A GIS Approach to Quantify Impact of Flooding on Shallow Groundwater Levels in the Wakool Irrigation District

(Final Draft)

Butian Wang, Shahbaz Khan, Natalie O'Connell

CSIRO Land and Water, Griffith Laboratory

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Executive summary

Environmental degradation associated with shallow saline watertables is a major threat to the sustainability of agricultural industry throughout the Murray-Darling Basin. Located in the western part of the Murray Valley of NSW, the Wakool Irrigation District has experienced a history of water table rise, including likely contributions from widespread flooding. The community is interested in scientific evidence quantifying the impact of flooding on the shallow groundwater, in order to target management actions to control water table rise and salinity in this area.

This study estimates the spatial and temporal impact of flooding on shallow groundwater for the Wakool Irrigation District through an extensive GIS analysis based on a large amount of piezometric data monitored over many years.

By compiling the piezometric data into a GIS database and analyzing the data in a GIS application, we are able to quantify the net recharge caused by flooding and to visualize the spatial extent of the impact of flooding on the shallow water table reflected by water table change.

The results show that flooding has a significant impact on the shallow groundwater. The floods during the record wet period of 1973-75 caused a net recharge of around $116\times10^3$ ML (0.52ML/ha in average) at the stage when water table rise reached its maximum value around December 1975.

Apart from the magnitude of flooding, the amount of the net recharge caused by a single flood event is also related to the initial water table before the flood, which affects the shallow groundwater storage capacity. The higher the initial water table is, the less the shallow groundwater storage capacity will be, and consequently there will be less room for the net recharge, as shown during the 1973-75 floods.

More frequent flooding such as the one experienced in 1981, whose recurrence interval is estimated as around 1 in 10 years, could result in $42.68\times10^3$ ML or an average of 0.19ML/ha net recharge at the stage around maximum water table mound, given the initial average water table depth being at 4.28m.

There are strong connections between the local rainfall, flood, and water table change, suggesting that the floods happened in this area are normally due to both upstream and local rainfall. The major flood recharge areas within the Wakool area are mainly located along the Edward – Niemur River system. The groundwater recession following a flooding is affected by a number of factors, such as the initial water table depth, the climate conditions, the management actions, and etc.

**Key words**: flood, GIS, groundwater, water table, Wakool, Murray.
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1. Introduction

The Wakool Irrigation District (WID) is one of the four irrigation districts of the Murray Irrigation Area. The Murray Irrigation Area is one of the largest irrigation areas in the well-known Murray Darling Basin (MDB) and is located in the south NSW, just north of the Murray River across NSW – Victoria border (Dept. of National Development, 1953). Most part of the Murray Land and Water Management Plan (LWMP) area belong to Murray Irrigation Area (Fig. 1).

The total area of the Wakool area is around 230,000 hectares. The climate in this area can be described as arid to semi-arid with a mean annual rainfall at Moulamein Post Office being 356mm (Jan-Dec, 1889 –1998 data).

Elevation in this area ranges from 60m in the northwest to 84m in the southeast. The average ground slope is approximately 15,000 from the southeast towards the northwest. Characterized by its geographical location in the lower MDB, its flatness and flood plain nature, and the highly variable climatic conditions, this area is prone to frequent flooding (see Fig. 1).

Irrigation in the Wakool area expanded significantly in both area and water use from the 1970’s to the 1980’s and stabilized since then (WCLWMP, 2001). The shallow water table has been rising with the increased area under irrigation and subsequently agricultural sustainability has been threatened by land salinity resulting from the overall water table rise in this area.

![Figure 1. Location of the Wakool Irrigation District and major irrigation areas in south NSW. (Most of the Murray LWMP area is Murray Irrigation Area under Murray Irrigation Ltd.)](image-url)
To control water table rise and salinity problem, management actions have been taken, such as the Wakool Tullakool Sub Surface Drainage Scheme (WTSSDS), which is a drainage system with a combination of groundwater pumping, subsurface drainage and evaporation basins (Water Conservation and Irrigation Commission, 1975). To justify the cost and effectiveness of the scheme, it is necessary to estimate the recharge to the shallow groundwater from various sources.

The initial purpose of this study is to quantify the impact of flooding on shallow water table in the Wakool area and to identify the spatial extent of the impact, and consequently to improve knowledge and understanding of the regional groundwater dynamics and to provide evidence for justification of land and water management in this area.

This report summarizes the results from a range of GIS analysis in quantifying the shallow groundwater response to major flood events in the Wakool area.

2. Classification of floods

According to its cause/source, floods in this area can be classified as the following:

a). Flood caused by local rainfall;
b). Flood caused by rainfall in the upstream catchment area;
c). Flood caused by water release from the upstream storages;
d). Combination of the above.

a). Flood caused by local rainfall.
The amount of groundwater recharged from this type of flood depends on rainfall intensity, extent, duration, and the antecedent soil water conditions, as well as the soil type. In terms of the groundwater recharge, this type of flood has the following characteristics as compared with other types of flood:

- It has the shortest path for rainwater to reach water table;
- Among the groundwater recharge sources, it has the best water quality, mainly due to less evaporation and dissolution of minerals along its path as compared with the water coming from other areas.

b). Flood caused by rainfall in the upstream catchment area and discharged downstream. Depending on the flood magnitude, this type of flood can be further classified as:

- Confined within the riverbanks. In this case, the interaction between the floodwater and the groundwater is similar to any other channel system.
- Overflowed the riverbanks and caused inundation of the adjacent areas.

c). Flood caused by water released from upstream storages. This can happen when the upstream storages reach their maximum limit and there is a need to release excess water to the downstream due to dam safety reasons. Then the situation would be similar to b) but it would be less likely that the water would overflow riverbanks and inundate adjacent areas.

d). Combination of the above. The majority of floods most likely belong to this category. This type of flood has the potential to cause a serious flood disaster.
3. Historical flood

Table 1 shows the year and magnitude order of the worst five flood events recorded at some major locations in the Murray Darling Basin since the 19th century. From Table 1 it can be seen that for the same order of flood magnitude the year in which the flood happened varies at different locations, indicating the variations in spatial/temporal rainfall patterns causing these floods.

