GIS-based Spatial Hydrological Zoning for Sustainable Water Management of Irrigation Areas

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Abstract: This study identifies hydrological zones in terms of their hydrologic suitability for sustainable irrigated agricultural development and management in the Murrumbidgee Irrigation Area (MIA) of Australia. Spatial data, including soils, groundwater level and salinity, recharge to watertable, as well as aquifer hydraulic properties were analysed within a GIS framework. Critical threshold values used in zoning process were defined based on experts’ knowledge and literature review taking into account significant issues in irrigation management, e.g. root-zone depth, water quality for crops to maintain a sustainable yield, and target recharge for rice industry. Spatial datasets were processed, integrated and analysed in ArcGIS. An integrative spatial modelling approach was applied for delineating hydrological zones. The results can be used to manage landuse and irrigation practices to reduce accessions to the watertable thus minimising the risk of waterlogging and salinisation due to rising water table levels. Landuse data were incorporated to reveal irrigation occurred in each zone. Recharge potential maps under various landuses were also combined with the zones to determine areas that are well-suited for irrigation without incurring a high risk of waterlogging and salinisation. The analysis provides hydrological indicators to assess current hydrologic suitability, landuse, and potential opportunities for improvement and expansion of irrigated areas in the MIA.

Keywords: Salinity; Waterlogging; Suitability; Groundwater; Aquifer; MIA

1. INTRODUCTION

Waterlogging and salination of irrigated land are major obstructions to the sustainability of agriculture. They are eroding the valuable irrigated croplands and posing a life-threatening threat to Australia’s food security (National Land and Water Resources Audit, 2001). As one of the most evident adverse effects of irrigation development, the prime cause of these natural hazards is the rising watertable due to inadequate drainage, although strong climatic aridity is a pre-condition for salinity (Smedema, 1990). A combination of waterlogging and salinity stresses is a severe threat to crop growth, development and yield in arid and semi-arid regions like the Murrumbidgee Irrigation Area (MIA). There is an urgent need to spatially define areas of varying suitability for irrigation to avoid salinity and waterlogging for a sustainable agricultural production. Therefore, the objective of this study is to develop a GIS modelling approach to classify these areas as zones with similar hydrological characteristics suitable for irrigation and other land management practices in order to reduce the risk of salinity and waterlogging in the MIA.

2. STUDY AREA

Situated in south-west New South Wales of Australia, the MIA is about 3,120 km² with its major town centre in Griffith (Figure 1). The area is a flat open plain with an elevation ranging from 100 to 135m. There are approximately 795km of supply and drainage channels, whilst Mirrool Creek and the Murrumbidgee River cover a distance of 255k
within the boundary of MIA (Khan and Abbas, 2007). The annual average rainfall and pan evaporation at Griffith are 406mm and 1797mm, respectively (Bureau of Meteorology, 2006).

The MIA is located in the Riverine Plain associated with the Murray Geological Basin. The aquifers in the area consist of semi-consolidated to unconsolidated sedimentary deposits. There are three major aquifer systems. The surface Shepparton Formation (late Pliocene-Pleistocene) is sandy-clays with some local areas of poorly sorted sands. It can be further subdivided into two layers: the Upper Shepparton and the Lower Shepparton. The late Miocene-Pliocene Calivil Formation is in the middle. It contains a high proportion of coarse quartz sand with some lenses of clay. This formation is generally the most productive aquifer system. The deepest aquifer is the late Eocene-early Miocene Renmark Group. It is predominantly clay but comprise extensive areas of medium-grained quartz sand. The regional hydraulic gradient is from east to west, aligned with the surface flow system (Xevi, et al., 2010). Figure 1 shows a 3D conceptual groundwater flow system in the MIA. Each flow system has an area of recharge, an area of through flow or transfer, and one of discharge. The zonation of these areas is basically determined by the geomorphology of the aquifers and by the direction of hydraulic gradient. Most of the Upper Shepparton is less than 20m thick. The Lower Shepparton ranges from close to zero thickness in an area in the northwest to 60m thick in the southwest. The majority of Calivil is between 40 and 70m. The thickness of the Renmark ranges between 200m thick in the southwest to close to zero in the north east where the aquifer is essentially non-existent.

