Feasibility assessment of managed aquifer recharge for cotton irrigation in the Namoi: Final case study report

Milestone 4.3 draft report for *Feasibility study of managed aquifer recharge for improved water productivity for Australian cotton production*

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Executive summary

Background

The project *'Feasibility study of managed aquifer recharge* [MAR] *for improved water productivity for Australian cotton production'* is investigating the potential to implement MAR at a regional scale in established and emerging irrigated cotton growing regions of Australia. The broad aim of the project case studies was to evaluate how MAR might be feasible for irrigated cotton production and associated cropping systems in the focus regions, and make recommendations on further work to evaluate local hydrogeological conditions, plan the necessary site-specific infrastructure, and establish the legal, social and organisational conditions for implementation of MAR.

The focus of this report is the third case study of the MAR feasibility project, the Lower Namoi valley in the Namoi River catchment. This case study experiments with using a desktop analysis to initiate discussion from an operational, site specific perspective based on currently available data that draws on, but distinguishes it from, the previous work on MAR in the catchment. The area of interest (AOI) for our sub-regional analysis is the area of previously mapped high MAR suitability in the east of the Lower Namoi groundwater source (between Narrabri and Wee Waa). This area is part of a highly developed irrigated agriculture industry (where cotton is an important crop) that already makes use of large capacities of farm dams, conjunctive surface and groundwater use, and flood water management.

The broad approach taken was to draw on evidence from a holistic feasibility assessment to scope a set of plausible but widely different opportunities ("scenarios") for MAR, and to test and refine these scenarios with local stakeholders and state government stakeholders. Given the developed nature of the AOI, any new water management solution (in this case MAR) is an attempt to optimise an existing capability rather than an initial attempt at meeting a need. In this respect, gains from optimising the *status quo* are unlikely to provide new water, but rather to provide greater control over where and when water is available.

Opportunities for MAR in the area of interest

The 'status quo'

On-farm water storages are critical to irrigators' ability to store and access water in normal conditions, in dry years, and from wet years, but they suffer from high evaporation losses. Between years, certain water allocation licence (WAL) types allow carryover of unused water up to a point. Increased use of groundwater during dry periods can provide further water security to irrigators with both surface and groundwater licences. Many irrigators already have both surface and groundwater licences, and on-farm storages and infrastructure, and to some extent monitor both resources. Historically, additional water in wet years could be accessed through overland flows (floodplain harvesting) and announced supplementary flow events. Rules around supplementary water and floodplain harvesting are currently in flux. Growth in use is still likely to be restricted and the impacts of rule changes on groundwater recharge are still unclear.

Scenario: MAR for low loss water storage

MAR could allow greater storage with reduced losses compared to on-farm storages. Storage of water in on-farm dams leads to significant evaporative losses and, with climate change, evaporative losses per unit area of water are expected to increase. MAR would be run on single farms by an individual owner or land manager and delivery of surface water would use existing infrastructure with on-farm storages used for temporary storage of MAR water. A water accounting grade estimate of recharge is critical to being confident that MAR provides an advantage over investing in reducing infiltration "losses", and to allow an allocation to be issued. As an initial step, MAR pilot studies could work with state government to test water accounting of recharge quantification methods in dedicated trial infiltration basins and test injection wells. Reducing uncertainty about evaporation and recharge rates is critical to comparing MAR as a low loss water storage solution to other evaporation or infiltration reduction alternatives. If land managers invest in improving understanding of aquifers under their land and quantifying seepage and evaporation over time, this will incrementally reduce uncertainty on the effectiveness and viability of MAR.

Scenario: Moving water north

In the Lower Namoi, there are areas of high drawdown north of Wee Waa that have been subject to trade restrictions, and water salinity tends to increase in the west, especially for the water table aquifer. Increasing recharge north of the river through MAR would involve moving water through existing channel infrastructure for recharge closer to drawdown areas, ensuring that groundwater is available when it is needed and reducing the risk of potential regional impacts. The initial use of syndicate channels and existing on-farm storages for temporary staging of MAR water, later supplemented with new infrastructure, requires collaboration between several land owners and protocols to determine how benefits, costs and responsibilities would be shared. Regulatory change is needed for recharged water to be accounted for in available water determinations.

A project to move water north could commence already. Increasing infiltration by selective filling of leaky channels or fields does not need approval, and would be approached as pilots with appropriate monitoring to support project approvals for new infrastructure and potential water injection. A partnership approach would bring together local data holders, infrastructure owners, regulators and expertise. The project could be set up to have an incremental mandate, starting with local data collection, knowledge management and sharing, moving on to supporting landholder water management, and then to development and operation of a larger MAR scheme, similar to that already operating in the Burdekin catchment in Queensland.

Scenario: River recharge as MAR

River leakage is a major contributor of recharge in the Lower Alluvium, with recharge increasing when the river is high or in flood. In principle, river regulation could also target groundwater recharge, raising water levels in reaches with high seepage to not just the water table but also the deeper production aquifer. Managing river recharge would involve a long-term transition to active self-management by a dedicated cooperative, led by landholders and overseen by government. Consensus would need to be reached on operating rules that reflect local context, respond to changing environmental circumstances, and target the economic, social and environmental sustainability of local irrigation communities without jeopardising downstream outcomes.

This scenario envisions a transformation of river operations, regulations and attitudes to water management but acknowledges the potential efficiency of river recharge to deliberately shift water from the surface to underground. The science to support active management is increasingly within reach through methods to identify high recharge reaches (which have already been applied in parts of the AOI) and high-resolution remote sensing to monitor and model the system. Investing in understanding the impact of existing river levels and management on groundwater recharge, and relative contribution of river recharge to recovery of aquifer drawdown, would build capacity to manage river recharge for multiple outcomes.

Active self-management of river recharge by collectives of irrigators is a radical change that would require long term societal and regulatory change. Building the necessary trust, capacity and relationships might need to start with other shared endeavours, such as the project described in moving water north.

Creating an enabling environment for MAR

Stemming from this case study, the general recommendations for CRDC, State government, landholders and/or other parties are to:

- Build a culture of and capacity for understanding groundwater dynamics at farm scale, and infiltration and recharge at field and channel scale.

- Invest in pilot studies of MAR that develop regulatory and farm management understanding of recharge consistent with water accounting requirements.
- Engage in the development of the policy framework for MAR within the NSW strategy to ensure that water sharing plan, pilot project, and collective management options remain possible in future.
- Explore the range of possible paradigms for managing aquifers as reservoirs to minimise impacts and maximise benefits

A staged approach to operationalising and implementing these recommendations should target initial no-regret actions that minimise initial investment and provide value regardless of which management paradigm and MAR innovation are later pursued. In principle, as the value of water increases, telemetry and automation have the potential to dramatically increase understanding of an irrigation system, provide savings through condition-based or predictive asset maintenance, and in the process yield high resolution understanding of infiltration and evaporation. Similarly, increasing farm data availability increases the benefits of information sharing and greater involvement of farmers and other emerging data holders in regulatory review and development processes. Investing in precision agriculture water management could therefore lay the groundwork for MAR in future.

All scenarios developed for the Namoi case study rely on the establishment of organisational structures and research and development support that will gradually increase local to subregional hydrogeological understanding. They place an emphasis on enhancing the ability of irrigators to evaluate the costs and benefits (in relation to the farm water balance and enterprise resilience) of proposed changes to their operational water management. There is a need for multi-stakeholder efforts to experiment with new regulatory frameworks and policy innovation niches that support sustainable irrigation industries. These are changes that would also be desirable more widely to improve capacity for whole-of-system water management in NSW and Australia. MAR is an ideal case to develop this improvement in governance but would also benefit from investments in improvements through other pathways, such as through greater cooperation in operational water delivery or regional system efficiency improvement mechanisms.

Contents

Executive summary i

Background i

Opportunities for MAR in the area of interest i

The 'status quo' i

Scenario: MAR for low loss water storage i

Scenario: Moving water north ii

Scenario: River recharge as MAR ii

Creating an enabling environment for MAR ii

Figures v

Tables viii

1. Introduction 1

1.1 The Australian cotton industry 1

1.2 The implications of water reforms and climate variability on irrigated cotton production 1

1.3 A brief history of MAR schemes in Australia 1

1.4 The CRDC MAR Feasibility project 3

1.5 Structure of this report 4

2. Overarching approach 5

3. Namoi Case Study 7

3.1 Catchment background 7

3.1.1 Climate 8

3.1.2 Geology and soils 9

3.1.3 Surface water and groundwater 10

3.2 Overview of MAR research in the Namoi 14

3.3. Area of Interest 16

4. Scenarios 20

4.1 The 'status quo' 20

4.2 MAR for low loss water storage (farm scale) 20

4.3 Moving water north (regional benefits) 21

4.4 River recharge as MAR (transformative change) 22

5. Feasibility Criteria Analysis 24

5.1 Effective demand for products 24

5.1.1 Variability of surface water allocations in the Lower Namoi 24

5.1.2 Groundwater extractions in the Lower Namoi 26

5.1.3 Irrigator demand for water 27

5.2 Water availability for MAR 27

5.2.1 Water allocation licences (WAL) in the AOI 28

5.2.2 Historic take in the Lower Namoi by WAL type 28

5.2.3 Floodplain harvesting 31
5.2.4 Evaporation losses 32
5.3 Technical feasibility 32
5.3.1 Surface water infrastructure to support MAR 32
5.3.2 Aquifer characteristics 34
5.3.3 Groundwater levels 37
5.3.4 Groundwater Salinity 45
5.3.5 Soils 48
5.3.6 Recharge 49
5.3.7 Implications for the design, planning and implementation of MAR strategies 54
5.4 Financial viability 56
5.4.1 Cost-benefit analysis of MAR and surface storage options under uncertainty 56
5.4.2 Implications of the scenarios to the business case for MAR 59
5.5 Environmental considerations 61
5.5.1 Environmental assets and watering 61
5.5.2 Flows into the Barwon River system 61
5.5.3 Effect of supplementary water capture on environmental flow delivery 63
5.5.4 *Water Sharing Plan for the Namoi Alluvial Groundwater Sources Order* 2020 64
5.6 Social acceptability 67
5.6.1 Conjunctive use of surface water and groundwater 67
5.6.2 Past social research into MAR and groundwater management 67
5.6.3 Preliminary feedback on MAR scenarios 69
5.7 Governance arrangements 71
5.7.1 Summary of relevant material from Milestone 4.1 report (Murrumbidgee Case Study) 71
5.7.2 Water Sharing Plans (WSP) covering the AOI 72
5.7.3 NSW Floodplain Harvesting Policy 77
5.7.4 NSW Water Strategy 77
6. Synthesis 79
6.1 Key learnings 79
6.2 Enabling environment for MAR 80
Acknowledgments 81
References 81

Figures

Figure 1 The area planted to irrigated and dryland cotton in Australia, 1990-2014 (Source: Figure 8 in Cotton Australia and CRDC (2014)) 2
Figure 2 The gross value of cotton lint production, 1990-2014 (Source: Figure 15 in Cotton Australia and CRDC (2014)) 2
Figure 3 Location of the project case study areas. This report focuses on the Namoi case study. 4

Figure 4 Argumentation approach used to investigate the potential feasibility of MAR in the Gilbert River case study. 5
Figure 5 The Murray-Darling Basin with the Namoi catchment shown in red (Source: CSIRO, 2007). 7
Figure 6 Land use in the Namoi catchment (Source: Green et al., 2011). 8
Figure 7 Average annual rainfall map in the Namoi catchment (Source: BOM, 2008 in DPIE, 2019). 9
Figure 8 Average annual evaporation in the Namoi catchment (Source: BOM, 2008 in DPIE, 2019). 9
Figure 9 Geology of the Namoi catchment (Source: DPIE, 2019) 10
Figure 10 Map of Australian soil classes (ASC) for the Namoi catchment (Source: https://www.bioregionalassessments.gov.au/assessments/11-context-statement-namoi-subregion/1121-physical-geography, accessed 18 Dec 2020). 11
Figure 11 Rivers and tributaries of the Namoi catchment (Source: Green et al., 2011). 12
Figure 12 Annual flows in the Namoi River at Gunnedah (Source: Green et al., 2011). 12
Figure 13 A simplified representation of the groundwater aquifer types in the Namoi catchment (Source: Green et al., 2011). 13
Figure 14 Groundwater quality and suitability in the Namoi catchment (Source: Green et al., 2011). 13
Figure 15 Location of the gravel pits in the Lower Namoi explored by (Woolley et al., 1994). The box indicates the area of interest for this study (see Section 3.3). 14
Figure 16 Suitability map for infiltration based MAR in the Namoi catchment produced by Fuentes and Vervoort (2020), where high values indicate high suitability. The blue arrow is added to highlight an area of high suitability that is the area of interest of this study. 15
Figure 17 Groundwater sources defined in the Water Sharing Plan for the Namoi Alluvial Groundwater Sources 2012 17
Figure 18 Namoi water management area defined by the Water Sharing Plan for the Upper Namoi and Lower Namoi Regulated River Water Sources 2016 18
Figure 19 Management zones covered by the Water Sharing Plan for the Namoi and Peel Unregulated Rivers Water Sources 2012 19
Figure 20 Cumulative total allocation volume (ML) for each water year within the Regulated River (General Security) licence category in the Lower Namoi Regulated River Source (blue columns) in relation to the sum of the licenced share component (volume of water in ML) for this licence type (Source: https://www.industry.nsw.gov.au/water/allocations-availability/water-accounting/historical-available-water-determination-data) 26
Figure 21 Historic supplementary share component in the Lower Namoi Groundwater Source (Source: https://www.industry.nsw.gov.au/water/allocations-availability/water-accounting/share-component-dashboard, 14 September 2021) 26
Figure 22 Lower Namoi groundwater extraction compared to the extraction limit compliance trigger (Source: https://www.industry.nsw.gov.au/__data/assets/pdf_file/0005/353192/lower-namoi-groundwater-source-2020.pdf, accessed 15 September 2021) 27
Figure 23 Historic take of secure water licence in the Lower Namoi Regulated River Source (Source: https://waterinsights.waternsw.com.au/11986-lower-namoi-regulated-river/research, 14 September 2021) 28
Figure 24 Historic take of supplementary licence in the Lower Namoi Regulated River Source (Data source: https://waterregister.waternsw.com.au/water-register-frame, 16 September 2021). 29
Figure 25 Incremental available water determination (AWD) for Lower Namoi general security as a proportion of share component (Burrell et al., 2021) 30
Figure 26 Historic take of general security licence in the Lower Namoi Regulated River Source (Data source: https://waterregister.waternsw.com.au/water-register-frame, 16 September 2021). 30
Figure 27 Stream, canals and dams in Lower Namoi groundwater zone (Australian Hydrological Geospatial Fabric (AHGF) (https://datasets.seed.nsw.gov.au/dataset/australian-hydrological-geospatial-fabric-geofabric)). 33
Figure 28 Stream, canals and dams in the area of interest (Australian Hydrological Geospatial Fabric (AHGF) (https://datasets.seed.nsw.gov.au/dataset/australian-hydrological-geospatial-fabric-geofabric)). 33

Figure 29 Offtakes of the Namoi River in the area of interest. Stream, canals and dams are also shown (Australian Hydrological Geospatial Fabric (AHGF) (https://datasets.seed.nsw.gov.au/dataset/australian-hydrological-geospatial-fabric-geofabric)). Offtakes were identified from aerial imagery and not all may be identified. 34
Figure 30 Diagram of groundwater system in the Namoi catchment (Source: URS Australia Pty Ltd (2007)).............. 35
Figure 31 Vertical connectivity of Namoi alluvium used in bioregional assessment Namoi groundwater model; <0.01 m/year suggests the aquifer is well connected and >0.1 m/year that the aquifer is poorly connected (Aryal et al., 2018) 36
Figure 32 Dendogram showing the top 17 levels of the hierarchical clusters (Blakers et al., 2011)............................ 37
Figure 33 Plan projections of the 17 bore clusters and the convex hulls enclosing them (Blakers et al., 2011). The approximate AOI is indicated by the red box. 37
Figure 34 WaterNSW Lower Namoi Groundwater Source monitoring sites (Source: DPIE, 2020a). The black box indicates our AOI.. 38
Figure 35 Hydrograph of monitoring bore GW030450 and GW025326 (Source: DPIE, 2020a)................................... 39
Figure 36 2015 maximum drawdown and recovery (reduced standing water level measured in meters above Australian Height Datum, AHD) in the lower aquifer. Inverse distance weighting was used to interpolate between borehole (black points) measurements. Canals (grey), rivers (dark blue) and Lower Namoi Groundwater Zone (shaded white) are also shown. 39
Figure 37 2016 maximum drawdown and recovery (reduced standing water level measured in meters above Australian Height Datum, AHD) in the lower aquifer. Inverse distance weighting was used to interpolate between borehole (black points) measurements (note few data points for this year). Canals (grey), rivers (dark blue) and Lower Namoi Groundwater Zone (shaded white) are also shown. 40
Figure 38 2017 maximum drawdown and recovery (reduced standing water level measured in meters above Australian Height Datum, AHD) in the lower aquifer. Inverse distance weighting was used to interpolate between borehole (black points) measurements. Canals (grey), rivers (dark blue) and Lower Namoi Groundwater Zone (shaded white) are also shown. 40
Figure 39 2018 maximum drawdown and recovery (reduced standing water level measured in meters above Australian Height Datum, AHD) in the lower aquifer. Inverse distance weighting was used to interpolate between borehole (black points) measurements. Canals (grey), rivers (dark blue) and Lower Namoi Groundwater Zone (shaded white) are also shown. 41
Figure 40 2019 maximum drawdown and recovery (reduced standing water level measured in meters above Australian Height Datum, AHD) in the lower aquifer. Inverse distance weighting was used to interpolate between borehole (black points) measurements (note the low number of data points). Canals (grey), rivers (dark blue) and Lower Namoi Groundwater Zone (shaded white) are also shown. 41
Figure 41 Monthly rainfall, as measured at Narrabri (Mollee), before, during and after the reported flood event. The dark blue dashed line highlights the date when the flood was reported to occur (mid-November, 2000-11-15) and the light blue dashed line highlights when additional flooding was reported to occur (late January/early February, 2001-01-31)... 42
Figure 42 Difference between mean reduced standing water level (RSWL) measured in meters above Australian Height Datum (AHD) and measured RSWL (meters AHD). Bores are in the upper aquifer as defined in data from DPIE. The dark blue dashed line highlights the date when the flood was reported to occur (mid-November, 2000-11-15) and the light blue dashed line highlights when additional flooding was reported to occur (late January/early February, 2001-01-31). 43
Figure 43 Difference between mean reduced standing water level (RSWL) measured in meters above Australian Height Datum (AHD) and measured RSWL (meters AHD). Bores are in the lower aquifer as defined in data from DPIE. The dark blue dashed line highlights the date when the flood was reported to occur (mid-November, 2000-11-15) and the light blue dashed line highlights when additional flooding was reported to occur (late January/early February, 2001-01-31). 43
Figure 44 Difference between mean reduced standing water level (RSWL) measured in meters above Australian Height Datum (AHD) and measured RSWL (meters AHD). Bores are in the upper aquifer as defined in data from DPIE. The dark blue dashed line highlights the date when the flood was reported to occur (mid-November, 2000-11-15)

and the light blue dashed line highlights when additional flooding was reported to occur (late January/early February, 2001-01-31). 44
Figure 45 Difference between mean reduced standing water level (RSWL) measured in meters above Australian Height Datum (AHD) and measured RSWL (meters AHD). Bores are in the lower aquifer as defined by data provided by Catherine Barrett. The dark blue dashed line highlights the date when the flood was reported to occur (mid-November, 2000-11-15) and the light blue dashed line highlights when additional flooding was reported to occur (late January/early February, 2001-01-31). 44
Figure 46 Salinity (uS/cm) in both upper and lower aquifer, where upper is delineated as having a screen depth less than 30 m. Inverse distance weighting was used to interpolate between borehole (black points) measurements (average of available data, with some bores having only single measurements). Canals (grey) and rivers (dark blue) are also shown. 46
Figure 47 Salinity (uS/cm) as measured at bore GW273314.1.1 over recent years. 47
Figure 48 Location of monitoring bore with salinity timeseries (GW273314.1.1). Canals (grey), rivers (dark blue) and Lower Namoi Groundwater Zone (shaded white) are also shown. 47
Figure 49 Sand % in the area of interest and surrounds at varying depths (0 - 5 cm, 5 - 15 cm, 15 – 30 cm, 30 – 60 cm, 60 – 100 cm and 100 – 200 cm). Data from: the Soil and Landscape Grid of Australia (https://www.clw.csiro.au/aclep/soilandlandscapegrid/) and the Australian Hydrological Geospatial Fabric (AHGF) (https://datasets.seed.nsw.gov.au/dataset/australian-hydrological-geospatial-fabric-geofabric). 50
Figure 50 Mapped waterbodies (i.e., farm dams) highlighting one possible deficiency of the soil data: areas under dams are noticeably sandier than adjacent areas. Data from: the Soil and Landscape Grid of Australia (https://www.clw.csiro.au/aclep/soilandlandscapegrid/) and the Australian Hydrological Geospatial Fabric (AHGF) (https://datasets.seed.nsw.gov.au/dataset/australian-hydrological-geospatial-fabric-geofabric). 51
Figure 51 Groundwater monitoring borehole hydrographs. Borehole 1 is in the unconfined aquifer and is slotted from 17.7–21.4 m. The large rises in head observable in borehole 1 are due to recharge from flood water. Boreholes 2 and 3 are in the semi-confined aquifer. Borehole 2 is slotted from 38.1–41.1 m and borehole 3 is slotted from 50.9–55.5 m. Water used for irrigation is extracted from the semi-confined aquifer. Source: Kelly et al. (2009) 52
Figure 52 A map of the changes in borehole water levels resulting from the 1984 flood. Source: Kelly et al. (2009) .. 52
Figure 53 Mean recharge estimates for different labelled monitoring wells along the lower Namoi River. All wells are assumed to be located in the upper aquifer. Source: Fuentes and Vervoort (2020) 53
Figure 54 Northern Namoi paleochannel and water table (mAHD) in the Narrabri formation (SWS, 2011 in Herr et al., 2018) 54
Figure 55 Bores in the region. Bore data is from the National Groundwater Information System (NGIS) (http://www.bom.gov.au/water/groundwater/ngis/). Stream, canals and dams are also shown (Australian Hydrological Geospatial Fabric (AHGF) (https://datasets.seed.nsw.gov.au/dataset/australian-hydrological-geospatial-fabric-geofabric)). 57
Figure 56 Planning unit 2, Boggabri to Wee Waa (Source: DPIE, 2020c) 62
Figure 57 High priority GDE map from the WSP for the Namoi Alluvial Groundwater Sources (https://legislation.nsw.gov.au/view/html/inforce/current/sl-2020-0346/maps, accessed 16 September 2021) 66
Figure 58 Total number of 1 ML shares, disaggregated by water allocation type, for each of the 13 farms in the AOI (Data source: https://waterregister.waternsw.com.au/water-register-frame, 16 September 2021) 67

Tables

Table 1 The seven feasibility criteria of Ticehurst and Curtis (2017). 24
Table 2 Summary of the scenario feasibility. 25
Table 3 Breakdown of water allocation licences (WAL) in the AOI 28
Table 4 Historic supplementary events and usage along the river sections crossing the AOI compiled from General Purpose Water Accounting Reports (available at https://www.industry.nsw.gov.au/water/allocations-availability/water-accounting/gpwar, accessed 25 November 2021) 29
Table 5 Extreme events stage and temporary water restrictions (Lower Namoi region) in 2019-20 (Source: Burrell et al., 2021) 31

Table 6 Gross margins and net farm income, irrigated and dryland (Arshad et al., 2013) 57
Table 7 Summary of cost-benefit analysis of water storage options on the hypothetical farm (Arshad et al., 2013). NPV = Net present value 58
Table 8 Single variable cross-over points in three scenarios, for which the preferred option may change from basin infiltration to surface storage or injection-based aquifer storage and recovery (ASR), or from surface storage to ASR. 59
Table 9 Cross-over point of greatest concern with basin infiltration vs. surface storage, using a subset of variables (Arshad et al., 2014). The colour of the text in the implication column indicates a change that favours MAR (blue), plays against MAR (red) or is neutral (black) 60
Table 10 Commonwealth environmental water holdings (CEWO) in the Namoi catchment at 31 May 2021 (Source: http://www.environment.gov.au/water/cewo/about/water-holdings, accessed 22 September 2021) 62
Table 11 Priority environmental assets and values (Source: DPIE, 2020c) 63
Table 12 Native fish objectives for the Narrabri to Wee Waa planning unit (PU2) defined in (Source: DPIE, 2020c) ... 63
Table 13 Environmental watering requirements for gauge 419039, the Namoi River at Mollee (Source: DPIE, 2020c) 65
Table 14 Proportion of respondents supporting MAR in the Namoi in 2011 (Source: Rawluk et al., 2013) 67
Table 15 Views about ASR in the Namoi catchment expressed in the 2011 Namoi groundwater management survey 68
Table 16 Views about collective management of groundwater from the 2011 Namoi groundwater management survey of Sharp and Curtis (2012). Respondents were asked to rate how much they agreed with the statements on a Likert scale of 1-5 from Strongly Disagree to Strongly Agree. Not Applicable was a separate response option. 68
Table 17 Mapping the content of this report against the viability assessment components recommended by the Australian Guidelines for Water Recycling: Managed Aquifer Recharge entry-level viability assessment and this report (NRMMC, EPHC & NHMRC, 2009). 73
Table 18 The Australian Guidelines for Water Recycling: Managed Aquifer Recharge entry-level degree of difficulty assessment: attributes to consider. 74
Table 19 In force WSP covering areas of the Namoi Valley 75
Table 20 Supplementary water event start and finish flows for downstream of the Namoi River at Narrabri (Source: Water Sharing Plan for Water Sharing Plan for the Upper Namoi and Lower Namoi Regulated River Water Sources 2016) 76
Table 21 Supplementary water event start and finish flows for downstream of the Namoi River at Narrabri (Source: Water Sharing Plan for Water Sharing Plan for the Upper Namoi and Lower Namoi Regulated River Water Sources 2021 submitted to the MDBA) 76
Table 22 Access rules for rivers and creeks and trading rules for the Spring and Bobbiwaa Creeks unregulated WAL. 77
Table 23 Investigation into MAR as part of the NSW Water Strategy (DPIE, 2021). 78

1. Introduction

1.1 The Australian cotton industry

The Australian cotton industry is an important sector agriculturally. The majority of the industry is focused in the south-east, through Queensland (QLD), New South Wales (NSW) and Victoria[1]. Small areas of cotton production are present in the North of Australia (Western Australia (WA), Northern Territory (NT) and QLD)[2]. Family-owned farms dominate the Australian cotton industry[3]. The Australian cotton industry is a large exporter, with export earnings of $2 million annually[4].

1.2 The implications of water reforms and climate variability on irrigated cotton production

The majority of cotton is produced from irrigated systems. In the past, the high water use of the Australian cotton industry attracted criticism, but the industry is now one of the most water efficient cotton industries in the world[5]. Between 2002 and 2012, the industry increased yields as a result of improved crop management, advances in plant breeding and the adoption of genetically modified varieties, while being more efficient users of water. These changes improved industry wide water use efficiency (WUE) by 40% (Roth et al., 2014). Select examples of farm management changes that led to the observed improvements in WUE, described in The Australian Grown Cotton Sustainability Report 2014 (Cotton Australia and CRDC, 2014), include:

- A 30% increase in the use of soil moisture probes since 2006, which are now used by 70% of irrigators
- 96% of furrow irrigation systems have been improved or changed to alternative systems
- 49% of irrigators have updated the flow or size of siphons
- 35% of irrigators have redesigned fields; for example, decreasing the distance between dams and fields to reduce evaporation losses

Even after the recent improvements in WUE, irrigated cotton production varies substantially between years (Figure 1), depending on water volumes available for irrigation (Cotton Australia and CRDC, 2014). The gross value of cotton lint is strongly associated with the area of irrigated crop production (Figure 2), decreasing in times of low water availability (Cotton Australia and CRDC, 2014). It follows that a key limiting factor on the cotton industry in Australia is water security, exacerbated by the potential for further policy changes to water allocations and future climate unknowns.

On average, groundwater contributes 15% of water used for the production of irrigated cotton (Cotton Australia and CRDC, 2014). In dry periods, dependence on groundwater increases. Managed aquifer recharge (MAR) could be used in this context by the Australian cotton industry; as a management strategy in the face of future surface water scarcity. Is it also possible that MAR has a place in 'greenfield' production areas to increase water security from the onset of industry development, limiting the unintended water scarcity seen in established regions.

1.3 A brief history of MAR schemes in Australia

MAR involves the purposeful recharging of aquifers using surface water, whether from rivers and other water bodies or recycled water, to be extracted when needed. Overseas MAR has been used to increase water security, with interest in MAR continuing to grow in Australia. MAR projects in Australia date back to the 1960s and the focus of these schemes are mostly urban (Dillon, 2009); MAR remains in its infancy in Australia in an agricultural setting.

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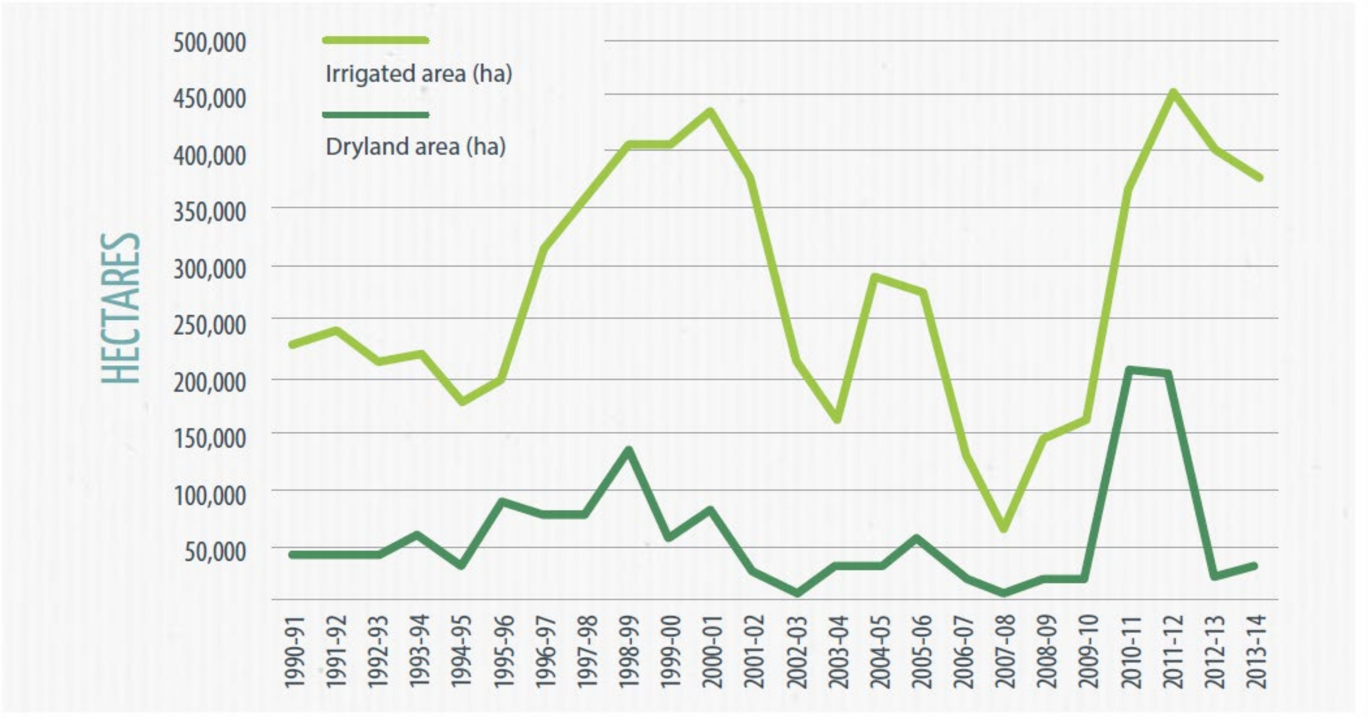
[1] https://cottonaustralia.com.au/industry-overview, accessed 30 August 2020
[2] https://cottonaustralia.com.au/industry-overview, accessed 30 August 2020
[3] https://cottonaustralia.com.au/industry-overview, accessed 30 August 2020
[4] https://cottonaustralia.com.au/industry-overview, accessed 30 August 2020
[5] https://cottonaustralia.com.au/industry-overview, accessed 30 August 2020



South Australia (SA) and Western Australia (WA) are home to the majority of Australia's MAR schemes (Dillon, 2009). The longest running MAR project in Australia is in Queensland's Burdekin Delta. The infiltration based system has maintained groundwater levels in the regions, preventing the intrusion of seawater, for decades (Dillon, 2009). Infiltration systems have also been used in WA since the 1980s as a way to recycle wastewater to irrigate public spaces, including playing fields (Vanderzalm et al., 2015). Multiple regions in SA inject stormwater runoff into aquifers, to be recovered as a water supply for irrigation and industry (Barnett et al., 2000, Miotliński et al., 2014, Yuan et al., 2016). Several MAR sites around Adelaide (SA) treat stormwater via artificial wetlands before injection into saline aquifers (Barnett et al., 2000). Water recovered as part of this project is of reduced salinity compared to the levels of the native aquifer, and can be used for irrigation purposes (Barnett et al., 2000). The Salisbury aquifer storage treatment and recovery (ASTR) scheme in SA spatially separates injection and recovery wells, allowing for the treatment of injected water during residence in the aquifer (Miotliński et al., 2014, Yuan et al., 2016). Pre-injection artificial wetlands are used to filter out total suspended soils, reducing clogging of wells (Yuan et al., 2016).

The MAR schemes currently operating in Australia show that well-planned projects can be successful. Although uptake in agricultural settings is limited, some have suggested that more MAR developments would increase water storage capacity and water security in a way that is economically viable compared to dams and other surface storages (Dillon, 2009, Khan et al., 2008).

1.4 The CRDC MAR Feasibility project

The *'Feasibility study of managed aquifer recharge for improved water productivity for Australian cotton production'* project (here-on-in referred to as the MAR Feasibility project) was funded by the Cotton Research and Development Corporation (CRDC) to investigate the feasibility of MAR at a regional scale in established and developing cotton growing regions in Australia. MAR has been discussed as an option in cotton regions previously, so the MAR Feasibility project has focused on whether MAR is a more feasible option then the current or alternate surface water options. Seven feasibility criteria based on those developed by Ticehurst and Curtis (2017) are used in conjunction with scenario development. Further research and resources should be directed to the more feasible options (scenarios), whether it be MAR or other water management options.

Three case study regions were selected in consultation with the project steering committee: the Murrumbidgee region in southern NSW, the Namoi region in northern NSW and the Gilbert region in northern Queensland (Figure 3). The Namoi and Murrumbidgee regions were selected as representing agricultural settings where the likelihood of MAR being feasible should be high, based on what was previously known about these systems across the different feasibility criteria. If the outcomes of these case studies did not support MAR, it would suggest that MAR should be ruled out as a water management option for the cotton industry.

The Lower Namoi is a mature irrigated agriculture region that already makes use of large capacities of farm dams, conjunctive surface and groundwater use, and flood water management. In this context, MAR would likely be considered an attempt to optimise an existing capability rather than an initial attempt at meeting a demand. In Section 4, we focus on three key capabilities here relating to ability to store and access water 1) in normal conditions, 2) in dry years, and 3) from wet years. Several studies have looked at aspects of MAR feasibility in the Namoi valley (Arshad et al., 2012, Arshad et al., 2013, Arshad et al., 2014, Fuentes et al., 2020, Fuentes and Vervoort, 2020, Rawluk et al., 2013, Woolley et al., 1994). The niche of this case study is that it takes an operational, site specific perspective based on currently available data to develop plausible scenarios for how MAR could work at a property to sub-regional scale.

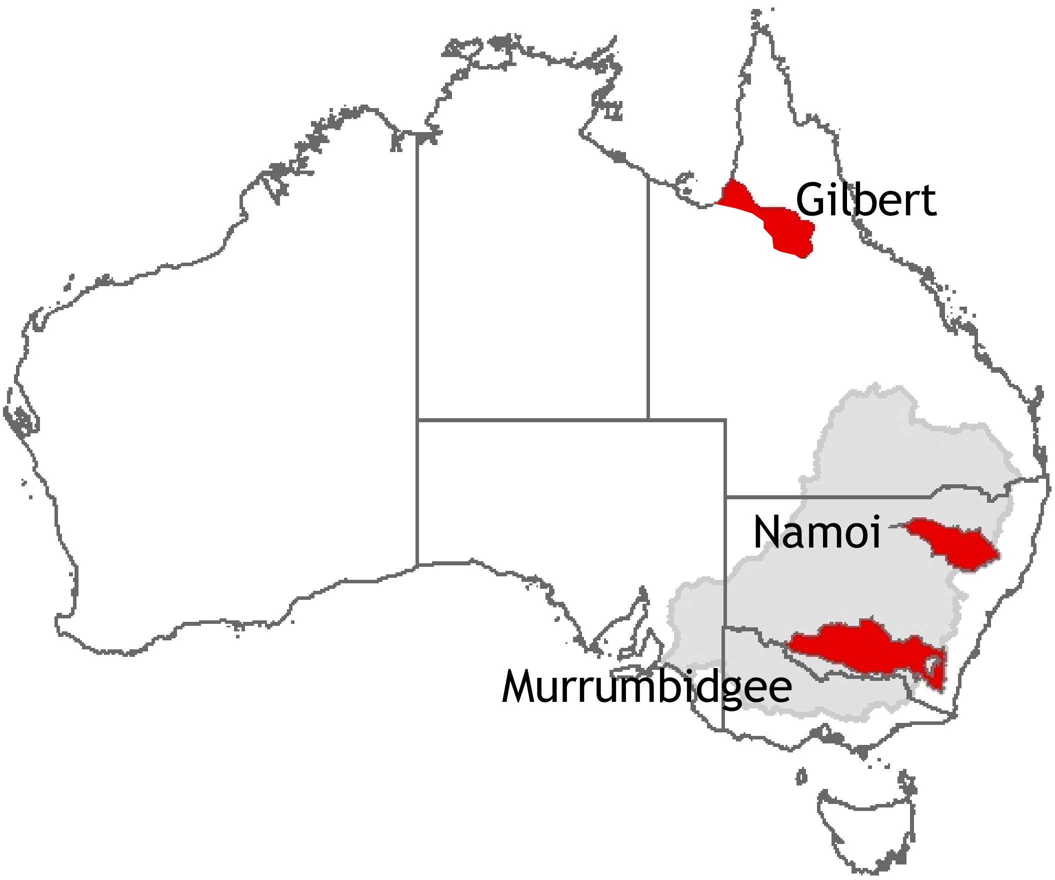


Figure 3 Location of the project case study areas. This report focuses on the Namoi case study.

1.5 Structure of this report

The Namoi catchment case study seeks to investigate and resolve some uncertainties associated with MAR at an operational level (individual properties to sub-regional scale) in the Lower Namoi (focusing on an area between Narrabri and Wee Waa). Past investigations on MAR have

- investigated the technical feasibility of MAR at particular locations or potential suitability across the catchment,
- compared the cost and benefits of dams, infiltration-based MAR and injection-based MAR in the Lower Namoi, and
- elicited the perspective of irrigators in the Namoi catchment on MAR as a concept.

This report draws on existing investigations and stakeholder expertise to critically assess the potential feasibility of MAR in the region and to identify next steps for research and development to guide investment by government or other funders. The approach and methods used to assess the feasibility of MAR is provided in Section 2. This is followed in Section 3 by a description of the Namoi River catchment system and the focus area in the case study. Three scenarios representing MAR options are identified and evaluated in Section 0, and discussed in relation to the *status quo* of irrigation water management. The development and evaluation of these scenarios drew on the detailed results of the feasibility criteria assessment provided in Section 5. For the final report to be submitted in December 2021, responses to these scenarios from local engagement (conducted online) will be reported and used to revise the scenarios and feasibility assessments. The report concludes in Section 6 with a statement of the potential for MAR in the region and recommendations for the CRDC and local and state-level stakeholders going forward.

2. Overarching approach

An argumentation approach has been used to guide the case study development. This reflects the high uncertainty in both project requirements and consequences associated with MAR innovations. A staged approach is more suitable in these situations, rather than trying to eliminate all uncertainty in one go. By firstly using available information to identify whether it's worth taking the next step in investigating the innovation, strategies that incrementally address critical uncertainties around the potential innovation can be identified. In this case study, our intent is to identify scenarios that support the hypothesis that MAR could be part of strategy centred on conjunctive use that attempts to optimise the ability to store and access water in normal conditions, in dry years, and from wet years. The questions guiding the 11 steps of the argumentation approach are shown in Figure 4; while represented as distinct steps in the diagram the process was highly iterative and underpinned by engagement throughout the duration of the case study.

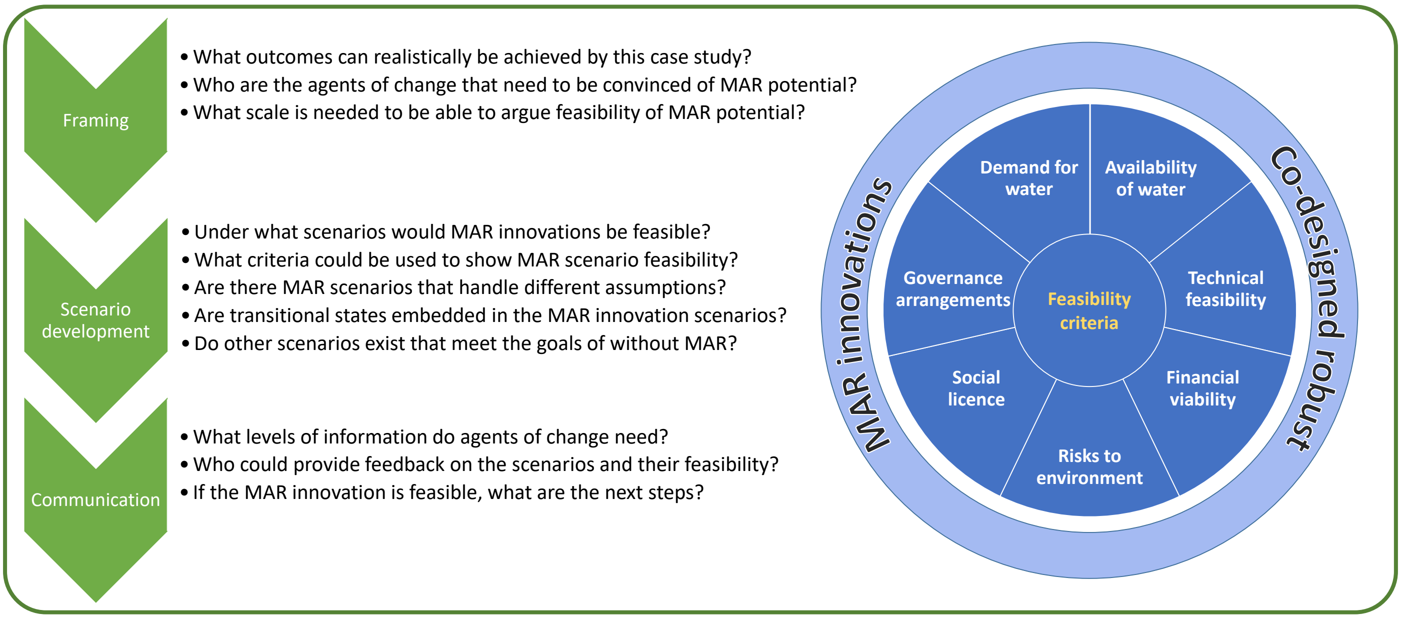


Figure 4 Argumentation approach used to investigate the potential feasibility of MAR in the Gilbert River case study.

The ***Framing*** phase identifies what we could achieve in the project, who needed to be convinced of the potential viability of MAR (the 'agents of change'), and what part of the Namoi River catchment we would focus on. With no scope to conduct in-depth field research, this project centred on analysis of existing investigations and supplementing these with focused analyses for an area of the Lower Namoi between Narrabri and Wee Waa. Given the mature nature of water policy in NSW and irrigated cropping in the catchment, the project needs to convince irrigators that MAR is worth investigating as a financially viable strategy to manage water. This in turn requires addressing any concerns around social license, environmental impacts, and the licencing and access of recharged water.

In the ***Scenario development*** phase, we developed MAR innovation scenarios and alternate scenarios that do not have a MAR component. These scenarios were supported by a systematic feasibility criteria assessment against the seven feasibility criteria of Ticehurst and Curtis (2017): Demand for Water, Water availability, Technical feasibility, Financial viability, Environmental risks, Social acceptability & social license, and Governance arrangements. This assessment involved the synthesis of available literature and data for the system. Initial investigations highlighted that the alluvial formations, which are the main groundwater sources for irrigation in the region and are particularly relied upon in dry periods, present the most promising aquifer system for MAR. Groundwater drawdown in these formations has been observed in the north-west of the Lower Namoi, indicating the capacity to store significant volumes of water. The work of Fuentes and Vervoort (2020) identified areas adjacent to the Namoi River between Narrabri and Wee Waa as being of potential high suitability for MAR. From this, we explored how MAR interventions in this Area of Interest (AOI) might work. Interventions were considered to operate at the scale of a property or collection of property (sub-region) and explicitly consider MAR within the existing surface water and groundwater schemes.

The ***Communication*** phase documented, and sought feedback on, the feasibility assessment used to develop scenarios and establish recommendations that address the next steps for assessment and implementation of the MAR. We engaged with NSW DPIE, the CRDC and our Steering Committee to identify data and literature to conduct the feasibility assessment with, and to select the area of interest to focus in on. Preliminary feedback on the scenarios and feasibility assessment was sought from a Lower Namoi irrigator, academic and NSW DPIE hydrogeology experts, and NSW DPI water policy experts.

3. Namoi Case Study

3.1 Catchment background

The Namoi catchment is located within the Murray-Darling Basin (MDB) in northern NSW (Figure 5). The area of the catchment is approximately 42,000 km^2 (Fuentes and Vervoort, 2020).

