Quantifying Rainfall and Flooding Impacts on Groundwater Levels in Irrigation Areas: GIS Approach

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Abstract: Landscapes continuously irrigated without proper drainage for a long period of time frequently experience a rise in water-table levels. Waterlogging and salinization of irrigated areas are immediate impacts of this situation in arid areas, especially when groundwater salinity is high. Flooding and heavy rainfall further recharge groundwater and accelerate these impacts. An understanding of regional groundwater dynamics is required to implement land and water management strategies. The purpose of this study is to quantify the impact of flood and rain events on spatial scales using a geographic information system (GIS). This paper presents a case study of shallow water-table levels and salinity problems in the Wakool irrigation district located in the Murray irrigation area with groundwater average electrical conductivity greater than 25,000 $\mu S/cm$. This area has experienced several large flood events during the past several decades. Piezometric data are interpolated to generate a water-table surface for each event by applying the Kriging method of spatial interpolation using the linear variogram model. Spatial and temporal analysis of major flood events over the last four decades is conducted using calculated water-table surfaces to quantify the change in groundwater storage and shallow water-table levels. The drainage impact of a subsurface drainage scheme partially covering the area has also been quantified in this paper. The results show that flooding and local rainfall have a significant impact on shallow groundwater. The study also found that postflood climatic conditions (evaporation and rainfall) play a significant role in the groundwater dynamics of the area. The spatial net average groundwater recharge during the flooding events ranges from 0.19 to 0.52 ML/ha. The GIS-based techniques described in this paper can be used for net recharge estimation in semiarid regions where it is important to quantify net recharge impacts of regional flooding and local rainfall. The spatial visualization of the net recharge in a GIS environment can help prioritize management actions by local communities.

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Introduction

Environmental degradation associated with shallow saline water-tables is a major threat to the sustainability of agricultural industry throughout the Murray–Darling Basin (MDB). The MDB is located in the southeast of Australia and covers 1,061,469 km^2, equivalent to 14% of the country's total area. The basin is defined by the catchment areas of the Murray and Darling Rivers and their many tributaries (Fig. 1). To the east and south, the Great Dividing Range forms the limit of the basin, including Australia's highest country, with Mount Kosciusko rising to 2,228 m. In the north, west, and southwest, the boundaries are much less distinct, particularly in the Wimmera to the southwest and with the Bulloo Basin to the northwest, both areas of internal drainage. Elsewhere, areas of low to medium altitude mark the Basin's limits, including the Mount Lofty Ranges in the southwest, the Grey and Barrier Ranges in the west, and the Chesterton and Warrego Ranges in the north. Most of the Basin is extensive plains and low undulating areas, mostly below 200 m above sea level. Of greatest extent are the vast plains, the Darling Plain in the north, drained by the Darling and its tributaries, and the Riverine Plain in the south, drained by the Murray and Murrumbidgee and their tributaries. The Murray–Darling Basin is spread over five States and Territories of Australia with areas in: New South Wales (57%), Victoria (12%), Queensland (25%), South Australia (6%), and the Australian Capital Territory (less than 1% of the Basin). The Murray–Darling Basin contains more than 20 major rivers as well as important groundwater systems. It is also an important source of fresh water for domestic consumption, agricultural production and industry.

An important consequence of the size of the Murray–Darling Basin is the great range of climatic conditions and natural environments encountered, from the rainforests of the cool and humid eastern uplands, the temperate mallee country of the southeast, the subtropical areas of the northeast, to the hot, dry semiarid, and arid lands of the far western plains. More than three-quarters of the Basin receives less than 600 mm of average annual rainfall. There is a considerable variation in runoff from one part of the Basin to another. Further, runoff bears little relationship to the

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Fig. 1. Major rivers and their tributaries of the Murray Darling Basin

catchment size. The catchments draining the Great Dividing Range on the southeast and southern margins of the Basin make the largest contributions to total runoff. For example, the Upper Murray, Murrumbidgee, and Goulburn river catchments account for 45.4% of the Basin's total runoff from 11% of its area. The Upper Murray catchment alone accounts for 17.3% of runoff from 1.4% of the Basin. By contrast, the Darling group of rivers contribute 31.7% of the Basin's mean annual runoff from 60.4% of its area. The Darling catchment itself accounts for 10.9% of the Basin's area but only 0.4% of mean annual runoff. Overall, some 86% of the Basin contributes virtually no runoff to the river systems, except during floods.

The Murray irrigation area (MIA) is one of the largest irrigation areas in the MDB and is located in south New South Wales (NSW), just north of the Murray River across the NSW–Victoria state border. The Wakool Irrigation District (WID) is one of the four irrigation districts of the MIA. The total area of the WID is stated to be around 235,000 ha (Wakool LWMP 2001). However, the total WID area used in present study is 223,000 ha, which is computed by geographic information system (GIS) application based on the WID boundary map available at the time of study. The climate in this area can be described as arid to semi-arid with a mean annual rainfall recorded at Moulamein Post Office (located in the town of Moulamein within the study area) being 356 mm (Bureau of Meteorology, www.bom.gov.au). Major crops grown in the area include rice, pasture, and cereals. About 99% of net irrigation demand is met by surface water and 1% from deep groundwater pumping as the shallow groundwater is highly saline.