3. METHODS

3.1 Spatial Data

The hydrological zones are defined in terms of their hydrologic suitability for sustainable irrigated agricultural development and management. Spatial datasets of the above variables were extracted within the framework of GIS to develop hydrological zones in the MIA. Digital elevation model (DEM) at a 50m resolution (Figure 2a) indicates a potential occurrence of the local groundwater flow. There are five major soil types (Figure 2b): Red Brown Earth (RBE); Self Mulching Clay (SMC) Non Self Mulching Clay (NSMC). Xevi et
al. (2009) provides more detailed description of soil classification and mapping. There is an intensive network of about 864 piezometers across the region. The active piezometers are monitored twice a year in March and September representing pre- and post-rainfall groundwater levels. Datasets of depth to groundwater for September 2002 and September 2006 were selected to represent “dry” and “wet” years, respectively. Two maps showing groundwater tables (the difference between ground surface and piezometric heads) were generated based on about 800 piezometer readings recorded for each year (Figure 2c and 2d). The maps were interpolated from the piezometric data points using an inverse distance weighted (IDW) technique (Child, 2004). Considering that the sampling points were sufficiently dense with regard to the local variation we attempt to simulate, the IDW method is preferred in order to obtain the best representation of the desired surfaces. Hydraulic gradient (HD) was calculated using the observed water level in September 2002 for the Upper Shepparton Formation (Figure 2e). In line with surface flow system, regional hydraulic gradient is from east to west. Figure 2f shows the spatial pattern of vertical hydraulic conductivity ($k_v$) of the Upper Shepparton derived from soil characteristics. Electrical conductivity (EC) of groundwater was observed for two different periods, February 1998 and July 2002. As irrigation is dominant in the summer season (October to March), EC of July 2002 for the Upper Shepparton Formation was interpolated using the IDW technique and the resultant map is given in Figure 2g. Transmissivity ($T$) is a combination of horizontal hydraulic conductivity ($k_h$) and aquifer formation thickness. An averaged $T$ map (Figure 2h) was derived by multiplying $k_h$ with the weighted aquifer thickness of each formation (Upper Shepparton, Lower Shepparton and Calivil).

![Figure 2.](image)

Figure 2. (a) DEM with 50m resolution for MIA. (b) Soils. (c) Depth to watertable (m) - September 2002. (d) Depth to watertable (m) - September 2006. (e) HD of Upper Shepparton - September 2002. (f) $k_v$ of Upper Shepparton. (g) EC (dS/m) - July 2002. (h) Average $T$ (m$^2$/d) of Upper and Lower Shepparton, and Calivil.
Figure 3 is the available potential groundwater recharge maps for different combinations of landuses and soils in the region under 2002/03 climatic conditions (Xevi, et al., 2010). The maps show recharge/discharge that will occur under each land use, assuming that a particular land use type occupies the entire area of the MIA. Net groundwater recharge was obtained with positive values indicating water entering the saturated zone and negative ones representing water being withdrawn, i.e. evaporation, from the saturated/unsaturated zone.

3.2 Zoning Approach

Spatial datasets were processed, integrated and analysed in ArcGIS environment. All data layers were projected into WGS84 UTM Zone 55S coordinate system. Benchmark thresholds for determining risks and suitability for productive and sustainable agriculture were established. An integrative spatial modelling approach was developed for the purpose of delineating hydrological zones and landuse suitability in the MIA (Figure 4). Table 1 lists three critical threshold values of groundwater table, groundwater quality (EC) and recharge used in this process. The threshold value for watertable was set taking into account the fact that the root zone of most crops is less than 2m depth. An EC value smaller than 8dS/m is regarded as safe for most crops to maintain a sustainable yield, as well as taking into account the salt tolerance for most native vegetation. The threshold value for recharge was derived statistically. A histogram of recharge values for nine different land uses, or crops, with combinations of five soil types and seven groundwater levels in the period 2002-2003 output from SWAGMAN modelling simulation were plotted. The value of 1ML/ha which occurs most frequently was adopted. In addition, Dwyer Leslie Pty Ltd (1992) also recommended the adoption of a rice industry target recharge figure of 1ML/ha (100mm).

