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Groundwater Allocation Using a Groundwater Level Response Management Method—Gnangara Groundwater System, Western Australia

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Abstract The Gnangara groundwater system (Gnangara system) is an important source of groundwater for Perth, Western Australia: in the order of 350 GL of groundwater is abstracted annually. The Gnangara system also sustains groundwater dependent ecosystems (GDEs), mostly wetlands and native vegetation. Declining groundwater levels across the system have led to impacts on a number of key GDEs. Western Australia's Department of Water recently prepared a Water Management Plan for the Gnangara system. Allocation limits were reviewed as part of the plan preparation. To assist in reviewing allocation limits, an adaptive Groundwater Level Response Management (GWLRM) methodology was developed and implemented. This paper describes the methodology and its application to the Gnangara system. The methodology was developed to be used as a corrective tool for the short- and medium-term, to assist in achieving long-term sustainability of groundwater management in the context of changing climate and declining groundwater levels. The GWLRM methodology is based on groundwater storage depletion and can be applied to existing allocation limits as an interim tool to assist in making management decisions aimed at recovering groundwater resources. The key to the GWRLM correction is that it will direct water allocation towards sustainable levels on the basis of measured trends. Allocations corrected through application of the GWRLM would therefore represent interim and improved water allocation figures. GWLRM can also identify potential problem areas where the principles or calculations used for long-term sustainable groundwater allocation would need to be reviewed. For the Gnangara system, the calculated storage changes or GWLRM corrections were

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considered together with results of predictive modelling as part of an expert panel process to derive a more sustainable interim groundwater allocation regime while further research is being completed.

Keywords Sustainable development · Groundwater management · Gnangara groundwater system · Groundwater dependent ecosystems (GDEs)

1 Introduction and Background to Groundwater Management Concepts

The goal for providing water for the environment is to maintain, and where necessary, restore GDEs. For aquifers connected to GDEs terrestrial groundwater discharge maintains GDEs and abstraction induced changes have most often been the principal concern of environmental flow considerations (Murray et al. 2003).

The sustainable development of a natural resource is the development that meets the needs of the present without compromising the ability of future generations to meet their needs: use of natural resources without jeopardizing their use by future generations. Sustainable development allows the use of part of the reserves (storage) before adapting to the rate of renewable resources (Custodio 2002).

Groundwater depletion is the inevitable and natural consequence of withdrawing significant amounts of water from an aquifer (Bredehoeft 1997; Konikow and Kendy 2005; Sophocleous 1997). The abstracted groundwater is initially sourced from the removal of groundwater from storage, but over time may increasingly be derived from decreased groundwater discharge to GDEs and increased recharge (Bredehoeft 1997; Konikow and Kendy 2005). Both can change but commonly the pre-development discharge is what changes and may make it possible to bring a ground water system into a new balance (Bredehoeft 1997).

The concept of safe yield was introduced to preserve the beneficial use of the groundwater (Custodio 2002) by defining how much groundwater can be abstracted from an aquifer, assuming that groundwater is a renewable resource. Safe yield means a groundwater management goal which attempts to achieve and maintain a long-term balance between the annual amount of groundwater withdrawn and the annual amount of natural and artificial recharge. Safe yield therefore should not be used without the accompanying assumptions about the acceptable effects of groundwater withdrawals (Alley and Leake 2004). Without these assumptions, the safe yield concept is flawed and may be unsustainable in the long term since it may not adequately consider the needs of GDEs.

Safe yield may not always account for potentially diminished surface-water flows or localized areas of depletion (Jacobs and Holway 2004). Recharge is often considered as the base of safe yield. However, surface waters can be depleted before the pumping reaches the magnitude of the recharge (Bredehoeft 1997).

2 Groundwater Allocation in Australia

In Australia, defining groundwater allocation limits is based, typically, on long term average recharge rates and existing water use at the time water use controls are initiated. Allocation limits are difficult to quantify and, often because of a poor scientific understanding or lack of data, do not adequately provide for non-consumptive users (river baseflow and ecosystems). Groundwater and surface waters are interactive components of the hydrologic system and cannot be treated in isolation (Hancock et al. 2005). Defining allocation limits and managing water resources on a sustainable level is therefore, at least, difficult.

3 Changes in Groundwater Storage

Changes in groundwater storage represent an aquifer's response to stressors, including climate, groundwater abstraction and land use. Any groundwater abstraction would cause some inherent storage depletion in a groundwater system or related surface water flows.

Significant and regional declines in groundwater levels indicate persistent storage depletion. This storage depletion is the equivalent of discharge (including abstraction) from an aquifer, at rates in excess of recharge to the aquifer. Conversely, increasing groundwater levels indicate an increase in storage: recharge in excess of discharge from the groundwater system.

The change in volumetric storage can be calculated as the factor of storage coefficient and trend in groundwater level, at each monitoring site. Spatial (GIS) modelling tools and numerical flow models can be used to spatially model storage depletion for regions or groundwater management units.

4 Groundwater Level Response Management

Water Level Response Management and Groundwater Level Response Management (GWLRM) refer to the management of groundwater based on the response of the aquifers and related surface water to stresses. If water levels exhibit anomalous trends, these trends are used as the base for corrective action (Department of the Environment and Water Resources 2007). For example, if undesired declines in groundwater level were detected, the GWLRM can be used to determine an appropriate reduction in the amount of water to be allocated from a system. The main attraction of GWLRM arises from the use of actual, measured data. As long as monitoring data reflect the real trends of groundwater levels, GWLRM corrections represent a simple and practical step towards sustainability.

The advantages of GWLRM are simplicity, transparency and the fact that only trends, not the causes of water level declines, need to be identified. Adaptive management tools lend themselves as corrective tools, on the short- and medium-term, towards achieving long-term sustainability goals.

GWLRM does not eliminate the need for research, rather complements it by allowing corrective actions to be taken at a time-scale that is considerably shorter than those necessary for research and groundwater modelling. GWLRM is an allocation tool that can be used in the context of changing climate, as groundwater levels inherently contain changes instigated by climate. The best use of GWLRM, probably, is as an interim tool towards the recovery of groundwater resources in areas where groundwater levels have declined significantly. GWRLM could be used as an interim management tool, working towards and eventually converging to long-term sustainability measures. In this context, GWRLM would represent steps, driven by groundwater system response, towards a long-term goal driven by the notion of sustainability.

