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Introduction

There is growing public and government awareness that the flows of water through the Australian environment to a large extent determine the health and character of our natural heritage. This awareness extends to the quality and amount of groundwater available to ecosystems. Management of groundwater must therefore consider the requirements of the environment; this idea is enshrined in the COAG (1996) agreement on provision of water to the environment. Application of this principle to any particular groundwater system is hampered by a generally poor understanding of the role that groundwater plays in most Australian environments, and how the environment might change following groundwater extraction (Hatton and Evans, 1998).

A borefield on the western side of the Howard River, Northern Territory, is currently operational. The proposed development of groundwater resources in the Howard East Basin as a future supply of water for Darwin anticipated the requirement for environmental protection with respect to provisions to the environment. It was recognised early on that little was known about the likely impacts of development on a range of ecosystems in the area. In 1993, the Northern Territory Government initiated a research project involving the Department of Land Planning and Environment, CSIRO and the Northern Territory University aimed at assessing ecosystem dependence on groundwater and vulnerability to groundwater resource development. This research received additional support from the Land and Water Resources Research and Development Corporation and the Cooperative Research Centre for Tropical Savannas in 1996.

Concern was held about the impacts on four components of the Howard East Basin environment: the eucalypt woodland savanna, the paperbark swamps, the monsoon vine forests and the aquatic systems of the Howard River. Early work focused on the hydrology of the woodland system (Hatton et al., 1997; Cook et al., 1998b), based on intensively monitored and investigated field sites in an area identified as likely for development. Later work focused on the hydrology of the paperbark swamps at a field site near the main woodland experimental site (Hatton et al., 1998). Inferences regarding potential impacts on the ecology of the Howard River, and to a lesser extent the monsoon vine forests are derived from this work as well.

This report considers the findings of the research, conducted over the period 1993–98, on the hydrology of the Howard East Basin, and derives from those findings a set of recommendations regarding the likely impacts of groundwater extraction and makes recommendations for future investigations and monitoring.

Rainfall and runoff

The study area is subjected to monsoonal rainfall between November and March, followed by up to 7 months of little or no rain. Annual rainfall averaged 1605 mm at the Darwin airport for the years 1870–1997, and ranged between 1025 and 2643 mm. Mean monthly rainfall ranges between 410 mm in January and less than 5 mm in June, July, and August.

Runoff from the Howard River catchment is monitored by means of a gauging station at Koolpinyah (Figure 1). The surface catchment area above the gauging station is 126 km^2. Over the 10-year period from 1964 to 1973, mean flow through the weir was 70 million m^3 in the wet season (November through April) and 2.3 million m^3 in the dry season (May through October). This gives a mean runoff of approximately 570 mm for the wet season, and 20 mm for the dry season. (Mean annual rainfall at Darwin airport over the same period was 1720 mm.) From February to May, total catchment runoff averages 60% of rainfall. In June and July, mean runoff is greater than mean rainfall, indicating that the Howard River is largely sustained by groundwater inflows at this time.