Elevation in this area ranges from 60 m in the northwest to 84 m in the southeast. The average ground slope is approximately 1:5,000 from the southeast towards the northwest (Khan et al. 2005). Characterized by its geographical location in the lower MDB, its flatness and flood plain nature, and the highly variable climatic conditions (both seasonality and magnitude of rainfall), this area is prone to frequent flooding and has been under heavy floods over last several decades.

Among the surface water features, the Edward River (one of a set of branching and rejoining rivers which form the Murray River system), is the major waterway off-taking water into the WID from the Murray River upstream of Deniliquin. The Edward River is then divided into two major waterway systems around the WID area when it passes town of Deniliquin; one can be described as the Edward–Niemur River system flowing through the central and northern part of the WID and the other can be described as the Wakool River system flowing around the southern and southwestern boundary of the WID (Fig. 2). Edward River joins the Wakool River before flowing back into the Murray River southwest of Balranald. Under major flood conditions, which refer to flood between 9.4 and 9.7 m while town levees operate at 9.4–9.97 m (NSW SFP 2001), floodwater passing through Deniliquin is approximately evenly distributed into these two systems (MCMA 2006) and (NSW WRC 1981). Hume Reservoir on Murray River has a storage capacity of nearly 3,000 gigalitre and is located 220 km upstream of Deniliquin.

In the WID, irrigation expanded significantly from the 1970s to the 1980s and stabilized since then (Wakool LWMP 2001). The shallow water-table has been gradually rising with the extensive clearing of land combined with increasing area under inefficient irrigation and subsequently agricultural sustainability has been threatened by land salinity resulting from the overall water-table rise in this area. The WID has experienced a history of water-table rise, including likely contributions from widespread flooding. The management authorities are interested in separating impact of rainfall and flooding from irrigation to the shallow groundwater rise, in order to target management actions to control water-table rise and salinity in this area. Moreover, to justify the cost and effectiveness of the drainage scheme, it is necessary to estimate the recharge to the shallow groundwater from various sources.

To control water-table rise and salinity problem, some management actions have already been implemented in the region such as during 1981 the Wakool Tullakool subsurface drainage scheme (WTSSDS) was installed. WTSSDS is an engineering solution, a combination of groundwater pumping, subsurface drainage, and evaporation basins; to drain shallow saline groundwater into evaporation basins covering an area of 2,100 ha for "disposal" (WCIC 1975). The WTSSDS consists of 54 pumps that pump saline groundwater from over 100 tubewells. The average capacity of each pump is 1.25 megalitre per day (ML/d). In addition to reclaiming agricultural lands, the scheme also intercepts and helps prevent saline groundwater from flowing into the Wakool, Niemur, and Murray Rivers. This helps increase overall viability of the drainage operation (Khan 2005). According to the current estimates the existing scheme protects around 50,000 ha of farmland in the WID by pumping around 36 ML/day (with an average electrical conductivity greater than 25,000 μS/cm of saline water to keep water-table deeper than 2.5 m. Estimated drainage rates for the existing scheme range from 0.23 to 0.6 ML/ha. The net interception of salts through the current operations is around 200,000 ton of salts per year (Khan and Rana 2006).

The focus of this paper is to improve knowledge and understanding of the regional groundwater dynamics; to estimate spatial and temporal impact of flooding on shallow water-table in the WID and to establish evidence for community action needed for land and water management to cope with the impacts of flooding in this area. This has been achieved through an extensive GIS analysis of the piezometric data monitored over more than four decades in the WID. To address the similar problems of irrigation-

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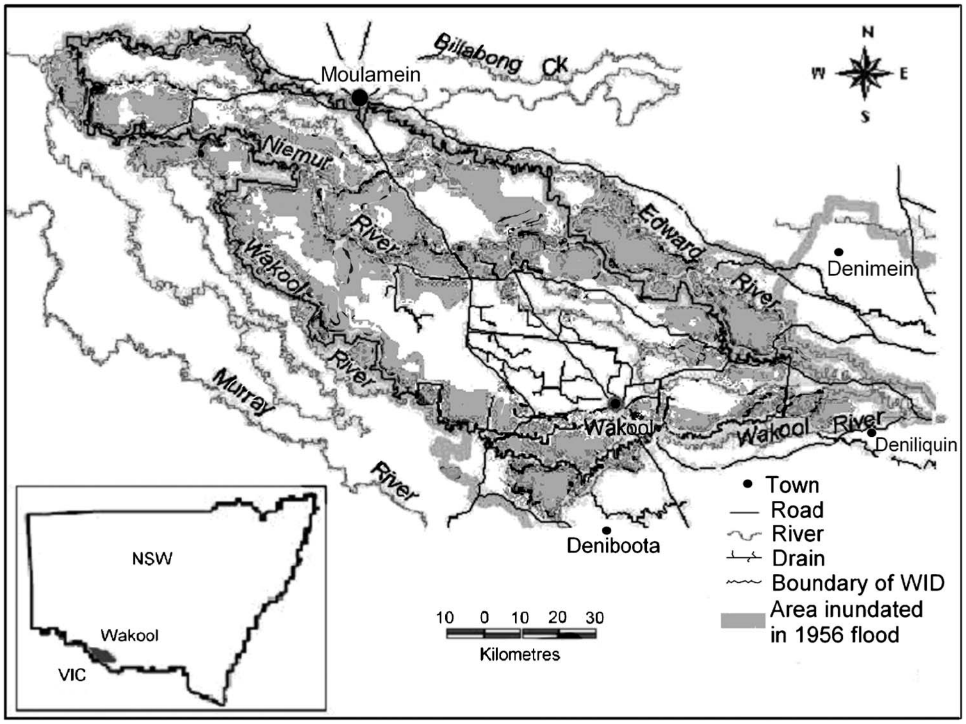