GWLRM also requires adequate monitoring data, both spatially and temporally, in addition to a reasonable level of understanding of the hydrogeology. GWLRM-corrected allocations can be announced on a periodic basis as a water allocation that will be provided to water access entitlements and fixed term licences on the basis of the measured trends in groundwater levels. The allocation would depend on the state of groundwater resource as reflected by measured trends over a defined time period, making GWLRM a short-term, reactive tool. A parallel example is that of the allocation of surface water from the River Murray in Australia (in the states of Victoria, New South Wales and South Australia) where allocations have been reduced in response to reduced river flows.

5 The Gnangara Groundwater System

The Gnangara system is one the most important sources of groundwater for Western Australia. In the order of 350 GL of groundwater is abstracted annually for the purposes of public water supply, irrigated agriculture, industry and public amenity. The Gnangara system also sustains a series of groundwater dependent ecosystems (GDE), which consist of wetlands and large areas of native vegetation. Since the 1970s, groundwater levels across the system have been in decline. This coincides with a general trend of declining annual rainfall in the south west of Western Australia. In recent years, the importance of climate as a factor affecting groundwater levels, and therefore groundwater dependent ecosystems, has been recognised. To address this, the Western Australian Department of Water (DoW) has prepared a Water Management Plan for the Gnangara system and has reviewed allocation limits for each groundwater management unit.

The Gnangara system covers an area of approximately 2,200 km^2 and is comprised of Cainozoic sediments. These sedimentary formations, in increasing distance from the coast, are the Tamala Limestone and Sand, Bassendean Sand, and the Guilford Formation (clay and sand). These sediments form an extensive unconfined aquifer, known as the superficial aquifer that is up to 50 m thick in places. Several confined aquifers, including the spatially limited Mirrabooka Aquifer; and the extensive Leederville and Yarragadee Aquifers, underlie the superficial aquifer and are extensively developed within the Perth Basin. The Perth Basin is a north to north–northwest trending, approximately 1,300 km long sedimentary basin situated along the south-western margin of the Australian continent. It contains freshwater in aquifers to depths in excess of 1,000 m.

The geology, hydrogeology, and groundwater resources of the Gnangara system are described by Davidson (1995) in detail and here only a simplified summary is provided. Regional horizontal groundwater flow in the unconfined aquifer is from the centre of a divide (commonly referred to as the Gnangara Mound) toward the north (Gingin Brook), the east (Ellen Brook); south (Swan River); or to the west (the Indian Ocean, Fig. 1).

Vertical hydraulic gradients are downward beneath the centre of the system (reflecting that it is a recharge area) while the potential for upward groundwater leakage exists near Ellen Brook, Swan River, and the ocean (the discharge areas of the Gnangara system). Estimated hydraulic conductivity and specific yields are respectively up to 100 m/day and 0.3 for the Tamala Limestone; up to 50 m/day and 0.2 for the Bassendean Sand; and up to 1 m/day and 0.05 for the Guilford Formation.

Mean annual rainfall is between 700 and 800 mm. Mean annual groundwater recharge is estimated by Davidson (1995) as between 70 and 250 mm/year. Rainfall is strongly winter-dominated (when temperatures and evaporation are low) and consequently groundwater recharge from rainfall occurs almost entirely from June to September. Rainfall recharge during the long and hot summers is negligible, while evaporation losses from wetlands and in shallow water table settings are considerable.

Groundwater is managed by the DoW through administrative boundaries known as Groundwater Areas and are further divided into management units known as groundwater sub-areas. Allocation limits have been set for all aquifers at either the groundwater area or groundwater sub-area level.

Groundwater has been managed using historical best estimates, simple recharge calculations, complex hydrogeology and flownet evaluation (Davidson 1995), and lately, numerical modelling using the PRAMS model (Davidson and Yu 2007). The principle used for groundwater allocation and numerical modelling has been to allocate approximately 70% of estimated rainfall recharge for unconfined aquifers, deemed as an acceptable portion of rainfall recharge (Yu 2006).

Following an assessment of proposals to abstract groundwater for public water supply in the 1980s, and in an attempt to protect GDEs from the impacts of abstraction, minimum water level criteria were set at a number of sites (Fig. 1) across the Gnangara system by the Minister for the Environment on the advice of the WA Environmental Protection Authority. In recent years, these water levels have not been met at a number of these environmental criteria sites.

Since the 1970s, groundwater levels across the Gnangara system have been in decline. This decline is attributed to declining rainfall, groundwater abstraction, and land use induced changes in water balance (Yesertener 2007). Groundwater level decline coincides with a general trend of declining annual rainfall across the south west of Western Australia. In recent years, the importance of climate as a factor affecting groundwater levels, and therefore affecting groundwater dependent ecosystems, has been recognised.

Most groundwater sub-areas across the Gnangara system are now considered to be fully or over allocated in the context of current (since 1990) rainfall. As part of the process to review allocation limits for the water management plan, particular consideration was given to identifying, through measured trends, a water balance deficit that is larger than that indicated by calculations or modelling. In several groundwater sub-areas, existing allocation limits had not been reached but monitoring data showed significant declines in groundwater levels. The GWLRM,