<table>
<thead>
<tr>
<th>River</th>
<th>Location</th>
<th>2nd Largest</th>
<th>3rd Largest</th>
<th>4th Largest</th>
<th>5th Largest</th>
</tr>
</thead>
<tbody>
<tr>
<td>Murray</td>
<td>Albury</td>
<td>1870</td>
<td>1917</td>
<td>1975</td>
<td>1974</td>
</tr>
<tr>
<td>Murray</td>
<td>Mildura</td>
<td>1870</td>
<td>1956</td>
<td>1931</td>
<td>1917</td>
</tr>
<tr>
<td>Murray</td>
<td>Morgan</td>
<td>1956</td>
<td>1870</td>
<td>1931</td>
<td>1917</td>
</tr>
<tr>
<td>Darling</td>
<td>Bourke</td>
<td>1864</td>
<td>1890</td>
<td>1976</td>
<td>1974</td>
</tr>
</tbody>
</table>

For example, according to Table 1, the 1956 flood is the largest recorded flood event at Morgan for the lower Murray River reach in South Australia, with the estimated recurrence interval of 1 in 160 to 180 years (SA Government, 1989), while flood happened in the same year is ranked as the second largest recorded at Mildura upstream of Morgan. The 1956 flood is not among the top five worst floods at further upstream locations such as Albury listed in Table 1, indicating that heavy rainfalls in the downstream area worsened the 1956 flood in the lower part of Murray Darling Basin significantly.

The 1956 flood extent data for the Wakool area obtained from DLWC Deniliquin office is shown in Fig. 2, which indicates around 50% of the total area was inundated at some stage during the flood.

Since the 1956 flood, the chances of flooding have been reduced for the lower Murray River reach due to development of irrigation and building of dams and reservoirs in the upstream area. For example, a previous study shows that at Chowilla of the Murray River (around SA/NSW border area) the probability in a year for getting a flood event with floodwater exceeding 100000ML/day would be 32% under natural condition rather than 9% under current regulated condition (Mussared, 1997).

The Edward River, which is branched from the Murray River near Mathoura and joined at around Deniliquin by several other waterways branched from the Murray River, is the major waterway carrying surface water from the upstream into the Wakool area. The Edward River is divided into two major waterway systems around the Wakool area when it passes Deniliquin, one can be described as the Edward – Niemur River system flowing through the central and northern part of the Wakool area and the other can be described as the Wakool River system flowing around the southern and south-western boundary of Wakool (see Fig. 2). Under normal major flood conditions floodwater passing through Deniliquin is approximately evenly distributed into these two systems (Water Resources Commission – NSW, 1981).
4. Data collection for this study

Information about streamflow gauging stations and some streamflow data were collected for an initial assessment for their applicability in this study. It is found that the available streamflow data does not have a good control of the streamflow flowing into and out of the Wakool area and thus can hardly be used in this study.

The data collection and analysis in this study was mainly concentrated on the piezometric data collected by Murray Irrigation Ltd (MIL). The shallow groundwater table has been monitored and recorded since 1963. Before 1978, the readings were normally taken in the months of Mar, Jun, Sep, and Dec of each year. After 1978, the piezometric readings are taken twice a year for most of the years, one around Feb and one around Aug.

The number and spatial distribution of piezometers with readings recorded at each of the reading months vary from time to time. The piezometric data collection is summarized in Table 2.

Table 2. Summary of piezometric data collected.

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of monitored piezometers:</td>
<td>1480</td>
</tr>
<tr>
<td>Total data period:</td>
<td>1963 Dec ~ 2001 Mar</td>
</tr>
<tr>
<td>Total number of years (up to 2001 Mar) covered by data:</td>
<td>38</td>
</tr>
<tr>
<td>Number of months in which readings were taken:</td>
<td>112</td>
</tr>
<tr>
<td>Maximum number of readings taken for a single piezo:</td>
<td>106</td>
</tr>
<tr>
<td>Maximum number of readings taken for a piezo in a year:</td>
<td>7 (in 1982)</td>
</tr>
<tr>
<td>Frequency of readings per year for most of the period:</td>
<td>Quarterly or biannually</td>
</tr>
<tr>
<td>Average number of readings taken per piezo over the whole data period (1963 Dec ~ 2001 Mar):</td>
<td>33.9</td>
</tr>
<tr>
<td>Number of piezos with no data (or data not available):</td>
<td>4.3%</td>
</tr>
</tbody>
</table>
5. Data processing

The piezometric data was converted to a ArcView GIS database so that spatial analysis of the water table change can be carried out.

In order to interpolate reliable water table surfaces at given dates from the GIS database for the whole Wakool area, the spatial distribution of piezometers with data available for each of the dates need to well cover the whole Wakool area. The piezometric data are further assessed for their temporal and spatial distribution. The number of piezometers with data available for each of the monitoring times and the description of their spatial coverage are listed in Table 3.

Table 3. Summary of temporal and spatial distribution of piezometers with data available for each monitoring round.