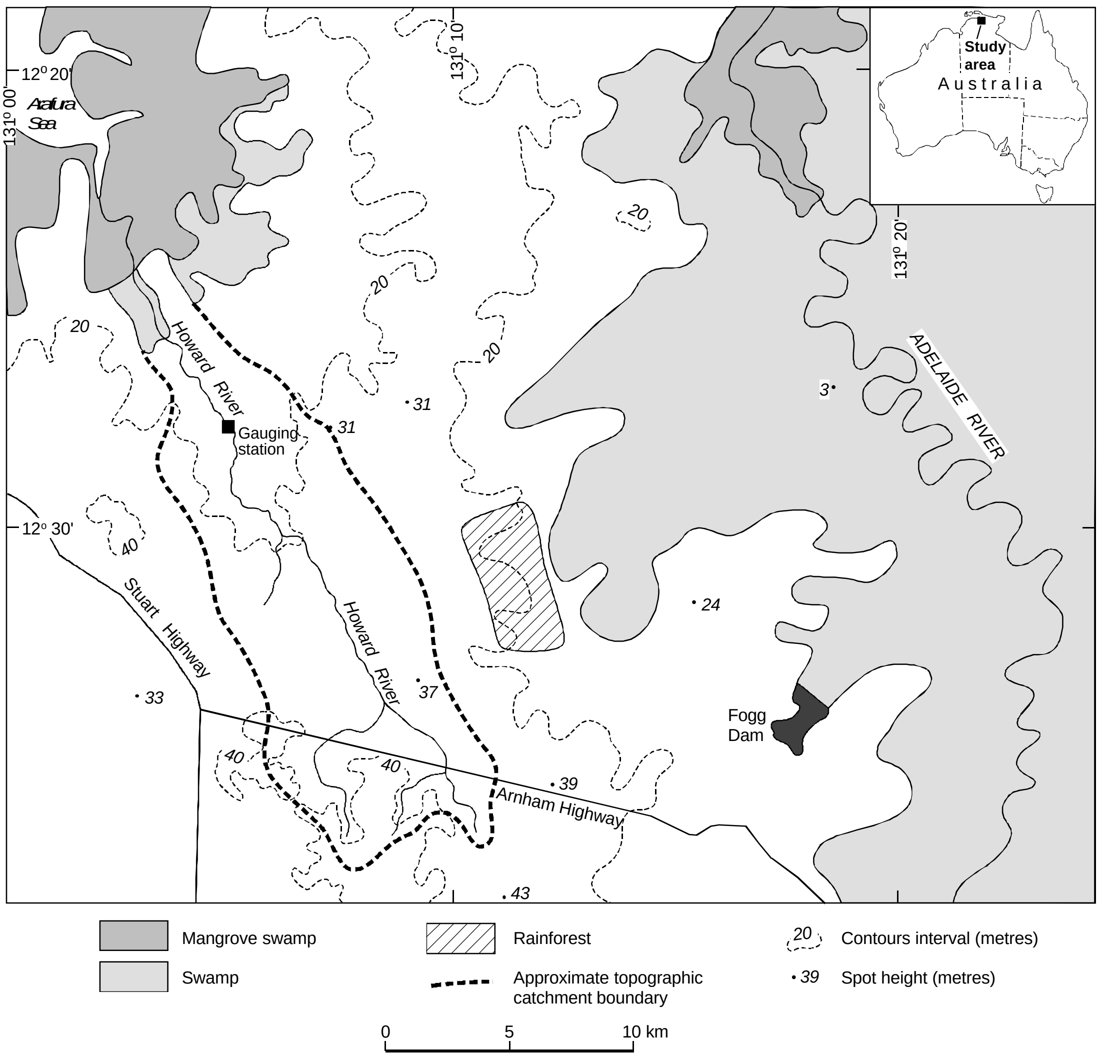

Figure 1. Location of the Howard River basin.

Eucalypt savanna ecosystem

The eucalypt savanna ecosystem covers the majority of the Howard River catchment. The dominant canopy species are *Eucalyptus miniata* and *E. tetradonta*, which account for more than half of the canopy. Other significant elements of the canopy include *E. porrecta*, *Erythrophleum chlorostachys* and *Terminalia ferdinandiana*. Understory consists of spear-grass, which senesces shortly after the end after wet season.

Mean wet season evapotranspiration from the savanna has been estimated to be approximately 810 mm, with 370 mm as transpiration by overstory trees. Mean dry season evapotranspiration is 300 mm, with 175 mm transpiration by overstory trees. Total evapotranspiration is thus estimated to be 1110 mm. The mean groundwater recharge rate has been estimated to be approximately 200 mm. Of this, 160mm enters the Howard River as base flow during the wet season, 20 mm enters the river as base flow during the dry season, and 20 mm represents the groundwater surplus (Figure 2). The groundwater surplus (estimated as rainfall less runoff and evapotranspiration) represents the likely magnitude of groundwater flow out of the woodland ecosystem, either to the ocean, or to minor ecosystems within the catchment (Cook et al., 1998a). (An error analysis suggests that the groundwater surplus may be as small as zero, or as large as 140mm.)