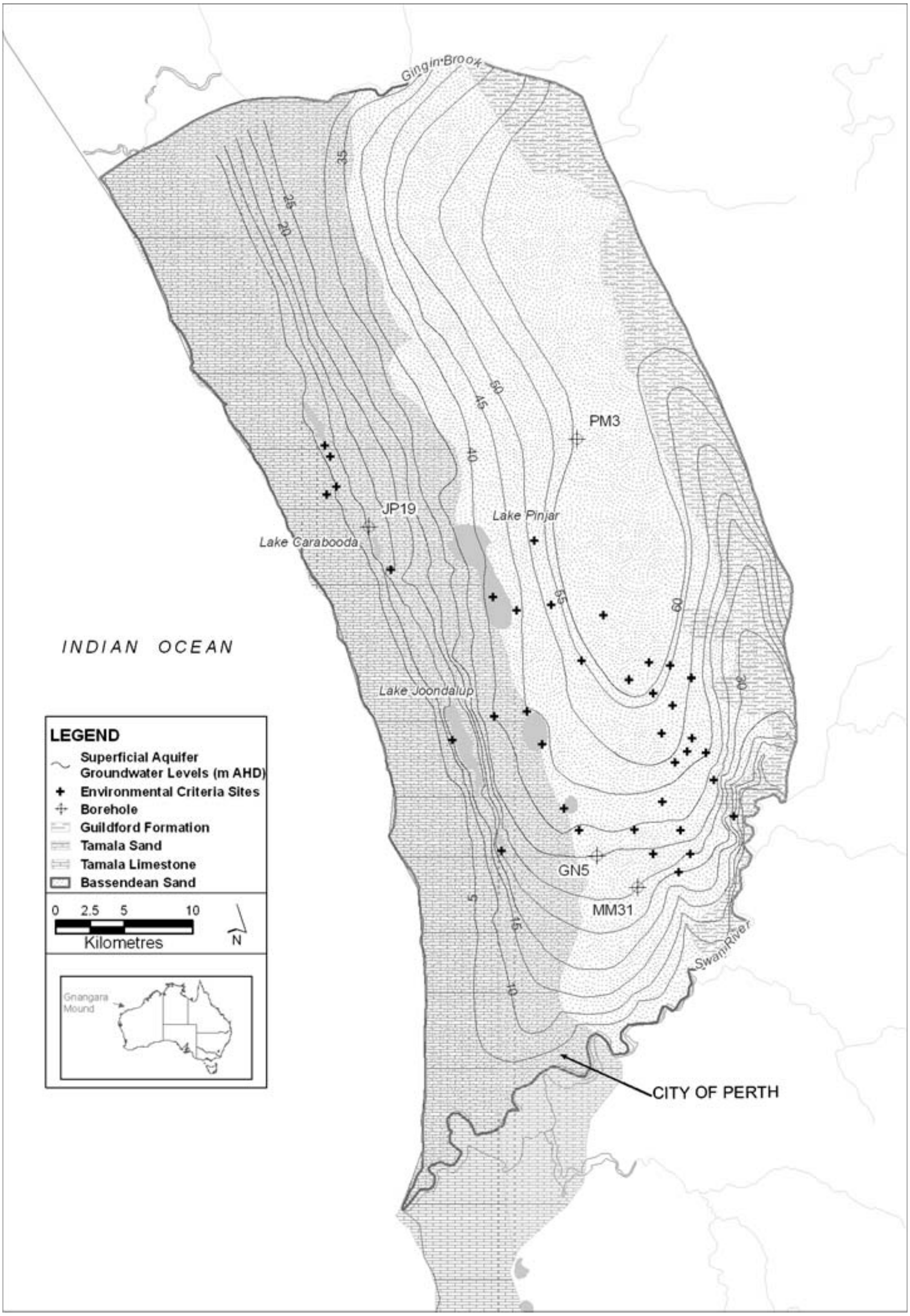


Fig. 1 The Gnangara groundwater system

based on measured trends, provided a suitable basis to reduce allocation limits in such cases.

6 Application of the GWLRM for the Gnangara System

Volumetric change in groundwater storage was calculated by estimating the trend in groundwater level (decrease or increase) and multiplying that change by the storage coefficient for each groundwater monitoring site. Spatial (GIS) modelling tools were subsequently used to spatially aggregate (model) point data on storage depletion to any spatial entity (such as a groundwater sub-area) or across the entire Gnangara system.

A GWLRM correction, equal or less to the calculated storage depletion, can be applied to existing allocation limits as an interim tool towards the recovery of groundwater resources. The GWRLM correction represents a step, driven by groundwater system response, towards long-term sustainability. Undesired declines in groundwater level would result in a reduction in groundwater allocation limits.

The objective of the application of this method was to calculate a single number, representing the volumetric change in groundwater, for each groundwater sub-area of the Gnangara system. The volumetric change is to reflect the spatially aggregated trend in groundwater levels or volumes within the appropriate sub-area.

A single number may not reflect different hydrogeological settings and processes acting and influencing groundwater levels in a sub-area. However, a single number (the allocation limit), along with impact management measures, has been used to date for allocation by DoW for each groundwater sub-area and this deterministic approach to groundwater allocation is likely to continue in the near future.

The GWLRM process was implemented for the Gnangara system and involved the following steps:

- Hydrograph analysis: trend evaluation
- Estimating the coefficient of storage for all aquifers and monitoring sites
- Estimating the factor of trend and storage for each monitoring site
- Spatially aggregating the above factor and deriving groundwater balance for each sub-area or area.

Once the spatially modelled trend was calculated, it was converted to a volumetric trend (dimension: volume/time).

The resultant volumetric trends were considered, together with additional hydrological modelling and assessment techniques, as a basis for corrective action to the existing allocation limits.

Trends were assessed for a total of 653 monitoring wells, located within or just outside of the Gnangara system. The vast majority of these wells are located within the superficial aquifer. Although in principle the methodology can be used for confined aquifers the remaining sections of this paper address the application of the methodology to the superficial aquifer only.

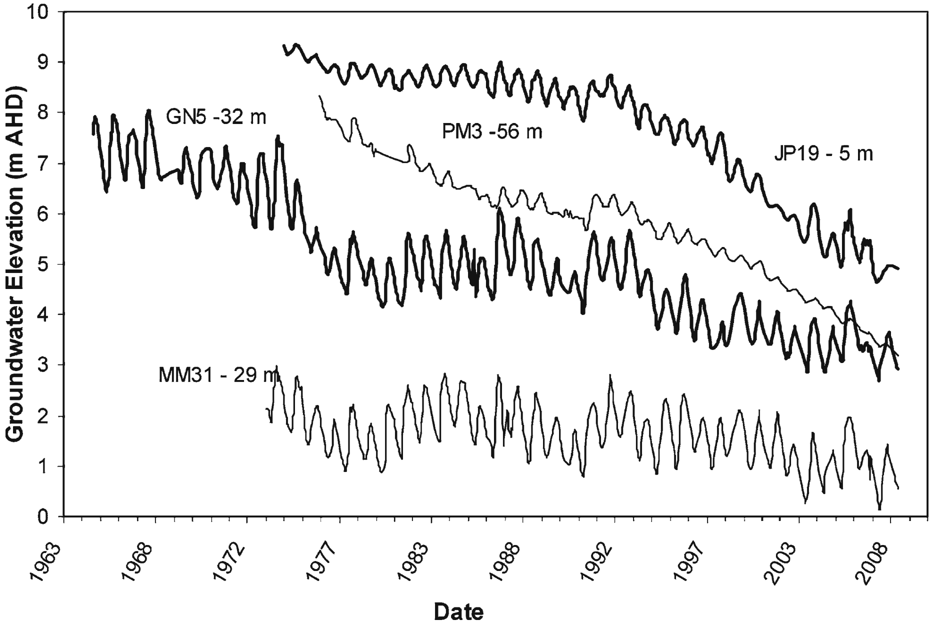


Fig. 2 Hydrographs for selected bores. Groundwater elevations in m AHD (Australian Height Datum) have been transformed to bring them to the same scale

7 Groundwater Level Monitoring

The DoW collects, processes and quality assures groundwater level data in more than 650 monitoring wells. The majority of measurements are taken at quarterly intervals using electronic dip meters. Yesertener (2007) describes the data in detail, including the selected hydrographs shown in Fig. 2.