<table>
<thead>
<tr>
<th>Date</th>
<th>Count</th>
<th>Spatial Coverage</th>
</tr>
</thead>
<tbody>
<tr>
<td>1973-Mar</td>
<td>339</td>
<td>full</td>
</tr>
<tr>
<td>1973-Jun</td>
<td>217</td>
<td>full</td>
</tr>
<tr>
<td>1973-Sep</td>
<td>195</td>
<td>full</td>
</tr>
<tr>
<td>1973-Dec</td>
<td>302</td>
<td>full</td>
</tr>
<tr>
<td>1974-Mar</td>
<td>358</td>
<td>full</td>
</tr>
<tr>
<td>1974-Jun</td>
<td>297</td>
<td>full</td>
</tr>
<tr>
<td>1974-Sep</td>
<td>269</td>
<td>full</td>
</tr>
<tr>
<td>1974-Dec</td>
<td>303</td>
<td>full</td>
</tr>
<tr>
<td>1975-Mar</td>
<td>417</td>
<td>full</td>
</tr>
<tr>
<td>1975-Jun</td>
<td>450</td>
<td>full</td>
</tr>
<tr>
<td>1975-Sep</td>
<td>426</td>
<td>full</td>
</tr>
<tr>
<td>1975-Dec</td>
<td>356</td>
<td>full</td>
</tr>
<tr>
<td>1976-Mar</td>
<td>448</td>
<td>full</td>
</tr>
<tr>
<td>1976-Jun</td>
<td>453</td>
<td>full</td>
</tr>
<tr>
<td>1976-Sep</td>
<td>455</td>
<td>full</td>
</tr>
<tr>
<td>1977-Mar</td>
<td>427</td>
<td>full</td>
</tr>
<tr>
<td>1977-Jun</td>
<td>445</td>
<td>full</td>
</tr>
<tr>
<td>1977-Sep</td>
<td>104</td>
<td>partial</td>
</tr>
<tr>
<td>1977-Dec</td>
<td>382</td>
<td>full</td>
</tr>
<tr>
<td>1978-Mar</td>
<td>450</td>
<td>full</td>
</tr>
<tr>
<td>1978-Sep</td>
<td>431</td>
<td>full</td>
</tr>
<tr>
<td>1979-Feb</td>
<td>482</td>
<td>full</td>
</tr>
<tr>
<td>1979-Aug</td>
<td>510</td>
<td>full</td>
</tr>
<tr>
<td>1980-Jan</td>
<td>544</td>
<td>full</td>
</tr>
<tr>
<td>1980-Aug</td>
<td>636</td>
<td>full</td>
</tr>
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<td>1981-Feb</td>
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<tr>
<td>1981-Aug</td>
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<td>712</td>
<td>full</td>
</tr>
<tr>
<td>1982-Apr</td>
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<td>partial</td>
</tr>
<tr>
<td>1982-May</td>
<td>424</td>
<td>partial</td>
</tr>
<tr>
<td>1982-Aug</td>
<td>804</td>
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<td>1982-Sep</td>
<td>98</td>
<td>partial</td>
</tr>
<tr>
<td>1982-Nov</td>
<td>451</td>
<td>partial</td>
</tr>
<tr>
<td>1982-Dec</td>
<td>105</td>
<td>partial</td>
</tr>
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<td>1983-Feb</td>
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<td>full</td>
</tr>
<tr>
<td>1983-May</td>
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<td>1983-Aug</td>
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<td>full</td>
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<tr>
<td>1983-Nov</td>
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<td>partial</td>
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<tr>
<td>1984-May</td>
<td>455</td>
<td>partial</td>
</tr>
<tr>
<td>1984-Jun</td>
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<td>partial</td>
</tr>
<tr>
<td>1984-Jul</td>
<td>869</td>
<td>full</td>
</tr>
<tr>
<td>1985-Feb</td>
<td>871</td>
<td>full</td>
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<tr>
<td>1985-Jul</td>
<td>860</td>
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</tr>
<tr>
<td>1986-Feb</td>
<td>885</td>
<td>full</td>
</tr>
<tr>
<td>1986-Jun</td>
<td>878</td>
<td>full</td>
</tr>
<tr>
<td>1987-Feb</td>
<td>750</td>
<td>partial</td>
</tr>
<tr>
<td>1987-Jun</td>
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<td>full</td>
</tr>
<tr>
<td>1988-Feb</td>
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<td>partial</td>
</tr>
<tr>
<td>1988-Jul</td>
<td>1128</td>
<td>full</td>
</tr>
<tr>
<td>1989-Feb</td>
<td>966</td>
<td>partial</td>
</tr>
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<tr>
<td>1990-Feb</td>
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</tr>
<tr>
<td>1990-Jul</td>
<td>1187</td>
<td>full</td>
</tr>
<tr>
<td>1991-Feb</td>
<td>885</td>
<td>partial</td>
</tr>
<tr>
<td>1991-Jul</td>
<td>871</td>
<td>partial</td>
</tr>
<tr>
<td>1992-Feb</td>
<td>916</td>
<td>partial</td>
</tr>
<tr>
<td>1992-Jul</td>
<td>910</td>
<td>partial</td>
</tr>
<tr>
<td>1993-Feb</td>
<td>889</td>
<td>partial</td>
</tr>
<tr>
<td>1993-Jul</td>
<td>904</td>
<td>partial</td>
</tr>
<tr>
<td>1994-Feb</td>
<td>891</td>
<td>partial</td>
</tr>
<tr>
<td>1994-Jul</td>
<td>909</td>
<td>partial</td>
</tr>
<tr>
<td>1995-Feb</td>
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</tr>
<tr>
<td>1995-Jul</td>
<td>861</td>
<td>partial</td>
</tr>
<tr>
<td>1996-Feb</td>
<td>125</td>
<td>partial</td>
</tr>
<tr>
<td>1996-Jul</td>
<td>750</td>
<td>partial</td>
</tr>
<tr>
<td>1997-Mar</td>
<td>387</td>
<td>partial</td>
</tr>
<tr>
<td>1997-Aug</td>
<td>389</td>
<td>partial</td>
</tr>
<tr>
<td>1998-Mar</td>
<td>348</td>
<td>partial</td>
</tr>
<tr>
<td>1998-Aug</td>
<td>389</td>
<td>partial</td>
</tr>
<tr>
<td>1999-Mar</td>
<td>385</td>
<td>partial</td>
</tr>
<tr>
<td>1999-Aug</td>
<td>389</td>
<td>partial</td>
</tr>
<tr>
<td>2000-Mar</td>
<td>385</td>
<td>partial</td>
</tr>
<tr>
<td>2000-Aug</td>
<td>507</td>
<td>full</td>
</tr>
<tr>
<td>2001-Mar</td>
<td>505</td>
<td>full</td>
</tr>
</tbody>
</table>
Maps showing spatial distributions of the piezometers with data available at each of the dates listed in Table 3 and surfaces representing the water table depth generated from those data using the ArcView GIS Spatial Analyst extension are presented in Appendix A.

