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Understanding surface-ground water connectivity using water balance and geoelectrical resistivity techniques

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Abstract: Water management tools for improving water use efficiencies at the system level may lead to environmental externalities and the regional sustainability of irrigation areas could be linked with the hydrogeological settings of the underlying aquifers. Given the restricted and regulated flows in the Macintyre Brook sub-catchment, South Queensland, a strong connectivity is perceived between surface and ground water. This study focuses on understanding this connectivity and characterising hydrogeologic settings using geophysical resistivity surveys for improving environmental management in the catchment. The pseudo section apparent resistivity images indicate the presence of different lithological structures characterized by low and high electrical resistivities. The light soils with resistivity ranging from 300 to 1000 Ω-m show the presence of a permeable zone up to approximately 15 m having strong connectivity between the shallow water table and the river water. The depth of the river bed is about 8 m from the average soil surface and the lighter soils sitting around the river section provide gateway for river water / subsurface to move across during peak flows after rainfall events. However, a low permeability zone in the deeper layers (beyond 15 m up to the investigation depth of 50 m) is associated with lower resistivity values. The resistivity in this formation ranges from 40 to 200 Ω-m. The water balance analysis shows water gain that obviously means the catchment is very responsive to rainfall events and peak water flows in the river. The water table observations at various bore locations along the river system also shows increasing levels after the events of increased river flows and vice versa. This suggests strong surface-groundwater connectivity, which is consistent with the in-situ findings of the geophysical survey and the water balance of the river flows. This work is a step forward to sustainable use of water resources for assessing loss and gains of the river system.

Keywords: *hydrological behavior, surface-groundwater connectivity, resistivity methods, water balance*

1. INTRODUCTION

Irrigation and environmental sustainability have been managed as competing enterprises under separate and divergent control. There is increasing support for a "Harmonised" business approach to sustainable use of land and water resources. The CRC IF System Harmonisation research program seeks to identify business opportunities for improving the management of surface and groundwater resources to satisfy environmental and consumptive demand in irrigated catchments.

In Macintyre Brook, the announced allocation system is based on the assumptions that there will be sufficient available water for the users each year. Figure 1 shows the water components that are taken into account when determining an announced allocation. The continuous sharing and accounting (also known as capacity sharing) has recently been adopted in a number of irrigation areas in Queensland (Queensland Department of Natural Resources and Water, 2008).

Previous work has shown the application of non-invasive investigation techniques (e.g geophysical surveys) to explore soil formations, water quality and water movements in the aquifer systems. Allen and Merrick (2003) used a floating electrode array for rapidly imaging the hydraulic connectivity between watercourses and aquifers. Rouhani and Hojat (2004) carried out geoelectrical surveys using resistivity methods to determine lithologic specifications of geological layers and the groundwater situation. Khan et al (2006) used marine based geoelectrical imaging for rapid assessment of seepage losses from irrigation channels.

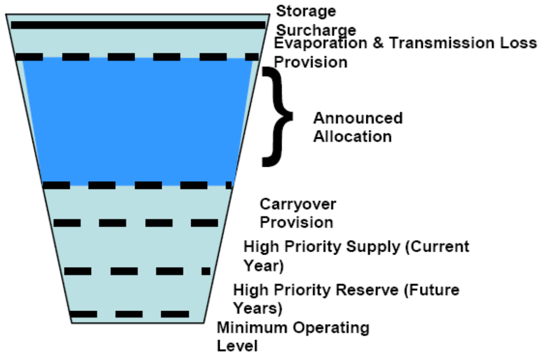


Figure 1. Conceptual model of the announced water allocation system

The benefits of new water sharing arrangements through hydrologic risk assessment are greatly realised. There is a need to characterise surface-groundwater connectivity and the level of harmonisation at multiple scales. It would help understand the hydrological implications of potential changes in selection of crop types, water use and irrigation system, which as a whole leads to the sustainability of the region. This study puts similar efforts together. The focus of present study is to understand the hydrologic settings of the surface and groundwater system in the irrigated area of the catchment. However, no similar work has been reported so far and the catchment lacks in biophysical data. These data gaps need to be filled by designing comprehensive field campaigns and fostering strong interaction between the research and the community. The specific objectives are:

- To collect field data and identify data gaps for the detailed hydrologic modelling
- To analyse available hydrologic data for the first-cut estimate of water balance
- To understand hydrogeologic settings of the river system for surface-ground water interactions.

2. STUDY AREA

Macintyre Brook River Sub-catchment is part of the Border Rivers Catchment extended between Queensland and New South Wales in the southwest (Figure 2). The Border Rivers catchment comprises the catchments of the Severn Rivers in the south-east, the Dumaresq River and Macintyre Brook in the east, the Macintyre River in the south and the Weir River in the north and north-west. The Macintyre Brook River Sub-catchment is a relatively small catchment covering an area of 4500 km^2 of which only 2050 ha (ANCID, 2005) are irrigated. The irrigated farmland is situated on both banks of the river. No irrigation supply channels exist in this area and water is directly pumped from the river. The major crops grown in the area include lucerne, sorghum, maize, olives and pastures for stock grazing. Based on field visits it is estimated that almost 90% of the irrigated land use is lucerne for hay and fodder. The total net crop water demand in 2004-05 was 13,145 ML with a peak demand of around 2,500 ML in January. The remaining part of the catchment is rain fed and comprises mainly with natural vegetation, production forestry and dryland farming.

The total surface water entitlement of the Macintyre Brook Irrigation Scheme is 24.5 GL which includes 11.2 GL of town water supply and end-of-system bulk water supply commitments for servicing (SunWater, 2005).

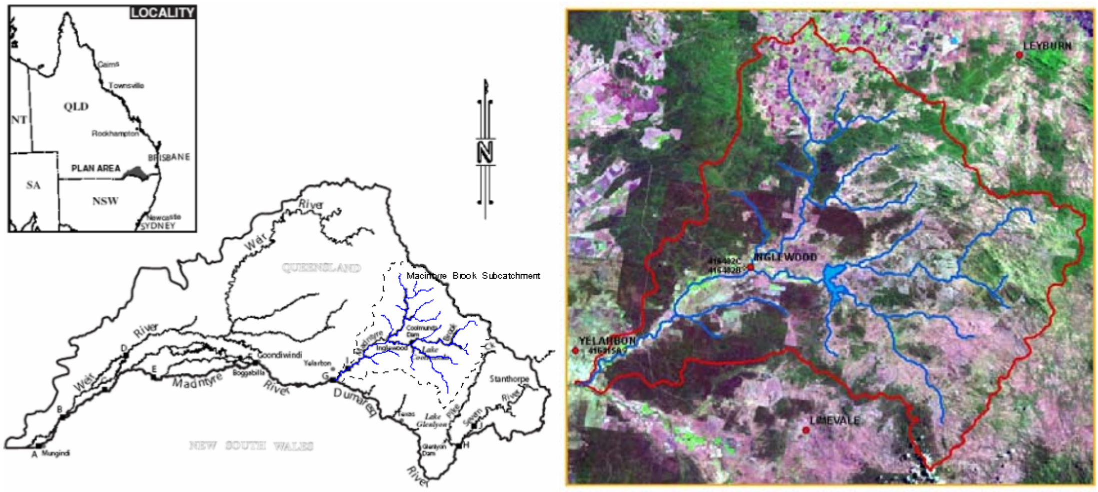


Figure 2. (a) Border Rivers Catchment, (b) the Macintyre Brook sub-catchment.

The average monthly climate data for the past 50 years since 1957 recorded at the Inglewood Post Office gauge is given in Figure 3(a). The average annual rainfall is 624 mm while average annual evaporation is 1847 mm. The annual rainfall data for the period 1957 to 2007 given in Figure 3(a) shows that 1962, 1975, 1983, 1988, 1996 and 1998 were the wettest years with over 800 mm of rain in the upper part of the study area. In drier years, stream flows in the Macintyre Brook River are dominated by releases from Coolmunda Dam. During wet periods, significant flows are contributed from the ungauged tributary creeks. Flows are monitored at a number of gauge stations. Daily flow release and daily dam storage data from the Coolmunda Dam is available only for last five years from 2002 to 2007 and is plotted in Figure 3(b). During last five years the storage level has never gone below 8,800 ML.

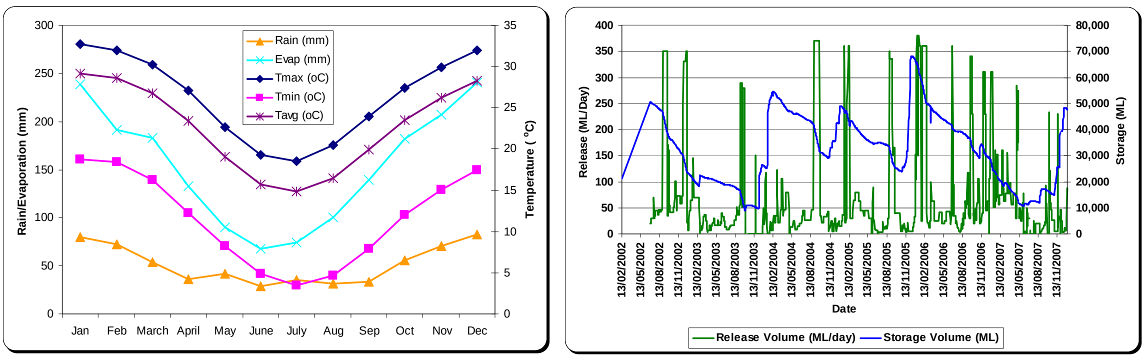


Figure 3. (a) Long-term (1957-2007) average climatic data (b) Daily storage volume and release rate from Coolmunda Dam.

3. CONTINUOUS SHARING AND ACCOUNTING SYSTEM (CSA)

The problem with the existing announced allocation/carryover approach is that all operational losses are apportioned across all users regardless of where and when the water is delivered. Thus individual water user behaviour can affect impact on the yield of water available for distribution and carryover water brought forward from the previous water year.

The CSA system is a conceptual method of water sharing that provides greater versatility in water management arrangements to customers while preserving their entitlements (Queensland Department of Natural Resources and Water, 2008). The concept of CSA (Figure 4) is based on individual management of water entitlements. It minimises the impact of the behaviour of one individual user on another, and provides maximum flexibility for the individual within the constraints of existing resource caps. Each user effectively has access to a share of the total combined storage capacities in the Scheme, and a share of losses and inflows according to pre-defined rules. In a CSA system the actions of an individual are not intended to be able to impact on the entitlement or opportunities of another individual. In CSA system the available storage can be conceptualized as being divided into vertical slices, with each slice representing an Individual Capacity Share (ICS) and each user manages his/her share.

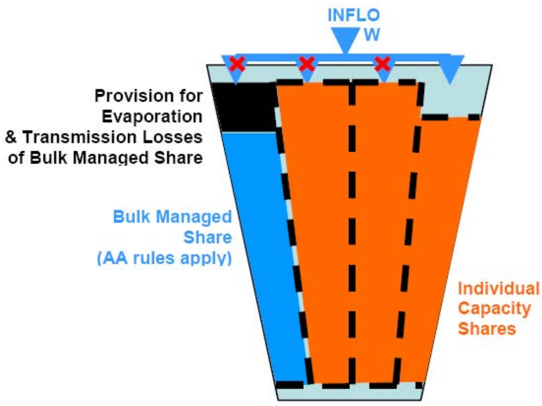


Figure 4. Conceptual model of CSA

4. METHODOLOGY

4.1. Field Measurements and Inverse Modelling

The methodology to assess water system performance will need to recognise spatial and time scales. Spatial scale ranges from farm to near-farm and their connectivity with river operation at the catchment level. Time scale ranges from real-time observations to seasonal river operations. This part of the project carries out a comprehensive assessment at the appropriate level of system's water balance. It will also determine the key drivers of surface-ground water connectivity. The water flow monitoring was conducted at 17 sites. Flow measurements were made on the main stream of the Macintyre Brook River and all its tributaries between Coolmunda Dam, Inglewood and Dumaresq River. The RiverCat discharge measurements were conducted at Macintyre Brook River and compared with stream flow-gauging station data.

The geophysical resistivity survey long the Macintyre Brook River was conducted to collect information about the hydrogeology of irrigated fields adjacent to the river to confirm the occurrence of surface-groundwater interactions. The 2-D geoelectrical survey was done by using the Wenner Schlumberger array for measuring both lateral and vertical resistivity variations.

The resistivity field data was imported by SYSCAL Pro Software (http://www.iris-instruments.com/index.html) and exported to RES2DINV (Geotomo, 2004) input format. The RES2DINV automatically subdivides the subsurface into a number of blocks, and it then uses a least-squares inversion scheme to determine the appropriate resistivity value for each block. RES2DINV is designed to invert large data sets (with about 200 to 21000 data points) collected with a system with large number of electrodes (Loke, 2003). Finite-difference modeling is used to calculate the apparent resistivity values. We display the result as pseudo sections of the surveys. The distribution of the percentage difference between the logarithm of the observed and calculated apparent resistivity is displayed by RMS error statistics.

4.2. Water Balance

The water balance of the river reach between Coolmunda Dam and end of the system (gauge before confluence with Dumaresq River) was carried out with the following simple equation:

$$\Delta S = I - O - D - Ev \qquad (1)$$

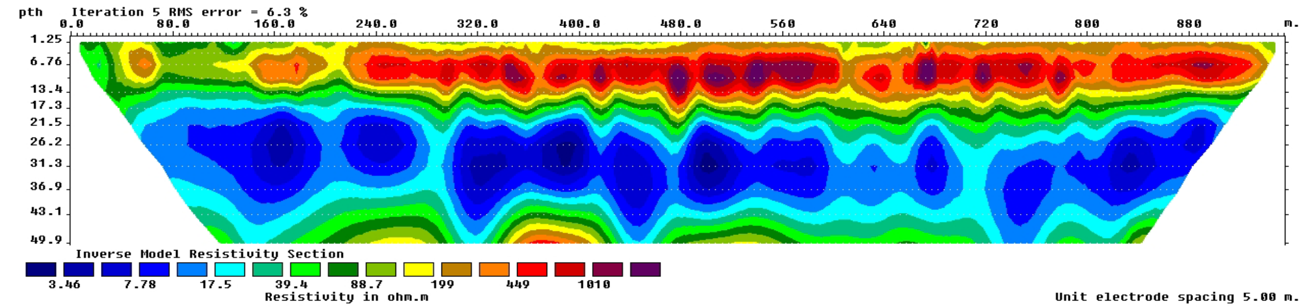
ΔS = net gain or loss, I = inflow to the system, O = outflow from the system, D = authorized diversions, and Ev = evaporation from river surface. The Ev term is negligible due to relatively very small magnitude. The "net gain or loss" represents surface-groundwater interaction, flow measurement and diversion errors.

5. RESULTS AND DISCUSSION

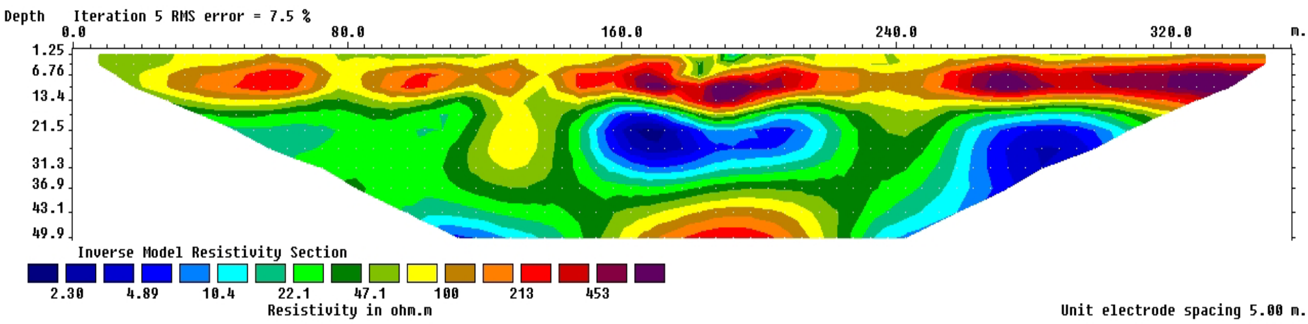
5.1. Geoelectrical Resistivity

Eight sites are examined using the roll-along capability of the SYSCAL Pro Switch (http://www.iris-instruments.com/index.html) and continuous data measurement is performed. The image gives an idea of the resistivity variations due to soil salinity, texture and degree of saturation of the spoil profile. The inverse modelling shows that the low resistivity zones reveal clayey formation, while the high resistivity area indicates more of sandy and profile saturation with fresh water reserves. A distinct contrast between the resistivity of the top soil, subsoil and the lower most soil layer is noticed. This shows the incidence of the higher resistivity layer up to 12-15 meters depth except few anomalies at some sites showing formations of relatively lower resistivity. The higher resistivity is an indication of strong connectivity between the river and the aquifer in the catchment. Very few discrepancies are noticed that could be neglected and we are much confident about the promising outcome of this survey.

Figure 5 (a) shows survey conducted in "Inglewood Farms" property. There is a sandy layer of higher resistivity in the top 13 m profile. This sandy layer is about 700 m in length along the survey line and could be said as a gateway for water connectivity in this farm. A clay formation is found beyond 17 m depth. Two distinct layers are found in this survey. This shows that the top soil is mainly sandy structures. The salinity of groundwater needs to be checked for very low resistivity in the deeper layers. Figure 5 (b) presents the image of the survey at olive farm with drip irrigation. From surface soil to 12 m depth, the apparent resistivity is high indicating coarser layers that provide a link for water flows to and from the river. There are strong vertical variations in the apparent resistivity showing variable structural formations. From 13 m to about 40 m depth, lower resistivities are observed indicating loam to clay loam structures. In the deeper layers, coarser material is again found which is shown in the middle part of the Figure 5(b). The contours in the images show presence of prior streams extending towards the river. The upper 12 m of the soil profile make up alluvium deposits and the lower layers make up clayey formations in the upper reaches of the river – Inglewood farms, Olive farms. The clayey formations are further deeper in the middle reaches of the river – Yarranbrook Farms, Organics Farms. There is strong surface water – groundwater connectivity as alluvium is



(a)



(b)

Figure 5. The inversion models of the apparent resistivity at two sites of the Macintyre Brook River valley.

directly linked with river cross-section. To quantify the surface groundwater interactions, data on water level in river and the groundwater is required. This work will be carried out once the required data is available for the detailed water balance analysis of the area.

5.2. Water Balance

The surface water balance was estimated for the river system starting from the Coolmunda Dam to the confluence with the Dumaresq River. A preliminary analysis of the available data is shown in Figure 6. The river system inflows represent the flow releases from Coolmunda Dam; the intermediate gauge is located at Inglewood just after the confluence of Canning Creek. The end-of-system flow is measured at Booba Sands, few kilometers upstream of the confluence with the Dumaresq River. The analysis indicates that there is imbalance between inflows, diversions and outflows (recorded at Booba Sands gauge) as shown in the Table 1. The evaporation term in equation 1 is neglected as being too small. The negative values in the last column represent system "gain" while positive figures represent system "loss". The net loss/gain term also includes the water that moved in/out of the aquifer system from/to the river system due to surface-groundwater interaction. The gain by the system indicates that the catchment is very responsive to rainfall events and therefore during wet periods and the irrigation diversions from the dam should be managed as part of resource management program. However, most of the system gains, which are very sensitive to rainfall events, come from tributary flows downstream of the dam and need to be monitored for accurate assessments of the flows in the catchment. One option is to build on-farm storages for rainfall harvesting during wet season and use the stored water to supplement irrigation during dry periods. Also

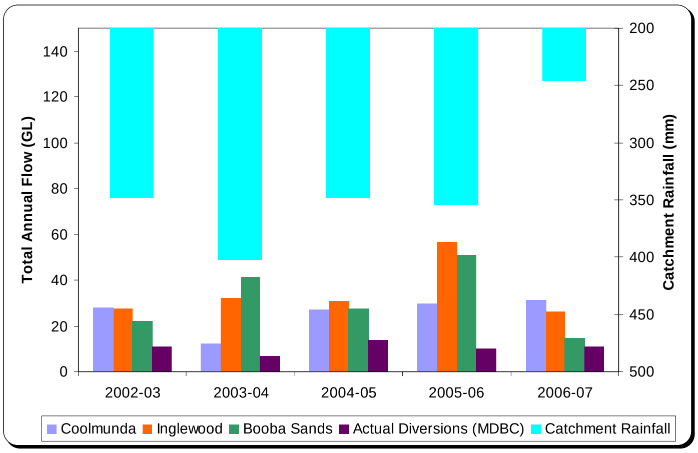


Figure 6. Catchment seasonal rainfall and average flows records

Table **1**. Water balance of the Macintyre Brook River. All values in GL.

Year	Inflows (*I*)	Outflows (*O*)	Inflow - Outflow	Actual Diversions (*D*)	Net Loss/Gain (ΔS)
2002-03	28.20	22.06	6.14	11	-4.86
2003-04	12.54	41.36	-28.83	7	-35.83
2004-05	27.16	27.52	-0.37	14	-14.37
2005-06	30.13	51.05	-20.92	10	-30.92
2006-07	31.48	14.71	16.77	11	5.77

Table **2**. In-situ measurements and water balance of river flows

Date	X	Y	Section (km)	Measured flow (ML/d)	Loss/gain (ML/d)
Section 1 5/02/08	321482	6853080		43.64	
	319727	6853567	2	88.98	-45.34
	318777	6853036	1	81.64	7.35
	317108	6853908	4	133.53	-51.89
	312431	6855877	9	262.77	-129.24
Section 2 6/02/08	312140	6857303		1767.92	
	311953	6855817	2	1977.09	-209.17
	307401	6855813	8	2322.26	-345.17
	302738	6851708	15	2177.97	144.29
Section 3 7/02/08	301933	6851915	9	2909.35	
	297923	6846210	6	2799.79	109.56
	297993	6844499	14	3164.66	-17.00
	293211	6840830	9	3106.17	58.49
Section 4 8/02/08	291551	6839099	2	2186.27	
	285590	6835324	2	2109.37	76.9
	282360	6830535	5	2092.35	17.02

there is a need to simulate the new allocation system of Continuous Sharing and Accounting (CSA) to investigate its effectiveness in terms of improvement in the system's efficiency.

The analysis of data in Table 2 indicates that most of the flow gain occurred upstream of Whetstone Weir. The main sources of surface flow contribution in the upper reach of the river (i.e. from kilometer 12 to kilometer 31) are the tributary creeks from the catchment with a major contribution from the Canning Creek. The most of the surface flow loss occurs along the second half of the river with major losses occurring along the middle section. This analysis is done for a measurement period during which heavy rainfall occurred in the catchment.

6. CONCLUSIONS

The water gains by the system indicate that the catchment is very responsive to rainfall events and irrigation diversions should be managed to minimize the end-of-system outflows. This also shows a strong interconnection between surface and shallow groundwater system. The discrepancies in surface flow data emphasize the need for efficient management of the new allocation system of Continuous Sharing and Accounting. The geophysical or resistivity survey results provide qualitative information about the subsoil material, which are helpful in identifying the subsurface material variations. Upper 12 m of the soil profile make up alluvium deposits and the lower layers make up clayey formations in the upper reaches of the river. However, it does not provide any quantitative information that can be used in building and calibrating a groundwater model. Quantification of surface-groundwater interactions is also not possible in the absence of complementary data including water levels and salinity of the river water and the groundwater in the adjoining areas.

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