The hydrographs for sites PM3, GN5 and JP19 (Fig. 2) indicate significant declines in groundwater levels (representing storage depletion) and varying rates of annual ranges (fluctuations caused by seasonal groundwater recharge–discharge patterns) due to changes in climate, land use/vegetation cover and nearby water abstraction. The influence of native bushland, reducing the recharge and therefore the annual fluctuation in PM3 is noticeable. Yesertener (2007) explained the effect of groundwater abstraction on JP19 (since 1998) and GN5 (since 1990). The hydrograph for MM31 indicates stable groundwater levels to the mid-1990s followed by a decline attributed to groundwater abstraction (Yesertener 2007).

8 Results of the Trend Analysis

Yesertener (2007) investigated the possible causes of groundwater level decline using a Cumulative Deviation from Mean Rainfall (CDFM) technique for approximately 100 hydrographs. In this study three trends were estimated: "long-term" (1979–2005), "medium-term" (1998–2006), and "short-term" (2001–2005). The periods for long-

Table 1 Summary of trend analysis

Period for trend estimation	Count	Minimum (m/year)	25th %ile (m/year)	Median (m/year)	75th %ile (m/year)	Maximum (m/year)	Comments
1979–2005	369	−0.250	−0.096	−0.038	−0.012	0.094	Long-term decline
1998–2006	504	−0.413	−0.150	−0.050	0.000	0.125	Moderate decline
2001–2005	529	−0.800	−0.200	−0.100	−0.038	0.390	Steep decline

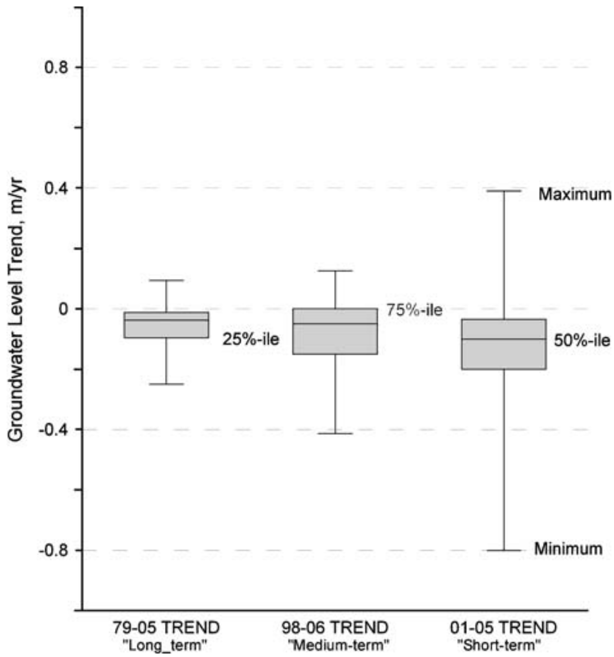
and short-term as defined by Yesertener (2007) were adopted for this GWLRM approach.

In the first stage, hydrograph trends were estimated visually and manually, examining each hydrograph, on the basis of annual mean groundwater levels. During the trend analysis no judgment was made on the cause of, or the spatial relations for trends observed. Only hydrographs that included data for the appropriate time period were used and hydrographs which had large gaps in data were excluded from the process.

In the second stage, the geographical spread of the estimated trends were checked using spatial modelling tools (GIS). Particular attention was paid to areas where there was a low density of monitoring sites. Hydrographs from these areas were revisited and re-evaluated (if appropriate) to boost evaluated trend density.

Trends were assessed for up to 529 sites (Table 1) in the superficial aquifer. The DoW groundwater monitoring network provided sufficient data to allow good spatial coverage of the superficial aquifer of the Gnangara system. This network has been expanded over time and as such there has been an increase in the number of bores from which short-term trends could be determined. Therefore short-term trends

Fig. 3 Box and whisker plot—groundwater levels 1998–2006



were able to be calculated at more sites than they were for long-term trends, as indicated by Table 1.

Monitoring data demonstrate a consistent groundwater level decline in the superficial aquifer since 1979, regardless of the time period used. These are indicated by the negative values in Table 1. As expected, short-term trends indicate a wider spread of trends than those obtained from analysis of medium (1998–2006) or long-term (1979–2005) data sets. Figure 3 suggest only minor differences in quartile statistics between medium and long-term.

9 Specific Yield and Storage Coefficients

Specific yield is the amount of water released, due to drainage from lowering the water table by a unit (1 m), from a unit area of an unconfined aquifer. Typically specific yield is two to four orders of magnitude larger than storativity (the term used for confined aquifers to indicate the amount of groundwater released due to a unit depressurization). Specific yields were estimated from Davidson and Yu (2007) and Commander (2007, personal communication):

Tamala Limestone: 0.30
Bassendean Sand: 0.20
Guildford Clay: 0.05

10 Converting Trends to Volumes

The factor of the storage coefficient and the groundwater level trend for 1998–2006 was calculated for each monitoring site included in the assessment. Trends in groundwater levels depend on many factors including climate, land use, water abstraction, drainage, soil types and aquifer hydraulic parameters. Groundwater level trends therefore may change abruptly across discrete boundaries of these factors. The trends therefore may not define a spatially continuous surface that can be contoured or mapped easily and large variations can be expected locally. The traditional approach is to group trends according to assumed hydrogeological behaviour, or assign representative hydrographs for each sub-area. In this study, however a spatial-modelling methodology has been developed based on the following criteria and features:

- Preserving the local variations when up-scaling point observations.
- Considering regional-scale changes as a smooth surface.
- Using a transparent spatial modelling process
- Using a spatial process that can be reproduced (in time) could incorporate additional trend sites in the future.
- Representing spatially weighted "average" change in groundwater volume for each sub-area.
- Including estimated trends both inside and immediately outside of a sub-area. This is to overcome large uncertainty for sub-areas that may contain very few or no trend observations.