Those water table surfaces generated from the piezometers with data available covering the whole Wakool area are used in the flood impact analysis.

6. Spatial extent and magnitude of water table response to the 1973-75 floods

The 1973 – 75 is the wettest period within the data period (1963 –2001) with major floods happened during this period ranked in the top five floods ever recorded at major locations in the Murray Darling Basin (see Table 1). There were 10 flood peaks occurred in the Murray Irrigation Area during the 1973-75 extremely wet period (Bogoda et al. 1995).

Water table in March 1973 (see Fig. 3) was selected as the reference water table as there was no significant water table change before that time and from that time onwards water table started to change significantly due to the flooding (see Fig. A23 - A45 in Appendix A).

Water tables after March 1973 were then compared with that in March 1973. From changes in the spatial extent of water table depth during the floods (see Fig. A37 – A49 in Appendix A), it is shown that there have been significantly change in water table in each of the three years of 1973-75. The maximum water table mound happened around December in each of the years. The floods happened in 1974 and 1975 were much worse than that in 1973.

GIS techniques, such as spatial analysis and 3D analysis, were applied to identify and visualize the spatial extent of water table change during the floods. Fig. 4-20 show the spatial extent of water table change at different stages during the floods, that is, the spatial extent of the difference between the water table in March 1973 and that in other respective months.

6.1. The nature of 1973-75 floods reflected by the spatial extent of water table rise

Both the spatial extent of water table rise area identified through GIS analysis and the rainfall data at Moulamein Post Office (refer to Table 4-5 and Fig. 23) suggest that the floods were caused by large-scale heavy rainfalls. The floodwater came from both upstream discharges and local rainfalls. This is indicated by that a large portion (82%) of the Wakool area had showed a water table rise between 0~3m from the March 1973 level in a short period of time to June 1973, instead of showing water table rise starting from a relatively small portion of areas along the waterways and in the low lying areas as it would if the floodwater were only from upstream area, suggesting that local rainfall at the early stage of the wet period was the major cause of the initial large extent water table rise.

The spatial extent of water table change at different times and the rainfall data at Moulamein Post Office also suggest that during 1973–75 at least three large flood events happened around the Wakool area, one during September 1973 – January 1974, one around June 1974 –
December 1974. Following the 1973-74 floods, another big flood event happened around December 1975 in this region (see also Table 1). Several large flood events happened in a relatively short period of time is a major characteristic of the 1973-75 floods and a reflection of the highly variable climate affecting this region.

6.2. The water table rise process and water table change spatial extent

As the floodwater from both local rainfall and upstream discharge continued recharging shallow groundwater, high water table area started to spread from the original high water table area in all directions but more extensively towards the northwest as shown in Fig A37 - A49 in Appendix A.

With floodwater from both local rainfall and upstream discharge filling up relatively low lying areas and causing inundation, water table in these areas rose much more greater than that in other areas and started to form new high water table spots (see Fig. 4 – 20 and Fig. A37-A49 in Appendix A).

Fig. 4 – 20 also indicate that, for the 1973 flood, the floodwater formed in the upstream area initially came from the Edward River and then flowed into the Niemur River, inundating low lying areas and forming high water table rise spots along the Niemur River. As the flood continued worsening, the Wakool River was overflown between June 1973 and September 1973 forming another high water table rise spot in the south-west border of the Wakool area. The spatial pattern of water table change for the 1974 flood was similar to that of 1973.

The spatial distribution of the high water table rise areas during the 1975 flood were mainly distributed along the Niemur River, which was different from that during 1973-74 floods and suggested that the flood coming into Wakool area have a larger proportion from the Niemur - Edward Rivers than that from the Wakool River, as compared with the 73-74 floods. It was estimated that 35% of the flood passing Deniliquin flowed into the Wakool River system in November during the 1975 flood instead of 50% in other major flood events prior to 1975 due to the effect of flood mitigation engineering work built between the 1974 flood and the 1975 flood, (Water Resources Commission – NSW, 1981).

Fig. 10 shows the water table change contour and the high water table rise spots where water table rose by more than 4m when the water table rise reached its maximum around September - December 1974 during the 1973-74 floods. At that stage water table in 96% of the Wakool area rose by more than 0.5m and water table in 75% of the area rose by more than 1m, as compared with the March 1973 water table (see Fig. 10-12 and Table 4-5).

For the 1975 flood there was no significant difference in water table change areas at its maximum water table mound around December 1975, as compared with the areas of water table change around September 1974 for the 1974 flood (see Fig. 19-20 and Table 4-5). However, the high water table rise areas were distributed more along the Niemur – Edward River system than along the Wakool River system, which is consistent with the estimation of floodwater distribution between the two major waterway systems for the 1975 flood (Water Resources Commission – NSW, 1981).

6.3. Comparison between water table change extent and the 1956 flood extent
Compared with the 1956 flood (see Fig. 2 and Fig. 10), the spatial extent of high water table rise areas during the 73-75 floods were approximately consistent with the inundated areas in the 1956 flood, suggesting that apart from the amount of floodwater the topography and the nature of waterways are the dominant factors affecting the spatial extent of flooding and subsequently the spatial extent of water table rise due to flooding. That is, water table rise due to the 73-74 floods was more dramatic in the same areas inundated in the 1956 flood than that in non-inundated area in the 1956 flood, with all the spots where water table rose more than 4m were in the 1956 inundated areas.

For the 1975 flood, most of the high water table rise areas were within the 1956 flood inundation zone, but mainly along the Niemur River as a larger portion of floodwater came from the Niemur – Edward River system than did other floods (Fig. 17).

Figure 3. Water table depth in March 1973 in the Wakool area.
Figure 4. Spatial extent of water table change between March 1973 and June 1973.