Fig. 2. Location of the Wakool Irrigation District and its major surface water features

induced salinity and waterlogging in an irrigated river valley, Burkhalter and Gates (2006) applied different approach using flow and mass transport models to predict and evaluate spatial and temporal responses of a suite of solution alternatives.

History and Classification of Floods in Lower MDB

Based on cause/source, floods in lower MDB can be classified as the following:

(a) Caused by local rainfall: Local rainwater finds the shortest path to reach water-table. However, it has the best quality among all the groundwater recharge sources.

(b) Caused by rainfall in the upstream catchment area: Floodwater discharged from upstream may remain confined within the riverbanks and increase interaction between channel floodwater and groundwater or it may overflow the riverbanks and cause inundation in the adjacent areas.

(c) Caused by water release from the upstream storage: It happens when upstream storage reaches its maximum storage level and excess water has to be released for dam safety.

Table 1. Largest Recorded Floods (in Terms of River Height) in Lower Murray–Darling Basin

		Order of floods and flood year				
River	Location	Largest	Second largest	Third largest	Fourth largest	Fifth largest
Murray	Albury	1870	1917	1975	1974	1931
Murray	Mildura	1870	1956	1931	1917	1975
Murray	Morgan	1956	1870	1931	1917	1974
Darling	Bourke	1864	1890	1976	1974	1950

Note: Adapted from Mussared (1997).

(d) Combination of the above factors: The majority of floods in the area most likely belong to this category. This type of flood has the potential to cause widespread flood impacts. For example during the 1956 flood more than 50% of the Greater Wakool area (the entire Wakool Shire) was inundated.

Table 1 shows the year and order of magnitude of the five worst flood events recorded at some major locations (Fig. 1) in the MDB since the 19th century. From Table 1 it can be seen for the same order of flood magnitude the year in which the flood happened varies at different locations. Flood magnitude differs throughout the system, indicating the variations in spatial and

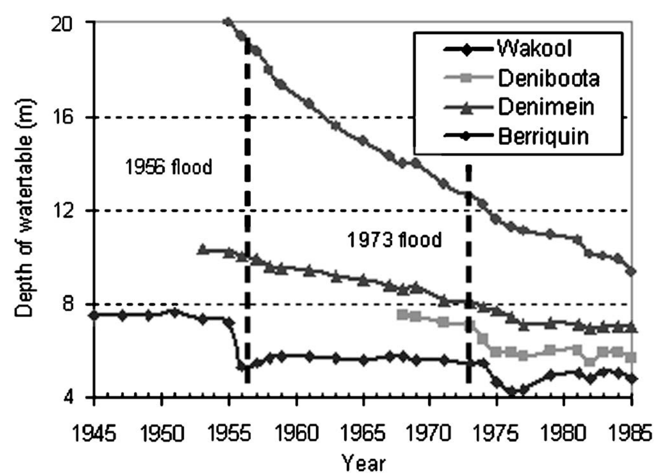

Fig. 3. Water-table levels for four irrigated districts in the NSW Murray area of MDB (adapted from MDBC Draft Salinity and Drainage Strategy 1988 and Ghassemi et al. 1995)

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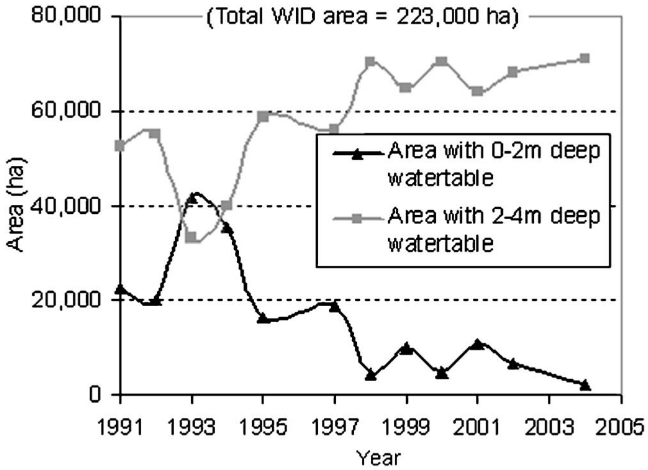

Fig. 4. Area of Wakool Irrigation District with water-table depths 0–2 m and 2–4 m from 1991 to 2004

Table 2. Summary of Piezometric Data Statistics

Data item	Value
Total number of monitored piezometers	1,480
Data period (Shallow piezometers only)	1963–2001
Total number of years covered by data	38
Number of months in which readings were taken	112
Maximum number of readings taken for a single piezometer	106
Maximum number of readings taken for a piezometer in a year	7 (in 1982)
Frequency of readings per year for most of the period	Quarterly or biannually
Average number of readings taken per piezometer over the whole data period	33.9
Number of piezometers with missing data	4.3%

temporal rainfall causing these floods. Ten flood peaks occurred in the MIA during the 1973–1975 that was extremely wet period (Bogoda et al. 1995). For instance, the extreme rainfall events associated with the 1974 flood have average recurrence intervals (ARI) greater than 50 years or a probability of less than 1 in 50 every year.

In 1944, eight years after irrigation commenced in the area, the average depth to the water-table was around 8 m. Fig. 3 shows that there have been significant rises in WIDs already shallow water-table during major flood events of 1956 and 1973–1975. However, the water-table from 1969 to 1973 does not show significant change suggesting that groundwater balance was essentially in a steady state prior to 1973. These groundwater levels have never receded to the levels prior to 1956 and 1973. This provides evidence of contribution of floods in shallow groundwater rise.

When the water-table is less than 2 m from the soil surface, the root zone of the plants becomes restricted and capillary upflows from the water-table start accumulating salts in the root zone and at the soil surface, causing reduction in crop yields (Kijne et al. 1998). Therefore water-table depth less than 2 m is not desirable especially for crops cultivation. Fig. 4 shows that in recent years there has been a decrease in areas with groundwater levels in the 0–2 m range. There are a number of reasons suggested for this decreasing trend. These include drier conditions in 1997–1998 and 2002–2003, better drainage of leaky paddocks and improved water management practices adopted by landholders to reduce groundwater recharge. Therefore, the prevailing view still remains that in the long term the areas underlain by shallow water-table will continue to increase especially after the flood events in the area.

Data Processing

The data analysis and processing in this study were concentrated on the piezometric data in the WID area. The shallow water-table has been monitored and recorded since 1963. Before 1978, the readings were normally taken four times a year in the months of March, June, September, and December. After 1978, the piezometric readings are taken twice a year, one around February and one around August. The number and spatial distribution of piezometers with readings recorded at each of the reading months vary from time to time. The general statistics of the collected piezometric data is summarized in Table 2.

The piezometric data was converted to an ArcView GIS database so that the temporal and spatial analysis of the water-table changes over time can be carried out. In order to interpolate reliable water-table surfaces at given months from the GIS database for the whole WID, the spatial distribution of piezometers with data available for each of the particular months need to well cover the whole area. The piezometric data are further assessed for the temporal and spatial distribution. A data set is defined as the set of piezometric readings at a particular reading month. With only 55 out of 112 data sets provided full spatial coverage of WID. The piezometric locations of remaining 57 data sets are concentrated in WTSSDS area which covers only south-western WID. Therefore, only those water-table surfaces generated from the

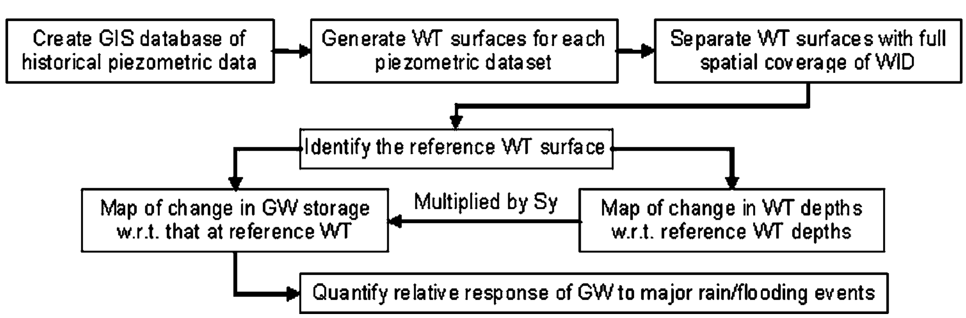

Fig. 5. General framework for quantifying impact of floods on shallow groundwater system

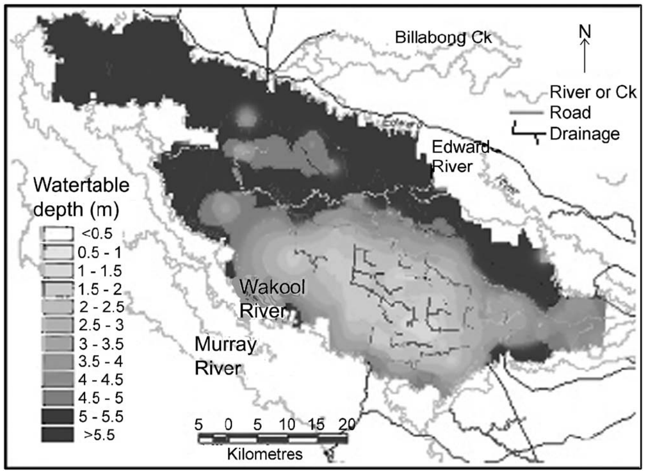

Fig. 6. Water-table depths in March 1973 (reference water-table) in the Wakool area

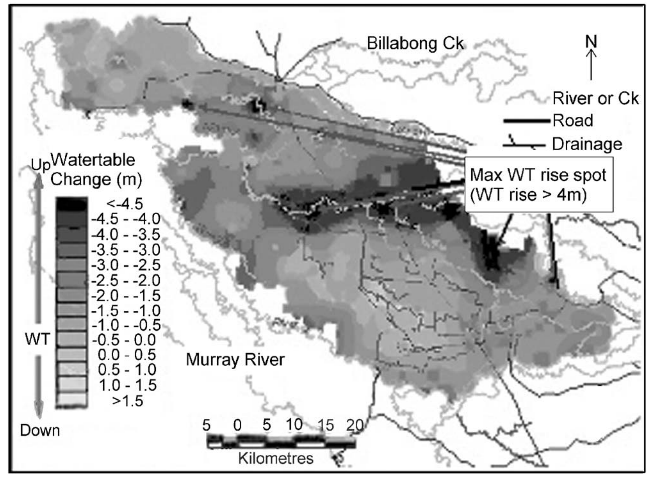

Fig. 7. Spatial extent of water-table change between March 1973 and December 1975

piezometers with data covering the whole area of WID were used in the flood impact analysis in this paper.

Methodology

A general framework of methodology adopted in this study to quantify spatial and temporal impacts of flooding on shallow groundwater is shown in Fig. 5. The GIS tool, ArcView, was applied in this process, such as spatial analysis, image analysis, and three-dimensional (3D) analysis were applied to demarcate and visualize the spatial extent of water-table change during the floods. The extent of flooding is assumed same as the water table changes computed in the GIS analysis. Kriging is a geostatistical gridding (interpolation) method which predicts unknown values from data observed at known locations. This method uses variogram to express the spatial variation, and it minimizes the error of predicted values which are estimated by spatial distribution of the predicted values (Cressie 1991). Water-table surfaces passing through the mesh of nodes were generated by Kriging method of interpolation among the piezometric water depths. Hence, each node point on the mesh/surface represents an interpolated value of water-table depth. The Kriging (point method) applied with the linear variogram model (slope=1) on a grid of 250 m generated reasonably accurate water-table surfaces covering the whole WID without any postprocess smoothing required.

A "reference water-table" was defined as one in which the water-table was relatively static prior to flooding impacts. The reference water-table was then used to assess the differences produced from flooding. At each grid, the saturated volume changes between two water surface tables were computed and multiplied by the average specific yield (S_y) in GIS to estimate the net equivalent change in water volume [Eq. (1)]

$$\begin{aligned}&\text{Groundwater recharge over a grid}\\&\quad=(\text{Present water-table surface}\\&\qquad-\text{Reference water-table surface})\times A\times S_y\end{aligned}\tag{1}$$

where A=area of the grid; and S_y=specific yield of saturated medium. Based on the soil types from bore log profiles for southern WID, S_y varies between 0.03 and 0.05. Considering the soil types in the rest of the WID tend to be clayey and heavier (Smith et al. 1943), 0.03 was adopted as a uniform average specific yield for the entire WID.

Table 3. Percent Area of Different Water-Table Rise during the 1973–1975 Floods

Year and month	Total WT rise area (%)	Area of different water-table rise range (%) 0–0.5 (m)	0.5–1 (m)	1–1.5 (m)	1.5–2 (m)	2–2.5 (m)	2.5–3 (m)	3–3.5 (m)	3.5–4 (m)	>4 m
March 1973	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
June 1973	82.0	57.0	15.6	4.7	2.5	1.4	0.6	0.1	0.0	0.0
September 1973	94.0	41.8	25.9	13.6	6.7	3.3	1.7	0.7	0.2	0.0
December 1973	98.0	18.1	39.2	18.7	10.6	5.5	3.3	1.7	0.8	0.1
March 1974	95.3	20.5	47.6	22.1	3.9	0.9	0.2	0.0	0.0	0.0
June 1974	98.0	5.9	25.7	27.8	18.6	10.2	4.9	2.6	1.6	1.1
September 1974	99.0	3.2	21.2	32.1	20.3	11.0	5.3	2.9	1.8	1.5
December 1974	98.0	6.7	18.6	21.0	25.1	12.5	6.9	3.5	2.1	1.5
March 1975	94.5	12.7	21.0	23.2	20.1	11.8	4.8	0.7	0.1	0.1
June 1975	95.1	13.6	26.1	30.2	15.8	7.9	1.3	0.1	0.1	0.0
September 1975	95.2	12.5	29.6	27.2	14.6	7.1	3.1	1.0	0.2	0.0
December 1975	98.8	5.3	19.3	17.7	19.8	17.3	8.1	6.1	3.3	1.9

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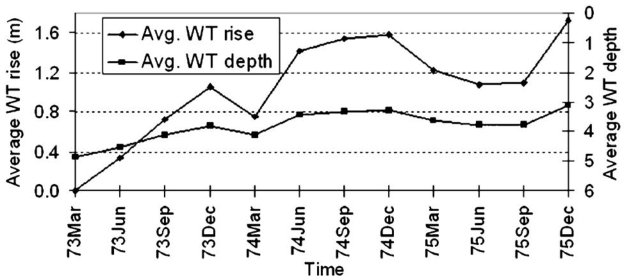

Fig. 8. Spatial average water-table change during 1973-75 floods as compared with water-table in March 1973

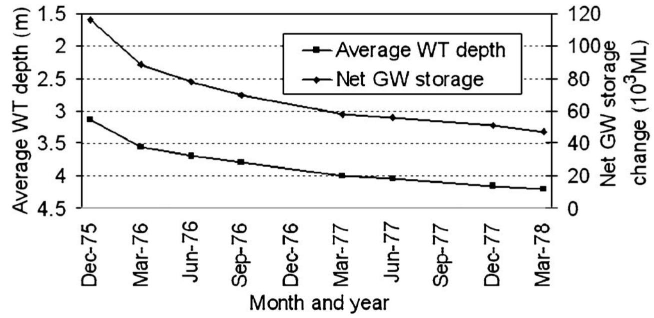

Fig. 10. Net groundwater change following the 1975 flood

Analysis and Discussion

Spatial Extent and Magnitude of Water-Table Response to 1973–1975 Floods

The 1973–1975 period was wet with several recorded flood events. The average annual rainfall occurred during this period was 651 mm, which is almost double the mean annual rainfall in the area. Following the definition of reference water-table, from the series of water-table surface, the water-table in March 1973 (Fig. 6) was assessed qualified as the reference water-table as there was not significant water-table change just before that time and from that time onwards water-table started to change significantly due to recharge from flooding. Water-table surfaces revealed after March 1973 from April 1973 and up to December 1975 were then compared with that in March 1973. During this period, the water-table rise exceeded 4 m at many spots in WID (Fig. 7).

Both the large regional spatial extent of water-table rise identified through GIS analysis and the rainfall data (Table 3 and Fig. 8) suggest that local rainfall significantly contributes to water-table rise. In fact, the floodwater came from both upstream discharge and local rainfall. This is indicated by a large portion (82%) of the WID area (Table 3) that showed a water-table rise between 0 and 3 m in a short period of time from March 1973 to June 1973, rather than local water-table rise along the waterways and in the low-lying areas as it would if the reflective of upstream floodwater were only from upstream area. This suggests that local rainfall at the early stage of the wet period was the major cause of the initial large extent water-table rise.

As the floodwater from both local rainfall and upstream discharge continued recharging shallow groundwater during the wet period, high water-table area started to spread from the original high water-table area (Fig. 6) into all directions but more extensively towards the northwest as shown in Fig. 7.

The spatial distribution of high water-table rise areas during the 1975 flood (Fig. 7) were mainly distributed along the Niemur River, which was different from that during 1973–1974 floods. It suggests that the flood coming into WID during 1975 have a larger proportion from the Niemur–Edward Rivers than that from the Wakool River, as compared with the 1973–1974 floods. It was estimated that 35% of the flood passing Deniliquin flowed into the Wakool River system in November 1975 flood instead of 50% in other major flood events prior to 1975. According to NSW WRC (1981), it was due to the effect of flood mitigation engineering work built between the 1974 flood and the 1975 flood.

Results from the GIS analysis showed that water-table at the start of the floods was already relatively shallow, with water-table depths in 70% of the WID area being less than 5.5 m (Fig. 6) and with an average water-table depth being 4.86 m. The floods in 1973–1974 had their maximum impact on the shallow groundwater around September–December 1974 (Fig. 8); the average water-table rose by 1.58 m from the March 1973 level, the average water-table depth was reduced to 3.28 m. Fig. 8 shows changes in the average water-table rise and average water-table depth at different stages during the 1973-1975 floods. With the 1975 flood, the average water-table depth was further reduced to 3.13 m (Fig. 8).

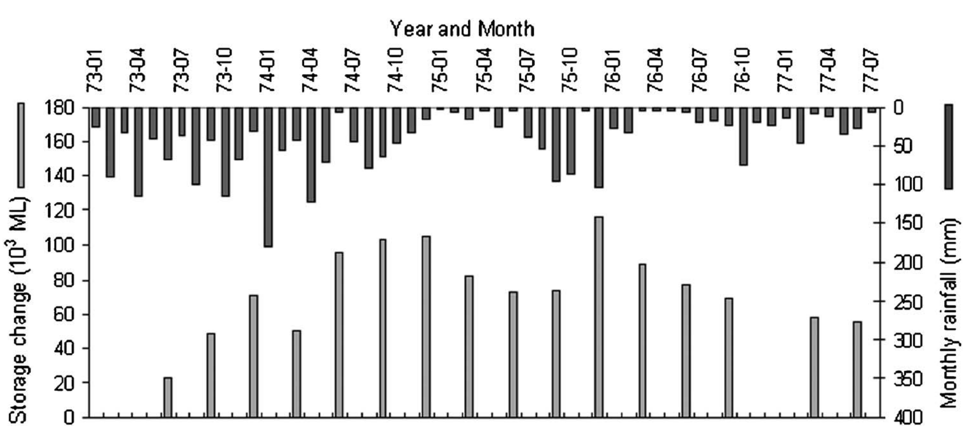

Fig. 9. Groundwater recession following the maximum water-table rise from the 1975 flood

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Table 4. Groundwater Recession 3 Months Following the Maximum Water-Table Mound during the 1973–1975 Floods

Month and year of maximum WT mound	Spatial average of WT depth (m)	GW storage change from March 1973 (10^3 ML)	GW storage change 3 months later (10^3 ML)	GW storage reduction (10^3 ML)
December 1973	3.81	70.10	50.51	19.59
December 1974	3.28	105.75	81.94	23.78
December 1975	3.13	116.08	88.49	27.59

Quantifying the Impact of 1973–1975 Floods on Shallow Groundwater Storage

GIS analysis was conducted to quantify the net shallow groundwater storage change as compared with the water-table level in March 1973. Using a specific yield (S_y) value of 0.03 for the soil types in WID, the estimated net groundwater storage changes starting from March 1973 to July 1977 over the whole WID area is presented in Fig. 9, along with the monthly rainfall recorded for the same period at Moulamein Post Office.

The results from Fig. 9 can be summarized as given below:

- There is a significant connection between the local rainfall and the water-table change, suggesting that the local rainfall has contributed a significant portion to the floods in WID;
- The maximum increase in the net shallow groundwater storage caused by flooding by the end of 1975 is around 116×10^3 ML (equivalent to an average net recharge of 0.52 ML/ha or an average water-table rise of 1.73 m from the March 1973 level);
- Following the water-table rise to its maximum extent, there was around $19 \times 10^3 - 28 \times 10^3$ ML of the groundwater discharged in the following three months for each of the large flood events during 1973–1975. The amount discharged appeared to be related to the water-table depth, that is, the higher the water-table the larger the amount discharged (Table 4), suggesting that higher water-tables created a higher hydraulic gradient which would accelerate groundwater discharge into adjoining river and a higher water-table would also accelerate evaporation from the groundwater;
- The groundwater recession after flooding slowed down gradually and subject to the weather conditions (evaporation and rainfall), the management actions (groundwater pumping and drainage) and aquifer storage following the flooding events. The aggregate groundwater recession is shown in Fig. 10, which shows groundwater recession following the maximum water-table rise after the floods from December 1975 to March 1978; and
- Apart from flood magnitude, the amount of floodwater recharged to the groundwater is also related to the groundwater storage capacity. The higher the water-table is, the less the groundwater storage capacity. Tables 4 and 5 show that at the early stage of the wet period where water-table was relatively deep, 70.1×10^3 ML flood water recharged to the groundwater during the 1973 flood. When the next flood came, as the water-table was already high, the maximum recharge reduced to around 55.2×10^3 ML for the 1974 flood. Similarly, the 1975 flood resulted in a further reduced net recharge of 44.2×10^3 ML.

Quantifying the Impact of 1981 Floods on Shallow Groundwater

The frequency of the flood in 1981 is roughly in the order of 1 in 10 years. In 1981, around 63% of the annual rainfall (519 mm, January–December) occurred between February and July of that year (329.4 mm). As a result (referenced to the water-table at February 1981 level with an average water-table depth being 4.28 m) by August 1981, the net groundwater storage increased by around 42.68×10^3 ML (an average of 0.19 ML/ha) and the average water-table depth reduced to 3.64 m. Under very dry climatic condition in 1982 (1,890.4 mm evaporation and only 140.8 mm rainfall), it took around one and half years from August 1981 for the water-table to return to the February 1981 level.

As compared with the water-table in February 1981, during the August 1981 the area where water-table rose more than 2 m was around 4% of the total WID area which reduced to 1% by February 1982. Similarly, the area where water-table rose more than 0.5 m was around 48% which reduced to 35% by February 1982. The recession in groundwater storage following the 1981 flood was almost linear with time under the dry conditions experienced in 1982 before the next flood event in 1983.

Shallow Groundwater Response for the Whole Data Period

All the available piezometric data are processed and groundwater changes referenced to the March 1973 level are calculated. Groundwater changes at those times for which water-table surface can be derived from the piezometric data for WID are shown in Fig. 11. Before the 1973 flood, the water-table fluctuated up and down not far away from close to the March 1973 level due to

Table 5. Net Recharge When the Water-Table Mound Reached a Maximum for Each Major Flood during 1973–1975

Month and year of maximum WT mound	Spatial average of initial WT depth before flood (m)	Spatial average of WT depth at maximum before flood (m)	Change in spatial average WT depth (m)	Net recharge caused by the flood	
				10^3 ML	ML/ha
December 1973	4.85	3.81	1.05	70.1	0.31
December 1974	4.11	3.28	0.83	55.2	0.25
December 1975	3.79	3.13	0.66	44.2	0.20

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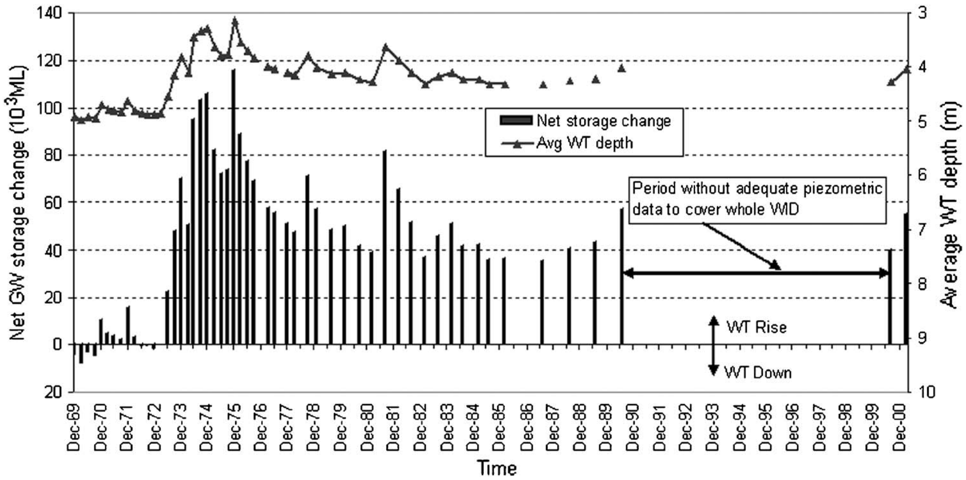

Fig. 11. Change in shallow groundwater storage and average water-table depth over the data period for the whole Wakool area

infrequent flooding events and the steady state groundwater balance. After the 1973–1975 wet period, the water-table rose considerably and has shown no sign of returning to the March 1973 level.

By March 2001, the average water-table was 0.82 m higher than that of March 1973 with corresponding net groundwater storage of 54.93×10^3 ML (Fig. 11) greater than that of March 1973. However, for most of the area within the WTSSDS boundary, the water-table was below the March 1973 level due to the drainage works effect of the scheme as shown in (Fig. 12). During 2003/2004, in response to continued dry conditions of 2002/2003, the optimized drainage pump operation remained below average. This resulted in extraction of 3.3×10^3 ML of saline water over 12 months, nearly 50% less than that in 2002/2003 with only 2,350 ha area having water-table within 2 m of surface in March 2004.

Conclusions

The net groundwater recharge caused by flooding and local rainfall in an irrigated area was mapped and quantified by compiling piezometric data into a GIS database and analyzing the data in a GIS application. This helped visualize the spatial extent of the impact of flooding on shallow water-table reflected by water-table change.

The flood during the record wet period of 1973–1975 caused an instantaneous maximum net recharge of around 116×10^3 ML (an average of 0.52 ML/ha) in December 1975.

Apart from the magnitude of flooding, the amount of net recharge caused by a single flood event is also related to the initial water-table prior to the flood, which affects shallow groundwater storage capacity. The higher the initial water-table, lesser the shallow groundwater storage capacity, and consequently there will be less room for net recharge, as shown during the 1973–1975 floods. Also the more frequent flooding such as experienced in 1981 (recurrence interval estimated as around 1 in 10 years), resulted in 42.68×10^3 ML or an average net recharge of 0.19 ML/ha (19 mm), which is equal to the average annual recharge during the wet period of 1973–1975, given the initial average water-table depth was 4.28 m.

The strong connections between local rainfall, floods, surface water features, and water-table change, suggest that the floods in this area are normally due to both upstream flows and local rainfall. Groundwater recession following a flood event is affected by a number of factors, such as initial water-table depth, climate conditions, management actions (pumping, subsurface drainage), etc. This study shows a rapid initial groundwater decline after the major floods which is followed by a low rate of decline.

The impacts of flooding on shallow water-tables last a long period of time, e.g., by March 2001, the groundwater levels show that the shallow groundwater storage and average water-table depth has still not returned to the March 1973 level. The net groundwater storage in March 2001 is still 54.93×10^3 ML higher than that in March 1973, equivalent to 0.82 m in average water-table rise. However, the spatial distribution of water-table depth has changed significantly. The water-table in most areas within the drainage scheme boundary shows a sign that high water-table area has been shifting towards the northwest. As a result of this trend revealed, the local authorities have already started setting up next phase of drainage studies to further protect an area of 6,000 ha in the northwest.

The GIS-based techniques described in this paper can be used for net recharge estimation in the semiarid regions where it is important to quantify net recharge impacts of regional flooding

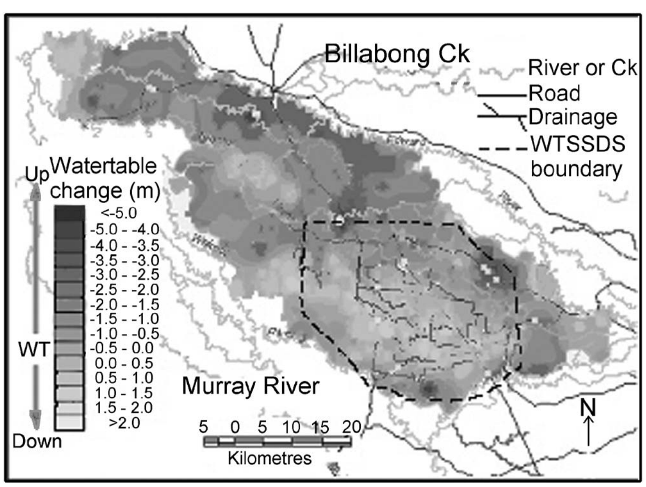

Fig. 12. Water-table change in March 2001 as compared with that in March 1973

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and local rainfall. The spatial visualization of net recharge in a GIS environment can help prioritize management actions by the local communities.

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