The methodology developed to satisfy these criteria used nearest-neighbour polygons:

1. 1998–2006 trends were mapped (contoured trends are shown in Fig. 4).
2. A set of Thiessen or nearest-neighbour polygons were built around each observation site, adjusted to (clipped to) the external boundary of the Gnangara system.
3. Trends were considered uniform, and equivalent to the trend observed at the sole observation situated inside each Thiessen polygon.
4. Thiessen polygons that overlap sub-areas were sub-divided (intersected with sub-areas; Fig. 5).
5. The factor of trends and storage (calculated for at each trend site) was multiplied by the area of the appropriate sub-divided Thiessen polygon (resulting in from step 4).
6. Results (from step 5) were spatially aggregated ('dissolved') to groundwater sub-areas representing storage changes. The results of this are shown in Fig. 6.
7. The shading of Fig. 6 indicates storage change, normalised to the area of the appropriate groundwater sub-area. Darker shades indicate large storage depletion per unit area and light fills indicate small increase, or no change in storage per unit area.

The uncertainty of the process is associated with uncertainty in the data and the spread of observations. The spread of observations can be evaluated, both visually (for example Fig. 4) and statistically. The number of trend observations for 1998–2006 is 504 for the superficial aquifer (Table 1). The 2,200 km^2 of the Gnangara system is divided into 51 groundwater sub-areas. An average sub-area unit would therefore include approximately 10 observation sites with the 'area of influence' for each trend site approximately 4.3 km^2; the mean spacing between observation sites is just over 2 km.

11 Results

Figures 4 and 6 indicate the results of trend analysis for the superficial aquifer as contoured trends (Fig. 4); and as groundwater sub-area volumetric changes (Fig. 6).

The largest decline, over 0.4 m/year, is centred over the Reserve sub-area; with smaller local anomalies beneath the Wanneroo and Gwelup groundwater sub-areas. The largest reductions, normalised to the area of appropriate groundwater sub-area (dark fills on Fig. 6), are needed in the Reserve sub-area and along the linear lakes (Carabooda, Nowergup, and Neerabup sub-areas) situated along the contact between the Tamala Limestone and Bassendean Sands. Groundwater from the Reserve sub-area moves laterally towards the linear lakes (Fig. 1).

The Reserve sub-area is a significant recharge area for the Gnangara system. As a result of decreased recharge, groundwater levels declined in the Reserve sub-area and, importantly, further downstream, in the Carabooda, Nowergup, Pinjar, and Neerabup sub-areas. These latter areas received not only less rainfall recharge but significantly decreased lateral through-flow from the Reserve sub-area. The declining trend in groundwater levels caused significant reductions in groundwater discharge to GDEs (linear chain of wetlands situated parallel to the coast) of significant ecosystem