Figure 5. Spatial extent of water table change between March 1973 and September 1973.
A GIS Approach to Quantify Impact of Flooding on Shallow Groundwater Levels in the Wakool Irrigation District

Figure 6. Spatial extent of water table change between March 1973 and December 1973.

Figure 7. Spatial extent of water table change between March 1973 and March 1974.
A GIS Approach to Quantify Impact of Flooding on Shallow Groundwater Levels in the Wakool Irrigation District

Figure 8. Spatial extent of water table change between March 1973 and June 1974.

Figure 9. Spatial extent of water table change between March 1973 and September 1974.
Figure 10. Water table change between March 1973 and September 1974 and in comparison with the inundated area of 1956 flood in the Wakool area (see also Fig. 2).

Figure 11. Water table rise > 0.5m area in September 1974 as compared with Water table depth in March 1973 in the Wakool area.
A GIS Approach to Quantify Impact of Flooding on Shallow Groundwater Levels in the Wakool Irrigation District

Figure 12. Water table rise > 1m area in September 1974 as compared with Water table depth in March 1973 in the Wakool area.

Figure 13. Spatial extent of water table change between March 1973 and December 1974.
A GIS Approach to Quantify Impact of Flooding on Shallow Groundwater Levels in the Wakool Irrigation District

Figure 14. Spatial extent of water table change between March 1973 and March 1975.

Figure 15. Spatial extent of water table change between March 1973 and June 1975.
A GIS Approach to Quantify Impact of Flooding on Shallow Groundwater Levels in the Wakool Irrigation District

Figure 16. Spatial extent of water table change between March 1973 and September 1975.

Figure 17. Spatial extent of water table change between March 1973 and December 1975.
Figure 18. Water table change between March 1973 and December 1975 and in comparison with the inundated area of 1956 flood in the Wakool area (see also Fig. 2).

Figure 19. Water table rise > 0.5m area in December 1975 as compared with Water table depth in March 1973 in the Wakool area.
7. Quantifying impact of 73-75 floods on shallow groundwater

7.1. Quantifying areas of different water table change

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 Wakool area being less than 6m and with an average water table depth being 4.86m.

By the time the 1973-74 floods reached its maximum impact on the shallow groundwater around September - December 1974, the average water table rose by 1.58m from the March 1973 level, the average water table depth was reduced to 3.28m. Fig. 21 shows changes in the average water table rise and average water table depth at different stages during the floods. With the 1975 flood followed, the average water table depth was further reduced to 3.13m (see also Fig. A48 in Appendix A).
Areas of different water table changes derived from the GIS analysis are summarized in Table 4 and Table 5. For the spatial extent of these areas, please see relevant figures in the previous section and Appendix A. (Note: the total Wakool area used in this study is 223.3x10^3 ha, which is calculated by GIS application based on the Wakool boundary data obtained from MIL.)

**Table 4. Area (%) of different water table rise during the 1973-75 floods.**

<table>
<thead>
<tr>
<th>Year and Month</th>
<th>73Mar</th>
<th>73Jun</th>
<th>73Sep</th>
<th>73Dec</th>
<th>74Mar</th>
<th>74Jun</th>
<th>74Sep</th>
<th>74Dec</th>
<th>75Mar</th>
<th>75Jun</th>
<th>75Sep</th>
<th>75Dec</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total WT rise area</td>
<td>0.0%</td>
<td>82.0%</td>
<td>94.0%</td>
<td>98.0%</td>
<td>95.3%</td>
<td>98.3%</td>
<td>99.3%</td>
<td>98.0%</td>
<td>94.5%</td>
<td>95.1%</td>
<td>95.2%</td>
<td>98.8%</td>
</tr>
<tr>
<td>0-0.5M</td>
<td>0.0%</td>
<td>57.0%</td>
<td>41.8%</td>
<td>18.1%</td>
<td>20.5%</td>
<td>5.9%</td>
<td>3.2%</td>
<td>6.7%</td>
<td>12.7%</td>
<td>13.6%</td>
<td>12.5%</td>
<td>5.3%</td>
</tr>
<tr>
<td>0.5-1M</td>
<td>0.0%</td>
<td>15.6%</td>
<td>25.9%</td>
<td>39.2%</td>
<td>47.6%</td>
<td>25.7%</td>
<td>21.2%</td>
<td>18.6%</td>
<td>21.0%</td>
<td>26.1%</td>
<td>29.6%</td>
<td>19.3%</td>
</tr>
<tr>
<td>1-1.5M</td>
<td>0.0%</td>
<td>4.7%</td>
<td>13.6%</td>
<td>18.7%</td>
<td>22.1%</td>
<td>27.8%</td>
<td>32.1%</td>
<td>21.0%</td>
<td>23.2%</td>
<td>30.2%</td>
<td>27.2%</td>
<td>17.7%</td>
</tr>
<tr>
<td>1.5-2M</td>
<td>0.0%</td>
<td>2.5%</td>
<td>6.7%</td>
<td>10.6%</td>
<td>3.9%</td>
<td>18.6%</td>
<td>20.3%</td>
<td>25.1%</td>
<td>20.1%</td>
<td>15.8%</td>
<td>14.6%</td>
<td>19.8%</td>
</tr>
<tr>
<td>2-2.5M</td>
<td>0.0%</td>
<td>1.4%</td>
<td>3.3%</td>
<td>5.5%</td>
<td>0.9%</td>
<td>10.2%</td>
<td>11.0%</td>
<td>12.5%</td>
<td>11.8%</td>
<td>7.9%</td>
<td>7.1%</td>
<td>17.3%</td>
</tr>
<tr>
<td>2.5-3M</td>
<td>0.0%</td>
<td>0.6%</td>
<td>1.7%</td>
<td>3.3%</td>
<td>0.2%</td>
<td>4.9%</td>
<td>5.3%</td>
<td>6.9%</td>
<td>4.8%</td>
<td>1.3%</td>
<td>3.1%</td>
<td>8.1%</td>
</tr>
<tr>
<td>3-3.5M</td>
<td>0.0%</td>
<td>0.1%</td>
<td>0.7%</td>
<td>1.7%</td>
<td>0.0%</td>
<td>2.6%</td>
<td>2.9%</td>
<td>3.5%</td>
<td>0.7%</td>
<td>0.1%</td>
<td>1.0%</td>
<td>6.1%</td>
</tr>
<tr>
<td>3.5-4M</td>
<td>0.0%</td>
<td>0.0%</td>
<td>0.2%</td>
<td>0.8%</td>
<td>0.0%</td>
<td>1.6%</td>
<td>1.8%</td>
<td>2.1%</td>
<td>0.1%</td>
<td>0.1%</td>
<td>0.2%</td>
<td>3.3%</td>
</tr>
<tr>
<td>&gt;4M</td>
<td>0.0%</td>
<td>0.0%</td>
<td>0.0%</td>
<td>0.0%</td>
<td>0.0%</td>
<td>0.0%</td>
<td>0.0%</td>
<td>0.0%</td>
<td>0.0%</td>
<td>0.0%</td>
<td>0.0%</td>
<td>1.9%</td>
</tr>
</tbody>
</table>

