property owners is not lost as a result of earlier development by others. Equal sharing works best for small developments such as farm dams as everyone can still have some development. It could prevent large developments such as irrigation and plantations because it means that only small fractions of an individual property could be developed, or large areas of land would need to be purchased most of which could not be developed. However, if full use of water is allowed on a property, that may remove water from properties immediately downstream and will prevent others in the catchment from developing their properties.

There are many combinations of rules at different scales between the two extreme examples given. Trade can be used as a mechanism to allow use to move from one property to another and change the local sharing arrangements to best suit the local uses.

For the Mt Lofty Ranges the 25% rule is applied to the total available water less the water that is required to sustain wetlands in the catchment, termed the wetland water requirement (WWR). The WWR is calculated from a mean annual water balance of each wetland, balancing inputs with outputs which include the wetland water demand, expressed as the potential evapotranspiration rate from the wetland (13). Expressing the water need for the wetland in this way implies a requirement that the wetland be kept sufficiently moist to always maintain evapotranspiration at the potential rate. In the absence of any more detailed information on actual water needs of this ecosystem, keeping swamps wet at all times seems like a logical basis for calculating their needs. It would be more transparent to state explicitly that maintaining potential evapotranspiration is the environmental water requirement that is used.

To establish more specific water requirements of wetlands would take considerable effort. A way to start, though, might be to examine the range of wetland situations across the Mt Lofty Ranges with a view to correlating their ecological condition with water inputs. That might indicate a level of water stress below which wetlands degrade.

The basis for calculating WWR with little specific information seems appropriate and is quite conservative. For example direct runoff from the wetland is the minimum likely value and could in fact be higher. WWR appears to be expressed in units of mm/yr and this becomes the amount of flow that needs to be provided from the upstream catchment. It should be made clear that the WWR is a depth of rainfall in mm/yr across the wetland area and not across the upstream catchment area. Thus if a wetland occupies 10% of a catchment then runoff from the rest of the catchment (expressed as mm/yr depth from the catchment) needs to be at a depth of 1/9th of the depth calculated for the wetland. If the wetland occupies 1/3rd of the catchment then the rest of the catchment need to supply 1/2 the runoff depth identified for the wetland.

Establishing the WWR through a water balance and comparing that against the ability of the upstream catchment to supply water has the advantage of providing a simple yet defensible and transparent way of varying environmental water needs from one catchment to another. Small catchments with large wetlands will be susceptible to other water uses. Large catchments which support only small wetlands could probably tolerate substantial water development without impacting on wetland condition. Thus the wetland water requirement could be viewed as superior to the 25% rule for identifying sustainable use limits. At the moment, for wetland catchments, the 25% rule is applied after the WWR is subtracted from the available water resource, and it is not clear what uses the other 75% of water is being reserved for, given that the rule applies at all scales and the environmental use has already been accounted for. Perhaps more than 25% of the remaining water could be used. Not all the remaining water could be used though because there will be dry years when water availability is lower than average, and wetland and consumptive water demands will be higher than average. A time series of annual water balances could be investigated to determine what mean annual amount of extraction can be supported while meeting water demands in almost all years. This is typically how water planning models are implemented.

In the Mt Lofty Ranges methodology plantations are calculated to consume 85% more water than pasture covers. The discussion in Sections 4 & 7 above shows that this rule is supported. It also includes commentary on other aspects of water sue such as forest area and growth stage of plantations.

The discussion in Section 8 shows that the requirement for a 50 m buffer around all stream and wetlands is not always supported on hydrological grounds. It will be appropriated for groundwater systems with relatively low hydraulic gradients. The work on the Mt Lofty Ranges identifies three conceptual models of hydrology, one of which is the Permian Sands Model. There wetlands are connected to regional groundwater and 50 m buffers and other considerations for groundwater rather than surface water systems should be made. We believe that it would be a useful and practical advance to describe conceptual models of the hydrology in region and use the models to guide transfer of water planning rules from one situation to another.

The final aspect of the documented requirements in the Mt Lofty Ranges is for a 5 m buffer between the outermost edge of the forest canopy and unmarked drainage lines (17). Again this requirement is justified on water supply grounds but there appears to be little justification for this rule in addition to the overall impact of 85% runoff reduction that result from plantations. The logic seems to discount the impact of trees outside the drainage line on throughflow to the drainage line. Preventing disturbance to soils and vegetation in drainage lines is needed to prevent local erosion (65) and associated water quality problems. This provides a better justification for the rule. An objective and practical definition of a drainage line needs to be given to implement the rule.

9.2. Lower South East

The Mallee to the Lower South-East Region represents one of the best studied areas in Australia for recharge. A range of techniques have been used over the last 30 years, suitable for different situations, including the comparison of different land uses. These appear to have been applied correctly to obtain Permissible Annual Volumes. The greatest uncertainty in the recharge studies is the extrapolation across large areas to underpin the permissible annual volumes (PAV) estimates. Uncertainty in the estimates would be up to 20%.

The definition of groundwater management zones reflects a balance between administrative efficiency and biophysical causes. Whenever a line is drawn for the purposes of natural resource management, it is likely to be challenged by parties who perceive that they are disadvantaged by being on one side of the line. Often the biophysical drivers for defining management zones (e.g. salinity, geology/geomorphology) occur over distances of kilometres with few piezometers/bores to help define this transition, while boundaries for administrative purposes need to be sharp.

The rationale for boundaries reflecting biophysical drivers is exemplified by the Riverine Plains systems of NSW (e.g. Lower Macquarie), where water tables are falling in areas of good water quality, while rising in areas of poorer water quality. The whole area is covered by a water sharing plan but is broken into a number of management zones, with groundwater trading rules to encourage transfer of water entitlements from stressed areas to less stressed areas. If the method to determine Permissible Annual Volumes (PAVs) was applied to the whole of the groundwater management unit to determine Extraction Limits, it would not adequately reflect any issues of high allocations, but if applied to individual management zones, it would reflect the high allocations but possibly exaggerate these.

To avoid gradient reversals, it will be necessary to define hotspots and have groundwater management zones defined to best address these. Potentially, broad management rules could be consistent across whole aquifer, but with thresholds and values defined for individual zones within this.

One would imagine that a groundwater model will need to be developed for the Lower South East in the near future and PAVs determined on the basis of outputs from such a model. Application of nested models to reflect hotspots within the broader groundwater flow system will address some of the issues above and give a better basis for application of different rules across the system.

The estimate of environmental requirements is not specifically associated with the impacts of plantations on water resources and hence marginal to the scope of the current study, except to show that system is highly allocated in some areas of the South-East. The notion of using a percentage of recharge for environmental purposes largely follows the surface water equivalent. Some through-flow at a range of scales will always be needed to avoid salinisation of the groundwater resource and 10% appears to be appropriate for this. The expectation would be that the framework for environmental allocations in groundwater system would change in the next 10 years to better reflect risk to environmental assets. Default values of 20-30% have been used both nationally and internationally. In some cases, this would be seen as a way of building in uncertainty.

There have been detailed studies of water use by plantations in the South-East, which have revealed considerably higher water use where the water table is within 6 m of the surface. In this situation, tree roots extend to the water table and directly pump water above the surface which is then lost as increased transpiration. Direct measurements of tree water use have demonstrated the process by recording annual water use that is greater than the total rainfall on the site for the year.

The application of a 6 m trigger does reflect the available information. Across the broader scientific literature, the relationship between tree water use with depth to groundwater is

complex, partly related to root distribution of different tree species in different situations, ability of the trees to access other water sources and even soil moisture conditions prior to the development of the plantation. The relationship appears not to be linear, nor a step change. In application of a depth 'trigger' to management, one also notes that there will be variations in depth to water table across an individual site, fluctuations of water table under plantations in response to recharge in the vicinity, changes in water table depth in response to direct groundwater use by the plantation and errors associated with mapping depth to water table. Given all of this variability and uncertainty, the value of 6 m appears to be appropriate.

The concept of a 'trigger' depth can be applied more broadly, provided both the groundwater use value and 'trigger' depth to water table can be varied. The groundwater use value will be dependent upon many variables but a primary constraint is that it must be less than the potential evaporation minus rainfall. Salinity will reduce this upper limit further. The work of George and Thorburn and colleagues can be used to develop a salinity relationship, where the TDS of groundwater exceeds a few thousand mg/L. Groundwater use by plantations also can be reduced by the ability of the aquifer and soils to supply the trees with sufficient water. For areas of lower transmissivity, the drawdown is likely to be greater and this alone will make the depth relationship more complex, let alone considering salinity. In the absence of further information, 6 m seems a reasonable trigger value to be used, but is likely to be lower but should be locally investigated.

Requirements for buffer strips around wetlands in the South-East are addressed in Section 8 above. There are broader considerations that need to be made than specifying a buffer distance.

9.3. Kangaroo Island

In areas of higher groundwater salinity, the plantation impact on groundwater processes may lead to reduced salt loads to streams. Secondary (anthropogenic) salinity results from land use change causing increased recharge, which in turn, leads to increased discharge of saline water to the land surface, streams or oceans. Plantation forestry has the potential to reduce salinity. If the salinity benefit outweighs the disbenefit on water, this will need to be considered as part of the water allocation framework.

In order to distinguish the trade-offs, it is important to consider the spatial context of each of these. Higher rainfall areas usually have good quality water at high availability and plantation forestry productivity high. The water resource disbenefit would outweigh the salinity benefit. Areas of low rainfall are often associated with lower quality water and with low water availability, but also low productivity for forests. The salinity benefit would outweigh the water resource disbenefit but these areas may be less attractive for forestry because of the productivity disbenefits. There may be some grey areas in between because of the terrain and the geology leads to a win-win situation.

Criteria for determining areas with potential salinity benefits need to be developed. Examples might be flow-weighted mean salinity of a catchment contributing to a water resource exceeding 1000 mg/L or having a salt output-input ratio exceeding 3. Both of these would require gauging information. In the absence of this, application of rules embedded within the salinity model BC2C might identify areas where salinity benefits may outweigh water disbenefits.

10. KNOWLEDGE NEEDS

There is a need to ensure that the level of knowledge applied to water planning decisions is commensurate with the level of risk associated with decisions. Typically, where there are large uncertainties about the water resources available, or about the environmental needs for water, conservative water allocations are made. As demand for more water allocations grows more detailed investigations are usually undertaken to reduce the uncertainties, and thus reduce the risk of making unsustainable water allocations.

This logic behind policy making has been formalized recently as the precautionary principle. In the context of environmental protection it is essentially about the management of scientific risk or uncertainty. It was defined in the Rio Declaration on environmentally sustainable development:

“Where there are threats of serious or irreversible environmental damage, lack of full scientific certainty should not be used as a reason for postponing measures to prevent environmental degradation.”

In terms of environmentally sustainable development of water resources it should mean that conservative decisions are made regarding water allocations until better knowledge is available. Thus, if the knowledge suggests that the sustainable limit to water use lies somewhere between 25 and 50% of mean annual flow than a precautionary approach would allocate 25% of available water at most.

If there is no demand for water use beyond the 25% allocated, there is little cost or risk from the decision. If there is considerable demand that cannot be met with a 25% allocation and there are significant environmental assets or other users are put at risk if water is over allocated then the scientific uncertainty and application of the precautionary principle has a high potential cost. The high uncertainty means that environmental and other existing water users can be put at risk if allocations are allowed to increase but the resource cannot sustain them. Alternatively, if the allocations are not increased and there is the ability to sustain that increase then resource development is unreasonably held back. In these cases the benefits of reducing the scientific uncertainty probably far outweigh the costs of the investigations.

The principles of the level of investigation matching the level of risk from the decisions have been used well for groundwater assessment. Where the resource is small, use is low and there are no major environmental assets a rudimentary groundwater assessment is typically undertaken. Where the size of the resource is large, there are significant demands on it, and important environmental assets are at risk, a detailed groundwater model is built supported by local field investigations. Essentially it is a process of prioritizing assessments and having a staged approach which grows in sophistication as pressure on the resource grows.

Applied to the three regions we have considered, the Lower South East has high risks from water allocation decisions but is supported by considerable regional data and hydrological modelling. The Mount Lofty Ranges and Kangaroo Island may be regions where pressure on the resource is sufficient to justify more investigations so that the general state wide rules can be replaced with more certain local assessments of the resource and demands on it.

Areas of investigation which could help reduce uncertainty include:

1. *Environmental water requirements.* This is probably the greatest uncertainty at present and the area of science addressed least in the literature provided. The amount, frequency, timing and quality of water required to sustain environmental values in each region is poorly known. While this is also true for many aquatic ecosystems across Australia, the environmental water requirements in the regions reviewed seem particularly poorly known.

2. *Conceptual models of regional hydrology.* Some relatively simple descriptive models of the key driving processes of surface and groundwater hydrology in each region would provide fundamental underpinning support to policy. The conceptual models could be used

to determine appropriate rules or parameter values for each catchment, to delineate boundaries between rules, and to guide transfer or local knowledge to other places. They could be used in particular to guide tradeoffs between salinity benefits and water resource disbenefits and to guide prediction of catchment runoff from gauged catchments to ungauged catchments.

3. *Measuring and predicting hydrological processes.* Pressure on water resources seems to be developing in some areas with very little background measurement of hydrology. Without such measurement water resource assessment will be inherently speculative. Examples include groundwater extraction by plantations beyond the SE region. Groundwater extraction is dependent upon many poorly understood factors so additional measurements of water use are needed in other regions to know if the use characteristics differ or not. The measurements should also be used to better understand the main controls on use. A second area of uncertainty is the surface water hydrology of the Fleurieu Peninsula and its associated perched wetlands, and distinctive climate. The hydrology may differ from other parts of the Mt Lofty Ranges but there appear to be few gauging stations to test this at present. There is also little firm basis to extrapolate runoff to ungauged catchments from gauged catchments.

11. BIBLIOGRAPHY

Papers 1 to 57 constitute the annotated bibliography which CSIRO was asked to review. Several columns from the bibliography have been removed here for ease of presentation. The numbered references in the text refer to the paper numbers in this list. Additional references have been added where they proved useful.

Paper ID	Title	Author	Date	Type of paper
1	Groundwater uptake and salt accumulation in radiata pine and blue gum plantations in SE South Australia	Richard Benyon, Fred Leaney, Tanya Doody, Saad Mustafa, Jeff Lawson		Draft paper
2	Land Use impact on water quality and quantity in the Lower South East, South Australia	Mustafa S., Lawson J, Leaney F, Osei-Bonsu K	2006	DWLBC Report
3	Salt Accumulation and Groundwater Uptake by Pine and Blue gum Forests in Bakers Range	Leaney FW, Mustafa S, Lawson J	2005	CSIRO Report
4	Water Use by Tree Plantations in South East South Australia	Benyon, R.G., Doody, T.M	2004	CSIRO Report
5	Impacts of tree plantations on groundwater in south-eastern Australia	Benyon, Theiveyanathan, S and Doody, T.M	2006	Aust J of Botany
6	A New Understanding on the Level of Development of the Unconfined Tertiary Limestone Aquifer in the South East of South Australia	Latcham, B, Carruthers, R & Harrington, G	2007	Technical

7	Impacts of Plantation development on the water resources of the middle river catchment, Kangaroo Island	Leon Bren	2004	University report
8	The Application and Limitations of Using Mean Annual Evapotranspiration and Rainfall in the Assessment of the Impacts of Plantation Forestry on Runoff	Greenwood	2007	DWLBC Report
9	Impacts of plantings of Benneys and Riverleas blocks on water resources of the middle river reservoir, Kangaroo Island	Leon Bren	2008	University report
10	Predicted Hydrological Impacts of proposed blue gum forest plantation in the Balquhider Catchment, Fleurio Peninsula, South Australia	C Gippel	2005	Consultancy Report
11	Review of DWLBC Technical Notes 12 and 13 Report to Mount Lofty Ranges Private Forestry	Gippel, C.J.	2008	Review
12	The Impact of Plantation Forestry on Runoff in the Mount Lofty Ranges, Case Study: Burnt Out Creek	Greenwood, A.J and Creswell, D.J	2007	DWLBC Technical note
13	Sustainable Water Resources Management, Plantation Forestry and a Method for the Provision of Environmental Flows to Wetland Ecosystems	Greenwood, A.J., Creswell, D.J., Fee, B.M. and Vanlaarhoven, J.M	2007	DWLBC Technical note
14	Paired catchments observations on the water yield of mature eucalypt and immature radiata pine plantations in Victoria, Australia	Bren, L and Hopmans, P	2007	Technical
15	An empirical comparative model of annual Radiata Pine Plantation water use	Bren, L., Lane, P and McGuire, D	2008	Technical

16	Tree water use in forestry compared to other dry land agricultural crops in the Victorian context	Benyon, England, Eastham, Polglase, White.	2007	Review
17	Plantation Forestry Design Guidelines for Sustainable Water Resources Management	Greenwood, A.J., Scholz, G and Vanlaarhoven, J.M	2007	DWLBC Technical note
18	Afforestation in a catchment context: understanding the impacts on water yield and salinity	Zhang L., Vertessy R., Walker G., Gilfedder M. and Hairsine P.	2007	Review
19	A Review of current measurement and management practices for the determination of run-off interception and the implications for the implementation of the National Water Initiative	Kate Dugan, Sara Beavis, Daniel Connel, Karen Hussey and Ben MacDonald	2008	Review
20	Water Use by Tree Plantations in the Green Triangle: A Review of Current Knowledge	Benyon, R.G	2002	Review
21	Watertable fluctuations under forest and pasture in a karstic region of southern Australia	Colville, J.S. and Holmes, J.W	1972	Report
22	South East Forest Industry Development Strategy.	Green Triangle Regional Plantation Committee	2001	Review
23	Forest hydrology in a karstic region of southern Australia	Holmes, J.W. and Colville, J.S	1970	Technical
24	Grassland hydrology in a karstic region of southern Australia	Holmes, J.W. and Colville, J.S	1970	Technical/ Historic

25	Water Yield from some afforested catchments in Victoria	Holmes, J.W., and Sinclair, J.A	1986	Technical/ Historic
26	The soil water regime in a young radiata pine plantation in south-eastern Australia	Mitchell, B.A. and Correll, R.L	1987	Technical/ Historic
27	Forestry, land use change and water management: a Green Triangle perspective	Hopton, H., Schmidt, L., Stadter, F. and Dunkley, C	2001	Review
28	Irrigation management and groundwater uptake in young tree plantations growing over high water tables	Polglase, P.J., Theiveyanathan, S. Benyon, R.G. and Falkiner, R.A	2002	<i>no paper</i>
29	Water and land use change study. Land use and hydrologic change in south-west Victoria	Sinclair Knight Merz	2005	Consultancy Report
30	Predicting the effect of vegetation changes on catchment average water balance.	Zhang, L., Dawes, W.R., and Walker, G.R	1999	Technical
31	Response of mean annual evapotranspiration to vegetation changes at catchment scale	Zhang, L., Dawes, W.R., and Walker, G.R	2001	<i>no paper</i>
32	Predicting the effects of large-scale afforestation on annual flow regime and water allocation: an example for the Goulburn-Broken catchments	Zhang, L., Dowling, T., Hocking, M., Morris, J., Adams, J., Hickel, K., Best, A. and Vertessy,	2003	Technical
33	Night-time water use in an irrigated Eucalyptus grandis plantation	Benyon, R.G	1999	<i>no paper</i>

34	Plantations, farm forestry and water: Proceedings of a national workshop, 20-21 July 2000	Nambier and Brown	2000	Conference
35	Failure of Eucalyptus globules plantations on previously irrigated pasture sites in south eastern Australia	Fife and Michael	2008	Technical
36	Inter-rotation Recharge Project, South East South Australia Newsletter No. 2, January 2008	Benyon and Doody	2008	Newsletter
38	The use of environmental chloride and tritium to estimate total recharge to an unconfined aquifer	Allison and Hughes	1978	Journal
39	Review of research on plantation forest water requirements in relation to groundwater resources in SE of South Australia	Dillon, Benyon, Cook, Hatton, Marvanek and Gillooly	2001	Review
40	Review of Water and Plantations Science and Policy Outcome: South East South Australia	Gippel and Watson	2006	Review
44	Tritium fallout in southern Australia and its hydrological implications	Allison, Holmes and Hughes	1971	J Hydrology
45	Plantations and water use	Parsons, Frakes and Gerrand	2007	Review
46	Plantations and water use: A review	Keenan, Parsons, O'Loughlin, Gerrand, Beavis, Gunawardana, Gavran and Bugg	2004	Review

47	Critique of Technical notes 2007/11-13 of the DWLBC, South Australia	Bren	2008	Review
48	Regional Scale of spatially explicit quantification of plantation forest water use	Benyon and Doody	2005	Technical
49	Growth, crop conductance and prediction of stem volume increment of irrigated and non irrigated radiata pine in non-weighing lysimeters	Rutter	1986	Journal
50	Review of groundwater resource condition and management principles for the Tertiary Limestone aquifer in the south east of South Australia	Brown, Harrington and Lawson	2006	Technical
51	Review of DWLBC Technical Note 2007/12'Plantation forestry design guidelines for sustainable water resources management'	Perry and Crewe	2008	Internal Review
52	Study of the causes, mechanisms and consequences of non-irrigated salinity on Kangaroo Island	Hartley, Roger	1980	Thesis for Master of Engineering Science, University of New South Wales
54	Effects of Forestry on Water Resources	Aquaterra	2009	Consultancy Report
55	Dryland salinity management on Kangaroo Island: Technical report NO. 255	Henschke, C. J.	1997	Technical review
56	Interactions between trees and groundwaters in recharge and discharge areas - A survey of Western Australian sites	George, R. J., Nulsen, R. A., Ferdowsian, R. & Rper, G. P.	1999	Technical

57	Long term monitoring of groundwater levels at 24 sites in Western Australian shows that integrated farm forestry systems have little impact on salinity	Bennett, D. and George, R.		Technical
58	Streamflow and salinity response to logging and regeneration in the southern forest of Western Australia.	Bari and Boyd	1993	Water Authority of WA Report No WS116
59	A review of reforestation experiments to control land and stream salinity in Western Australia.	Bari and Boyd	1994	Water Authority of WA Rpt No WS141
60	Stream and groundwater response to logging and subsequent regeneration in the southern forest of Western Australia.	Borg, King and Loh	1987	Water Authority of WA Rpt No WH34
61	Groundwater response to reforestation in the Darling Range of Western Australia.	Bell, Anson and Loh	1988	Water Authority of WA Rpt No WS24
62	Preliminary empirical models to predict reductions in total and low flows resulting from afforestation.	Scott, D. F. and Smith, R. E.	1997	Water South Africa 23: 135-140
63	A review of paired catchment studies for determining changes in water yield resulting from alterations in vegetation.	Brown A. E., Zhang L., McMahon T. A., Western, A. W., Vertessy, R. A.	2005	J Hydrology 310, 28-61
64	Analysis of streamflow generation following deforestation in southwest Western Australia	Ruprecht J. K. and Schofield N. J.	1989	J Hydrology 105, 1-17
65	Riparian land management technical guidelines	Lovett, S and Price P.	1999	LWRRDC Technical Report
66	Towards a framework for predicting impacts of land-use on recharge: a review of recharge studies in Australia.	Petheram, C., Walker, G., Grayson, R., Thierfelder, T., and Zhang, L.	2002	Australian Journal of Soil Research, 40: 397-417
67	Studies in Catchment Hydrology: The Basics of Recharge and Discharge.	Zhang, L., and Walker, G	1998	CSIRO Report