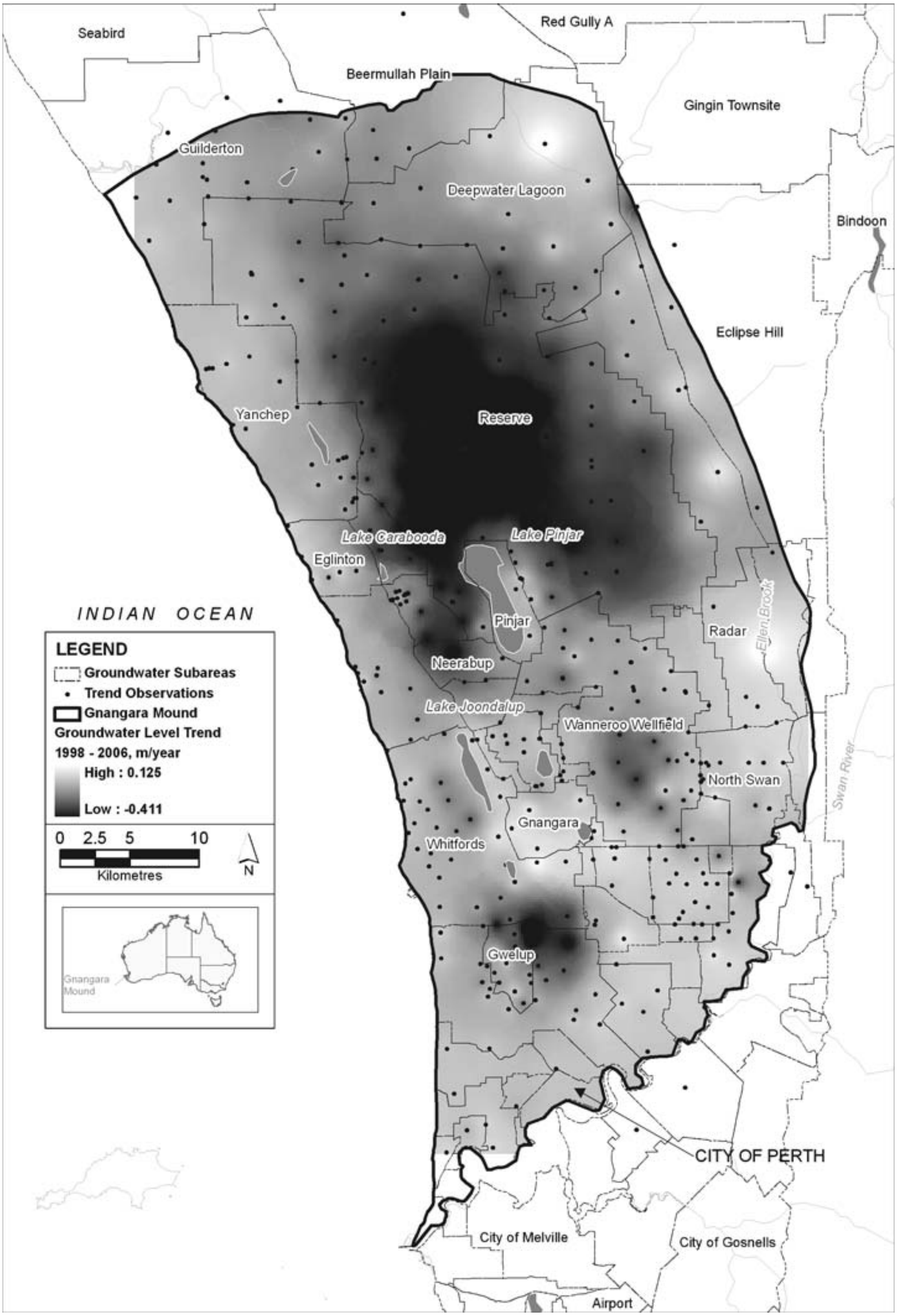


Fig. 4 Contoured trends in superficial groundwater levels 1998–2006

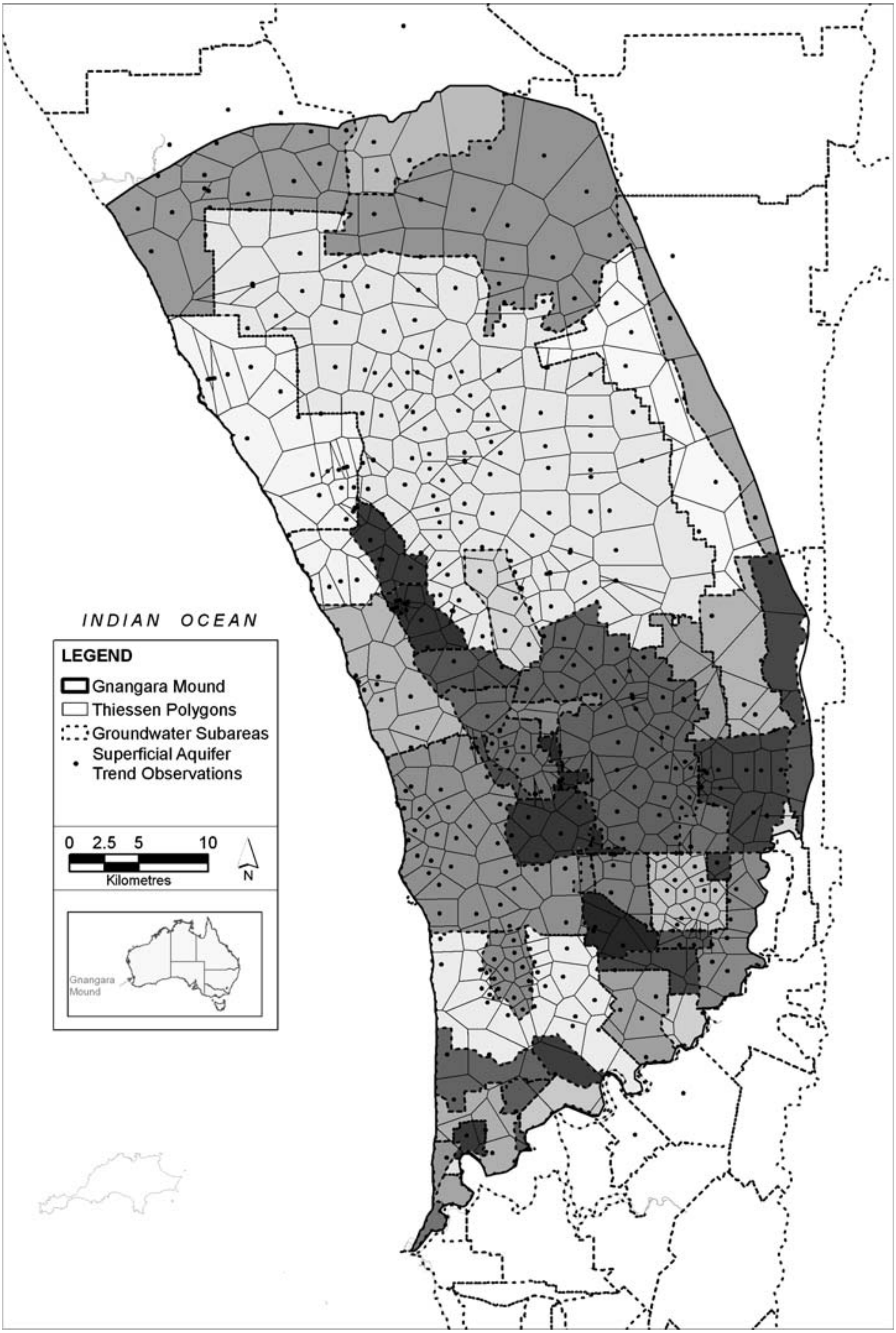


Fig. 5 Thiessen polygons and groundwater sub-areas. Trends were considered uniform, and equivalent to the trend observed at the sole observation situated inside each Thiessen polygon. Thiessen polygons were intersected with sub-areas and volumetric storage changes in groundwater were calculated for each intersected polygon