**Figure 21.** Average water table change (spatial average) during 1973-75 floods as compared with water table in March 1973.
Table 5. Area (%) of different water table depth during the 1973-75 floods.

<table>
<thead>
<tr>
<th>Year and Month</th>
<th>73Mar</th>
<th>73Jun</th>
<th>73Sep</th>
<th>73Dec</th>
<th>74Mar</th>
<th>74Jun</th>
<th>74Sep</th>
<th>74Dec</th>
<th>75Mar</th>
<th>75Jun</th>
<th>75Sep</th>
<th>75Dec</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-0.5m</td>
<td>0.0%</td>
<td>0.0%</td>
<td>0.0%</td>
<td>0.1%</td>
<td>0.0%</td>
<td>0.2%</td>
<td>0.4%</td>
<td>0.0%</td>
<td>0.0%</td>
<td>0.0%</td>
<td>0.0%</td>
<td>0.0%</td>
</tr>
<tr>
<td>0.5-1m</td>
<td>0.0%</td>
<td>0.7%</td>
<td>0.6%</td>
<td>1.7%</td>
<td>0.4%</td>
<td>7.2%</td>
<td>8.5%</td>
<td>0.5%</td>
<td>0.1%</td>
<td>0.1%</td>
<td>0.4%</td>
<td>1.0%</td>
</tr>
<tr>
<td>1-1.5m</td>
<td>1.3%</td>
<td>4.3%</td>
<td>7.3%</td>
<td>12.0%</td>
<td>3.8%</td>
<td>13.8%</td>
<td>11.4%</td>
<td>9.6%</td>
<td>2.0%</td>
<td>3.8%</td>
<td>4.4%</td>
<td>11.8%</td>
</tr>
<tr>
<td>1.5-2m</td>
<td>5.5%</td>
<td>9.0%</td>
<td>12.1%</td>
<td>10.3%</td>
<td>12.7%</td>
<td>7.5%</td>
<td>10.1%</td>
<td>18.6%</td>
<td>12.6%</td>
<td>11.2%</td>
<td>10.5%</td>
<td>20.2%</td>
</tr>
<tr>
<td>2-2.5m</td>
<td>8.2%</td>
<td>7.4%</td>
<td>7.0%</td>
<td>7.6%</td>
<td>8.1%</td>
<td>6.8%</td>
<td>7.4%</td>
<td>13.7%</td>
<td>12.5%</td>
<td>10.0%</td>
<td>11.2%</td>
<td>12.5%</td>
</tr>
<tr>
<td>2.5-3m</td>
<td>6.3%</td>
<td>5.5%</td>
<td>5.9%</td>
<td>7.1%</td>
<td>5.7%</td>
<td>7.4%</td>
<td>8.7%</td>
<td>13.1%</td>
<td>14.6%</td>
<td>10.4%</td>
<td>11.7%</td>
<td>13.3%</td>
</tr>
<tr>
<td>3-3.5m</td>
<td>5.4%</td>
<td>6.9%</td>
<td>5.8%</td>
<td>9.0%</td>
<td>5.9%</td>
<td>12.6%</td>
<td>8.9%</td>
<td>8.4%</td>
<td>14.3%</td>
<td>14.1%</td>
<td>13.4%</td>
<td>10.6%</td>
</tr>
<tr>
<td>3.5-4m</td>
<td>5.1%</td>
<td>3.4%</td>
<td>9.0%</td>
<td>11.0%</td>
<td>14.2%</td>
<td>8.7%</td>
<td>10.0%</td>
<td>6.3%</td>
<td>9.1%</td>
<td>10.1%</td>
<td>10.1%</td>
<td>4.6%</td>
</tr>
<tr>
<td>4-5m</td>
<td>17.0%</td>
<td>21.6%</td>
<td>21.2%</td>
<td>13.4%</td>
<td>18.0%</td>
<td>13.9%</td>
<td>11.9%</td>
<td>9.7%</td>
<td>12.3%</td>
<td>15.3%</td>
<td>12.2%</td>
<td>8.4%</td>
</tr>
<tr>
<td>5-6m</td>
<td>21.3%</td>
<td>16.5%</td>
<td>9.9%</td>
<td>9.4%</td>
<td>12.4%</td>
<td>9.2%</td>
<td>14.4%</td>
<td>9.7%</td>
<td>13.4%</td>
<td>12.4%</td>
<td>7.1%</td>
<td></td>
</tr>
<tr>
<td>6-7m</td>
<td>15.2%</td>
<td>11.7%</td>
<td>10.4%</td>
<td>10.2%</td>
<td>12.8%</td>
<td>8.5%</td>
<td>7.3%</td>
<td>8.2%</td>
<td>6.7%</td>
<td>11.4%</td>
<td>9.1%</td>
<td></td>
</tr>
<tr>
<td>7-8m</td>
<td>13.4%</td>
<td>11.1%</td>
<td>9.3%</td>
<td>7.4%</td>
<td>4.8%</td>
<td>3.6%</td>
<td>0.9%</td>
<td>2.0%</td>
<td>2.2%</td>
<td>2.3%</td>
<td>2.0%</td>
<td>1.2%</td>
</tr>
<tr>
<td>8-9m</td>
<td>1.2%</td>
<td>1.2%</td>
<td>1.0%</td>
<td>0.6%</td>
<td>0.9%</td>
<td>0.5%</td>
<td>0.1%</td>
<td>0.2%</td>
<td>0.3%</td>
<td>0.3%</td>
<td>0.2%</td>
<td>0.1%</td>
</tr>
<tr>
<td>9-10m</td>
<td>0.1%</td>
<td>0.5%</td>
<td>0.4%</td>
<td>0.2%</td>
<td>0.1%</td>
<td>0.0%</td>
<td>0.0%</td>
<td>0.0%</td>
<td>0.1%</td>
<td>0.1%</td>
<td>0.0%</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>99.9%</td>
<td>99.8%</td>
<td>99.8%</td>
<td>99.9%</td>
<td>100.0%</td>
<td>100.0%</td>
<td>100.0%</td>
<td>100.0%</td>
<td>100.0%</td>
<td>100.0%</td>
<td>100.0%</td>
<td></td>
</tr>
</tbody>
</table>