Water depth and EC are two key factors which play significant roles the zoning process. A general declining trend in the watertable of less than 2m depth was found in the MIA due to drought and decreased area grown to rice (Figure 5a and b). However, the plotted area in 2006 was much smaller than in 2002. Figure 5c indicates changes in watertable between the two years. Figure 5d presents areas with EC values greater than 8dS/m in 2002.

Figure 3. Recharge maps for various landuse types (2002/2003). Values > 0 represent recharge, and < 0 discharge/evaporation.
Table 1. Definition of threshold values for critical factors.

<table>
<thead>
<tr>
<th>Factor</th>
<th>Threshold</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water depth</td>
<td>≤2m</td>
<td>≤2m is regarded as shallow watertable</td>
</tr>
<tr>
<td>EC</td>
<td>&gt;8dS/m</td>
<td>&gt;8dS/m is regarded as saline watertable</td>
</tr>
<tr>
<td>Recharge</td>
<td>≤1ML/ha</td>
<td>≤1ML/ha is regarded as low recharge, and &gt;1ML/ha high recharge</td>
</tr>
</tbody>
</table>

Groundwater flow and aquifer hydraulic properties are also critical in defining the zones. HD, \( k_h \), and \( k_v \), as well as formation thickness in the study area are relatively constant and independent to changes in watertable and the other water balance components (Xevi, et al., 2010). These aquifer characteristics were used to derive a new factor called flux:

\[
\text{Flux} = T \times HD = k_h \times \text{Thickness} \times HD = V \times \text{Thickness}
\]

where \( V \) is Darcy’s velocity (m/d), and the product of \( V \) with thickness is a kind of flux per unit width (m²/d).

Although salinity and water table fluctuation in the Upper Shepparton Formation significantly affect salinisation and crop yield via capillary rise, the Lower Shepparton and Calivil Formations could also have impact on these issues through vertical connectivity, e.g., pumping and return flow. This is especially important to prolonged irrigation fields, such as MIA. In order to incorporate the influence of vertical connection among various formations, an average \( T \) of three layers, rather than \( T \) of the Upper Shepparton only, was used in equation 1. The flux map was intersected with the \( k_v \). Three classes were interpreted and linked to the drainage capacity (Table 2) with the help of DEM (Figure 6a). Areas where watertable is always high (≤2m) in both 2002 and 2006, or watertable is high (≤2m) and EC > 8dS/m in 2002, were mapped as severe waterlogging areas (Figure 6b). The map of severe waterlogging areas was then used as a mask to identify a new class in addition to Figure 6a. The hydrological zones were then generated as shown in Figure 6c.
4. RESULTS AND DISCUSSIONS

Four hydrological zones (Figure 6c) derived from GIS-based spatial modelling provide critical management zones to define hydrologic suitability for sustainable irrigated agriculture in the MIA. It is useful for managing key issues in water resource management, e.g., salinity and waterlogging. Irrigation development may proceed in the good and intermediate zones with reduced risk of waterlogging and salinisation. Irrigation development in the poor zones poses a high risk for waterlogging and salinisation.

Recharge maps shown in Figure 3 were incorporated into the map of hydrological zones (Figure 6c) using the criteria listed in Table 3. The results of the integration of these maps (Figure 7) provide hydrological indicators to assess current hydrologic suitability and land use, as well as potential opportunities for improvement in MIA. The maps in Figure 7 actually represent the hydrologic suitability of each landuse type over the entire MIA. In other words, if there is a choice to develop irrigated land within MIA, which areas are most and least suited to a particular land use type considering the risk of waterlogging and salinisation. The resultant maps also allow managers to look at recharge threshold for different crops, and to optimise crop combinations in each zone, so as to apply different management strategies to achieve sustainable development and ecological benefits of land and water resources.

Table 2. Criteria used to define drainage capacity.

<table>
<thead>
<tr>
<th>Class</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low drainage capacity</td>
<td>flux (\leq 4 \text{m}^2/\text{d} ) (or (k_v) is very low)</td>
</tr>
<tr>
<td>Medium drainage capacity</td>
<td>(4 \text{m}^2/\text{d} &lt; \text{flux} &lt; 42 \text{m}^2/\text{d} )</td>
</tr>
<tr>
<td>High drainage capacity</td>
<td>\text{flux} (\geq 42 \text{m}^2/\text{d} )</td>
</tr>
</tbody>
</table>

Figure 6. (a) Drainage capacity map showing groundwater flow and aquifer properties. (b) Areas with severe water logging. (c) Hydrologic suitability map.

Table 3. Criteria used to define hydrologic suitability of crops.

<table>
<thead>
<tr>
<th>Zones</th>
<th>High Recharge ((\geq 1 \text{ML/ha}))</th>
<th>Low Recharge (&lt; 1 ML/ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Good Drainage</td>
<td>Suitable</td>
<td>Suitable</td>
</tr>
<tr>
<td>Intermediate</td>
<td>Intermediate</td>
<td>Intermediate</td>
</tr>
<tr>
<td>Poor Drainage</td>
<td>Unsuitable</td>
<td>Unsuitable</td>
</tr>
<tr>
<td>Waterlogging</td>
<td>Unsuitable</td>
<td>Unsuitable</td>
</tr>
</tbody>
</table>
The land use map of 2000/2001 season (Figure 8a) representing the wettest year (for the project period) was overlaid with the hydrological zones (Figure 6c) to generate Figure 8b. This is to assess the hydrologic suitability of the land use in the wettest year and the potential risk for waterlogging and salinisation as a result of the irrigation development in the MIA. The analysis revealed that about 45% of irrigated agriculture occurred in “good” and “intermediate” zones; 13% was in the “good” zone, while approximately 32% was in the “intermediate” zone. There was 48% of total area of irrigated crops in the “poor” zone and the rest 7% happened in waterlogging area. Irrigation in the “good” zone should be retained since limitations to irrigated cropping in this zone can be overcome by standard irrigation management practices. These areas can be modernised for irrigation agriculture to improve the water use efficiency through land and water management plans. Limitations to irrigated agriculture in the intermediate zone need to be recognised because a decline in productivity caused by waterlogging and salinisation may occur over time and a range of land use problems may also develop if this land is used and managed inappropriately. There may be a need for irrigated land retirement from the poor zone areas. Irrigation practice in severe water logging zone should be restricted and consider for potential retirement. Finally, we believe a large area of good lands distributed in northwest of the MIA has a great potential to be intensified as irrigated agricultural land. We emphasise that our analysis was conducted without considering all factors needed to produce a comprehensive land suitability map. Such analysis will also require, among others, agronomic factors such as soil fertility and other morphological factors of the landscape.

Figure 8. (a) Irrigated land use for 2000/2001 season. (b) Irrigated crops in hydrological zones (2000/2001).
5. CONCLUDING REMARKS

We defined a hydrological zone as a component of a region with similar hydrological characteristics. This, in turn, determines the suitability for managing land use and irrigation practices to reduce accessions to the water table thus minimising the risk of water logging and salinisation due to rising water table levels. The hydrological zones were developed using spatial distribution of soils, groundwater characteristics and aquifer hydraulic properties. The suitability maps derived are valuable for discussions about the impact of recharge, land use and groundwater salinity on irrigated agriculture. They provide a blueprint for identifying areas that require a different management strategy in terms of land use change, or improvement in irrigation technology, or large scale water logging and salinity mitigation schemes. When the approach is implemented for actual use, cares should be taken regarding human intervention and the range of parameters that were applied for the definition of hydrological zones, e.g., unsuitable land could be developed or irrigated for crops or vine with high economic value by installing tile in the poor drainage areas. Results from this study will be used to aid the planning of management guidelines concerning current irrigation practices as well as future irrigation development in the MIA, such as the EnviroWise program which aims to maintain and enhance the sustainability of farming, rural industries and associated communities by funding from both the Federal and State Governments. The incorporation of such information into the program will support the protection and enhancement of the region’s natural resources, and to ensure that some key objectives of the EnviroWise program, that is to maintain or increase irrigated agriculture productivity and to keep drainage water quality within agreed standards, are being met.

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