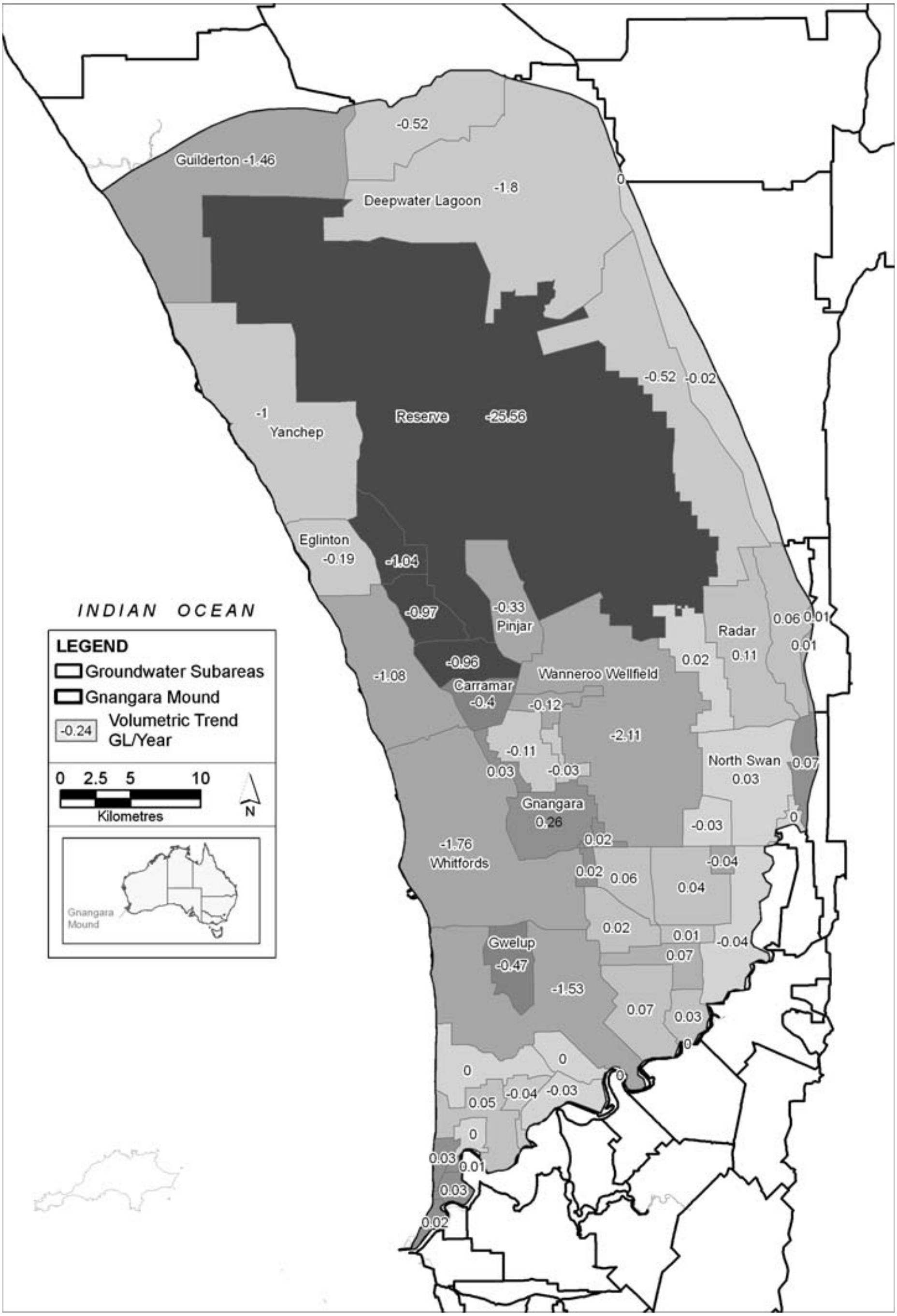


Fig. 6 Storage changes in the superficial aquifer 1998–2006. The *shading of polygons* indicates storage change, normalised to the area of the appropriate groundwater sub-area. *Darker shades* indicate large storage depletion per unit area and *light fills* indicate small increase, or no change in storage per unit area

values. Therefore management in the Reserve sub-area area holds the key to the management of groundwater in most of the Gnangara system.

Small declines or stable trends are indicated near groundwater discharge areas (where large water bodies, hydraulically connected to the superficial aquifer buffer water level changes). Especially along the coast, the proximity of the ocean, lakes and the Tamala Limestone (having a high transmissivity and a large specific yield) have so far suppressed most propagation of large declines from the recharge area.

There is a stable groundwater level zone (represented by light fill on Fig. 6) between Wanneroo and Gwelup. This northwest–southeast oriented zone coincides with land use changes that are considered to have increased the groundwater recharge (from market gardening to urban) and the presence of damplands or wetlands that may control groundwater levels in their vicinity.

12 GWLRM Corrections

Figure 6 indicates volumetric groundwater changes between 1998 and 2006: negative numbers represent groundwater storage depletion. For example, storage depletion in the Pinjar sub-area (situated in the middle of the Gnangara system) was calculated at 0.33 GL/year. The allocation limit for this sub-area was set at 2 GL/year with current use estimated at 0.9 GL/year. Thus, administratively, 1.1 GL/year of water was still available for allocation. Trend analyses and the negative volumetric trend (storage depletion) indicated significantly declining groundwater levels. The GWLRM method suggested a reduction of up to 0.33 GL/year was required. Allocation limits for the Pinjar sub-area were subsequently modified taking into account the results of the GWLRM. This example demonstrates how GWLRM can identify potential problem areas of water allocation: the principles and calculations used for groundwater allocation would need to be reviewed for the Pinjar sub-area. In particular, the uniform 70% of estimated rainfall recharge that has to date been used for groundwater allocation, needs to be scrutinised. Continuing of the use of 70% of rainfall recharge for the Gnangara system appears to be inappropriate in some sub-areas.

Overall, based on the results of the GWLRM, it was identified that a reduction in total allocation of up to 41 GL/year was required in the superficial aquifer. More than half of this correction, up to 25 GL/year, was required in the Reserve sub-area. This figure represents 2.5 times the total estimated use from this sub-area (10.1 GL/year), indicating a reduction in the abstraction of water will not be enough to address the groundwater decline in this sub-area and that factors other than allocation are also important in the Reserve sub-area. The factors most likely to impact on recharge in this sub-area are reduced rainfall and changes in landuse.

Significant groundwater depletion also occurred during 1998–2006 in sub-areas situated in the northern and south-western coastal sub-areas of the Gnangara system (City of Stirling, Gwelup, Whitfords, Carramar, Quinns Rocks, Yanchep, and Guilderton).

13 Environmental Criteria Sites

Most of the sites for which water levels have been set to protect GDEs, the environmental criteria sites, are either in the south-east part of the Gnangara system

Table 2 Groundwater allocation for the gnangara system, 2007

DoW groundwater		Current allocation limit	Total estimated use	GWLRM change in storage	Model[a]	New allocation limit	Guiding factors for new allocation limit						
Area	Sub-area	GL/year					GWLRM	Model[a]	GDE	Land use	CDFM[b]	Water Use	Other[c]
Gnangara	Reserve	n/a	10.19	−25.57	37.91	9.00	X	X		X		X	X
Gnangara	Wanneroo Wellfield	12.00	17.81	−2.11	22.47	12.00	X		X			X	
Gwelup	Gwelup	7.95	9.02	−0.47	3.90	7.95		X			X	X	
Mirrabooka	Ballajura	8.31	6.80	0.02	4.55	6.00	X	X				X	
Mirrabooka	Beechboro	1.00	0.59	0.01	−0.49	1.00	X			X		X	X
Mirrabooka	Henley Brook	2.00	1.70	−0.04	0.51	1.60	X	X	X				
Mirrabooka	Improvement Plan 8	8.89	6.04	0.06	3.78	5.50	X	X			X	X	
Mirrabooka	Landsdale	1.60	1.58	0.02	0.44	1.40			X			X	X
Mirrabooka	Plantation	0.70	0.70	0.02	0.44	0.60		X		X			
Mirrabooka	State Forest	0.67	1.25	−0.03	1.48	1.00	X			X		X	
Mirrabooka	Whiteman Park	3.37	2.19	0.04	2.63	1.00	X	X					
Perth	City of Bayswater	2.30	7.90	0.07	7.75	2.30	X			X		X	
Perth	City of Nedlands	2.60	3.25	0.05	4.60	2.60	X					X	X
Perth	City of Perth	2.10	1.98	−0.03	1.14	1.50	X	X				X	X
Perth	City of Stirling	11.15	17.76	−1.53	22.64	11.15						X	X
Perth	City of Subiaco	1.00	1.33	−0.04	1.92	1.00	X					X	X
Perth	Eglington	15.45	2.02	−0.19	5.30	15.45	X	X	X			X	X
Perth	Quinns Rocks	24.65	17.67	−1.08	13.55	24.65	X	X	X				
Perth	Shire of Peppermint Grove	0.10	0.21	0.01	0.27	0.10			X				X
Perth	Town of Bassendean	0.50	1.40	0.03	2.27	0.50	X					X	X
Perth	Town of Cambridge	3.50	3.40	0.00	4.87	2.00						X	X
Perth	Town of Claremont	0.70	0.84	0.00	1.38	0.70	X						X