7.2. Quantifying the impact on shallow groundwater storage

GIS techniques were applied to quantify the net shallow groundwater storage change as compared with the water table level in March 1973. The volumes between the water table surfaces were calculated in the GIS application. Then an appropriate average specific yield ($S_y$) was selected for the estimation of the net equivalent water volume.

Based on the soil types in the profile recorded in the bore logs for the south part of the Wakool area and the estimated $S_y$ for a certain soil type, it is estimated that for the soil types in the Wakool area, the average $S_y$ over the whole Wakool area is approximately between 0.03 and 0.05. Considering the soil types in the rest of the Wakool area tend to be clayey and heavier (Smith et al., 1943), 0.03 was used for the estimation.

The estimated net groundwater storage change from the March 1973 level over the whole Wakool area is presented in Fig. 23, along with the monthly rainfall recorded for the same period at Moulanem Post Office.

The results (see Fig. 23) show that:
• There is a significant connection between the local rainfall and the water table change, suggesting that the local rainfall have contributed a significant portion to the floods in the Wakool area.
• The first maximum water table mound appeared around December 1973, after that water table start to decline. With the 1974 flood followed, the water table rose again and reached the maximum water table mound around September – December in 1974.
• The maximum increase in the net shallow groundwater storage caused by the flooding by the end of 1975 is around 116x10^3 ML (equivalent to an average net recharge of 0.52ML/ha or an average water table rise of 1.73m from the March 1973 level).
• After water table rise reached its maximum extent, there was around 19 ~ 28x10^3 ML of the groundwater discharged in the following three months for each of the large flood events during 1973-75. 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 6), suggesting that a higher water table created a higher hydraulic gradient which would accelerate groundwater discharging and a higher water table would also increase evaporation from the groundwater.
• The groundwater recession after flooding slowed down gradually and subject to the weather conditions and the management actions following the flooding. A typical groundwater recession process is shown in Fig. 22, which shows groundwater recession following the maximum water table mound of the 1975 flood from December 1975 to March 1978, just before the 1978 flood, during which there appeared no significant events affecting the water table.
• 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 will be. Table 6 and Table 7 shows that at the early stage of the wet period, as water table was relatively low, there was 70.1x10^3 ML recharged to the groundwater by the 1973 flood at the stage of maximum water table mound. When the next flood came, as water table was already high, the maximum recharge due to 1974 flood reduced to around 55.2x10^3 ML. Similarly, the 1975 flood resulted in a further reduced net recharge of 44.2x10^3 ML.

Table 6. Groundwater recession three months later following maximum water table mound during the 1973-75 floods.

<table>
<thead>
<tr>
<th>Date of maximum WT mound</th>
<th>Average WT depth (m)</th>
<th>GW storage change (from 73Mar) (10^3ML)</th>
<th>GW storage change 3 mths later (10^3ML)</th>
<th>GW storage reduced by (10^3ML)</th>
</tr>
</thead>
<tbody>
<tr>
<td>73Dec</td>
<td>3.81</td>
<td>-70.10</td>
<td>-50.51</td>
<td>19.59</td>
</tr>
<tr>
<td>74Dec</td>
<td>3.28</td>
<td>-105.72</td>
<td>-81.94</td>
<td>23.78</td>
</tr>
<tr>
<td>75Dec</td>
<td>3.13</td>
<td>-116.08</td>
<td>-88.49</td>
<td>27.59</td>
</tr>
</tbody>
</table>

Table 7. Net recharge when water table mound reached maximum for each major flood during 1973-75.

<table>
<thead>
<tr>
<th>Date of maximum WT mound</th>
<th>Initial average WT depth before flood (m)</th>
<th>Average WT depth at max. WT mound (m)</th>
<th>Change in average WT depth (m)</th>
<th>Net recharge caused by the flood (10^3ML)/ML/ha</th>
</tr>
</thead>
<tbody>
<tr>
<td>73Dec</td>
<td>4.86</td>
<td>3.81</td>
<td>1.05</td>
<td>70.10/0.31</td>
</tr>
<tr>
<td>74Dec</td>
<td>4.11</td>
<td>3.28</td>
<td>0.83</td>
<td>55.2/0.25</td>
</tr>
<tr>
<td>75Dec</td>
<td>3.79</td>
<td>3.13</td>
<td>0.66</td>
<td>44.2/0.20</td>
</tr>
</tbody>
</table>
Figure 22. Groundwater recession process following the maximum water table mound of the 1975 flood. (Negative storage change means increase in groundwater storage from March 1973 level.)
Figure 23. Net groundwater storage change as compared to water table in March 1973.
8. Quantifying impact of more frequent floods on shallow groundwater.