Groundwater levels beneath the eucalypt woodland typically rise to 2 m beneath the land surface at the end of the wet season, and fall to 9 m depth by the end of the dry season. Calculations based on measured soil hydraulic properties indicate an available soil moisture storage (between field capacity and wilting point) between 2 and 9 m depth of approximately 340 mm. This is greater than the dry season evapotranspiration demand. Furthermore, direct measurements of soil moisture profiles reveal that this store has not been exhausted by the end of the wet season, and that water is still available to plants at depths less than 5 m. Both of these observations suggest that dry season evapotranspiration can be entirely sustained from the unsaturated soil store, and the plants are not dependent on, and do not use groundwater.

In contrast to our findings, O'Grady et al. (in press) found dry season transpiration rates of *E. miniata* and *E. tetradonta* to be approximately equal to or even slightly greater than wet season transpiration rates. Hutley (unpublished) measured dry season evapotranspiration rates of 1.55 mm day^{-1}, 25% less than measured by Hatton et al. (1997). Use of this lower value for dry season evapotranspiration would increase the estimated groundwater surplus to 70 mm, and reduce the estimate of groundwater inflow to the river to 130 mm (110 mm during the wet season), but would otherwise not affect the conclusions of this study. Furthermore, the relatively strong dry season transpiration measured by O'Grady et al. (in press) is further evidence that the vegetation is not water stressed during the dry season.[1]

[1] On the basis of the large measured dry season transpiration, O'Grady et al. (in press) concluded that the trees are able to exploit groundwater reserves during the dry season. Similar conclusions were reached by Myers et al. (1997). However, these studies did not distinguish between soil water and groundwater reserves. Our study suggests that it is soil water, and not groundwater, which is exploited by the vegetation throughout the dry season.

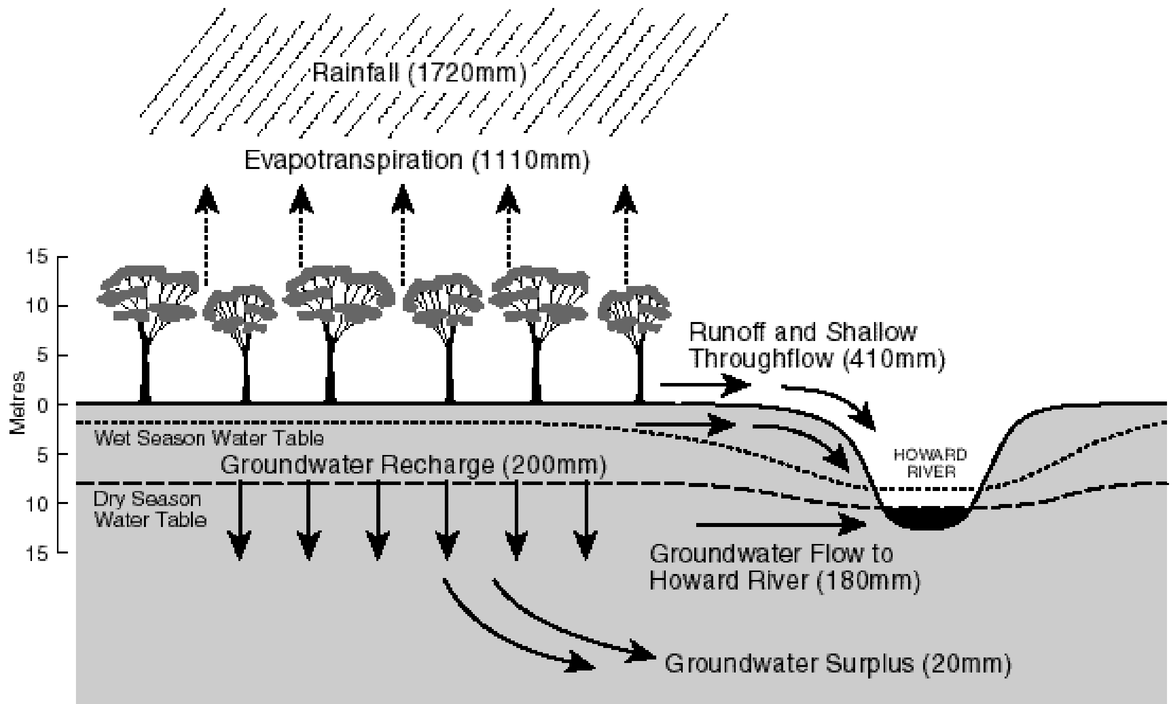

Figure 2. Annual water balance for the eucalypt savanna ecosystem.

Paperbark swamp ecosystem

Paperbark (*Melaleuca viridifolia*) swamps form a relatively minor fraction of the natural landscape of the Howard River basin, occupying small, low, run-on sites within the surrounding savanna woodland. They are characterised by a nonspecific overstory of paperbark trees, with an understory of floating and emergent herbs that largely disappear during the dry season. During the wet season, standing water levels rise up to 1m above the ground surface, and the swamps are generally inundated between December and June.

Transpiration of the paperbark trees was determined to be approximately 300 mm during the period of inundation (December through June) and 240 mm during the remainder of the year (July through November). Direct evaporation of surface water during the wet season and soil evaporation during the dry season may account for a further 420 mm and 100 mm respectively.

The watertable beneath the paperbark swamp is above the land surface for much of the wet season. During the dry season, the watertable beneath the swamp falls to around 2.5 m depth, but appears to be elevated above the watertable level beneath the surrounding eucalypt savanna. The low conductivity soils beneath the swamp appear to maintain a perched water table here. The available soil water between saturation and wilting point to a depth of 2.5 m is estimated to be 340 mm. The difference between field capacity and wilting point over the same depth interval is 210 mm. Hence, so long as a reduction in the regional water table does not affect the development of the perched layer beneath the swamp, then the soil moisture store beneath the swamp should be sufficient to satisfy the evapotranspiration demands of the paperbarks during the dry season. Additionally, stable isotope concentrations in groundwater beneath the swamp are distinct from those beneath the eucalypt savanna suggesting that there is a net recharge beneath the paperbark swamp, and that the groundwater surplus from the eucalypt savanna does not discharge to the swamps.

Effect of groundwater extraction

Based on estimates of their average annual water balance, it appears that neither the eucalypt savanna nor the paperbark swamp ecosystems are dependent on groundwater for transpiration. Provided that infiltration wets the soil to field capacity each wet season, there appears to be enough available soil water to sustain the transpiration needs over the dry season. Thus groundwater extraction should not impact these systems.

These calculations however, do not consider year-to-year climatic variability. It is possible that the groundwater provides a reservoir that is only used by the vegetation during drought periods. Groundwater extraction that lowers the watertable may thus increase the susceptibility of the vegetation to droughts. For example, if the soil storage is not replenished due to lower than average rains during one wet season, then in the absence of a backup groundwater system, the vegetation may undergo water stress in the following dry season.

However, if wet season rainfall (mean of 1585 mm) is used firstly to satisfy wet season evapotranspiration requirements (810mm), secondly for soil infiltration, thereby increasing the soil water content to field capability (165 mm), thirdly for groundwater recharge, thereby raising the water table (200 mm), and lastly for runoff (410 mm), then it would appear that only 975 mm of wet season rainfall is required to provide sufficient soil water storage to sustain the vegetation through the following dry season. This rainfall has been achieved in every year since records were kept. Low wet season rainfall should therefore result primarily in reduced runoff.

Until recently, the conventional wisdom has been that the sustainable groundwater extraction rate is equal to the recharge rate. Of course, this ignores environmental requirements. Any groundwater extraction represents a loss to the environment. The groundwater recharge rate beneath the eucalypt savanna has been estimated to be approximately 200 mm yr^{-1}. Because the eucalypt savanna represents the dominant ecosystem, the total basin recharge is also likely to be close to this value. This would put a limit on the extraction rate (equivalent to 25 000 ML yr^{-1} over the catchment upstream of Koolpinyah). Groundwater extraction greater than this would result in a depletion of the resource, with eventual drying up of bores.

Under natural conditions, the 200 mm yr^{-1} recharge is distributed as: 160 mm yr^{-1} discharge to the Howard River during the wet season, 20 mm yr^{-1} discharge to the Howard River during the dry season, 20 mm yr^{-1} groundwater surplus. The groundwater surplus is likely to include groundwater flow to the sea, but may also include lateral flow to other ecosystems such as the monsoon vine forests. Any groundwater extraction will result in a decrease in one or more of these discharges.

If groundwater extraction takes place within the wet season, then it is likely that the wet season discharge to the Howard River would be reduced. The environmental consequences of this would probably be limited, because this discharge is a relatively minor component of the river flow at this time (total wet season flow is 570 mm). There is also a possibility that groundwater extraction during the wet season will increase aquifer recharge. Currently, water tables rise within 2-3 m of the land surface, usually within 2-3 months of the onset of the wet season. It is not until this time that large volumes of runoff are generated. It is possible that groundwater pumping during the wet season will simply slow the rate of rise of water tables, and the onset of significant runoff. If this were the case, then it might be possible to extract more than 200 mm yr^{-1} from the groundwater during the wet season, with consequent reduction in surface runoff and shallow throughflow (currently 410 mm).

However, if groundwater extraction takes place during the dry season, then it is likely that dry season discharge to the Howard River would be reduced. The environmental consequences of this may be considerable, because this is the only source of river flow at this time. Dry season pumping may also reduce the groundwater surplus, with as yet unknown consequences. On the other hand, it may be possible to reduce the impact of dry season pumping on river baseflow if pumping was concentrated in areas remote from the river. Thus a local cone of depression may be created, which would be filled the following wet season.

The uncertainty on the estimated recharge rate is believed to be approximately ±50%. Also, the figure represents a spatial average, and it is likely that groundwater recharge will be higher than this in some areas and lower in others. This may have important implications for groundwater extraction.

Another unknown relates to the connection between the deeper aquifer and the shallower system. Groundwater extraction will take place from the deeper, dolomite aquifer, and our analysis has assumed that the reduction in pressures will be immediately transmitted to the shallow system, with consequent reduction in the watertable. In some ways, our assumption represents a worst-case scenario.

Recommendations

On the basis of currently available data, it appears that groundwater extraction will not seriously affect the health of the eucalypt woodland or paperbark swamp ecosystems. However, there remain some unanswered questions, most notably concerning the possible impact on dry season baseflows to the Howard River, and the vulnerability of the monsoon vine forests. If groundwater pumping is to proceed, it is recommended that:

- Careful consideration be given to the timing of pumping and the location of pumping bores. Pumping at certain times of the year, and at bore locations remote from the Howard River may minimise any reduction in baseflow. Bores should also be located remote from monsoon vine forests.

Valuable information could also be obtained from an investigation of McMinn's borefield (west of the Howard River), where groundwater extraction has been taking place since 1966. Therefore, it is recommended that:

- Assessments of vegetation health be made concurrently in Howard East (undeveloped) and McMinn's borefield (developed) to determine whether the eucalypt savanna is suffering water stress towards the end of the dry season.

An improved surface water and groundwater network would also allow the impacts of development to be carefully monitored. It is recommended that:

- Consideration be given to an improved monitoring network, designed specifically to measure the impact of groundwater extraction on watertable levels and river flows. This could include instrumentation for measurement of river flows upstream of Koolpinyah, and installation of bores adjacent to the Howard River to determine groundwater gradients between the aquifer and the river.

Further work would help fill some of the gaps in our present understanding of the system, although we do not believe these are sufficiently serious to delay development. Nevertheless, additional work in the following areas would increase our understanding of the hydrology of the system:

1. Groundwater flow to the sea has not been directly estimated. As much as is possible, bounds for this figure should be established by determining hydraulic gradients, aquifer hydraulic conductivities and cross-sectional areas. This may help refine the current 20 mm yr^{-1} groundwater surplus figure.

2. The potential groundwater dependence of the monsoon vine forests could be further examined.

3. A more thorough analysis could be made of the effects of year-to-year variability of rainfall on available soil water.

4. Comparisons of the pressure responses of deep and shallow bores in McMinn's borefield could be made to determine how groundwater extraction from the deep aquifer is affecting the shallow water table.

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