Perth	Town of Cottesloe	0.30	0.37	0.03	0.65	0.65						X	X
Perth	Town of Mosman Park	0.50	0.61	0.03	1.09	0.50	X					X	X
Perth	Town of Vincent	1.00	1.47	0.00	2.92	1.00	X					X	X
Perth	Whitfords	22.43	25.06	−1.76	31.61	22.43			X			X	
Swan	Bandy Spring	0.40	0.35	0.01	n/a	0.35						X	X
Swan	Central Swan	1.60	1.78	0.00	0.03	1.00		X				X	X
Swan	Cockman Bluff	1.90	1.47	0.06	0.56	1.50		X					X
Swan	East Swan	1.00	0.96	0.07	0.37	0.75		X	X				X
Swan	Neaves	3.80	3.58	0.02	1.11	2.00		X	X				X
Swan	North Swan	3.30	3.41	0.03	1.37	2.00		X	X				X
Swan	Radar	3.40	2.77	0.11	0.06	2.00		X				X	
Swan	South Swan	4.25	4.28	−0.04	5.13	4.00	X					X	X
Wanneroo	Adams	2.10	1.30	−0.12	1.01	1.00	X	X	X		X		
Wanneroo	Carabooda	7.40	8.79	−1.04	4.71	5.00	X	X			X		X
Wanneroo	Carramar	2.40	1.80	−0.40	3.12	1.40	X	X					
Wanneroo	Jandabup	0.20	0.22	−0.03	0.59	0.20			X	X	X	X	X
Wanneroo	Joondalup	2.10	1.62	0.03	1.47	1.50	X	X			X		
Wanneroo	Lake Gnangara	10.00	9.09	0.26	5.74	6.00	X	X	X		X		X
Wanneroo	Mariginiup	5.40	4.92	−0.11	3.49	4.00	X	X	X		X		X
Wanneroo	Neerabup	2.65	3.49	−0.96	3.01	2.65							X
Wanneroo	Nowergup	2.75	2.81	−0.97	3.94	2.00	X	X	X		X		
Wanneroo	Pinjar	2.00	0.89	−0.33	0.45	0.50	X	X	X				X
Yanchep	Yanchep	10.87	2.10	−1.00	1.01	10.87	X	X	X				X

[a]Based on Yu (2006).

[b]Based on Yesertener (2007).

[c]Include regulatory guidelines and existing commitments.

(Whiteman Park, North Swan, Neaves, and Wanneroo Wellfield) or along the coast, in the north-west portion of the system (Yanchep, Carabooda, Nowergup, Pinjar, and Neerabup sub-areas). Groundwater levels at most of the environmental criteria sites, situated in the south-eastern sub-areas, were reasonably stable during the period 1998–2006.

Several monitoring sites, located in the vicinity of lakes and wetlands in the Yanchep, Carabooda, Nowergup, Pinjar, and Neerabup sub-areas indicate steep groundwater level declines, in excess of 0.1 m/year. Groundwater levels near criteria sites adjacent to the wetlands, situated at the contact between the Bassendean Sand and Tamala Limestone, are likely to suffer further reductions in groundwater input as more and more of the groundwater level declines propagate from the Reserve sub-area. As discussed earlier, some or most of these declines have been buffered by the relatively large bodies of surface water and the Tamala Limestone to date. Some of the wetlands, however, have started to show decline in water levels even in-spite of artificial augmentation systems that are currently operating. Large declines in the Reserve and Wanneroo sub-areas have propagated further downstream and the associated reduced groundwater inflow has started to impact GDEs. The management of GDEs, therefore, will require prudent groundwater allocation in the entire Gnangara system.

14 Setting New Allocation Limits

The resultant volumetric trends were considered during a recent review of allocation limits undertaken by the DoW. Through this process they served as a basis for corrective action to the existing allocation limits and were considered alongside data collected through other hydrological techniques including modelling. Table 2 lists the calculated changes in groundwater storage or GWLRM corrections and other factors (predictive groundwater modelling, ecological values, and risks posed by climate, land use, and groundwater use on GDEs) considered in the allocation limit setting process by a panel of experts that included resource planners, hydrogeologist and environmental scientists.

Returning to the example of the Pinjar sub-area (Table 2) the current allocation limit was set at 2 GL/year and groundwater use was estimated as 0.9 GL/year. Results of the GWLRM suggested a 0.33 GL/year depletion of the uppermost aquifer; groundwater modelling using PRAMS suggested that a total of 0.45 GL/year could be allocated. Based on these values, the allocation limit was changed to 0.5 GL/year.

15 Summary and Conclusions

Groundwater trends for 1998–2006 were estimated for a large number (504) sites and spatially aggregated to represent a change in volumetric storage in groundwater for each groundwater sub-area.

The key to the GWRLM correction is that it will direct water allocation progressively towards sustainable levels of abstraction based on measured trends. The GWRLM-corrected allocations would therefore represent interim and improved water allocation figures. GWLRM can identify potential problem areas of water allocation where the principles or calculations used for long-term sustainable groundwater allocation would need to be reviewed. The calculated storage changes or GWLRM corrections developed as a result of the analysis completed for the Gnangara system were considered in a recent review of allocation limits for this resource.

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