8.1. The 1981 flood

Based on the weather conditions represented by the rainfall data at Moulamein Post Office, the frequency of the flood in 1981 is roughly in the order of 1 in 10 years. In 1981, there was around 63% of the annual rainfall (519mm, Jan – Dec) fell between February and July of that year (329.4mm), 75% of which fell in March (93.2mm), June (77mm) and July (77.8mm). Fig. 24 and Fig. 25 show water table in February 1981 and August 1981 respectively. The water table change between them is shown in Fig. 26.

Referenced to the water table at February 1981 level with an average water table depth being 4.28m (Fig. 24), by the time in August 1981, the net groundwater storage increased by around $42.68 \times 10^3$ ML (an average of 0.19ML/ha) and the average water table depth reduced to 3.64m, estimated in the same way as mentioned previously (Fig. 24-26).

![Water table depth in 1981 February](image)

**Figure 24.** Water table depth in February 1981 in the Wakool area.
Figure 25. Water table depth in August 1981 in the Wakool area.

Figure 26. Water table change between February 1981 and August 1981.
By the time in February 1982, the water table had not returned to the level of a year ago, as the net groundwater storage was still $2.693 \times 10^3$ ML greater than that in February 1981. It took around one and half years from August 1981 for the water table to return to the February 1981 level under a very dry condition in 1982, with only 140.8mm rainfall for that year (Jan-Dec) and being the second driest year recorded at Moulamein Post Office (1889-1999 data).

Compared with the water table in February 1981, by August 1981 the area where water table rose more than 2m was around 4% of the total Wakool area and the area where water table rose more than 0.5m was around 48% (see Fig. 26).

By February 1982, the area where water table was still 0.5m higher than that in February 1981 reduced to 35% and the area where water table was still 2m higher than that in February 1981 reduced to less than 1% of the total Wakool area.

The recession in groundwater storage following the 1981 flood was almost linear with time before the next flood event in 1983 under the dry conditions experienced in 1982, as shown in Fig. 27.

![Groundwater Change around 1981 Flood](image)

**Figure 27.** Groundwater recession process following the maximum water table mound of the 1981 flood. (Negative storage change means increase in groundwater storage from March 1973 level.)

### 8.2. The 1992 flood

Based on the rainfall data at Moulamein Post Office, the frequency and magnitude of the 1992 flood is similar to that of 1981 flood. Around 56% (293.8mm) of the annual rainfall (528.4mm, Jan-Dec) in 1992 fell in the summer months from October to December. Due to lack of the piezometric data around 1992, the impact of 1992 flood was not estimated. However, it can be expected that the initial impact would be similar to that of 1981 flood.
As 1992 and 1993 were both relatively wet years, water table change following the 1992 flood would be different from that of the 1981 flood.

8.3. Change in shallow groundwater 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 can be derived from the piezometric data for the whole Wakool area are shown in Fig. 29 (see also Table 3 and Appendix A).

Before the 1973 flood, the water table fluctuated up and down not far away from the March 1973 level. After the 1973-75 wet period, water table rose considerably and has showed no sign of returning to the March 1973 level, except the unknown period of the 1990s due to lack of data.

By March 2001, the average water table was 0.82m higher than that of March 1973 with corresponding net groundwater storage of $54.93 \times 10^3$ ML (an average of 0.25ML/ha) greater than that of March 1973. However, for most of the area within the WTSSDS boundary, water table was below the March 1973 level due to the drainage effect of the scheme (see Fig. 28).

**Figure 28.** Water table change in March 2001 as compared with water table in March 1973.
Figure 29. Change in shallow groundwater storage and average water table depth over the data period for the whole Wakool area.
9. Summary and conclusions.

By compiling piezometric data into a GIS database and analyzing the data in a GIS application, we are able to quantify net recharge caused by flooding and to visualize the spatial extent of the impact of flooding on shallow water table reflected by water table change.

Restricted by the available data, the quantification of flood impact is mainly carried out for those years with sufficient piezometric data available.

The results show that flooding has a significant impact on shallow groundwater. The floods during the record wet period of 1973-75 caused a net recharge of around $116 \times 10^3$ ML (0.52 ML/ha in average) at the stage when the water table rise reached its maximum value around December 1975. In a big flood event, such as experienced during 1973-75, recharge from other sources other than flood may be negligible.

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 before the flood, which affects shallow groundwater storage capacity. The higher the initial water table is, the less shallow groundwater storage capacity will be, and consequently there will be less room for net recharge, as shown during the 1973-75 floods.

More frequent flooding such as the one experienced in 1981, whose recurrence interval is estimated as around 1 in 10 years, could result in $42.68 \times 10^3$ ML or an average of 0.19 ML/ha net recharge at the stage around maximum water table mound, given the initial average water table depth being at 4.28 m.

The major flood recharge areas within the Wakool area are mainly located along the Edward – Niemur river system.

Groundwater recession following a flooding is affected by a number of factors, such as initial water table depth, climate conditions, management actions and etc.

The average specific yield (Sy) is a critical parameter in estimating the net recharge and is very difficult to determine accurately. Sy=0.03 was used in this study based on the borelog analysis in the Wakool area and the experience in this area.

There are strong connections between local rainfall, flood, and water table change, suggesting that the floods happened in this area are normally due to both upstream and local rainfall.

By the time of March 2001, the shallow groundwater storage and average water table depth has not returned to the March 1973 level. The net groundwater storage in March 2001 is still $54.93 \times 10^3$ ML (an average of 0.25 ML/ha) 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, with water table in most areas within the WTSSDS boundary dropped below the March 1973 level and showing a sign that high water table area has been shifting towards the northwest.
Acknowledgement

This study is done in collaboration with Murray Irrigation Ltd (MIL) under funding from Rice CRC. The piezometric data and base GIS layers (roads, rivers, Murray LWMP area and Wakool boundaries) used in this study are supplied by MIL. The GIS data about the 1956 flood extent and some streamflow data are obtained from DLWC Deniliquin office.

The authors acknowledge feedback and suggestions from Mr. Ary van der Lely, a prominent hydrogeologist in the NSW Riverina region.

Reference:


