

Assessing the Potential of Managed Aquifer Recharge: Preliminary Hydrological Findings from a Scoping Study in the Lower Namoi Valley, Australia

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Abstract

Groundwater overdraft in many aquifers in Australia provides the motivation for exploring more reliable water supply options. Demand management to date has not reversed the pattern of falling groundwater levels in many highly developed irrigation districts of Australia. The potential of MAR in Australia has not been fully realised and assessed in rural farming landscapes, an exception being a saline mitigation and aquifer recharge scheme in the Burdekin catchment in north Queensland. This limited uptake is due to several uncertainties surrounding MAR, which include that the benefits have not been economically validated, suitable sites have not been identified, and existing surface water and groundwater policies make implementation difficult. Another impediment is that reliable sources of water for aquifer recharge have not been identified. This paper examines source water availability for MAR in the Lower Namoi irrigation district within the Murray-Darling Basin. Forty years of daily streamflow data has been used to examine the occurrence of floods and to estimate water availability for aquifer storage. On average once every four years, 340 GL (85GL/year) of water may be available from high streamflow periods and floods under the current water allocation rules. The preliminary findings on water availability indicate that there are favourable conditions for implementing MAR in the Lower Namoi. Other MAR suitability conditions that remain to be assessed include the: hydrogeology and estimating the storage potential of the aquifers; regulatory and governance issues; methods of recharge; the costs of building, running and maintaining MAR infrastructure; and identifying the environmental risks.

Introduction

Groundwater plays an important role in supporting environmental and agricultural water demands in arid and semi-arid areas. In the last sixty years, cheaper well installation and pumping costs has resulted in exploitation of groundwater resources for domestic, industrial, and agricultural supplies. Globally, groundwater withdrawals total between 750 km³ and 800 km³ per year (Shah, 2000). While the economic gains from groundwater use have been substantial (Biriol *et al.*, 2010), aquifers in many parts of the world are stressed due to over extraction beyond the sustainable aquifer yield (Shah, 2000; Wada *et al.*, 2010). In many areas,

groundwater depletion has led to irreversible aquifer damage, with impacts including land subsidence, water quality deterioration, saline intrusion and damage to groundwater dependent ecosystems. In some locations around the world, groundwater mining has caused well yields to decrease to such an extent that pumping groundwater is uneconomical (Konikow and Kendy, 2005).

Due to the highly variable nature of surface water availability, groundwater use for irrigation has substantially increased since the 1960s in Australia. In many irrigation regions the volumes of water pumped from aquifers are much larger than their natural recharge, resulting in a continual drop in groundwater pressures (Nevill, 2009; MDBA, 2012). There has been a 90% increase in groundwater use across Australia since 1985, now averaging 5,000 GL/year (Khan, 2008). The National Land and Water Resources Audit (2001) highlighted that, of the 538 groundwater management units in Australia, 168 are over-allocated resulting in falling groundwater levels in the shallow unconfined systems and decreasing groundwater pressures in the semi-confined systems (MDBA, 2012).

Whilst there have been reductions in groundwater allocations for consumptive uses in many catchments under the Water Sharing Plan (WSP) mechanism (NSW Office of Water, 2012), the mechanism is not expected to reverse the pattern of falling groundwater levels in highly developed irrigation districts of Australia. The WSPs were not designed to restore groundwater levels, rather they were designed to balance recharge estimates with extraction rates, and the aquifers are yet to reach their new equilibrium. In addition, current water management approaches may not be sufficient to cope with the impacts of climate change and climate variability on the reliability of water supplies (Watts *et al.*, 2011). Climate change predictions and the occurrence of recent extreme droughts and devastating floods in eastern Australia have increased the need to re-examine water management options. Climate change and climate variability therefore is creating more risk to water security for the Australian landscape. In the near future rainfall variability is likely to increase and more frequent floods and droughts are anticipated (Bates *et al.*, 2008). In the southern Murray-Darling Basin (MDB), the climate is projected to become increasingly dry, and droughts are likely to be more regular and severe than ever (Wei *et al.*, 2011). Climate variability and groundwater overdraft in many aquifers in Australia motivate the need to explore reliable groundwater supply and innovative water management options. In the absence of a strategic water management response, climate change will threaten the viability of irrigated agriculture and other water-dependent industries in Australia (Khan, 2008).

There seems to be the potential to store large volumes of Australia's freshwater resources underground to avoid evaporation losses and to offset the impact of climate change. Managed Aquifer Recharge (MAR) has been demonstrated to be technically successful and cost-effective in many locations in the United States, India and the Middle East when compared with alternative surface water storage options. Benefits of storing water underground may include recharging depleted aquifers, increasing reliability of supply, enlarging storages without building new dams, reducing evaporative losses, reconnecting surface water and groundwater, and creating strategic water reserves for the future. MAR can compensate for the groundwater overdraft in stressed aquifers provided that environmental risks and water entitlements downstream are addressed as part of the assessment process. The potential role for MAR in Australia has not been fully realised (Parsons *et al.*, 2012). This is evident from the fact that MAR schemes exist only in concentrated pockets of Adelaide and Perth and in some rural areas. We highlight opportunities for MAR in the Lower Namoi irrigation district of New South Wales (NSW), where the concern regarding groundwater over-extraction has led to the development and commencement of WSP, resulting in significant reductions in groundwater allocation for consumptive uses.

The few quantitative MAR suitability studies have been conducted lack an interdisciplinary focus, failing to consider the whole range of suitability factors such as hydrology, hydrogeology, social, economic, regulatory, technical and environmental risks. In the current paper, we examine the potential of MAR in the Lower Namoi from the viewpoint of water source availability. We characterise forty years of daily streamflow data from 1972 to 2012 and examine the frequency of large flood and high flow periods.

Suitability of Managed Aquifer Recharge

Managed Aquifer Recharge is the intentional treatment and storage of water in aquifers. Managed Aquifer Recharge, groundwater banking and artificial recharge of groundwater are the terms used interchangeably in the literature. Dillon (2005) describes MAR as an umbrella term used for a variety of methods to effect intentional storage and subsequent recovery of water in aquifers. Water can be recharged by a number of methods including infiltration via basins or by injection wells. Much of the current literature on MAR deals with water quality aspects of the recharged and recovered water, and MAR operation and maintenance issues. Dillon *et al.* (2009) have summarised the current status and potential for MAR in Australia, while GHD Pty Ltd and AGT Pty Ltd (2011) discussed opportunities and major challenges of irrigation related MAR projects in Australia.

In many locations, MAR has been used successfully to address problems of aquifer overdraft, control saline intrusion to freshwater aquifers and increase the reliability of water supply in stressed aquifer systems. Aquifer suitability depends on a number of factors including aquifer size, depth, permeability and connections with other aquifers, rivers and ecosystems. Evaluating the suitability of MAR requires quantifying water availability, characterising the hydrogeology of the receiving aquifer(s), assessing the social acceptability and regulatory conditions, costing the technological options and quantifying the environmental risks. In contrast to other water infrastructure projects such as dams, weirs and barrages, the suitability of each MAR project is a unique combination of its topography, hydrology and aquifer characteristics (Bouwer, 2002).

At each location where MAR has been successfully undertaken around the world there are unique climatic, hydrologic, geologic, economic and social conditions. This has resulted in a variety of methods being devised to recharge shallow and deep aquifers. Two broad approaches to accomplish recharge include basin infiltration and well injection methods (Bouwer, 2002). Basin infiltration methods are suitable to recharge shallow unconfined aquifers with minimal treatment and may include deep, large diameter isolated wells, infiltration ponds and galleries, induced bank infiltration, leaky and recharge dams, floodwater spreading basins and redirecting floodwaters over the wider landscape to supplement areal recharge. Filtration methods require large surface areas and permeable soils to be effective (Bouwer, 1996; Pedretti, *et al.*, 2012). Boreholes have the advantage of targeting a desired aquifer for recharge (Pyne, 1995). Thus, zones of saline water or clay layers can be bypassed. However, boreholes are costly and require treated water for injection, and if clogging occurs they are difficult to repair. Passive borehole recharge requires limited mechanical assistance, but the infiltration rate is relatively low. Water injection using pumps can greatly improve the rate of aquifer recharge; however the pumps require constant maintenance and are costly to run. The risk of clogging is common to all active MAR methods. Solutions to this issue include stabilisation through settlement ponds, filtration through gravel and sand beds or accepting ongoing maintenance via bottom scraping of silts and clays.

Several MAR suitability studies have focused on the identification of potential MAR sites. The studies combine thematic maps of different layers in a GIS environment and generate qualitative maps of potential sites. Such MAR site suitability studies have been used widely worldwide (Saraf and Choudhury, 1998; Scatena and Williamson, 1999; Anbazhagan, 2005; Ravi Shankar and Mohan, 2005; Hostetler, 2007; Helm *et al.*, 2009; Kalantari *et al.*, 2010 and Malekmohammadi *et al.*, 2012). In Australia, two important studies contributed to site selection of MAR; Hekmeijer (2002) carried out a GIS based identification of MAR sites within the Port Phillip catchment of Victoria. To identify potential MAR locations, the study used multi-criteria analysis with sixteen suitability factors, the four most important being i) hydrology, ii) hydrogeology, iii) water demand and iv) environmental risks. Following Hekmeijer (2002) the Bureau of Rural Science Australia (Hostetler, 2007) used a multi-criteria approach and mapped nationwide locations across Australia where MAR could be successful. Both Hekmeijer (2002) and Hostetler (2007) weighted source water availability, favourable hydrogeological conditions, i.e. aquifer recharge, aquifer storage and aquifer delivery potential, as the most important factors dictating the suitability of MAR. The resultant nationwide GIS map is a significant resource to identify regions where MAR could be of potential benefit. However, GIS based MAR suitability studies are mainly qualitative and only identify locations where MAR can be potentially feasible. Such studies do not, for example, provide quantitative estimates of the volume of water for aquifer storage.

The recharge performance of a MAR system can be difficult to measure directly (Gale *et al.*, 2002) when there is more than one source of recharge and discharge within the same aquifer. Thus, only a detailed water balance study can provide quantitative estimates of the contribution of a scheme to groundwater recharge. Neumann *et al.* (2004) used a numerical modelling approach to give a quantitative measure of the effectiveness of artificial recharge structures in India. Their study examined effectiveness at three spatial scales; i) the reservoir scale to quantify the recharge performance of the infiltrating basin, ii) the aquifer scale to identify zones of recharge and iii) the community scale to quantify the overall benefit of MAR. Khan *et al.* (2008) evaluated potential costs and gains from a hypothetical MAR project in the Murrumbidgee irrigation region of Australia from hydro-economic perspectives. Similarly Kalantari *et al.* (2010) conducted site selection and economic analysis of aquifer recharge in the Baghmalek plain of South West Iran. Recently, Smith and Pollock (2012) studied behaviour of aquifer recharge from the hydrogeological domain and used a simple quantitative approach to assess the artificial recharge potential of infiltration ponds in a coastal plain of Perth, Australia. Such quantitative modelling studies in many instances are time and cost prohibitive. The previous MAR studies in the Lower Namoi were conducted with a limited scope and did not undertake any quantitative assessment with detailed hydrologic and hydrogeological analysis. For example, Woolley *et al.* (1994) focused only on areas where pilot MAR projects could be tested.

Potential of MAR in the Lower Namoi

In the current and following sections we discuss and highlight water availability from large flood events as an opportunity for implementing a regional scale Managed Aquifer Recharge scheme in the Lower Namoi valley of NSW (Figure 1 below).

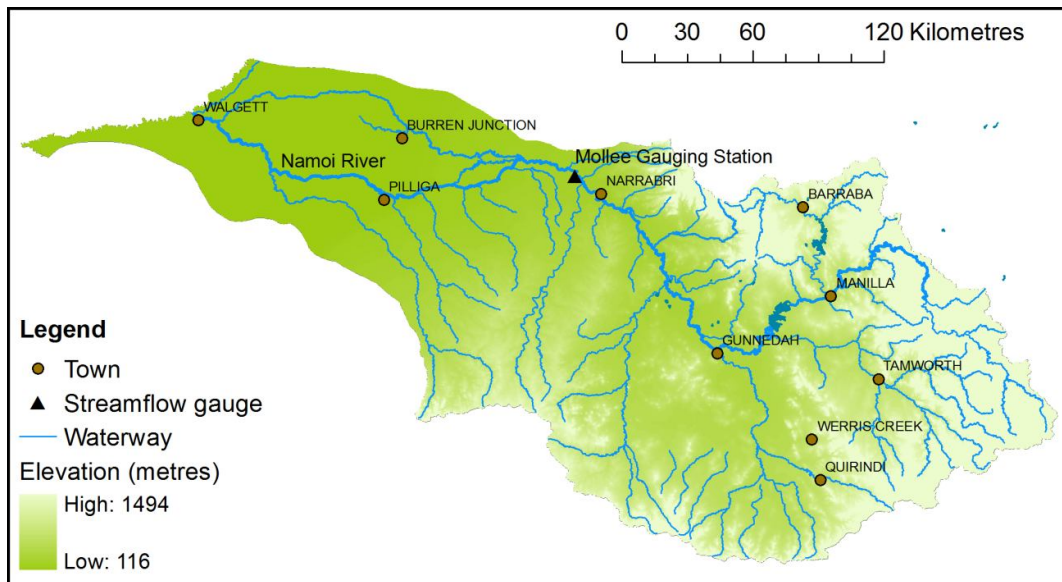


Figure 1. Map of the Namoi Catchment, NSW

The Namoi River Catchment is located in the central-north of the State of NSW within the Murray Darling Basin. The Lower Namoi is one of the most highly developed groundwater zones in NSW; as a result groundwater levels have been declining throughout the alluvial aquifer since the late 1960's. For the Lower Namoi aquifer system, the NSW Office of Water's regional groundwater model sets the operational sustainable yield as 86 GL/year (CSIRO, 2008). The catchment has a total land area of 42,000 square kilometres and the main agricultural activities are irrigated cotton, wheat and sheep farming. Cotton Australia (2006) estimated that the irrigated cotton area covers 440 square kilometres in the Lower Namoi. The Namoi River is a regulated river with three major surface water storage dams: Keepit Dam (425,510 ML); Chaffey Dam (61,830 ML); and Split Rock Dam (397,370 ML). An estimated 140,000 ML of off-river storages as on-farm dams is diverted during high flow periods (Burrell, 2011). Groundwater in the Namoi River Catchment supports an irrigation industry worth in excess of \$380 million per annum (Namoi CMA, 2011), as well as being the water supply for towns and intensive industries. The groundwater sources include water contained in the unconsolidated alluvial sediments associated with the Namoi River and its tributaries. The groundwater resources in the Lower Namoi are drawn from alluvial sediments which are up to 120 m deep (NSW Office of Water, 2012).

The alluviums of the Lower Namoi spread out in a fan extending approximately 100 km downstream from Narrabri (Figure 1) and are subdivided into three formations (Williams, 1986). The upper Narrabri formation consists of minor sand and gravel beds, while the middle Gunnedah formation is the main productive aquifer for irrigation wells and consists of gravel and sand with minor clay beds. At the base of the sequence is the Cubbaroo formation, consisting of sand and gravel with inter-bedded brown to yellow and grey clay. The alluvium of the Lower Namoi has a the potential to store large quantities of water as over-abstraction in the last fifty years has dropped water levels and depressurised the semi-confined aquifers. Future work will evaluate the capacity of the aquifers within the Lower Namoi to store water.

Water sources for MAR

In Australia, urban stormwater has been the major source of water for aquifer recharge. There has been little research on potential sources of water for MAR in rural settings. Under the current water allocation arrangements in Australia, particularly in the rural context, there are few opportunities to capture water for the purpose of MAR. A recent national workshop examining the potential for MAR in the Murray-Darling Basin identified three possible sources of water in regulated river systems (NCGRT, 2012). These are: a part of locally captured run-off (10% in NSW for dryland farms; no runoff is allowed from irrigation farms); and “supplementary water” during flood and periods of high streamflow. A third potential source of water for MAR could be the environmental water purchased by the governments from licence holders for environmental releases. The desired environmental outcomes may be achieved through storage in shallow aquifers, thus reconnecting rivers and aquifers.

“Supplementary water” is water that can be extracted from the river when a high river stage trigger has been reached. Such high flows may occur in response to inflows from tributaries downstream of the major storages or from dam storage spills when there is little or no immediate demand for the consumptive use. Such policies encourage the use of large-scale on-farm storages, from which there may be considerable water loss from both evaporation and leakage into underlying shallow saline aquifers. In many areas of Australia, including the Lower Namoi, supplementary water and local run-off is captured and stored in farm dams for stock supply and irrigation. Currently, farm dams across the Murray-Darling Basin have a combined capacity of 2,000 GL (CSIRO, 2008). Craig *et al.* (2005) estimated that up to 40 percent (800 GL) of this storage volume can be lost each year to evaporation. MAR can provide a low or no evaporation option for storage of water under these circumstances. Most situations in which there are opportunities for such water capture are on floodplains in the lower parts of major catchments. In these situations the alluvial sediments offer storage opportunities either through surface recharge or deep injection into alluvial aquifers, depending on local hydrogeology. Both irrigation water demand and its economic value in the Lower Namoi are high (ranging from tens to hundreds of dollars per ML), particularly during dry years when supplies from surface water are limited. The recent drought resulted in a significant decline in cotton production in the region. According to The Australian Cotton Grower (2012), in the wetter year of 1998/1999 about 60,000 hectares of cotton were grown in the Lower Namoi, whereas in the drought year of 2003/2004 only 26,300 hectares were planted due to limited access to surface water supplies and reductions in groundwater allocations.

High flood events in the Lower Namoi

The Namoi River follows an irregular flow pattern with moderate to large variability in inter-annual and inter-decadal flows. Figure 2 plots historical streamflow data of the Namoi River, highlighting peak events since 1900. The large floods observable in 1900, 1910 and 1955 would now only occur if the dams at the head of the catchment reached spilling point. The 1955 pre dam construction flood peaked at 800,000 ML/day. In contrast, the average flow of the Namoi River at Gunnedah is about 11,000 ML/day.

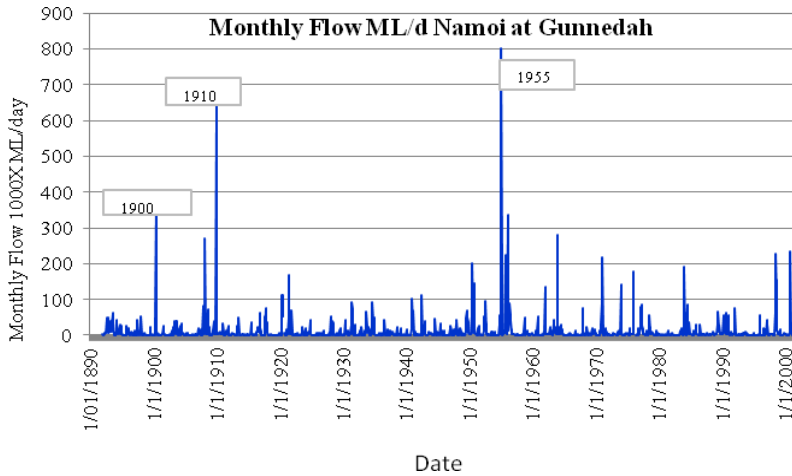


Figure 2. Flood peaks in the Namoi River (1900-2008). Source: NSW, Office of Water, 2008

Figure 3 highlights floods from the river flow data (1970-2008) further downstream at the Mollee gauging station where mean monthly flow during the floods of 1964, 1971, 1974, 1976, 1984, 1998 and 2000 exceeded 200,000 ML/day. This is approximately 36 times the median flow (553 ML/day) at Mollee indicated by the horizontal bar in Figure 3.

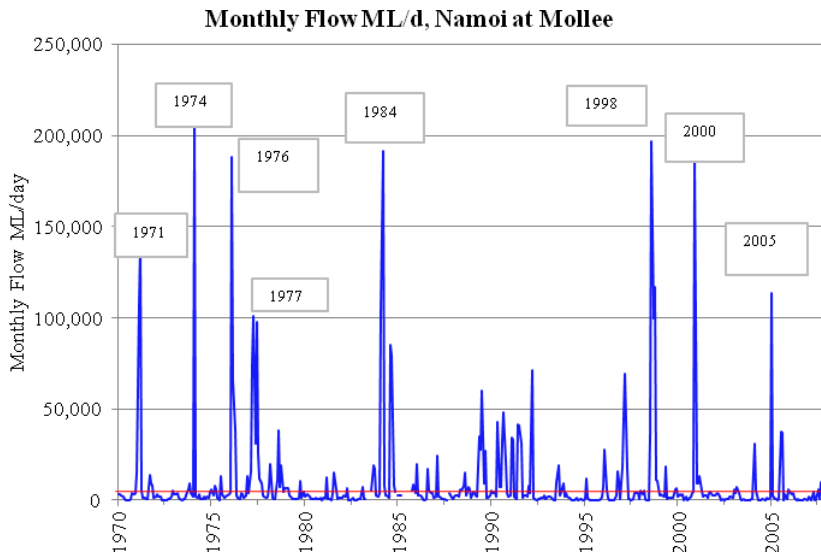


Figure 3. Flood peaks in the Namoi River (1970-2008)
Source: NSW, Office of Water, 2008

From the flood frequency and magnitude data, it is evident that a significant volume of water could be available for MAR while satisfying environmental flow and ecological requirements. The magnitude of floods in the Lower Namoi suggests that part of this water can be used to

recharge aquifers without affecting the important ecological role of floods in the river systems. A recent study on the social acceptability of MAR (Rawluk *et al.*, in press), indicates that most groundwater licence holders in the Namoi irrigation district supported MAR using water from large floods. Such peaks may be more frequent in future under climate change (Barron *et al.*, 2010; Barron *et al.*, 2011; Chiew *et al.*, 2011).

Supplementary water availability during high flows

In the Lower Namoi irrigation district water for aquifer recharge could come from within or from outside existing entitlements. The Water Sharing Plan (The Plan) for the Upper Namoi and Lower Namoi Regulated River Water Sources (NSW DIPNR, 2004) commenced on 1 July 2004 and applies for a period of ten years to 30 June 2014. It is a legal instrument made under the Water Management Act 2000. The Plan includes rules for protecting the environment, regulating surface water extractions, managing licence holders' water accounts, and overseeing water trading in the area.

Under The Plan, flood water that is not already allocated is assumed to be environmental water. The current regulatory set up as outlined in The Plan states that holders of supplementary water access licences can extract water during the announced supplementary periods. As mentioned earlier, supplementary access periods are typically during floods and periods of high streamflow, when dams spill and flows are in excess of licensed obligations and environmental needs (Burrell *et al.*, 2011). The volume that may be taken over a water year from each supplementary water access licence is set by an available water determination made at the start of each water year. As defined in The Plan, the volume of water available for extraction under supplementary water access licences in the Lower Namoi depends on the time of year. Supplementary access between 1 July and 31 October may not exceed 10 per cent of the event volume, while at all other times up to 50 per cent of the event volume may be made available to licence holders.

We make a quantitative assessment of the volume of water available through the announced supplementary high flow periods under the rules of The Plan to estimate the volume of supplementary water that can be extracted for the purpose of aquifer storage. This is achieved by analysing daily streamflow data from 1972-2012 at the Mollee gauging station for high flow periods over the past 40 years. Daily instantaneous flow data for the Namoi River at Mollee gauging station from 1972-2008 was obtained from Historic data on the DVD "PINNEENA" for Continuous Monitoring PINNEENA CM - version 9.2 (NSW, Office of Water, 2008). The most recent (2009-2012) instantaneous streamflow data was downloaded from the NSW Office of Water website.

The Plan provides all the basic rules for share and capture of water during each supplementary event. However, the rules defining the threshold for the announcement of a supplementary access event are quite fluid and depend on several factors. The rules in The Plan detail the various start, stop and flow triggers for different locations and the different scenarios that apply depending on the volumes of water allocations in the regulated river, including general security access licence accounts. In addition, the available volume of water for extraction varies for different times of the year, from 10% to 50%. A water user is only able to extract supplementary water when, amongst other things, their supplementary water account balance is in credit. After meeting all other requirements, supplementary access is only available when the uncontrolled flows are surplus to other needs and is only permitted in accordance with announcements made by the Minister's Office of Water.

In the absence of any defined threshold number to define supplementary water access, we selected a threshold of 37,800 ML/day to carry out the analysis. The rationale for selecting the

stated threshold is based on the fact that the Namoi River peaked at 37,800 ML per day on 1 August 2011 at Gunnedah; this represents a flow of around one metre higher than the bank full level (Burrell *et al.*, 2011). It is assumed that all the basic environmental and ecological requirements are met with this level of inundation in the floodplain.

Preliminary Findings

By applying the stated supplementary access rules in the Water Sharing Plan, Figure 4 bifurcates shares of irrigation and environmental water for each of the supplementary water events in the Lower Namoi from 1972- 2012. The total volume of irrigation water for each decade is also shown.

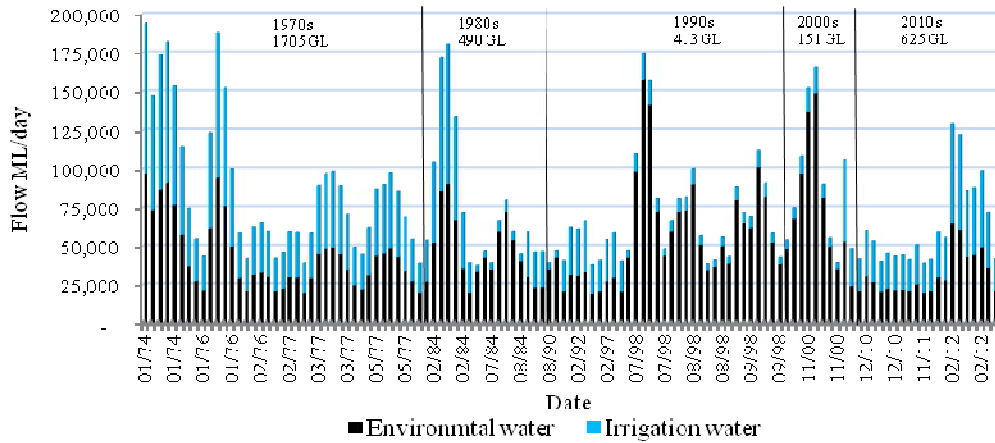


Figure 4. Shares of Irrigation and Environmental Water (1972-2012). Supplementary access set at a threshold of 37,800 ML/day, Namoi at Mollee. Data Source: NSW, Office of Water 2012

In the 40 years period between 1972 and 2012, there were 120 high flow events exceeding the threshold of 37,800 ML/day. These flows provided an average 85 GL of water per year for aquifer storage (Table 1).

Table 1. Number of supplementary water access events and share of Irrigation and Environmental water (1972-2012). Source: NSW Office of Water, 2012

Year	No of Flood events > 37,800 ML/day	Irrigation water (ML)	Environmental water (ML)
1974	8	546,143	546,143
1976	11	468,064	468,064
1977	20	691,316	691,316
1984	14	413,861	712,866
1989	3	76,255	76,255

1990	3	10,638	95,743
1991	1	20,244	20,244
1992	4	113,748	113,748
1997	4	96,953	96,953
1998	22	171,180	1,540,616
2000	8	73,855	664,697
2004	2	76,837	76,837
2010	7	163,548	163,548
2011	6	143,380	143,380
2012	7	318,458	318,458

Conclusion

In summary, the availability of supplementary water access depends on the rules in The Plan, the nature of the event, any water restrictions that may be applicable at the time and the account balances of supplementary access licences. During times of high streamflow, including large floods, water is still available for extraction for consumptive purposes under the rules of The Plan. In practice, demand is very low during times of flood thus water extraction is low in comparison to the flood volume.

The estimated average volume of 85 GL/year is a significant amount of water that can be stored within the large aquifers of the Lower Namoi. Historical groundwater extraction, supporting the irrigation industry since the 1960s, has been in excess of groundwater recharge. This has generated a storage space within the alluvial aquifer. The captured supplementary water could be placed in either the shallow unconfined aquifer, or the semi-confined aquifers (from which the irrigation bores extract groundwater). On average once every four years, 340 GL of water may be available under current supplementary allocation rules. According to the water accounting report of the Lower Namoi during the water year 2010-2011, a total of 279,184 ML of supplementary water was announced which is consistent with the findings of our preliminary analysis.

Our preliminary results indicate that high streamflow periods and floods offer a significant opportunity for diverting river water, and storing it in the aquifers of the Lower Namoi. However, the amount of supplementary irrigation water is highly variable from year-to-year, ranging from 1 GL in 1990 to 691 GL in 1997. This large variability in the volume of water potentially available for MAR will require a dynamic management framework and handling system, with staged surface storage(s) to capture and stabilise the water before recharging it into the aquifers. Another aspect that needs to be considered is how to maintain MAR infrastructure when there is little or no water available during droughts.

Other perspectives that need to be addressed but are not considered here include: hydrogeological investigations to map aquifer storage space and zones of recharge, the

technical evaluation of recharge methods, cost benefit analysis to compare MAR with alternate surface water storage, the costs of building, running and maintaining MAR infrastructure; and identifying the environmental risks. Also, before MAR could be implemented further work is required on the legal and policy framework.

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