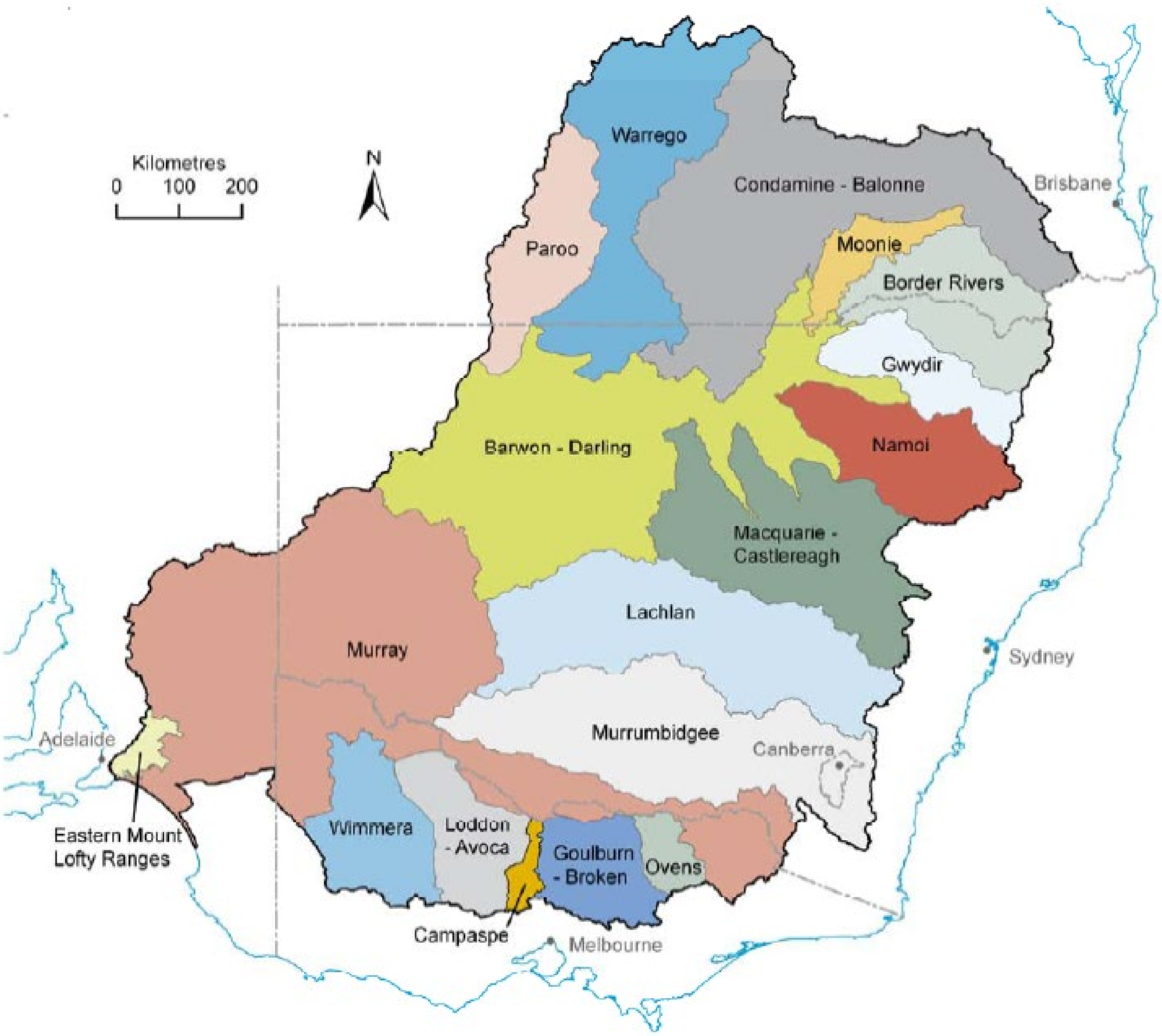


Figure 5 The Murray-Darling Basin with the Namoi catchment shown in red (Source: CSIRO, 2007).

The Namoi catchment lie within the traditional lands of the Gomeroi/Kamilaroi Nation [6]. The population of the Namoi catchment exceeds 100,000 people, with the majority living along the major rivers (Green et al., 2011). Tamworth is the most populated town in the catchment, having a population of 41,006 people (based on 2016 census data) [7]. Gunnedah, the next largest town, has a population of 9,726 (based on 2016 census data) [8]. Narrabri is

[6] https://www.industry.nsw.gov.au/water/plans-programs/water-sharing-plans/status/namoi-region, 13 Sep 2021

[7] https://quickstats.censusdata.abs.gov.au/census_services/getproduct/census/2016/quickstat/1031?opendocument, accessed 17 Dec 2020

[8] https://quickstats.censusdata.abs.gov.au/census_services/getproduct/census/2016/quickstat/SSC11812?opendocument, accessed 17 Dec 2020

smaller again, with a population of 7,606 (based on 2016 census data) [9]. Domestic water supply to the towns in the catchment are supplied by the numerous river and creeks.

Both dryland and irrigated agriculture represent a significant proportion of output from the catchment (Green et al., 2011). Major industries, shown in Figure 6, include livestock, cotton, grain and horticulture (Green et al., 2011). Cropping is common along the alluvial floodplains of the catchment (Green et al., 2011). Cotton is the main irrigated crop (Green et al., 2011). However, in the long-term there is expected to be a decrease in cotton lint production due to an increasing number of +35°C days in the region (Wilson, 2019). Modelling has suggested that of farms in the region do not adapt to climate change their economics are negatively affects and adapting early is beneficial (Wilson, 2019). Adaptions are not a silver bullet and climate change can be expected to impact farms (Wilson, 2019).

Land set aside for conservation makes up over 3% of the catchment. Aside from this land and areas where forestry is practiced, much of the native vegetation has been cleared for agriculture, both grazing and cropping (Green et al., 2011). This widespread clearing combined with poor grazing practices have caused soil degradation and erosion, as well as weed invasion (Green et al., 2011). Although there are no large wetland systems, there are smaller wetlands and lagoons, as well as floodplain woodlands, in the Namoi catchment (Green et al., 2011).

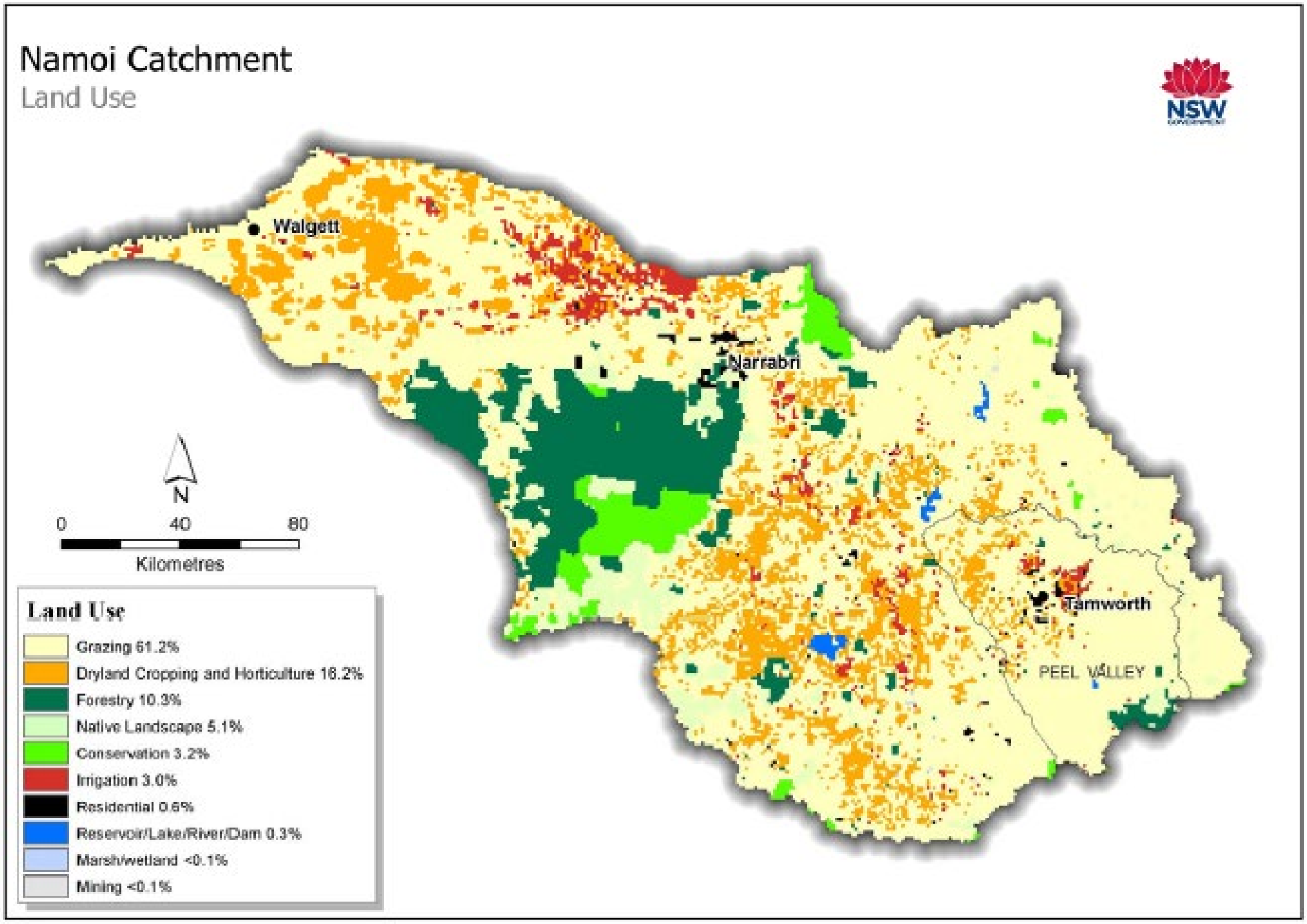


Figure 6 Land use in the Namoi catchment (Source: Green et al., 2011).

3.1.1 Climate

The catchment has a large rainfall gradient with upwards of 1,150 mm falling in the east to a little over 400 mm in the west (Figure 7). There is a seasonal pattern to rainfall in the catchment, with highest monthly rainfall common in summer. Similar to rainfall, evaporation rates peak in summer although the spatial trend is reversed with evaporation increasing to the west (Figure 8).

[9] https://quickstats.censusdata.abs.gov.au/census_services/getproduct/census/2016/quickstat/SSC12903?opendocument, accessed 17 Dec 2020

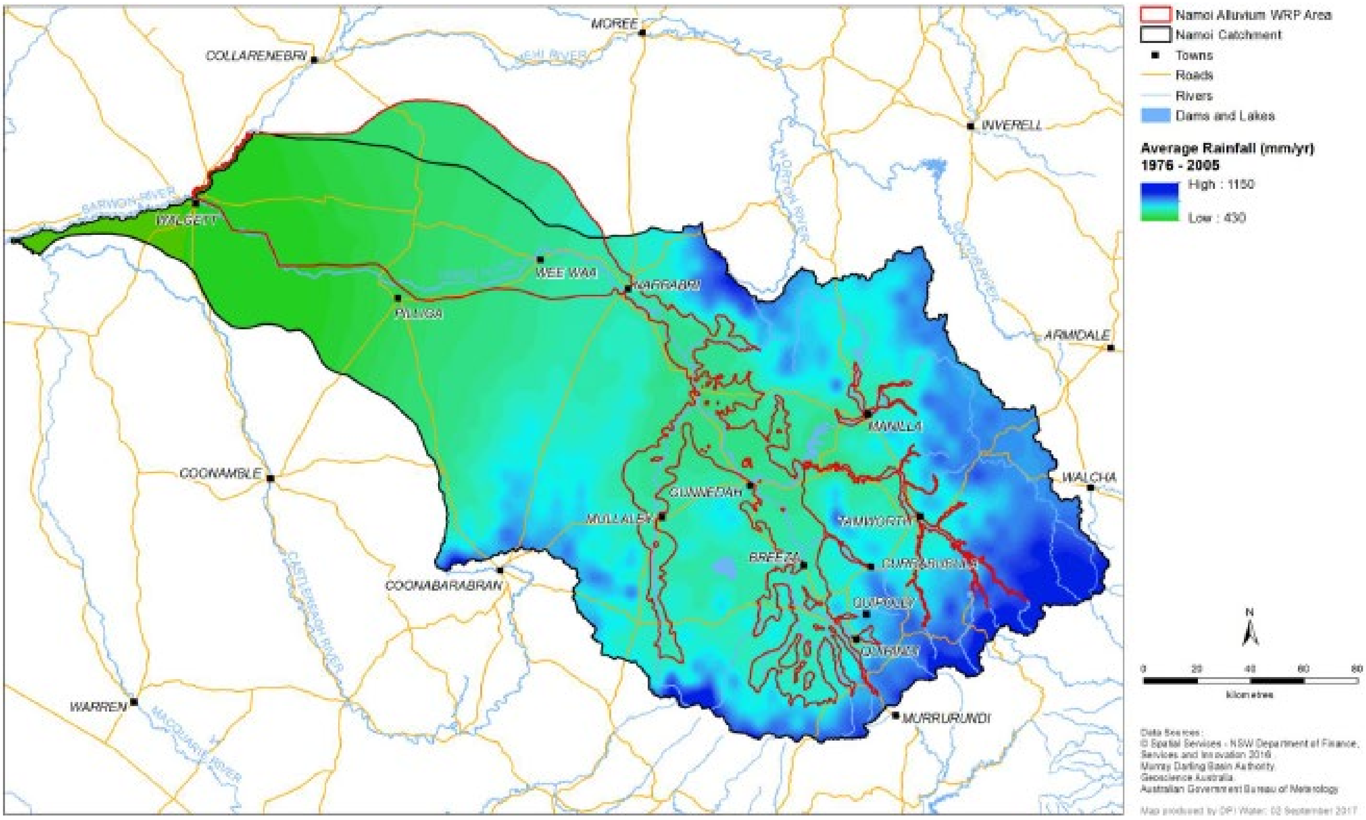


Figure 7 Average annual rainfall map in the Namoi catchment (Source: BOM, 2008 in DPIE, 2019).

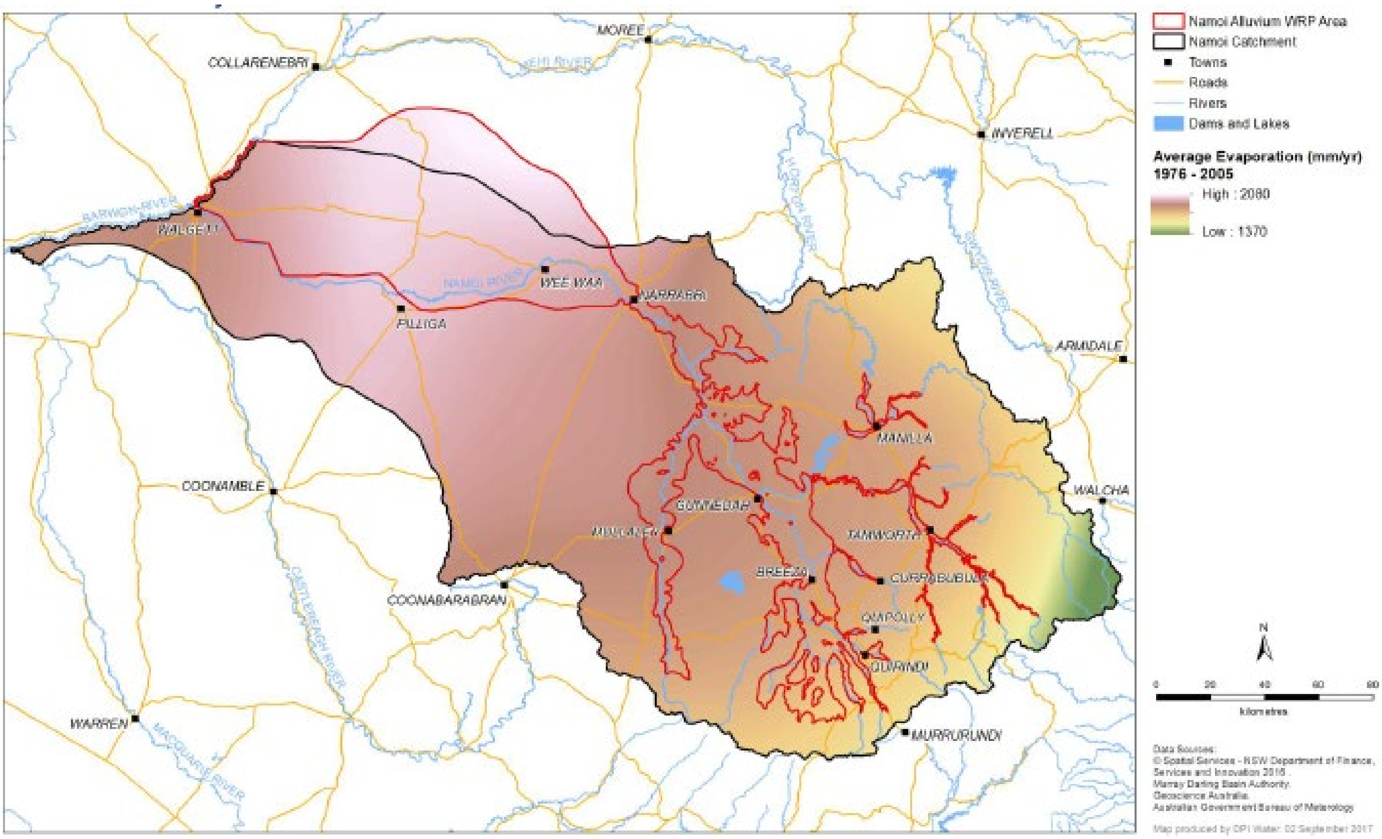


Figure 8 Average annual evaporation in the Namoi catchment (Source: BOM, 2008 in DPIE, 2019).

3.1.2 Geology and soils

The Palaeozoic New England Fold Belt, Palaeozoic to Mesozoic Gunnedah Basin, Mesozoic Great Artesian Basin (GAB), and unconsolidated sediments and Cenozoic extrusive volcanics comprise the five main surface geological units in the Namoi catchment shown in Figure 9 (DPIE, 2019). The Cenozoic unconsolidated sediments are comprised of alluvial or colluvial deposits of clay, silt, sand and gravel and cover the majority of the area west of Narrabri, including the Lower Namoi Alluvium (DPIE, 2019). A range of soil types are present in the Namoi catchment (Figure 10). The heavy black and grey clays, resulting from the volcanic geology, and the alluvial floodplains are commonly targeted for agriculture (Green et al., 2011).

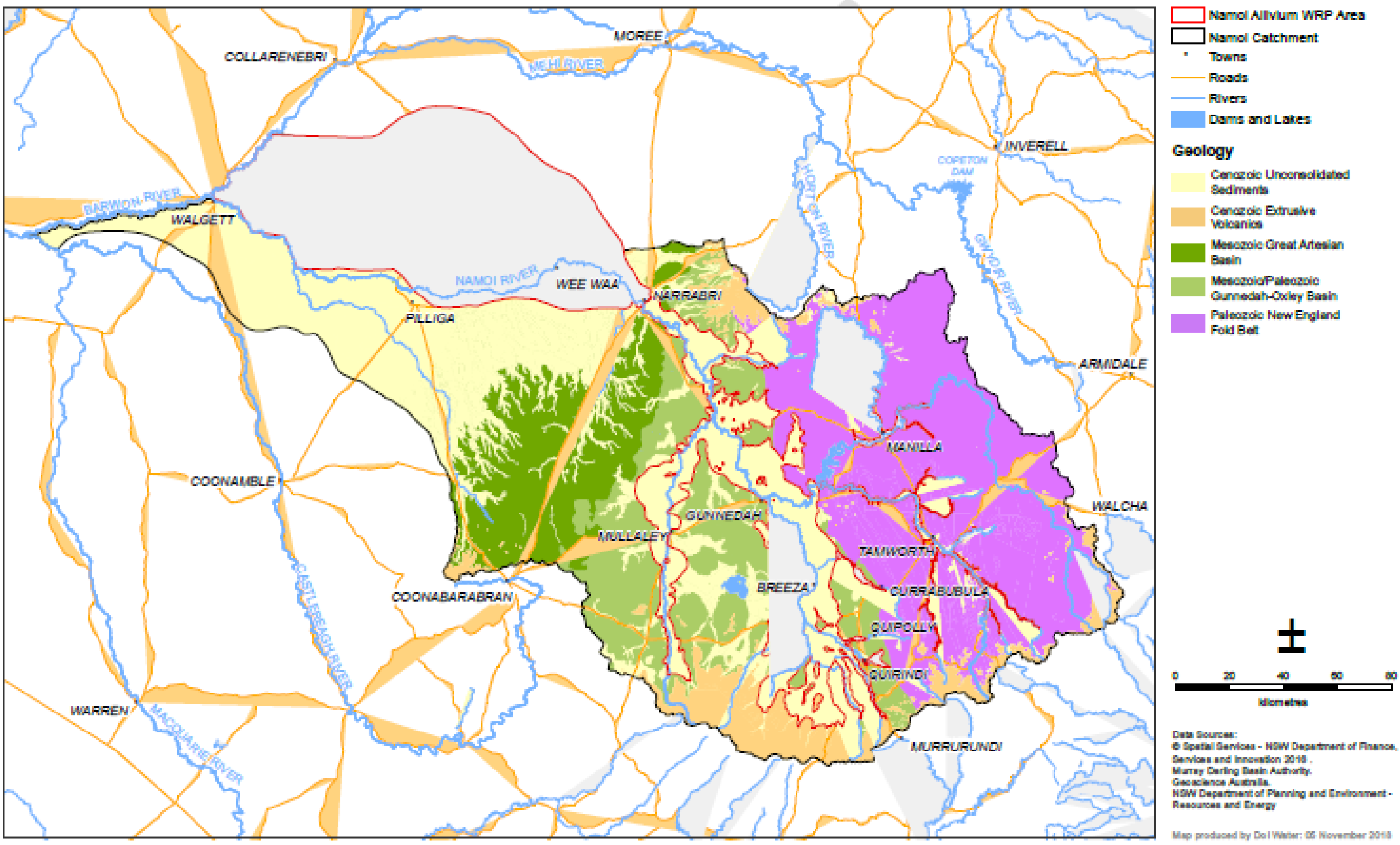
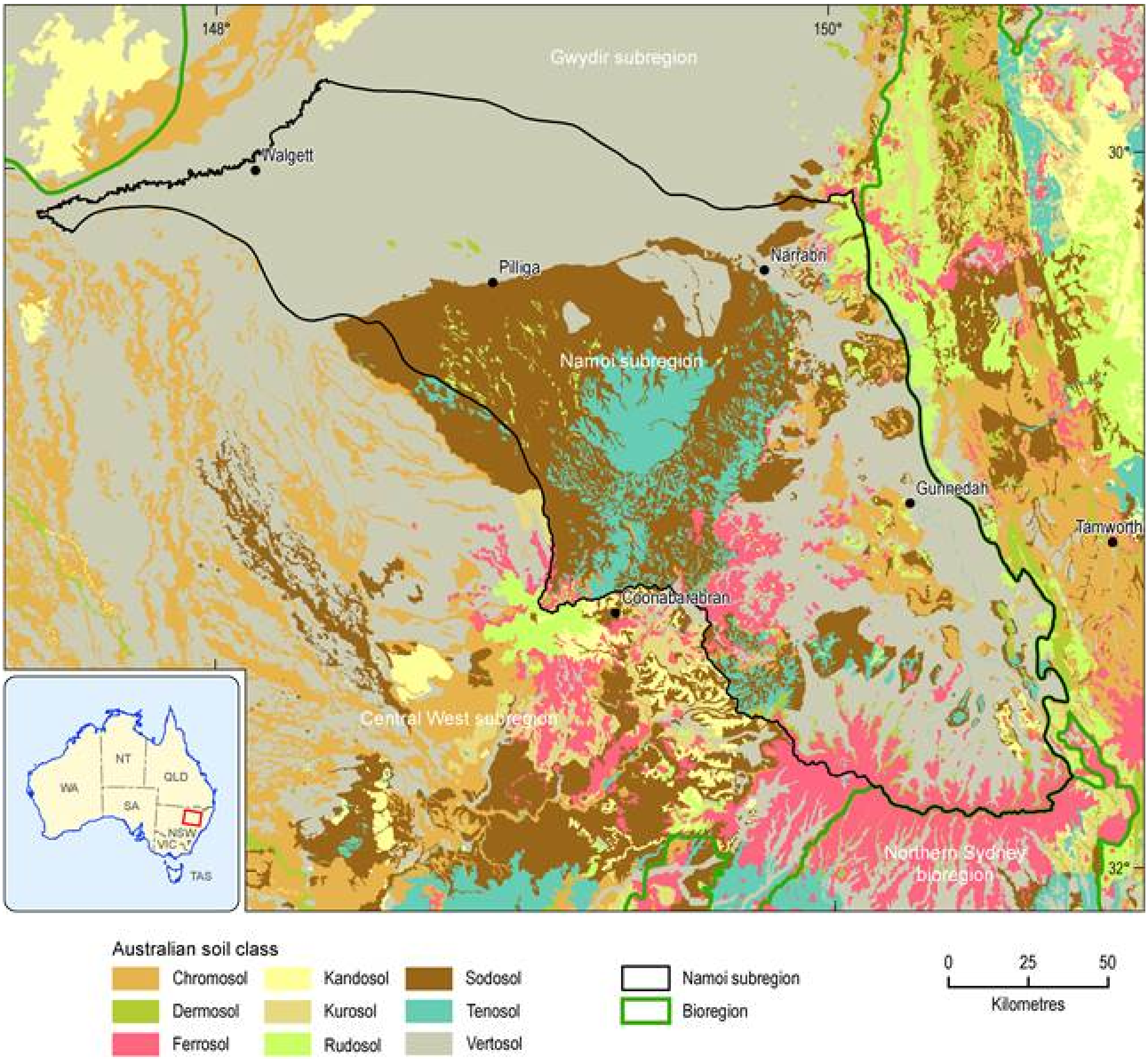


Figure 9 Geology of the Namoi catchment (Source: DPIE, 2019)

3.1.3 Surface water and groundwater

The Namoi River runs west to the outlet of the catchment from the Great Dividing Range, with its major tributaries being the Mooki, Peel, Manilla, and McDonald Rivers (Figure 11). There are three regulating dams in the catchment: Keepit Dam (Namoi River), Split Rock Dam (Manilla River) and Chaffey Dam (Peel River) (Figure 11). The average annual flow of the Namoi River at Gunnedah is 696,000 ML (Green et al., 2011), however there is a large amount of variation between years (Figure 12).

The alluvial sediments along the Namoi River (and its tributaries) contain groundwater (Figure 13), which currently provide water for a variety of used including irrigation (Green et al., 2011). In some areas of the Lower Namoi the alluvium is up to 120 m deep, producing bore yields in excess of 200 L/sec (Green et al., 2011). In the Upper Namoi yields from the alluvium aquifer are lower, ranging from 10 – 40 L/sec (Green et al., 2011). The salinity of groundwater in the Namoi catchment varies spatially (Figure 14).



https://www.bioregionalassessments.gov.au/assessments/11-context-statement-namoi-subregion/1121-physical-geography, accessed 18 Dec 2020).

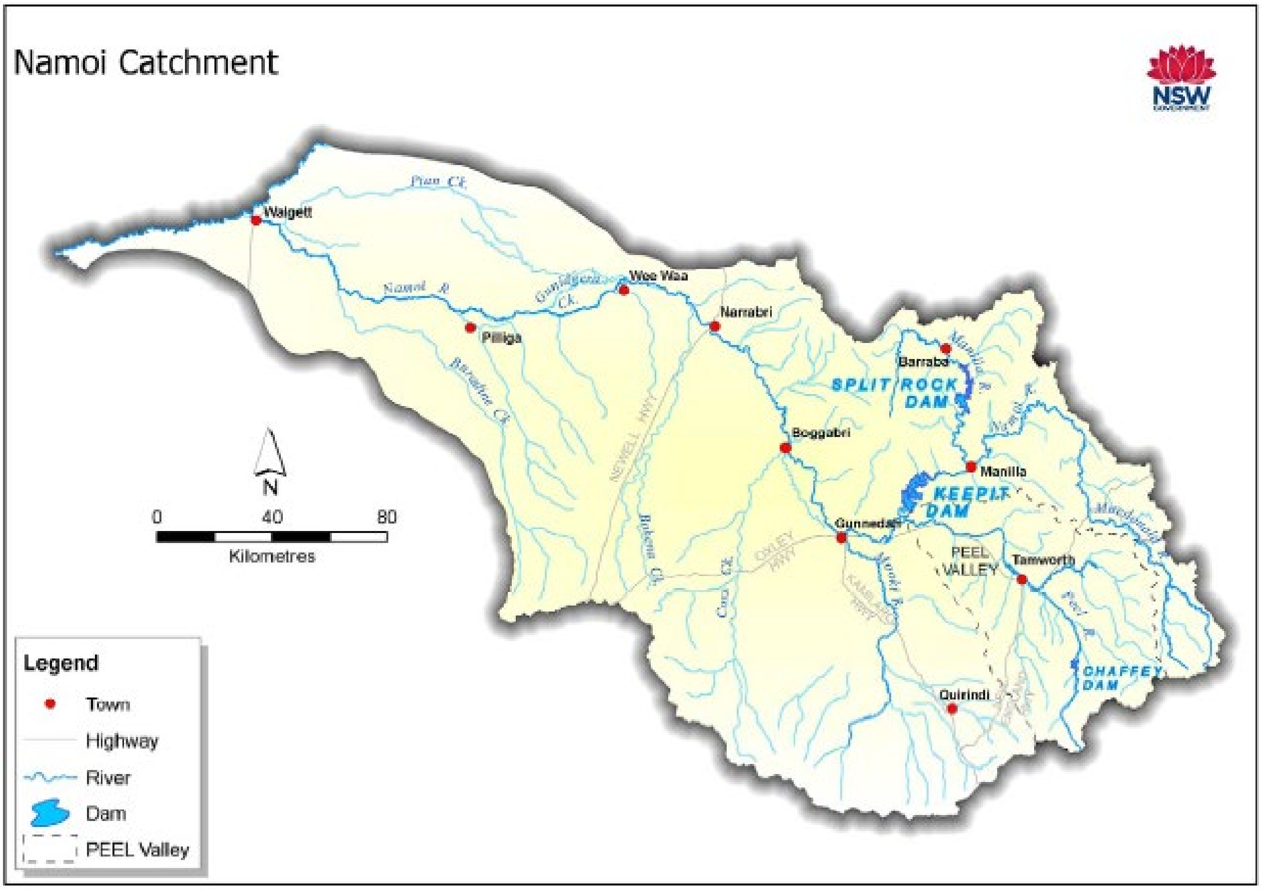


Figure 11 Rivers and tributaries of the Namoi catchment (Source: Green et al., 2011).

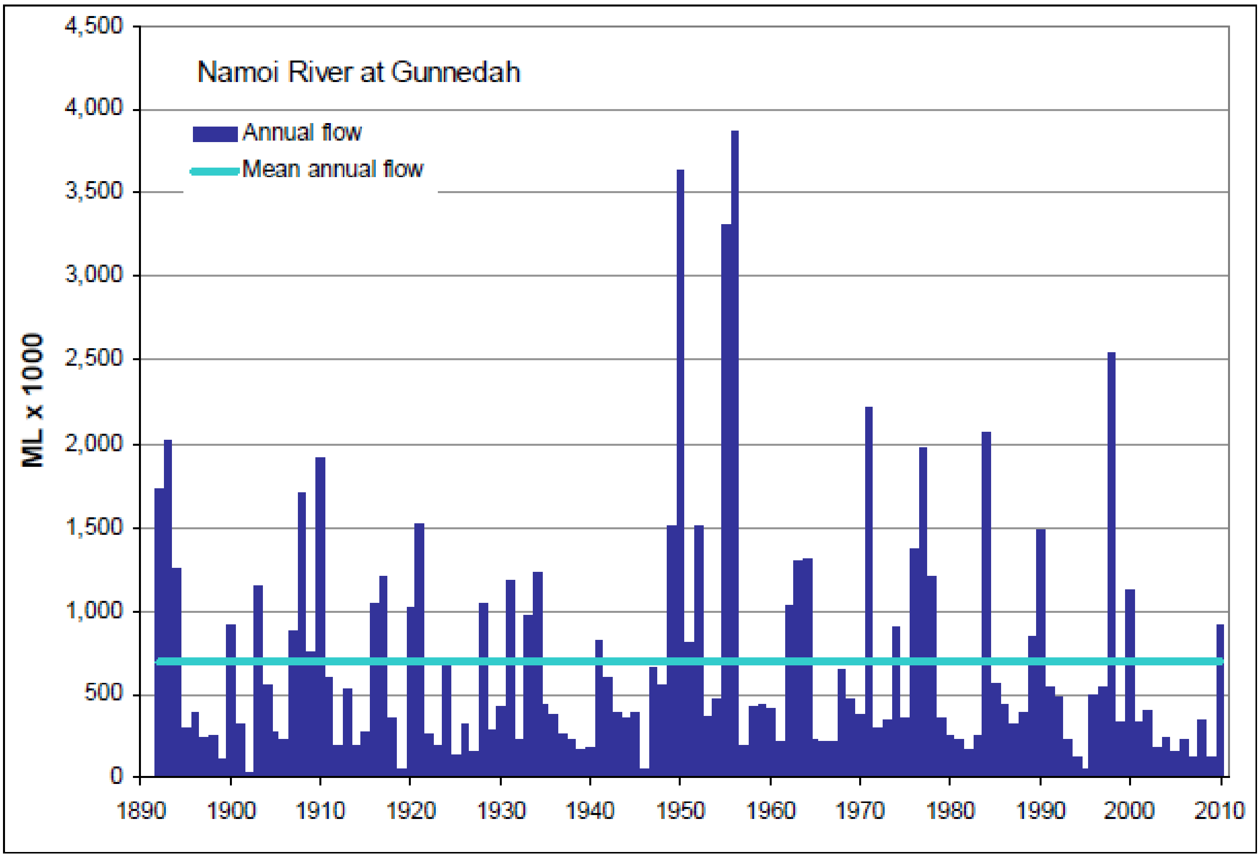


Figure 12 Annual flows in the Namoi River at Gunnedah (Source: Green et al., 2011).

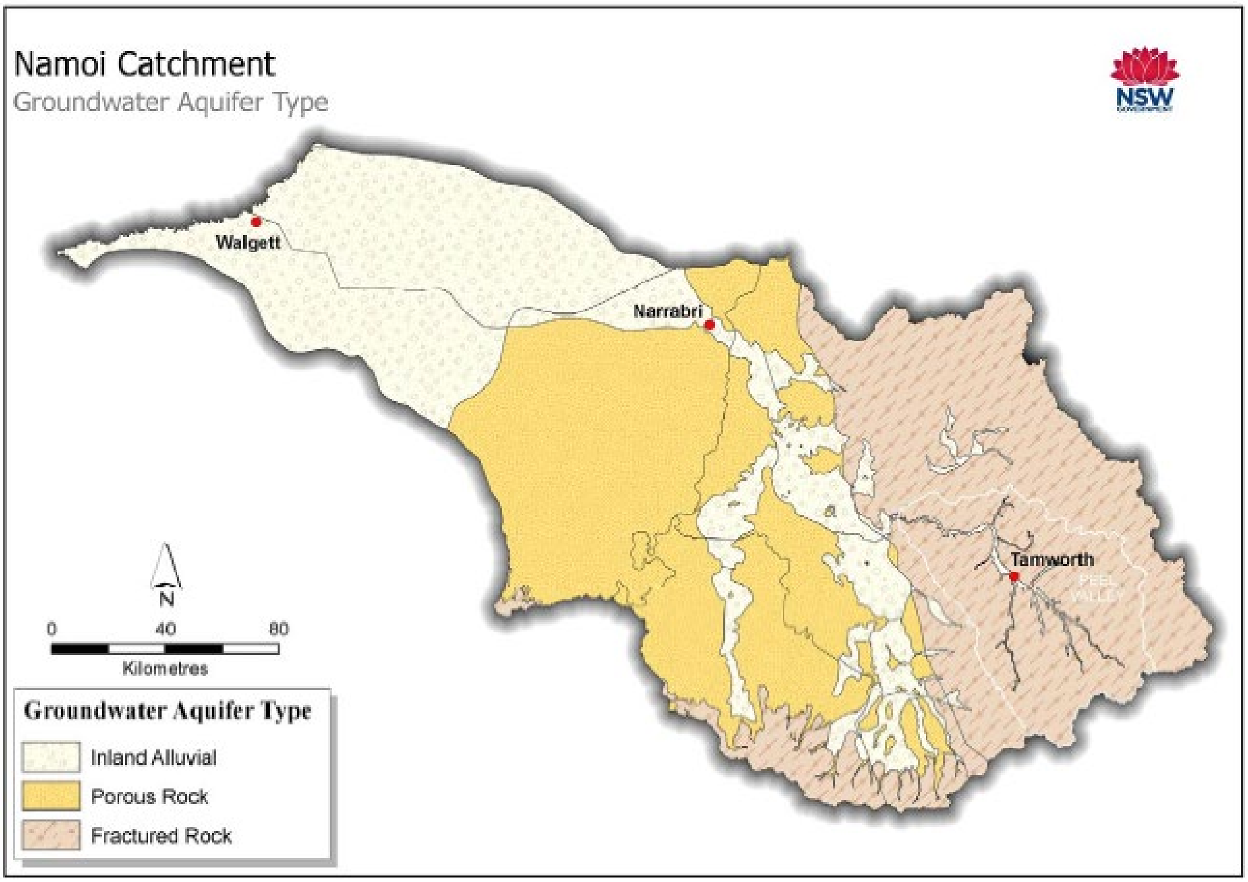


Figure 13 A simplified representation of the groundwater aquifer types in the Namoi catchment (Source: Green et al., 2011).

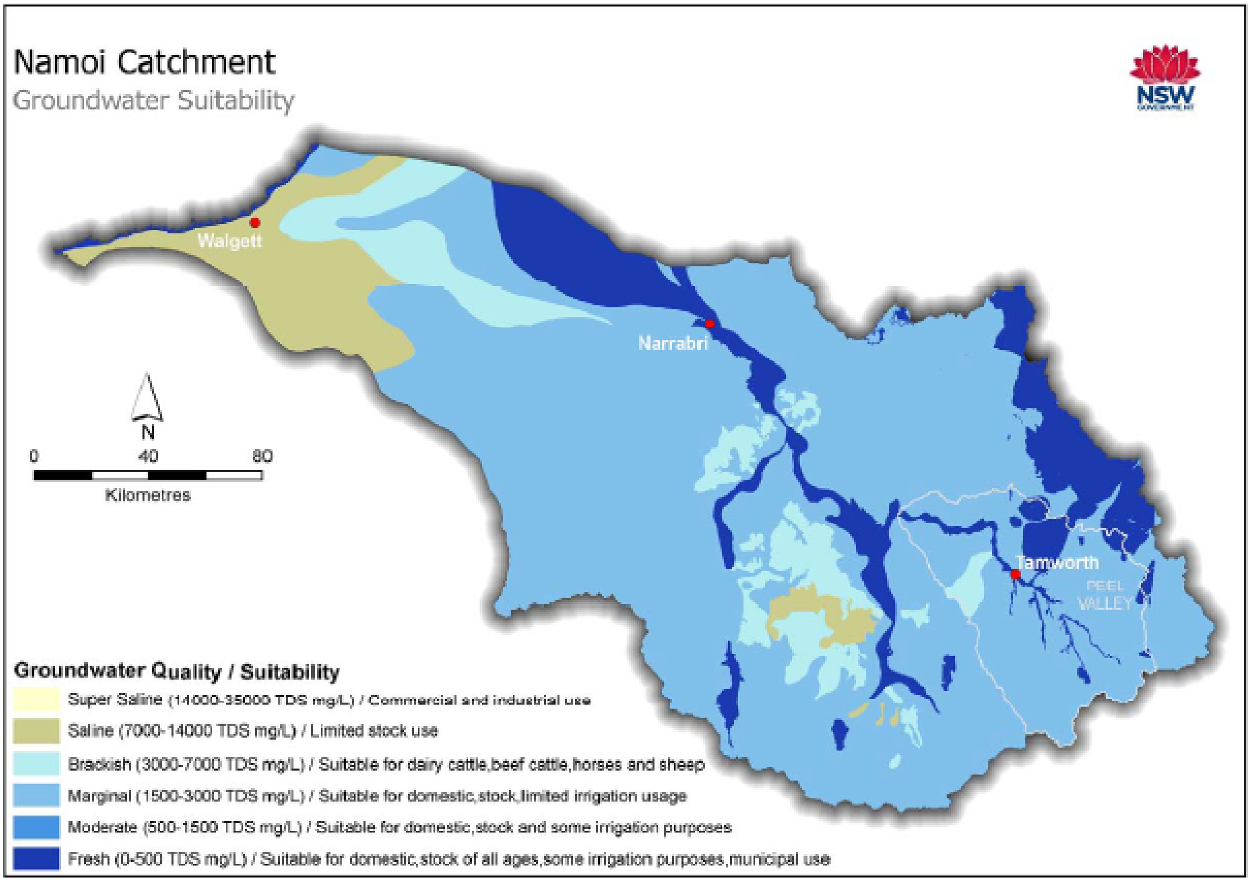


Figure 14 Groundwater quality and suitability in the Namoi catchment (Source: Green et al., 2011).

3.2 Overview of MAR research in the Namoi

MAR has been discussed as a water management option in the Namoi catchment for many years, from a variety of angles (Arshad et al., 2014, Arshad et al., 2012, Arshad et al., 2013, Fuentes and Vervoort, 2020, Rawluk et al., 2013, Woolley et al., 1994). It has been proposed that the large amount of already constructed on-farm surface storages could be used as temporary storages (and sedimentation ponds) before infiltration or injection (Arshad et al., 2014). The channel system could also be used directly for MAR as unlined supply channels could be used to directly to infiltrate water into the below surface aquifer (Fuentes and Vervoort, 2020).

Technical feasibility

Woolley et al. (1994) examined the general requirements for artificial recharge in the Namoi and considered representative parts of the valley to assess 'possibly suitable trial sites': the Mooki River and Quirindi Area in the Upper Namoi and two gravel pits in the Lower Namoi Valley. One preferred site for a trial was Borambil Creek at Quirindi which would have involved the construction of a low-level sheet pile weir, associated bank stabilisation and periodic maintenance to scrape-up the river bed. An advantage of this was that it could be associated with a town water supply operation. The other preferred site was the gravel pit north-west of Merah North (see Figure 15) which had suitable shallow sand layers in an area located close to a water source. To our knowledge, potential trials in either of these sites were not developed any further. The use of a single gravel pit, however, may have limited potential for regional-scale MAR given the slow rates of groundwater movement and observed mounding in this part of the Namoi system.

Fuentes and Vervoort (2020) used multicriteria decision analysis focused on technical aspects (e.g., slope, distance to river, aquifer characteristics) to produce a suitability map of infiltration (including in-channel) MAR in the Namoi catchment (Figure 16). Their analysis used 10 hydrologic and hydrogeologic criteria (slope, distance to rivers, distance to users, drainage density hydrogeological unit, aquifer Ks, aquifer yield, aquifer salinity, groundwater depth, soil Ks). The areas of highest suitability tend to be close to stream channels.

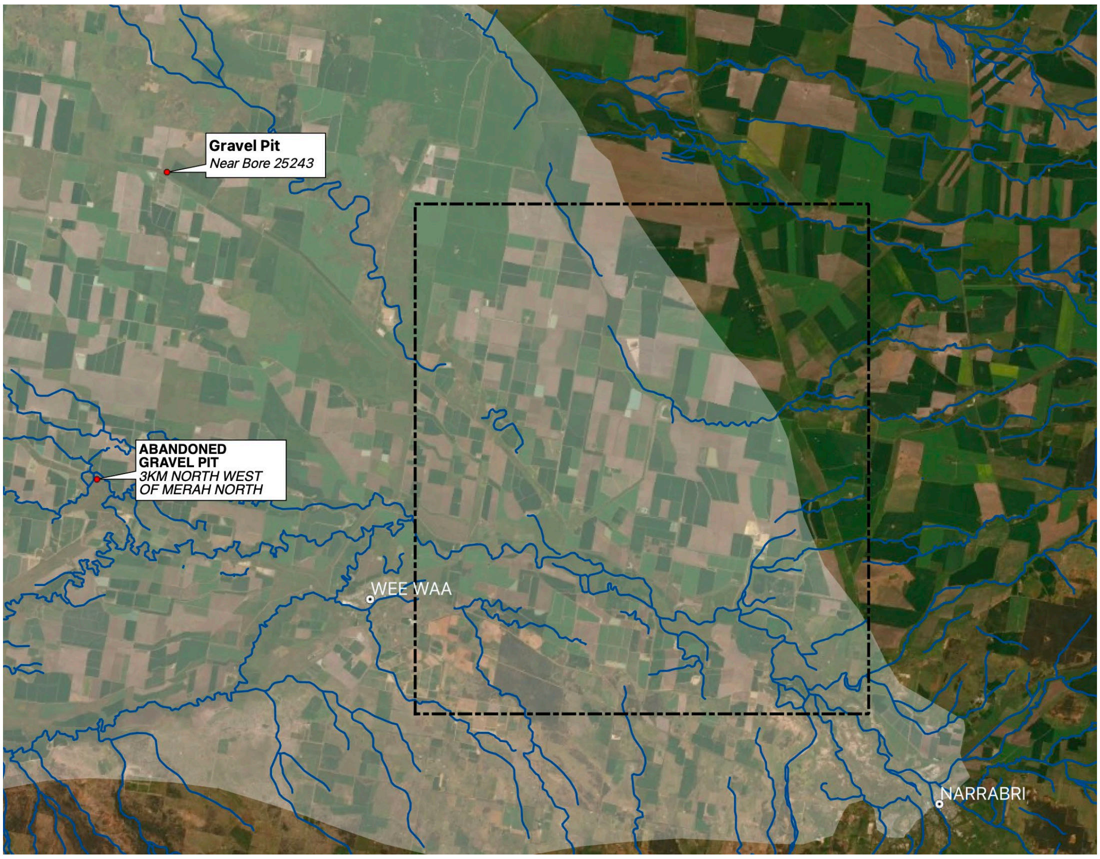


Figure 15 Location of the gravel pits in the Lower Namoi explored by (Woolley et al., 1994). The box indicates the area of interest for this study (see Section 3.3).

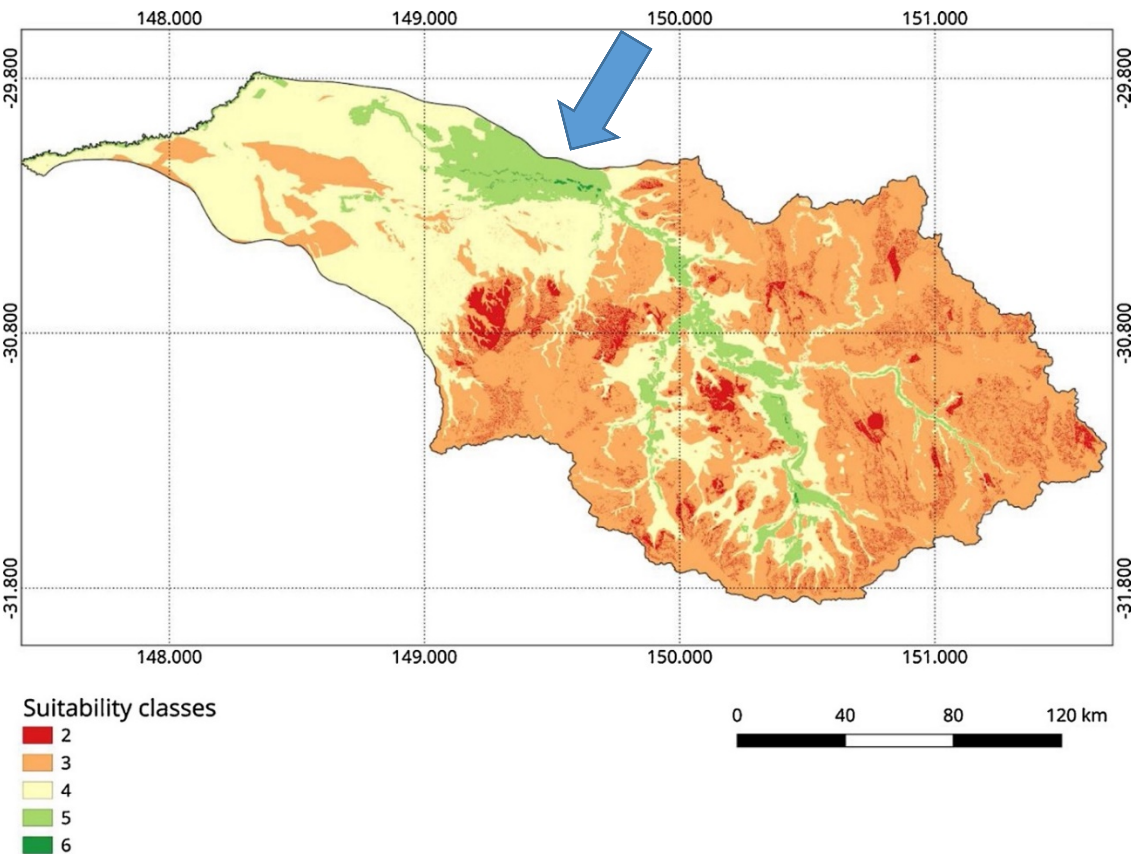


Figure 16 Suitability map for infiltration based MAR in the Namoi catchment produced by Fuentes and Vervoort (2020), where high values indicate high suitability. The blue arrow is added to highlight an area of high suitability that is the area of interest of this study.

Water availability

Arshad et al. (2012) assessed water availability for MAR from high streamflow periods (i.e. flood events) in the Lower Namoi. It was determined that, on average, once every four years 340 GL of 'flood' water was available under the water sharing rules although the large variability associated with floods would need to be factored in during MAR planning and management (Arshad et al., 2012). Fuentes and Vervoort (2020) estimated that 33 GL per day that might be allocated for recharge but that whole event totals may be more important than single day totals. During one flood event an estimated 240 GL of water exceeded channel limits (Fuentes and Vervoort, 2020).

Financial viability

Arshad et al. (2013) compared the cost and benefits of dams, infiltration-based MAR and injection-based MAR in the Lower Namoi. If MAR can be kept below $500/ML it was suggested as a financially viable option (Arshad et al., 2013). The presence of existing on-farm storages in the region was highlighted as a benefit, as these could act as temporary storages for floodwater before infiltration or injection (Arshad et al., 2013).

Arshad et al. (2014) also compared the cost of surface storage and MAR using both infiltration and injection, looking for crossover points where MAR would no longer be financially viable due to reduction in infiltration rate or increase lose, etc. The high capital and water treatment costs of injection, even using existing wells, made this option uneconomical compared to surface storage and infiltration-based MAR (Arshad et al., 2014). Although infiltration based MAR was initially more financially worthwhile, a reduction in infiltration rate, increased loss or a drop in cotton crop prices all caused the cross over point between surface storages and MAR to be reached, with surface storages becoming more financially viable (Arshad et al., 2014).

Social acceptability

Sharp and Curtis (2012) and Rawluk et al. (2013) assessed the social acceptability of MAR using flood water from the point of view of irrigators. The majority of respondents were in favour of MAR, seeing that MAR has merit, however, environmental impacts, impacts on groundwater quality and the possibility of over-exploitation were all concerns raised (Rawluk et al., 2013).

Governance arrangements

Arshad et al. (2012) and Rawluk et al. (2013) both highlighted that the lack of policy and governance systems to support MAR in NSW was a barrier to MAR in rural settings. As of 2021, pilots for recharge and monitoring can already go ahead with current regulatory frameworks (Ross, 2019), and these are needed to build confidence and expertise and to properly evaluate MAR (Woolley et al., 1994). Whilst MAR policies are not yet in place, there is NSW government interest in this space which is an opportunity to ensure in any new policy that rules play to the strengths of MAR while minimising associated risk (Guillaume et al., 2020). Essential to any MAR policy is that recovery entitlements should be clearly specified and linked to the volume actually recharged, and included in groundwater allocation plans (Ross, 2019). Metering and reporting of recharge and recovery is essential to support recovery entitlements.

3.3. Area of Interest

Given the previous work on MAR in the catchment, this case study takes an operational, site specific perspective based on currently available data. The area of interest (AOI) for our sub-regional analysis is the area of high suitability mapped by (Fuentes et al., 2020) shown in east of the Lower Namoi groundwater source (between Narrabri and Wee Waa; blue arrow in Figure 16) [10]. This area is part of a highly developed irrigated agriculture industry where cotton is an important irrigated crop. It is located within the Lower Namoi Groundwater Source zone (Figure 17), the lower Namoi Regulated River Source (Figure 18) and primarily encompasses the Spring and Bobbiwaa Creeks water source under the *Water Sharing Plan for the Namoi and Peel Unregulated Rivers Water Sources 2012* (Figure 19 Management zones covered by the Water Sharing Plan for the Namoi and Peel Unregulated Rivers Water Sources 2012).

[10] The Upper Namoi Zone 1 (Borambil Creek Groundwater Source) near Quirindi was raised as a possible site on which to focus as it was an area where water allocations had been cut by 80%; it was also one of the preferred sites to pilot MAR identified by WOOLLEY, D., FOREST, J., GREEN, J., LATTY, K. & WILLIAMS, R. M. 1994. Proposals for Artifical Recharge in the Namoi Valley Department of Water Resources. It was not selected as the AOI for this study as there is no irrigated cotton production and the biggest water user, the town of Quirindi (1.5GL), is soon to get a pipeline from surface infrastructure.

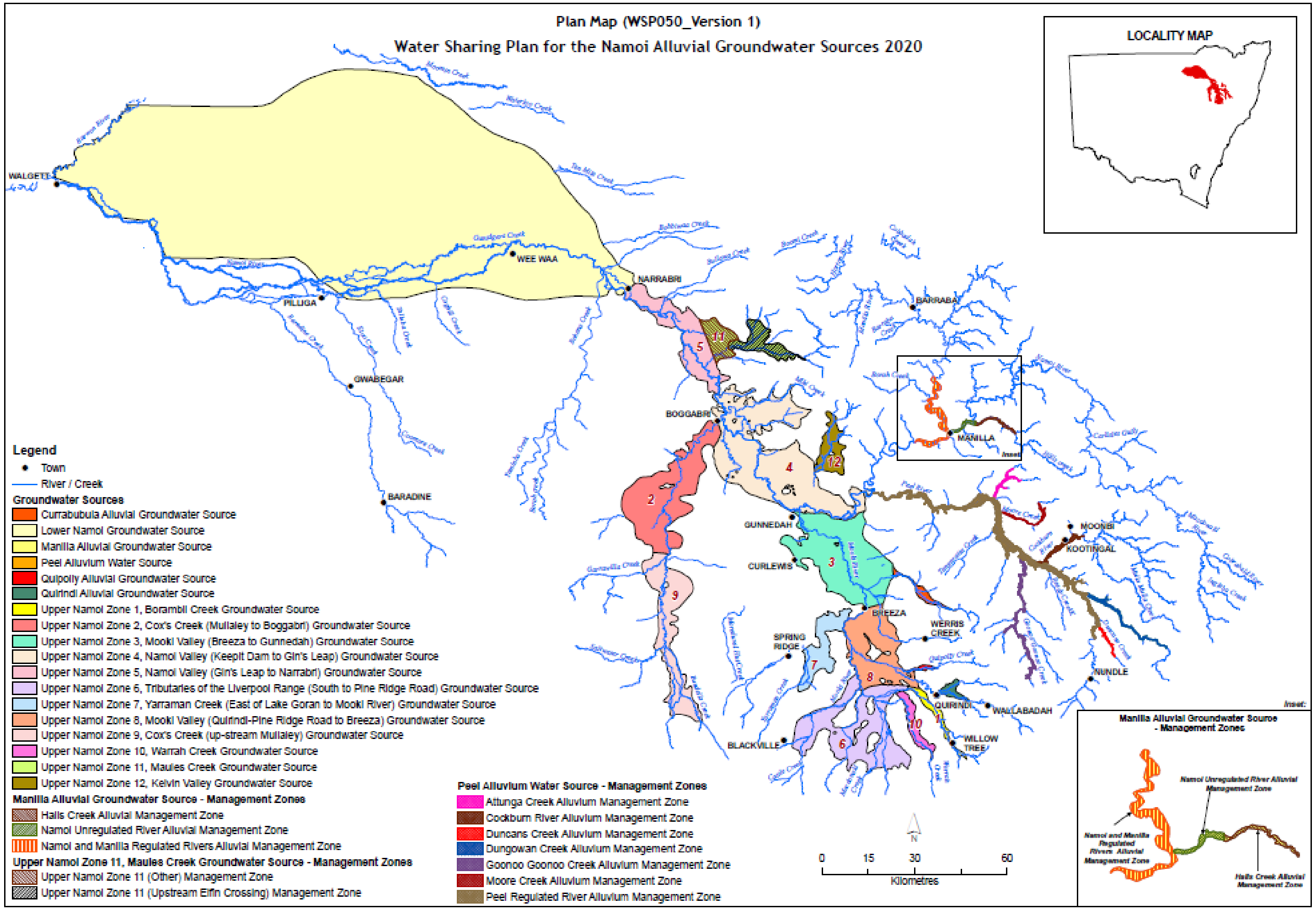


Figure 17 Groundwater sources defined in the Water Sharing Plan for the Namoi Alluvial Groundwater Sources 2012 [11]

[11] https://legislation.nsw.gov.au/view/pdf/map/267559e4-dd5d-4709-ba00-0a8bad2de23e; accessed 13 September 2021

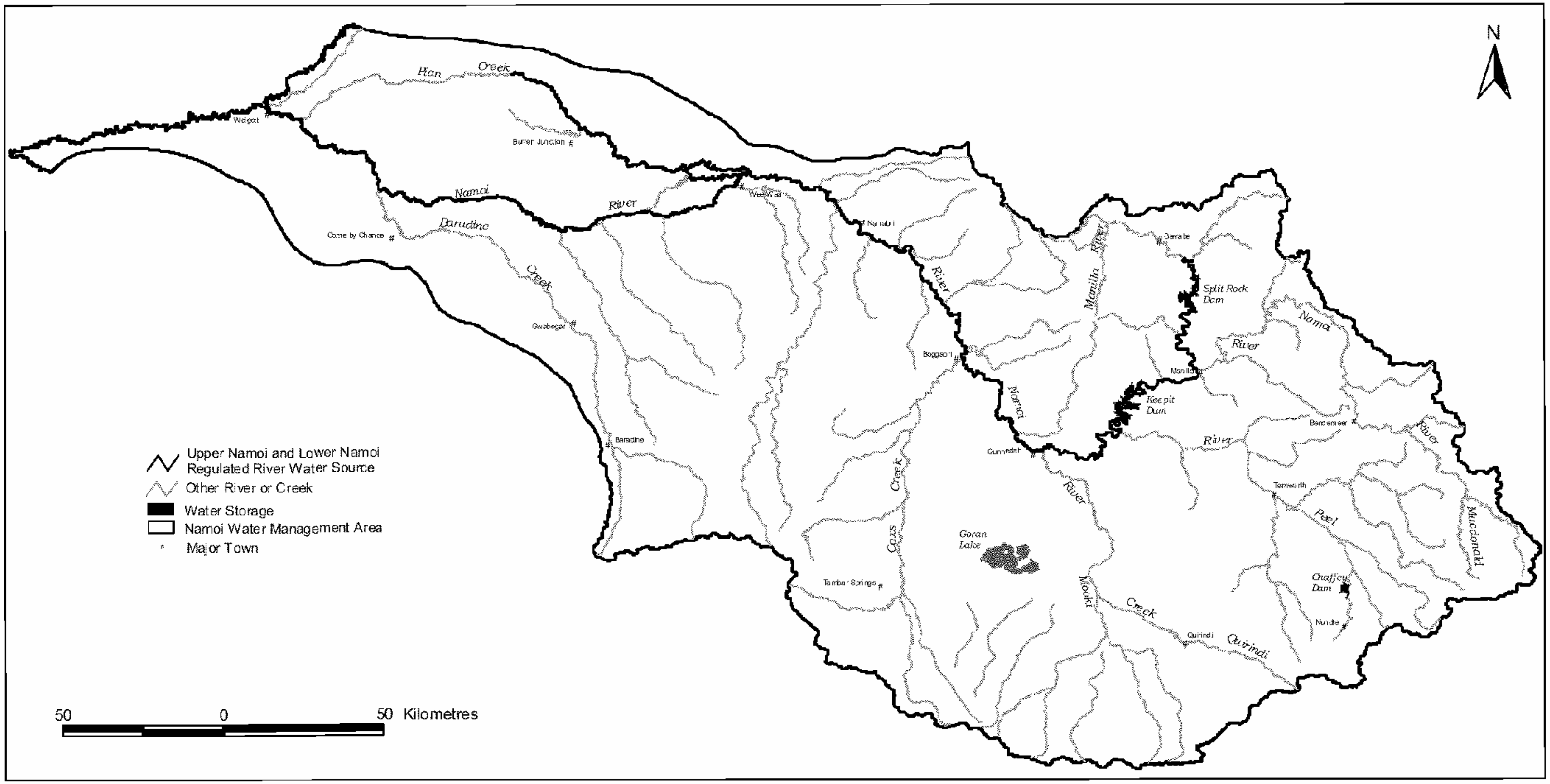


Figure 18 Namoi water management area defined by the Water Sharing Plan for the Upper Namoi and Lower Namoi Regulated River Water Sources 2016 [12]

[12] https://legislation.nsw.gov.au/image/((Type%3D%22subordleg%22)%20AND%20(No%3D0631)%20AND%20(Year%3D2015)%20AND%20(%22Historical%20Document%22%3D0))/g1.gif; accessed 13 September 2021

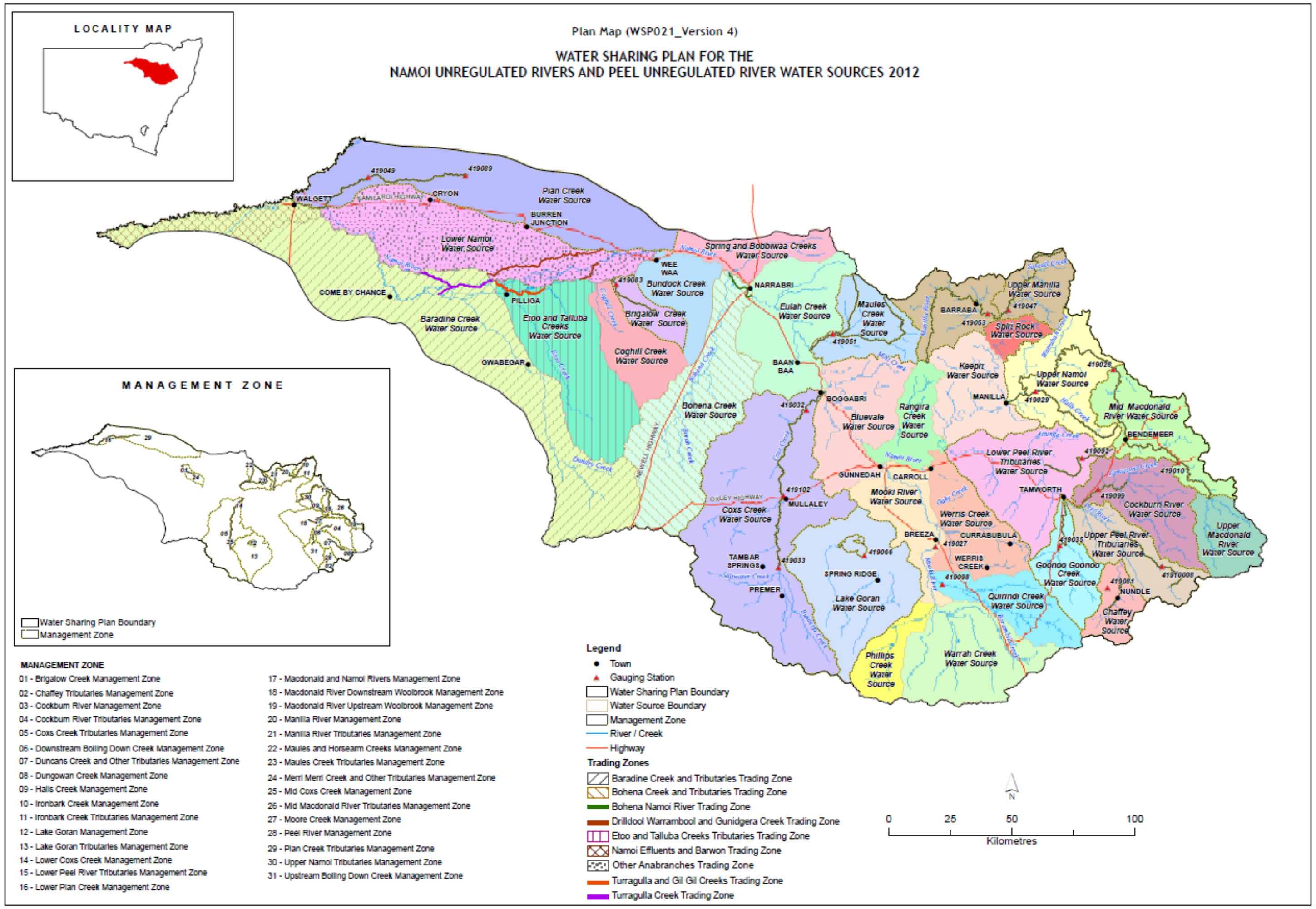


Figure 19 Management zones covered by the Water Sharing Plan for the Namoi and Peel Unregulated Rivers Water Sources 2012[13]

[13] https://legislation.nsw.gov.au/view/pdf/map/5dbb6137-6ae5-4e3b-98f2-3917304c1152; accessed 13 September 2021

4. Scenarios

The proposed scenarios were drafted in September 2021 from preliminary feasibility analyses pertaining to MAR in the Namoi catchment and were refined based on preliminary engagement with local stakeholders and experts as well as further assessment of potential feasibility. Note that these scenarios do not constitute an endorsement for a particular course of action. Rather, they highlight possible opportunities for MAR in the Namoi catchment, contrasting these scenarios against the 'status-quo' situation.

4.1 The 'status quo'

The Lower Namoi is a highly advanced irrigated agriculture region that already makes use of large capacities of farm dams, conjunctive surface and groundwater use, and flood water management. Any new water management solution (e.g. managed aquifer recharge) can likely be considered an attempt to optimise an existing capability rather than the first attempt at meeting a need. We focus on three key capabilities here relating to ability to store and access water 1) in normal conditions, 2) in dry years, and 3) from wet years. On-farm water storages are a lynchpin to all three conditions, but suffer from high evaporation losses, especially in hot and dry periods. Between years, both general security surface water and groundwater carryover rules allow accumulation of unused water up to a point, beyond which excess carryover is shared with other water users by influencing available water determinations. Increased use of groundwater during dry periods (and decreased use in wet) provides further water security, limited by carryover and groundwater allocations. Accumulation of groundwater allocations is limited by rules to avoid excessive drawdown from concentration of pumping, particularly through assessments of trade applications. Historically, additional water in wet years could be stored in surface storages or used instead of other allocations through overland flows (floodplain harvesting) and announced supplementary flow events. Rules around supplementary water and floodplain harvesting are currently in flux [14]. Growth in use is still likely to be restricted and the impacts of rule changes on groundwater recharge are still unclear. Gains from optimising the status quo are unlikely to provide new water, but rather to provide greater control over where and when water is available. While there is interest in innovations like MAR, there is an expectation that the benefits would need to be clear in order to invest.

4.2 MAR for low loss water storage (farm scale)

MAR could allow greater storage with reduced losses compared to on-farm storages. On-farm storages are already used to capture and bank water during wet periods, for example supplementary water or overland flows captured through floodplain harvesting. Storage of these waters in on-farm dams leads to evaporative losses and, with climate change, losses per unit area of water are expected to increase [15]. MAR would be a calculated improvement in water balance and while it comes at the expense of greater pumping costs it has two critical advantages. Firstly, in contrast to technologies that keep an existing storage full by reducing evaporation, MAR increases total storage capacity through use of the aquifer. Secondly, other existing infrastructure could in principle also be used for MAR, e.g. by careful identification of locations of high infiltration and adequately quantifying the resulting recharge. This would tie in well with trend towards greater telemetry and automation and the use of remote sensing technologies to 'close' the water balance [16]. While farm-specific cost assessments will be required, as also encouraged by programs to foster and enhance farm resilience to drought, MAR is expected to provide financial benefit to irrigators, in part due to reducing costs of energy, but will require care in managing capital and operating costs. It also depends on

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[14] See Section 5.7.2

[15] See Section 5.2.4; FUENTES, I., VAN OGTROP, F. & VERVOORT, R. W. 2020. Long-term surface water trends and relationship with open water evaporation losses in the Namoi catchment, Australia. *Journal of Hydrology,* 584**,** 124714.

[16] This is an active area of research; one example is that of the WaterSense project (https://cordis.europa.eu/project/id/870344, accessed 7 December 2021)

clear rules around recovery of entitlements and the broader policy framework to enable MAR currently in development through the NSW Water Strategy [17,18].

MAR would be run on single farms by an individual owner or land manager, potentially in collaboration or with outside support for the assessments, to share costs and access expertise in groundwater investigation and monitoring. Delivery of surface water would follow existing mechanisms, with on-farm storages used for temporary storage of MAR water. Recharge could occur through infiltration basins, channel seepage, controlled field flooding (known as “AgMAR”), or injection in existing or new wells [19]. Appropriate options depend on local aquifer characteristics which are highly variable in the Lower Namoi [20]. Many irrigators already have both surface and groundwater licences, and on-farm storages and infrastructure, and to some extent monitor both resources. Recovery of water would occur through existing wells. Given the similarity of recharged and aquifer water quality, limits on recovery would likely be based on volumes rather than requiring the same water to be recovered as was recharged.

Both from a regulatory and farm management perspective, an understanding of recharge consistent with water accounting requirements is critical to being confident that MAR provides an improvement in control over the water balance, and to allow an allocation to be issued. Irrigation “return flows” to aquifers or rivers currently contribute to available water determinations, so impacts of MAR from existing infrastructure on water sharing plans may raise some controversy. In the meantime, MAR pilot studies could work with state government to test frameworks for regulating MAR in dedicated trial infiltration basins and test injection wells. Perhaps more importantly, land managers and supporting R&D institutions can already invest in improving understanding of aquifers under their land, including high resolution soil mapping, infiltration rates, spatial variation in groundwater level response, and quantifying seepage and evaporation over time. Reducing uncertainty about evaporation and recharge rates is critical to comparing MAR as a low loss water storage solution to other evaporation or infiltration reduction alternatives.

4.3 Moving water north (regional benefits)

From an aquifer perspective, MAR raises groundwater levels/pressure, and can therefore help counteract negative impacts of overextraction. MAR could be targeted at managing drawdown with the intention of avoiding reductions in available water determinations and maintaining flexibility in groundwater trade. Currently, long dry periods with groundwater extractions exceeding the long-term annual extraction limit need to be followed by reductions in available water to maintain long term averages within compliance limits. MAR provides an additional means to ensure sustainability and manage impacts, including excessive drawdown and worsening water quality.

In the Lower Namoi, there are areas of high drawdown north of Wee Waa that have affected the ability to trade, and water salinity tends to increase in the west, especially for the water table aquifer [21]. Increasing recharge north of the river through MAR could alleviate concerns regarding drawdown. There are reportedly restrictions to lateral groundwater flow that limit the effect of river recharge, and vertical recharge is insufficient to support current levels of pumping, leading to an increased hydraulic gradient in the region. MAR would involve moving water through existing channel infrastructure for recharge closer to drawdown areas, ensuring that groundwater is available when it is needed and reducing the risk of potential regional impacts.

Further investigation of the magnitude and distribution of benefits of reduced drawdown is needed to determine how costs and responsibilities would be shared. While moving water north appears to be possible, it would make use of syndicate channels and existing on-farm storages for temporary staging of MAR water, and therefore require

[17] https://dpie.nsw.gov.au/water/plans-and-programs/nsw-water-strategy/the-strategy, accessed 27 September 2021
[18] See Section 5.7.3
[19] See Section 5.3.5
[20] See Section 5.3.2
[21] See Section 5.3.3

collaboration between several land owners (including neighbouring dryland farmers). Similarly to *MAR for low loss water storage*, this is potentially an opportunity, however, to gradually optimise regional water operations, providing a project context in which infiltration and possible recharge from shared channel infrastructure can be investigated, and any concerns about pumping reliability can be tackled together. Initial work using existing infrastructure can be supplemented by new channel capacity and new injection or infiltration facilities as understanding of the aquifer and recharge mechanisms improves.

While regulatory change is needed for recharged water to be accounted for in available water determinations, a MAR project to move water north could begin now already. This would involve a stocktake of current hydrogeological knowledge about recharge in the area of drawdown and of impacts and potential benefits of alleviating that drawdown. Farm water data (e.g. telemetry) can inform estimates of seepage and information sharing about groundwater levels/pressure and soil properties could help complete state long-term monitoring records to achieve the high spatial and temporal resolution aquifer understanding that is essential in a spatially variable system like the Lower Namoi Alluvium. A partnership approach would be adopted to bring together local data holders, infrastructure owners, regulators, and expertise. Increasing infiltration by selective filling of leaky channels or fields does not need approval, and would be approached as pilots with appropriate monitoring to support project approvals for new infrastructure and potential water injection. The project could be set up to have an incremental mandate, starting with local data collection, knowledge management and sharing, moving on to support landholder water management, and then to development and operation of a larger MAR scheme, similar to that already operating in the Burdekin catchment in Queensland.

4.4 River recharge as MAR (transformative change)

River leakage is a major contributor of recharge in the Lower Alluvium, with recharge increasing when the river is high or in flood. The river is already regulated by both weirs and upstream dams, with Mollee Weir acting as a site of enhanced recharge. In principle, river regulation could also target groundwater recharge, raising water levels in reaches with high seepage to not just the water table but also the deeper production aquifer. This would be a major change in terms of river operations, attitude to surface water, and regulatory context, but if the aim of MAR is to move surface water to aquifers, then the potential efficiency of river recharge cannot be discounted.

In the current context, it is envisaged that managing river recharge would involve a long-term transition to active self-management by a dedicated cooperative, led by landholders and overseen by government. River recharge departs sufficiently from traditional river operations that it would likely be instigated by a grass roots farmer organisation that reaches critical mass in both understanding of the system and support for the scheme for government to support a change in governance and management arrangements, radically revisiting existing rules, including permitting the potential development of new infrastructure on Crown land. The required level of understanding of the local river system can likely only by achieved by a local dedicated organisation. Consensus would need to be reached on operating rules that reflect local conditions, environmental circumstances and target the sustainability (economic, social, and environment) of local irrigation communities without jeopardising downstream outcomes.

Similar to how the other scenarios recognise channel “losses” as potential recharge, river “losses” would be recognised as contributing to local groundwater availability, with the associated groundwater system supporting both economic and environmental outcomes. Where currently river losses are accepted as part of delivery of high security, general security and supplementary water, and for irrigation, town, and environmental use, a sufficiently advanced local understanding and supporting regulating infrastructure would allow varying those losses over time, decreasing recharge to increase delivery efficiency of pulses of water, and increasing recharge at other times. The rules for this kind of recharge are far from being drafted, but a possible precedent would be to treat the reaches affected as a regulated system with a conveyance license to be managed by the responsible organisation. The science to support active management is increasingly within reach. Geophysics and other analyses have already begun to identify high recharge reaches [22]. High resolution remote sensing provides unprecedented ability to monitor and model the system. Confidence in ability to manage river recharge for multiple outcomes could be enhanced by investigation of the impact of existing river levels and management on groundwater recharge, and relative contribution of river recharge to recovery of aquifer drawdown.

The fact remains that active self-management of river recharge by collectives of irrigators is a radical change that would require long term societal and regulatory change. Previous studies suggest that collective management is supported in the region [23], although river recharge has not specifically been investigated and would likely be particularly controversial. It might be that the necessary trust, capacity, and relationships do not start with the river, but rather other shared endeavours, such as the project described in moving water north. With a sufficiently sophisticated understanding of local hydrogeology, ultimately such a collective might not stop at the river, with management of recharge in the floodplain and tributaries potentially also yielding benefits. Working towards managing river recharge is then also symbolic of a desire to ensure that surface and groundwater are regulated together in the region, rather than apart.

[22] FUENTES, I. & VERVOORT, R. W. 2020. Site suitability and water availability for a managed aquifer recharge project in the Namoi basin, Australia. *Journal of Hydrology: Regional Studies,* 27**,** 100657.; KELLY, B., ALLEN, D., YE, K. & DAHLIN, T. 2009. Continuous electrical imaging for mapping aquifer recharge along reaches of the Namoi River in Australia. *Near Surface Geophysics,* 7**,** 259-270.; see Section 5.3.5

[23] SHARP, E. & CURTIS, A. 2012. Groundwater management in the Namoi: a social perspective Charles Sturt University: Institute for Land, Water and Society.; see Section 5.6.2

5. Feasibility Criteria Analysis

This section presents the data, information, analysis and assumptions that have been made in order to inform the potential feasibility across the seven criteria outlined in Table 1 of the four scenarios presented in Section 4. An overview of key points for each scenario and feasibility criteria is given in Table 2.

Table 1 The seven feasibility criteria of Ticehurst and Curtis (2017).

Criteria	Example questions and considerations
Demand for Water	• Is there demand for more water, or a greater water security? • Who wants the water and when?
Water availability	• Is water available to be banked underground (e.g. unused surface water shares, surface water traded in when prices are low)?
Technical feasibility	• Is there space in the aquifer systems to store surface water for drier times? • How can the water be recharged, stored and extracted?
Financial viability	• Financial viability and profitability of MAR schemes are influenced by many factors including the MAR type, water source, infiltration and recovery rates, groundwater depth, water markets, crop prices and yields, groundwater pumping costs
Environmental risks	• Are there any significant effects on water quality & quantity (positive or negative)? • What are the consequential impacts of any change on farm land and ecosystems?
Social acceptability	• Is it a socially acceptable option to irrigators, stakeholders and the wider community? • What are people's values, knowledge and beliefs about MAR? • Do they perceive risks about its implementation in their region?
Governance arrangement	• Are the legislative and policy settings appropriate to support a MAR system? • If not, how would they need to be changed?

5.1 Effective demand for products

The Lower Namoi is a mature irrigated agricultural region that already makes use of large capacities of farm dams, conjunctive surface and groundwater use, and flood water harvesting. In this context, MAR would likely be considered an attempt to optimise an existing capability rather than an initial attempt at meeting a demand. In Section 4, we focus on three key capabilities here relating to ability to store and access water 1) in normal conditions, 2) in dry years, and 3) from wet years. To assess the effective demand for these capabilities, we first explore the variability in surface water allocations (Section 5.1.1) and groundwater extractions (Section 5.1.2) in the Lower Namoi then consider irrigation industry demand for water (Section 5.1.3).

5.1.1 Variability of surface water allocations in the Lower Namoi

The historic allocation volume announcements for general security water allocation licences (WAL) within the Lower Namoi Regulated River Source (Figure 20) illustrates that this is not a secure source of water in the region. In three of the 15 years, allocations exceeded the sum of the licenced share component but are 31% or less in all other years; zero allocations were announced in 2014-15, 2015-16 and 2018-19. Other consumptive WAL types are reliable but are not of large volumes (see Section 5.2.2, page 28).

Table 2 Summary of the scenario feasibility.

Scenario	Status quo	MAR for low water loss storage	Moving water north	River recharge as MAR
1. Effective demand for products	Existing sophistication means that remaining options for increasing water security or supply tend to be experimental, risky, expensive, or facing diminishing returns.	High value of water and traditional water sources and storage options already tapped, leading to interest in complementary strategies [5.6.2]	Existing drawdown is considered a risk factor, with trade limited. Distribution of benefits from alleviating drawdown needs further investigation.	Ubiquitous groundwater use with near full utilisation of groundwater dry periods, which managing recharge could tackle.
2. Water availability	Fully allocated system, with any significant growth in use of existing allocations also likely to be limited, and retention of carryover likely to come at expense of available water determinations.	Redirection of existing surface water allocations from on-farm storages to infiltration or injection into the aquifer	Water drawn from existing surface water entitlements at low cost times (possibly purchased by a consortium) with intention that it replaces groundwater extracted at high cost times.	Radical change in water management that could start by treating current river “losses” as a conveyance water allocation
3. Technical feasibility	Existing infrastructure able to handle both surface and groundwater, including flood management [5.3.1]. High ability to move water across the area of interest.	Infrastructure exists for delivery and temporary storage of MAR water [5.3.1]. Recharge dependent on highly spatially variable hydrogeological conditions [5.3.2]. Options include infiltration basins, injection, channel infiltration, and field AgMAR [5.3.7].	Potential to start with existing irrigation infrastructure to move water north and recharge by increasing water residence times and levels. Project assessments and approvals would inform new MAR infrastructure development.	Large portion of recharge comes from river and is dependent on flow levels. Existing geophysics and other analyses have started identifying high recharge areas.
4. Financial viability	Financial performance dependent on climate, but in general capital is available for further developments.	Need to calculate farm-specific benefits from reduced evaporation and greater storage capacity, dependent on evaporation and recharge rates, and on cost management [5.4]. Possibility for collaboration to reduce shared costs.	Regional benefits of coordinated recharge management are difficult to estimate, but expected to arise from greater reliability of groundwater supply from lower drawdown and reduced water quality risks. Seek to share R&D costs.	Transformative change that provides greater control over groundwater availability during drought. Partnership approach would be needed to share initial R&D costs, with new infrastructure subject to case-specific cost-benefit analysis.
5. Environmental risk	Continuing pressure on health of Barwon-Darling system [5.5.2]. Risks for downstream environment and local groundwater dependent ecosystems expected to be managed by existing regulation [5.5.2, 5.5.4].	Limited additional risk to ecological communities given existing use of surface water storages and allocations and licensing conditions [5.5.4]. Risks of aquifer contamination would be managed [5.5.4, 5.7.1].	Risks of waterlogging would be explicitly managed, and management of drawdown would consider potential environmental benefits.	Environmental management objectives would need to be part of consensus on operating rules and government oversight, with potential for river management to also contribute to environmental outcomes.
6. Social acceptability	Openness to new options given high policy pressure on use of existing water sources.	Need for ‘visibility’ of stored water, with clear monitoring. Could build on improving understanding of water balance.	Further analysis of the distribution of costs and benefits would be needed to make a case for cooperation [5.63]	Sharp & Curtis (2012) identified support for collective groundwater management, though direct management of the river is expected to be controversial and current uncertainty is likely a barrier.
7. Governance arrangements	Driven by state government with freedom to operate within allocations and other licensing conditions. Supporting industry groups, but limited other existing structures for collective self-management.	Dependent on policy framework for MAR currently being developed under NSW Water Strategy but monitoring of infiltration and rules for recovery are essential [5.7.4]. Would benefit from information sharing for high resolution understanding of groundwater system.	Initial development possible now, but best wrapped in a project approval process for further work. Collaboration and coordination essential and would be considered a co-benefit. SDL compliance is currently only based on actual take and would need to be altered to account for recharge and/or drawdown.	Would probably require local initiation of collective management and has precedents elsewhere in Australia. This would be a radical change that would likely require building trust, knowledge, and relationships over many years, possibly starting with less ambitious recharge management efforts.

5.1.2 Groundwater extractions in the Lower Namoi

Under the *Water Sharing Plan for the Namoi Alluvial Groundwater Sources 2020,* the long-term average annual extraction limit (LTAAEL) for the Lower Namoi Groundwater Source is 88,255 ML/year [24]. This limit is a roughly 20 GL reduction from the nearly 105 GL limit in 2006-07, and to offset reduced allocations supplementary shares were temporarily made available from 2006-07 to 2014-14 to offset reduced allocation (Figure 21). In most years, extraction from the resource is close to or exceeds the extraction limit [25]. This plot indicates the heavy reliance on groundwater in the Namoi, which is only moderated in wet periods.

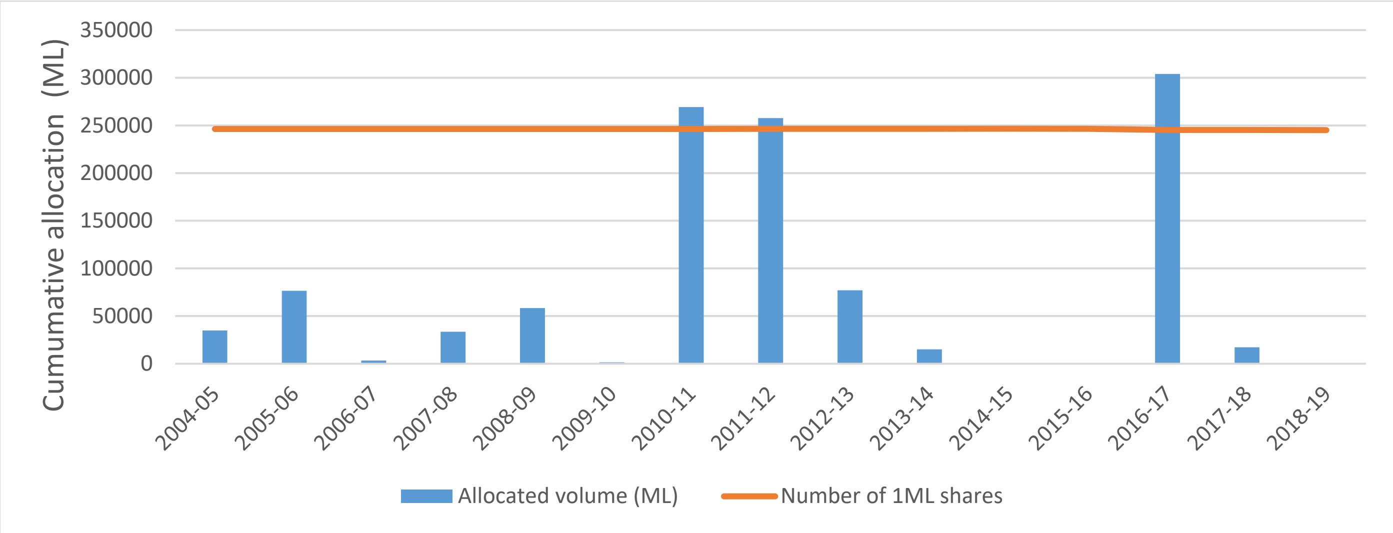

Figure 20 Cumulative total allocation volume (ML) for each water year within the Regulated River (General Security) licence category in the Lower Namoi Regulated River Source (blue columns) in relation to the sum of the licenced share component (volume of water in ML) for this licence type (Source: https://www.industry.nsw.gov.au/water/allocations-availability/water-accounting/historical-available-water-determination-data)

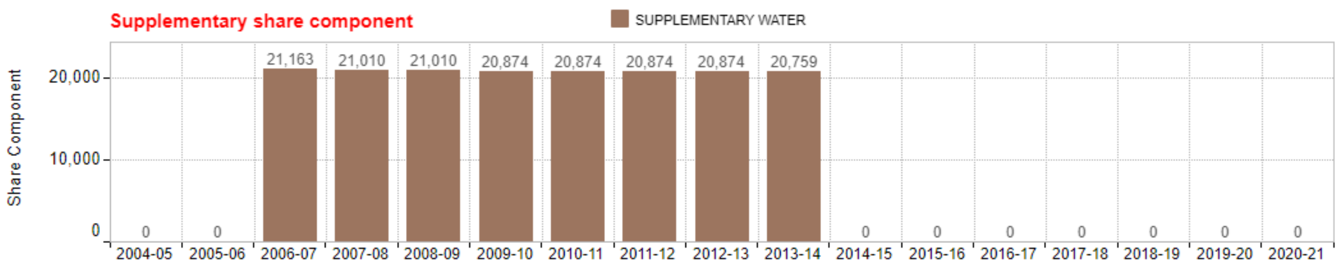

Figure 21 Historic supplementary share component in the Lower Namoi Groundwater Source (Source: https://www.industry.nsw.gov.au/water/allocations-availability/water-accounting/share-component-dashboard, 14 September 2021)

[24] *Water Sharing Plan for the Namoi Alluvial Groundwater Sources Order 2020*, https://legislation.nsw.gov.au/view/html/inforce/current/sl-2020-0346#sec.24, accessed 15 September 21

[25] If the five-year average of extractions exceed the LTAAEL by more than 5% (the compliance trigger), the maximum water account debits or available water determinations will be used to return the average extraction volume to the LTAAEL (Source: https://www.industry.nsw.gov.au/__data/assets/pdf_file/0011/312968/namoi-alluvial-groundwater-sources-2020-rule-summary-sheets.pdf, accessed 14 September 2021)

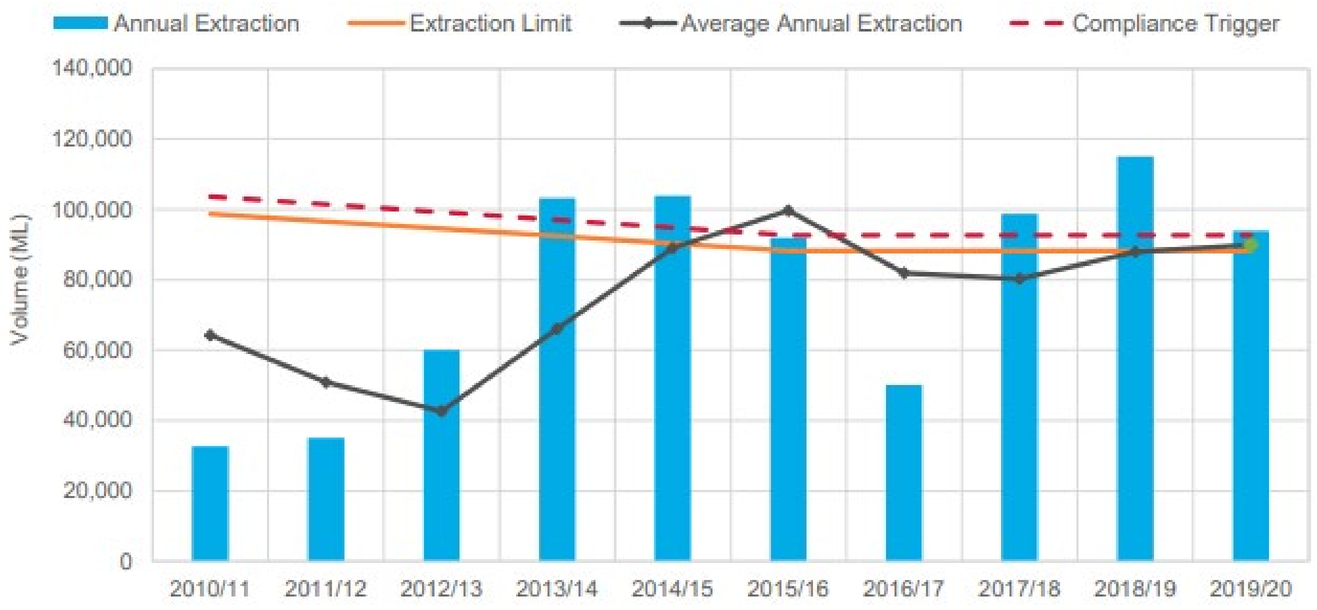

Figure 22 Lower Namoi groundwater extraction compared to the extraction limit compliance trigger (Source: https://www.industry.nsw.gov.au/__data/assets/pdf_file/0005/353192/lower-namoi-groundwater-source-2020.pdf, accessed 15 September 2021)[26]

5.1.3 Irrigator demand for water

There is a high level of irrigation development in the Namoi catchment, with cotton being an important irrigated crop (Fuentes and Vervoort, 2020, Arshad et al., 2013, Arshad et al., 2012). Groundwater resources in the Namoi are the most intensively developed in the state, with up to half of water used within the catchment extracted from groundwater sources (CSIRO, 2007). 547 bores with the purpose of production are registered across the Lower Namoi Groundwater Source (DPIE, 2020a). In dry periods when surface water supplies are low farmers in the region (who have both surface and groundwater entitlements) depend heavily on their groundwater allocations [27] (Figure 22).

5.2 Water availability for MAR

Previous MAR assessments have highlighted flood or high flow events as a possible water source for MAR in the Namoi catchment (Fuentes and Vervoort, 2020, Arshad et al., 2012). During flood events it was estimated that 33 GL per day could be recharged and it is common for flood events in the area to last for multiple days (Fuentes and Vervoort, 2020). For example, during one flood event 240 GL of water was recorded as exceeding the channel limit (Fuentes and Vervoort, 2020). Arshad et al. (2012) estimated that 340 GL of water may be available once every four years as a result of high streamflow events, under the allocation rules in place at that time.

Under the *Water Sharing Plan for the Upper Namoi and Lower Namoi Regulated River Water Sources 2016 (2015 SI 631)* the types of water allocation licences (WAL) in the Upper and Lower Namoi are stock and domestic, local water utility, high security, general security and supplementary water. High and general security entitlements vary based on water availability, with the former much more reliable than the latter (CSIRO, 2007). In the *Namoi And Peel Unregulated Rivers Water Sources 2012*, the types of WAL are domestic and stock, domestic and stock (stock) and unregulated river.

[26] Note legend for black line should read *5-year* average annual extraction
[27] https://www.abc.net.au/news/2019-05-12/cotton-farmer-defends-water-use-as-namoi-river-runs-dry/11104440, accessed 10 July 2021

5.2.1 Water allocation licences (WAL) in the AOI

The breakdown of WAL in the AOI shows that general security and supplementary entitlements comprise the majority of water entitlements (Table 3).

Table 3 Breakdown of water allocation licences (WAL) in the AOI

Source	WAL type	# of unique licences	Total 1 ML shares
Lower Namoi Regulated River Water Source	High security	2	150
	High security [Research]	1	486
	General security	15	95,010
	Domestic & Stock	11	216
	Supplementary	25	36,225.4
Lower Namoi Groundwater Source	Aquifer	12	15,191

5.2.2 Historic take in the Lower Namoi by WAL type

Historic take of surface water in the following section are freely available from the WaterNSW WaterInsights portal for the Lower Namoi Regulated River Water Source (which includes the AOI).

Secure water licences

Domestic and stock, high security and local water utility licence types are all secure water, where an allocation of 100% will *usually* be made at the start of the water year. For these entitlements, carryover is not allowed and the water allocated in a water year will never exceed 100% of the entitlement.[28] The historic take of secure water licence in the Lower Namoi Regulated River Source is shown in Figure 23.

12 high security water allocation licenses (WAL) from the Lower Namoi Regulated River source exists. The majority of 1 ML shares (3000) are held by one WAL, whilst another WAL with 486 shares is listed as High Security (Research). It is unlikely that stock and domestic or high security licenses would be banked because their current supply is already very secure. Given that high security licenses cannot be carried over, MAR could in theory provide an opportunity for high security water to effectively be carried over. However, the volumes are very small (particularly in the AOI; see Table 3) and MAR is not likely to provide a financially viable option for the irrigators with these entitlements.

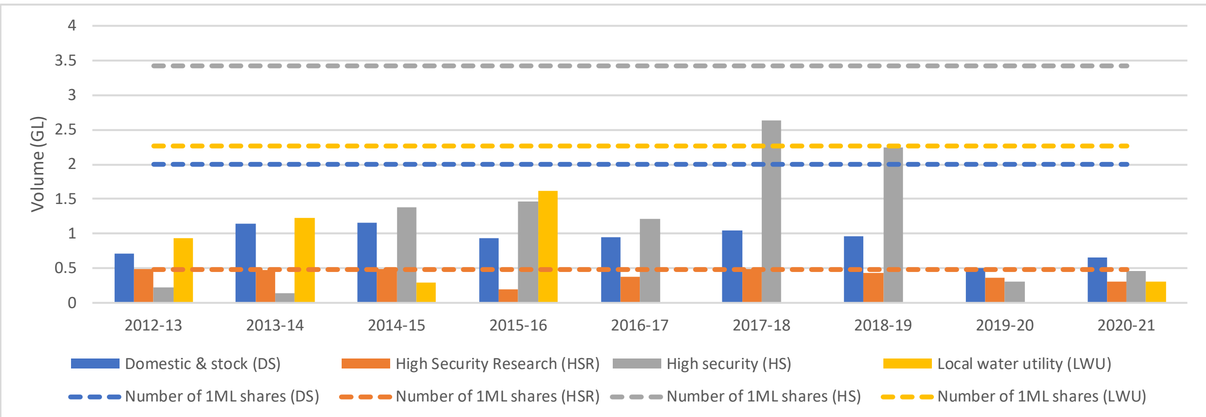

Figure 23 Historic take of secure water licence in the Lower Namoi Regulated River Source (Source: https://waterinsights.waternsw.com.au/11986-lower-namoi-regulated-river/research, 14 September 2021)

[28] https://waterinsights.waternsw.com.au/11986-lower-namoi-regulated-river/rules, accessed 14 September 2021

Supplementary entitlements

Under current arrangements in rural agriculture regions like the Namoi, water available for MAR is scarce (Arshad et al., 2012). Supplementary water allocations, available during period of high streamflow/flooding, have been suggested as a possible MAR water source in regulated river systems (Arshad et al., 2012). Current water policy encourage the use of on-farm dams to store any captured supplementary allocations (Arshad et al., 2012). On-farm dams, although common throughout the region, have obvious drawbacks, for example, losses due to evaporation and seepage (Arshad et al., 2012). One positive of using supplementary flows in the Lower Namoi is that environmental flows, which serve ecological purposes, are able to be satisfied alongside extraction due to the large flows available at the time of the flood event (Arshad et al., 2012) and the rules in place (see Section 5.7.2, p74Water Sharing Plans (WSP) covering the AOI). Beyond the rules of the applicable Water Plan, the nature of the flood event (single day vs. multiday), the presence of any additional water restrictions and the account balance of supplementary licences (i.e., is this the first high streamflow event of the year or the 7th) would all impact supplementary water availability. The Lower Namoi has a large number of unit shares to extract water using supplementary water access licences [29], totaling 115.5 GL although the full supplementary entitlement has never been used to date (Figure 24). Actual allowable takes are prescribed by clause 48 of the *Upper Namoi and Lower Namoi Regulated River Water Sources 2016* and ensure that only a certain percentage of supplementary event water volumes can be taken (see Section 5.7.2). The historic availability and take of supplementary events for the river sections crossing the AOI are compiled in Table 4.

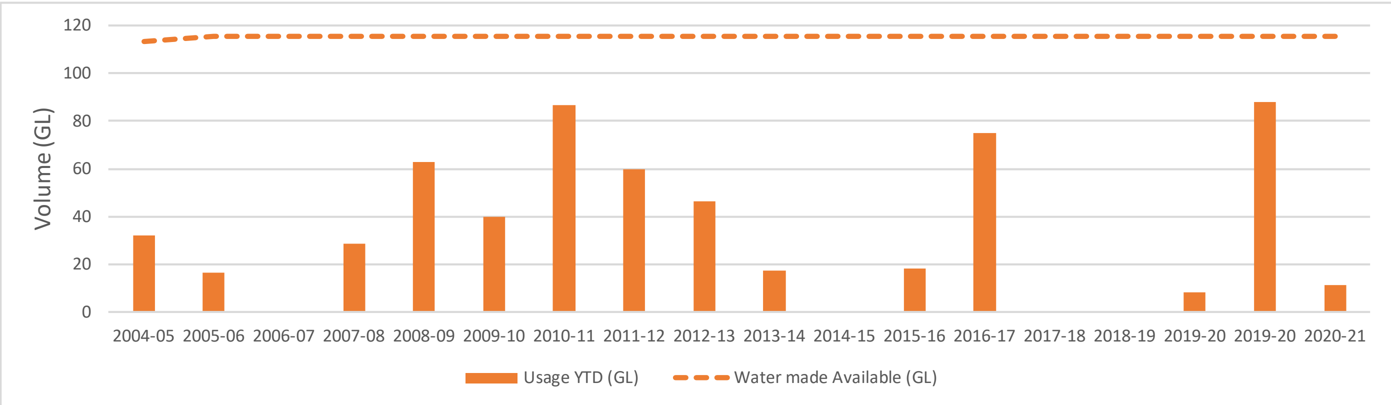

Figure 24 Historic take of supplementary licence in the Lower Namoi Regulated River Source (Data source: https://waterregister.waternsw.com.au/water-register-frame, 16 September 2021)

Table 4 Historic supplementary events and usage along the river sections crossing the AOI compiled from General Purpose Water Accounting Reports (available at https://www.industry.nsw.gov.au/water/allocations-availability/water-accounting/gpwar, accessed 25 November 2021)

Water year	Namoi River (Narrabri to Mollee Weir)			Namoi River (Mollee Weir to Gunidgera Weir)		
	# of calls	Total days	Usage (ML)	# of calls	Total days	Usage (ML)
2010-11	6	81	206.7	6	81	30487
2011-12	3	83	328	3	83	16678
2012-13	3	27	301	4	28	12066
2013-14	NA	NA	NA	NA	NA	NA
2014-15	0	0	0	0	0	0
2015-16	0	0	0	4	13	5831
2016-17	2	43	237	3	58	22905
2017-18	0	0	0	0	0	0
2018-19	0	0	0	0	0	0
2019-20	2	17	0	1	2	1275

[29] https://legislation.nsw.gov.au/view/whole/html/inforce/current/sl-2015-0631#sec.25, accessed 19 July 2021

General security entitlements

The IQQM long-term simulations suggest the General Security water availability (carryover plus available water determination) will be 200% for 9% of the time and 100% for 44% of the time at the start of the season and that by the end of the water year water availability would equal or exceed 100% for 73% of the time (Burrell et al., 2021). The incremental available water determination for general security is shown in Figure 25 as a proportion of the share component, illustrating the recent conditions have the lowest water availability since WSP management commenced. Availability was so low that temporary water restrictions were applied for the 2019-20 reporting period (Table 5), where take of water was negligible (Figure 26).

The current carryover system is a method of purposely saving water to be used in the future, where licence holders are able to carryover saved water entitlements from one year to the next (for up to three years). In this way, the carryover of surface water entitlements from past years has been used to ride out the times when entitlements have been severely reduced [30]. This is a similar concept to one that could be implemented using MAR, with the difference being that instead of surface water being kept large in-stream storages carryover water would be recharged to be used later. Depending on the rules around recovery of stored water, MAR might mitigate the risk of the recent restrictions applied to carryover. However, this WAL type might not be a desirable source of water for MAR from an irrigator perspective (See Section 5.6.3, page 69).

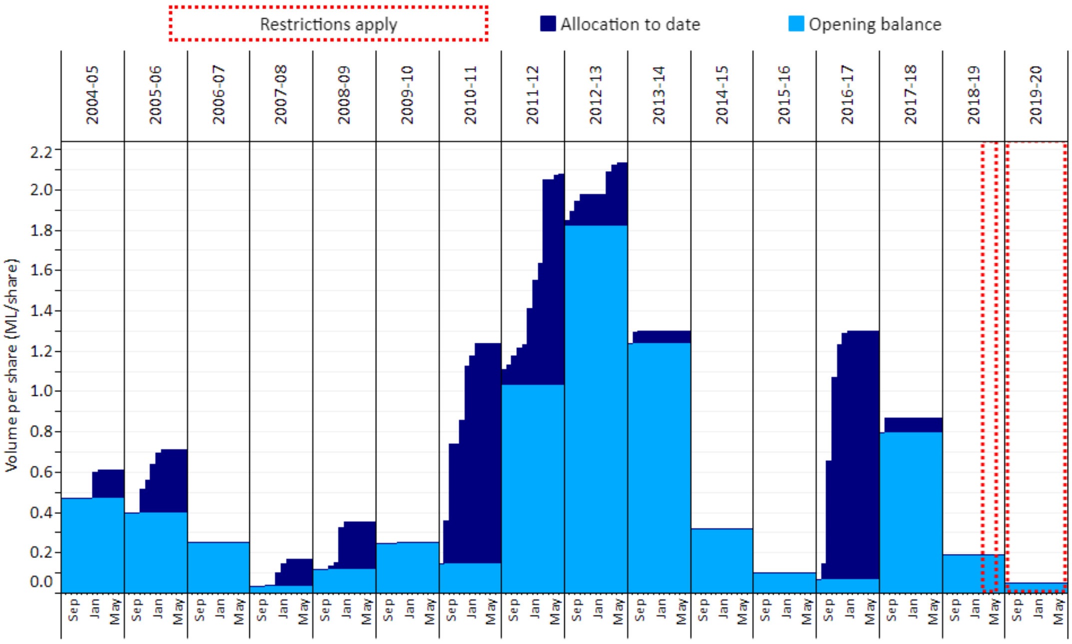

Figure 25 Incremental available water determination (AWD) for Lower Namoi general security as a proportion of share component (Burrell et al., 2021)

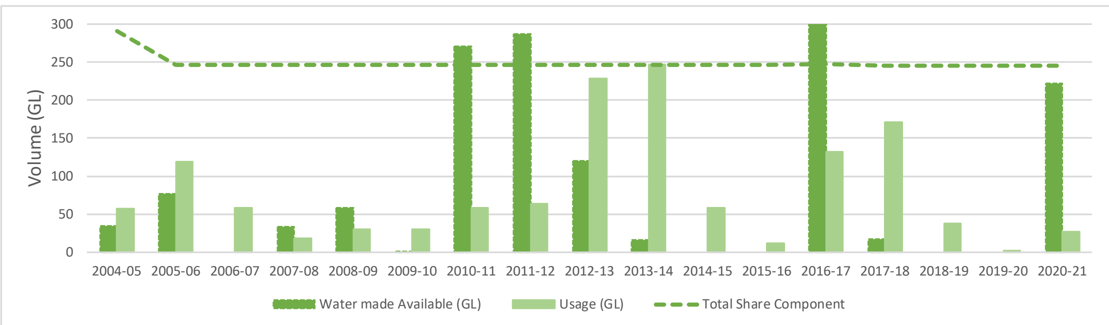

Figure 26 Historic take of general security licence in the Lower Namoi Regulated River Source (Data source: https://waterregister.waternsw.com.au/water-register-frame, 16 September 2021)

[30] https://www.abc.net.au/news/2019-05-12/cotton-farmer-defends-water-use-as-namoi-river-runs-dry/11104440, accessed 10 July 2021

Unregulated river licences

The water source encompassing the AOI for this study is the Spring and Bobbiwaa Creek water source (see Figure 19). The WaterNSW water register (https://waterregister.waternsw.com.au/water-register-frame, accessed 24 November 2021) lists four Unregulated River WAL with a total of 1476 share components (1 ML). Annual usage in (ML) recorded on this site is not extensive with only 150 ML recorded as used in the 2019-20 water year with no usage recorded in other years of record.

Table 5 Extreme events stage and temporary water restrictions (Lower Namoi region) in 2019-20 (Source: Burrell et al., 2021)

Temporary water restrictions for the reporting period
• A temporary restriction was placed on groundwater access licences in the Maules Creek Groundwater Source to protect supply for basic landholder rights and aquatic systems as the groundwater is highly connected to surface water in this area. This restriction was in effect from 18 October 2019 until 30 June 2020. • A temporary water restriction was placed on all water held in general security carryover accounts in the Lower Namoi. This restriction was in place from 1 July 2019 until 25 February 2020, when it was repealed when conditions improved. • Under the Northern Basin restrictions, from 17 January to 13 February high security access in the Lower Namoi was not permitted and unregulated river access until 21 February (with some limited exemptions). Floodplain harvesting access was restricted from 7 February to 21 February for the Upper Namoi floodplain and 23 February for the mid Namoi and Lower Namoi floodplains.
Extreme events stage
• The Lower Namoi started the water year in stage 4 critical. The valley was eased to stage 3 severe in March 2020 and remained in that stage for the remainder of 2019–20. Storage inflows to Keepit were below average for all months excepting February 2020 (Figure 28). • No releases were able to be made from Keepit Dam for most of the water year due to extremely limited storage resources. Dam levels began to rise in February and a small release was made in March 2020 to supply users close to the dam with stock and domestic water. For all other users, access was only available from tributary inflows downstream of Keepit dam. • Looking at 2-year natural storage inflow (removing impact of Split Rock transfers), as an indicator of drought severity sequences to Keepit Dam between 1961 and current, illustrates that the period between 1 July 2018 to 30 June 2020 totalled 71,221 megalitres, and was the lowest 2-year period in this timeframe. This inflow total was 84% lower than the median two year

5.2.3 Floodplain harvesting

Floodplain harvesting is the capture of overland flow water (e.g. including floodwater and rainfall runoff); from the outset of water management under WSP, provisions were made to create flood harvesting licences but these have not yet been implemented (see Section 5.7.3 for more detail). In 2012, based on available models, an estimated volume of 210 GL/yr of floodplain harvesting occurred across the northern Basin (both QLD and NSW). The NSW DPIE note that the information used to develop this estimate was poor and the river system models used were not developed to be used to make some estimate and the expectation is that this number will change with improved data and models [31]. The NSW Government is currently developing valley-specific, peer-reviewed technical reports which describe the modelling process and the data being used to re-estimate these legal limits; the first report available being the Border Rivers valley [32].

The Namoi Valley report and estimate of floodplain harvesting volumes is not yet available. However, in their submission to the draft NSW Floodplain Harvesting Policy May 2010, Namoi Water noted that many of their 800+

[31] https://www.industry.nsw.gov.au/water/plans-programs/healthy-floodplains-project/about/impact-of-floodplain-harvesting-growth-in-the-northern-basin, accessed 16 September 2021

[32] https://www.industry.nsw.gov.au/water/plans-programs/healthy-floodplains-project/about/impact-of-floodplain-harvesting-growth-in-the-northern-basin, accessed 16 September 2021

voluntary members depended financially on access to floodplain flows, particularly due to droughts and cutbacks to other water access, and that this history of access extended back to the 1960's [33].

5.2.4 Evaporation losses

On-farm water storages are popular in the cotton industry and in the Namoi catchment (Arshad et al., 2013) as they are relied upon to store excess water available during high periods (Arshad et al., 2012). However, the high evapotranspiration rates in the area, when compared to rainfall, further strains water availability. Evaporative water losses from surface storages popular throughout the region, and the Murray-Darling Basin more generally, are high (Arshad et al., 2013).

Fuentes et al. (2020) used supervised classification of Landsat images between 1988 and 2018 together with climate trends based on month SILO gridded to explore long-term surface water trends and relationship with open water evaporation losses in the Namoi catchment, Australia. They generally found an increasing trend in the number of farm dams over this time period as well as increased reference evapotranspiration and evaporation per unit area of water. Annual evaporative losses averaged 201.9 GL, which Fuentes et al. (2020) noted is greater than the annual total account usage of surface water in the catchment. The authors conclude that there is evidence of *"a loss of blue [freshwater in lakes, rivers and aquifers] and green [soil] water in the catchment, and … of an overall intensification of the hydrologic cycle as predicted under climate change"*.

The current extent of evaporative losses and increasing trend per unit of area provide an argument for using MAR as a strategy to reduce losses (see Section 4.2) although was not considered a critical concern by a local irrigator (see Section 5.6.3).

5.3 Technical feasibility

This section is structured to provide information on the surface water infrastructure that could support MAR (Section 5.3.1), aquifer characteristics (Section 5.3.2), groundwater levels (Section 5.3.3), groundwater salinity (Section 5.3.4), soil characteristics (Section 5.3.5) and recharge (Section 5.3.6) which is needed to inform the design, planning and implementation of MAR strategies (Section 5.3.7).

5.3.1 Surface water infrastructure to support MAR

On-farm dams and intricate channel infrastructure are abundant throughout the Lower Namoi (Figure 27) and the AOI (Figure 28) of this study. This is to support the widespread irrigated agriculture industry in the region. There are also multiple large in-stream surface storages in the Namoi catchment, including Split Rock Dam and Keepit Dam [34]. However, Namoi Water note the reliance upon farm dams as the river operator is unable to provide continuous flow and that (depending on availability) the water delivered from regulated storages needs to last the farmer for up to 3-6 months [35]. These storages are used to store multiple sources of water: rainfall, used agricultural water, overland flow, floodplain harvesting, groundwater, supplementary water, unregulated water and general security [36].

Offtakes from the Namoi River that would supply the canal system were identified via aerial imagery (Figure 29). It is possible that not all offtakes were captured using this method.

The canal system could be used to transport water to be recharged to MAR sites. The dams present in the area could be used as temporary storages before recharge. The temporary storage of water would be particularly important if MAR water would be sourced from flood waters. This would allow for infiltration or injection rate limitations to be overcome, as more water could be diverted for recharge then what could be recharged during the limited flood period.

[33] https://namoiwater.com.au/bakeehom/2020/05/Namoi-Water-floodplain-policy-10528-2.pdf, accessed 16 September 2021
[34] https://legislation.nsw.gov.au/view/html/inforce/current/sl-2015-0631, accessed 19 July 2021
[35] https://namoiwater.com.au/, accessed 24 November 2021
[36] https://namoiwater.com.au/, accessed 24 November 2021

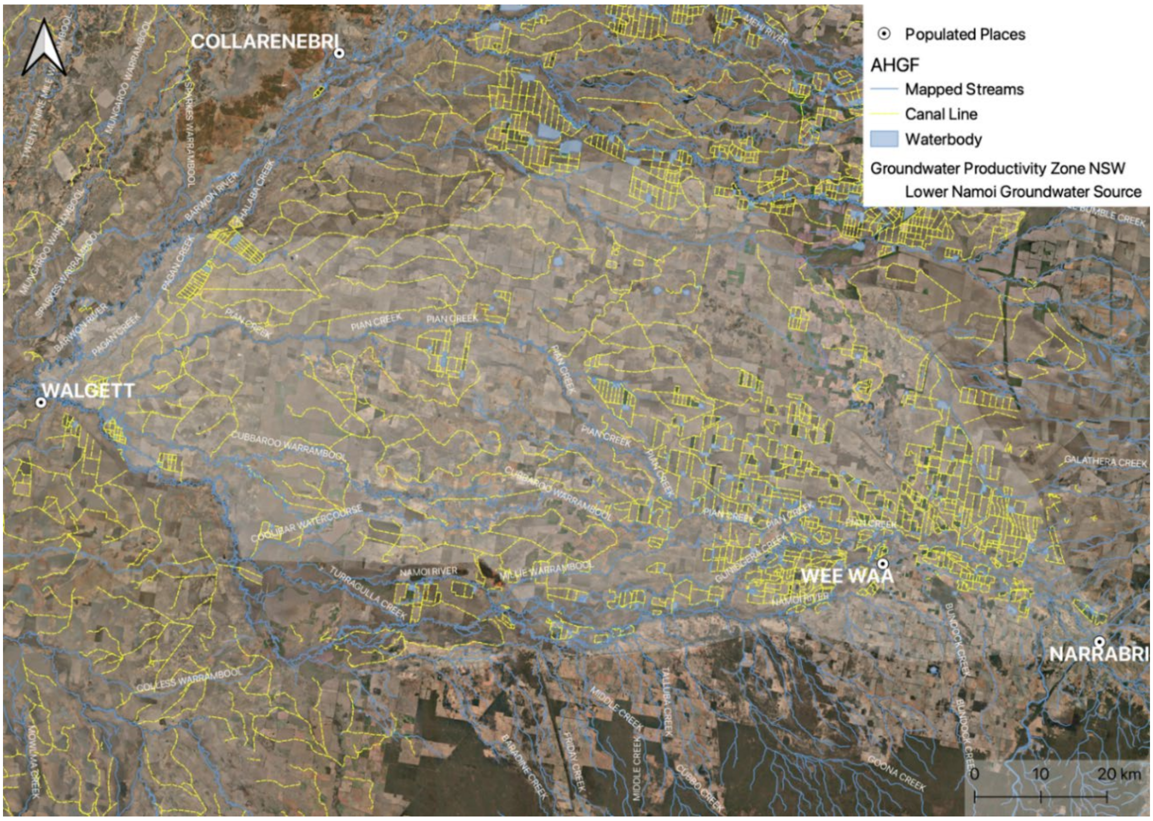

Figure 27 Stream, canals and dams in Lower Namoi groundwater zone (Australian Hydrological Geospatial Fabric (AHGF) (https://datasets.seed.nsw.gov.au/dataset/australian-hydrological-geospatial-fabric-geofabric)).

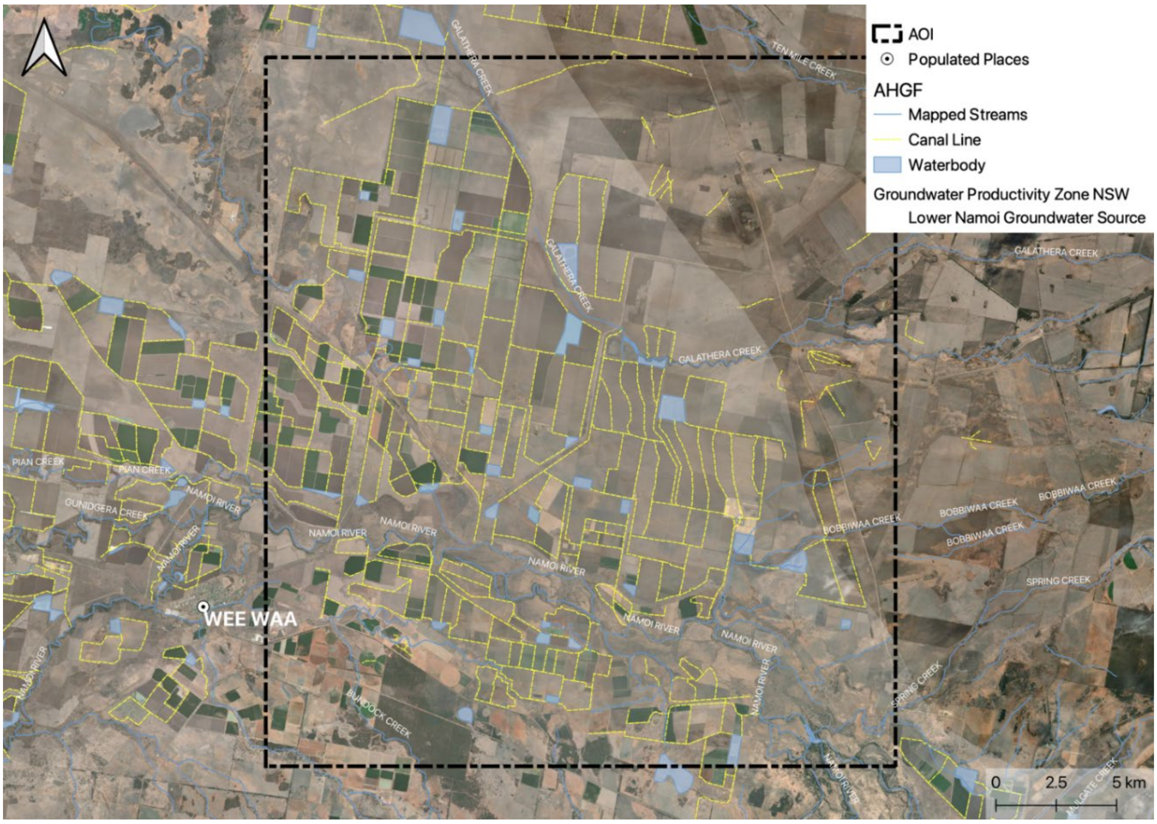

Figure 28 Stream, canals and dams in the area of interest (Australian Hydrological Geospatial Fabric (AHGF) (https://datasets.seed.nsw.gov.au/dataset/australian-hydrological-geospatial-fabric-geofabric)).

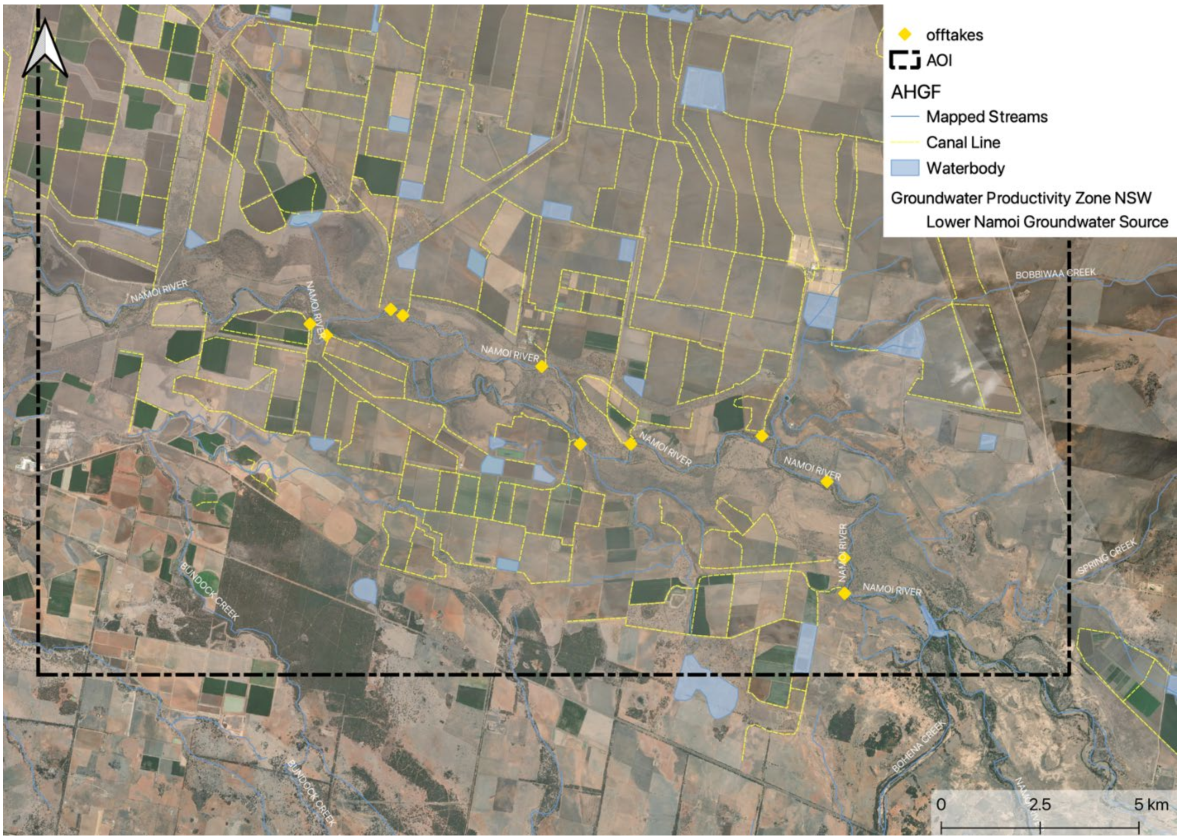

Figure 29 Offtakes of the Namoi River in the area of interest. Stream, canals and dams are also shown (Australian Hydrological Geospatial Fabric (AHGF) (https://datasets.seed.nsw.gov.au/dataset/australian-hydrological-geospatial-fabric-geofabric)). Offtakes were identified from aerial imagery and not all may be identified.

5.3.2 Aquifer characteristics

Alluvial aquifer characteristics

The major near surface formations in the area are termed the Narrabri, Gunnedah and Cubbaroo (Fuentes and Vervoort, 2020) [37] and are comprised mainly of alluvial sediments up to 120 m in depth (Arshad et al., 2012). These are the main groundwater sources for irrigation in the region (Arshad et al., 2014, CSIRO, 2007, Rassam et al., 2013).

The shallow Narrabri Formation (Figure 30) is an unconfined aquifer that can be up to 70 m deep but is typically 30 to 40 m deep [38]. It contains distinct sand/gravel paleochannels [39] amongst the floodplain silts and clays. Transmissivities in this aquifer system are less than 250 m^2/day (Arshad et al., 2014). Recharge of this aquifer occurs via seepage from stream/river channels, overbank flooding and rainfall infiltration (CSIRO, 2007). Infiltration from the Narrabri Formation recharges the underlying Gunnedah Formation (CSIRO, 2007) which is comprised of moderately well-sorted sands and gravels with minor clay beds up to 70m depth and in some parts acts as a single aquifer with the Narrabri Formation [40]. The Cubbaroo formation is a confined aquifer associated with the main paleochannel in the central and northern parts of the valley.

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[37] The Narrabri, Gunnedah and Cubbaroo formations are a useful way to reference upper and lower portions of the alluvial sequence only, and are used by many to describe the aquifers in the region. Other possible naming conventions for the aquifers in the region include the simple ‘upper’ and ‘lower’ delineation.

[38] https://www.bioregionalassessments.gov.au/assessments/11-context-statement-namoi-subregion/1141-hydrostratigraphic-units, accessed 16 September 2021

[39] Although commonly referred to as paleochannels, the sandy areas in the region are lateral accretions, which form from the sideways migration of the meandering rivers (Dr. Bryce Kelly, *pers. comm.* December 2020). For consistency with past research in the Namoi, the term paleochannel will be used in this report.

[40] https://www.bioregionalassessments.gov.au/assessments/11-context-statement-namoi-subregion/1141-hydrostratigraphic-units, accessed 16 September 2021

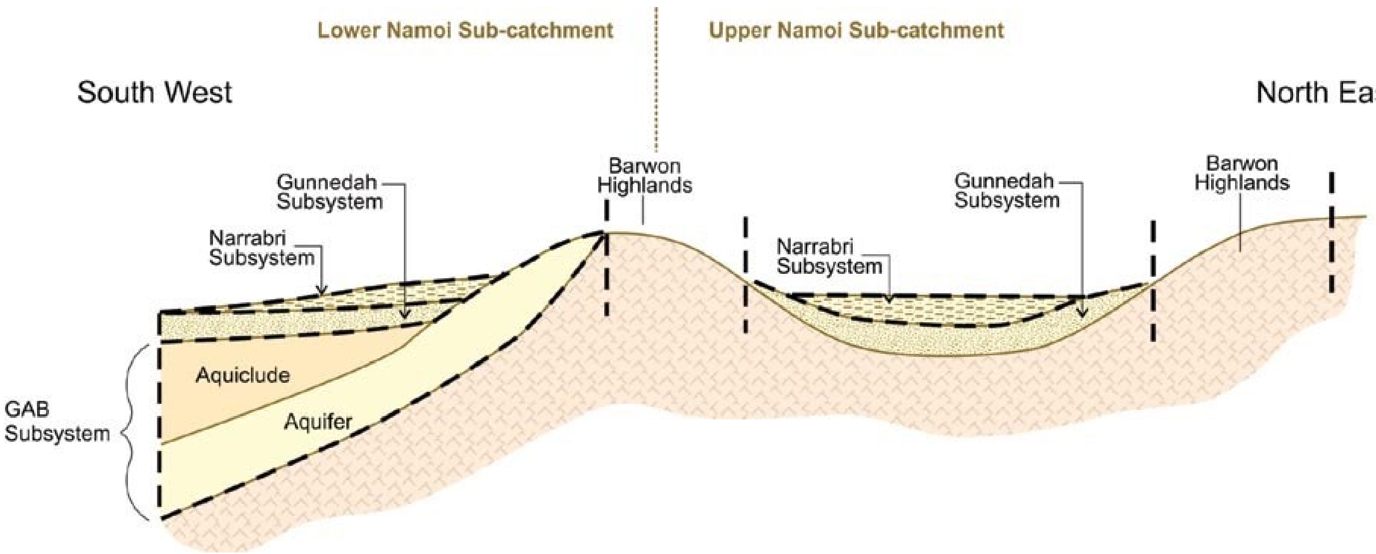


Figure 30 Diagram of groundwater system in the Namoi catchment (Source: URS Australia Pty Ltd (2007))

Many of the deposits that form alluvial aquifers in the region have a clay layer which reduces hydraulic connectivity to the underlying aquifers (Fuentes and Vervoort, 2020). Aryal et al. (2018) estimated the vertical conductivity of the Namoi alluvium, for use in the bioregional assessment Namoi groundwater model for 347 nested piezometer sites with between two to six piezometers. The linear trend in groundwater levels was calculated for the 30-year period and the maximum difference in the slope of the trend line between piezometers in the same nest was recorded. Noting that the simplistic analysis ignores stresses such as irrigation, Aryal et al. (2018) assumed poor vertical connections if there were significant differences in the water level trends at a nested site. These point data were kriged to the alluvium boundary to create the spatial layer of the difference in groundwater level in Figure 31.

Kelly et al. (2007) notes the heterogeneity of the system and that the preceding alluvial sequence under-represents the complexity in that the dominant sediments in each formation (sand, gravel, clay) vary spatially, which means that the hydraulic parameters and flow pathways within the alluvial aquifer sequence are hard to conceptualise. This complexity was demonstrated by Blakers et al. (2011) who used hierarchical clustering of groundwater hydrographs to surmise the structure and connectivity within the complex aquifer system of the Lower Namoi. The authors created a cluster dendrogram (Figure 32) that enabled them to map 3D spatial connectivity. From the plan projections of the 17 bore clusters (Figure 33), the clusters most relevant to our AOI are 4-9 and 13. Blakers et al. (2011) notes that clusters 4-7 are hydrologically and spatially similar and extend almost the full thickness of the aquifer, concluding that this indicates “excellent vertical connectivity”. Cluster 13, on the other hand, drops into the deep paleochannel (Cubbaroo Formation) and corresponds to an area of high groundwater abstractions and where the aquifer has become disconnected from the river; this large signal distance between this cluster and clusters 4-9 (Figure 32) indicate that it is not well connected to the surrounding aquifer. It is not clear based on current evidence whether MAR could reconnect this aquifer, and therefore what implications there might be beyond the need to better understand this highly heterogeneous system.

Great Artesian Basin

The Great Artesian Basin (GAB) is also present at depth (CSIRO, 2007), but its contribution to groundwater resources and applicability for MAR may be limited (Fuentes and Vervoort, 2020) and is not considered further in this report.

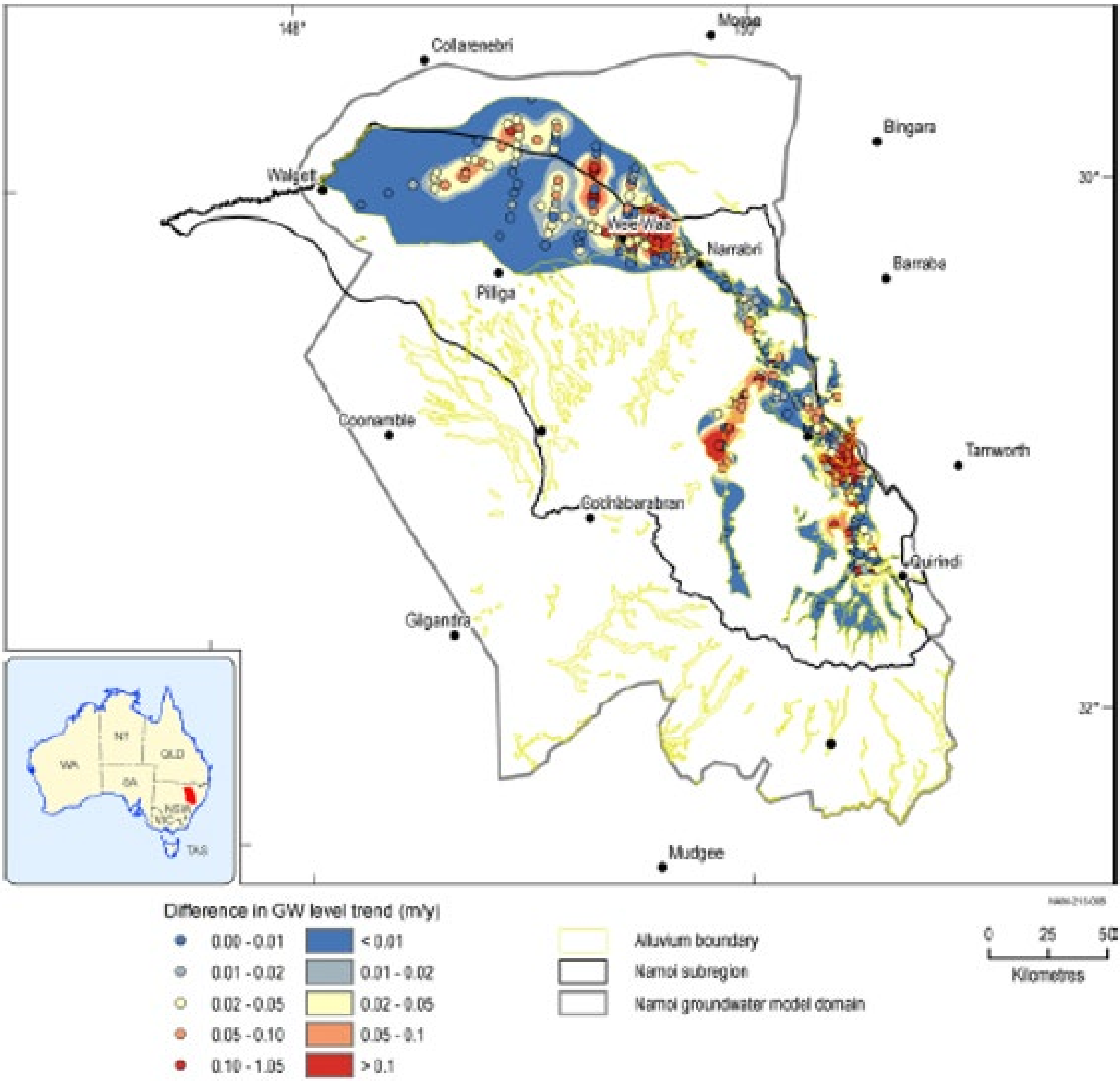


Figure 31 Vertical connectivity of Namoi alluvium used in bioregional assessment Namoi groundwater model; <0.01 m/year suggests the aquifer is well connected and >0.1 m/year that the aquifer is poorly connected (Aryal et al., 2018)

Future analyses that could improve understanding of the system

Although there has been significant research in both the Namoi catchment and the Lower Namoi, there are still knowledge gaps about the aquifer system and how MAR could be implemented in the system. In November 2021, Dr. Bryce Kelly, a researcher with a research history in the Lower Namoi, suggested a number of analyses that could be conducted to address some of these gaps [41]. An existing Mathematica model (Kelly et al., 2014) could be used to assess storage potential in our selected area of interest. A Menyanthes model (KWR Water 2000 [42]) could perform time series analysis to identify the role of flooding vs other drivers of groundwater levels. The stochastic modelling approach demonstrated in the Lower Namoi by Comunian et al. (2014) could be used to quantify uncertainty due to

[41] These analyses were not able to be conducted with the remaining time and resources available to the project team.
[42] https://www.kwrwater.nl/en/tools-producten/menyanthes/, accessed 30 November 2021

under-constrained hydrogeological heterogeneity, and hence inform the location of further lithological logs or other investigations.

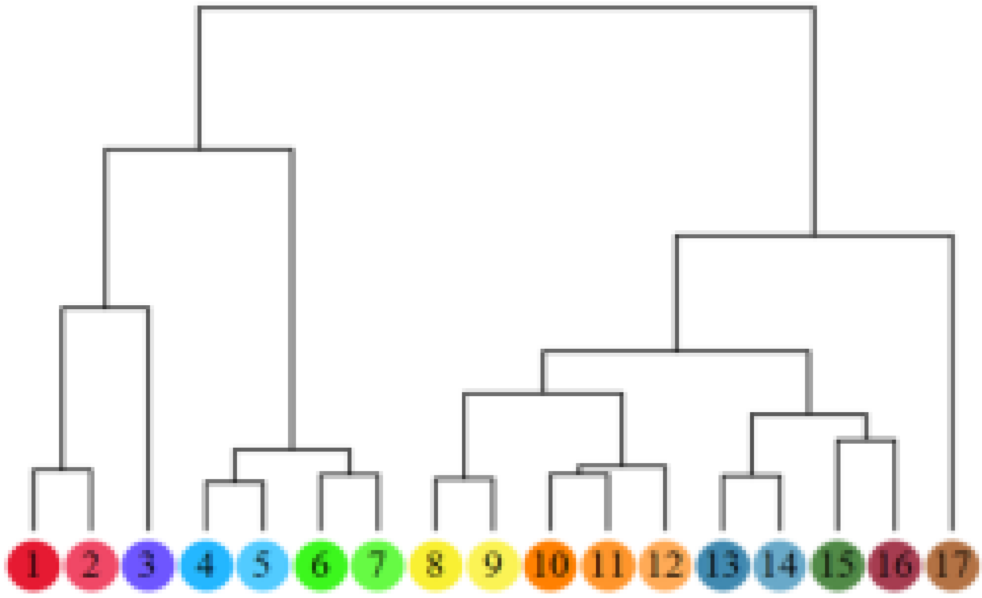


Figure 32 Dendogram showing the top 17 levels of the hierarchical clusters (Blakers et al., 2011)

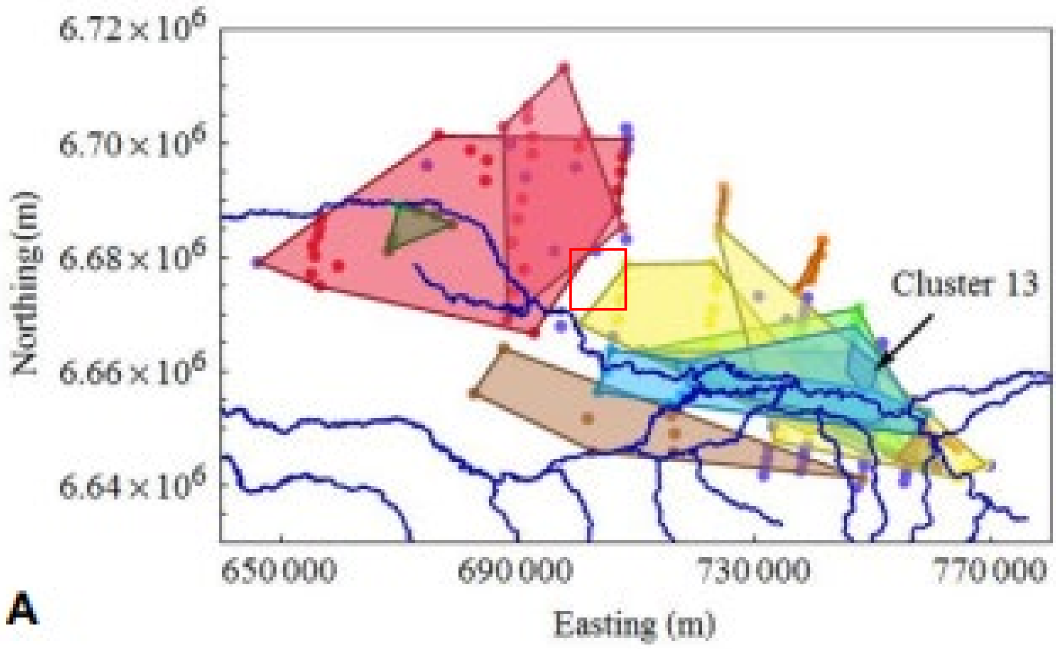


Figure 33 Plan projections of the 17 bore clusters and the convex hulls enclosing them (Blakers et al., 2011). The approximate AOI is indicated by the red box.

5.3.3 Groundwater levels

Trends in groundwater levels

The literature reports that historically gaining sections of the Namoi River have become losing sections as a result of groundwater extraction in the region (Fuentes and Vervoort, 2020); the river reach from Narrabri to Wee Waa (our AOI) is characterised as losing (Ivkovic, 2009). Large decreases in groundwater levels (up to 30 m) away from the river have been reported (Fuentes and Vervoort, 2020, Arshad et al., 2012). These drawdowns in the alluvial aquifers also imply potential to store large volumes of water (Arshad et al., 2012).

Groundwater levels at 580 monitoring bores at 250 sites in the Lower Namoi Groundwater are monitored by WaterNSW (Figure 34). WaterNSW is currently undertaking a review of water levels that will highlight 'any areas of concern and any further extraction management *that* may be required' (DPIE, 2020a). For our area of interest, hydrographs for groundwater levels at two bores GW030450 and GW025325 are shown in Figure 35.

The first step in groundwater level analysis is allocating boreholes in the area to their respective aquifer – upper (Narrabri formation) and lower (Gunnedah formation), where they show different behaviours. Past studies have used a screening depth of 30 m to delineate the boreholes into formations (Fuentes and Vervoort, 2020). Data provided from DPIE where boreholes were assigned into formations manually was used in this work for aquifer delineation.

The water level data in the lower aquifer was the focus as this is the aquifer that is used most for irrigation. Years 2015 to 2019 are shown, where maximum drawdown is the lowest measured water level in the respective bores during the calendar year and recovery is the highest measured water level in the respective bores during the calendar year. The method used to interpolate between measure boreholes was inverse distance weighting (Kollias et al., 1999, Kravchenko, 2003, Kravchenko and Bullock, 1999, Nalder and Wein, 1998, Schloeder et al., 2001), where unknown areas use surrounding points for prediction with closer points having more influence on the prediction. Some years have fewer data available resulting in a smaller area for interpolation and increased uncertainty.

Both maximum drawdown and recovery are more extreme in the northwest of the region, with this trend consistent over the years shown (Figure 36 to Figure 40).

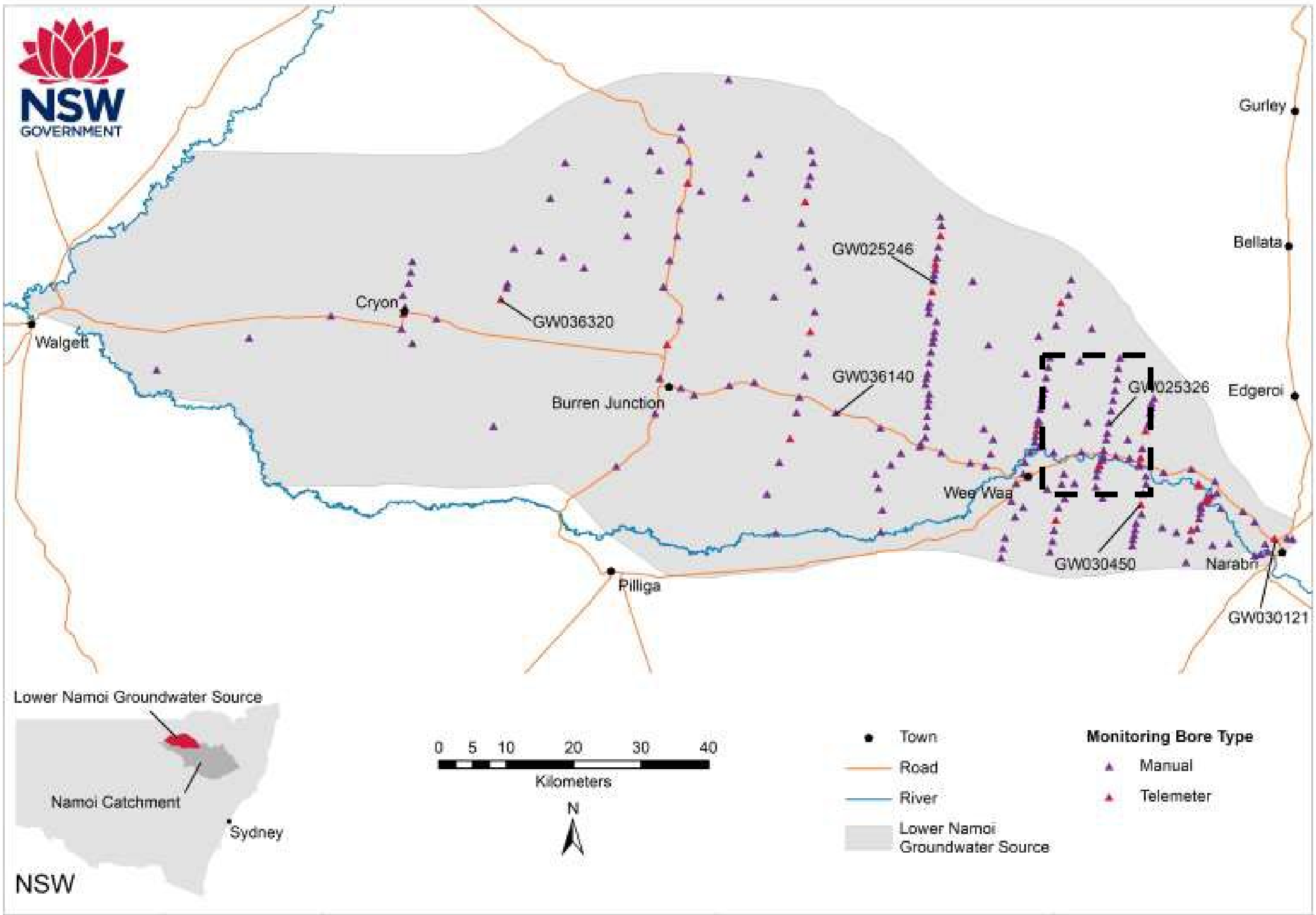


Figure 34 WaterNSW Lower Namoi Groundwater Source monitoring sites (Source: DPIE, 2020a). The black box indicates our AOI.

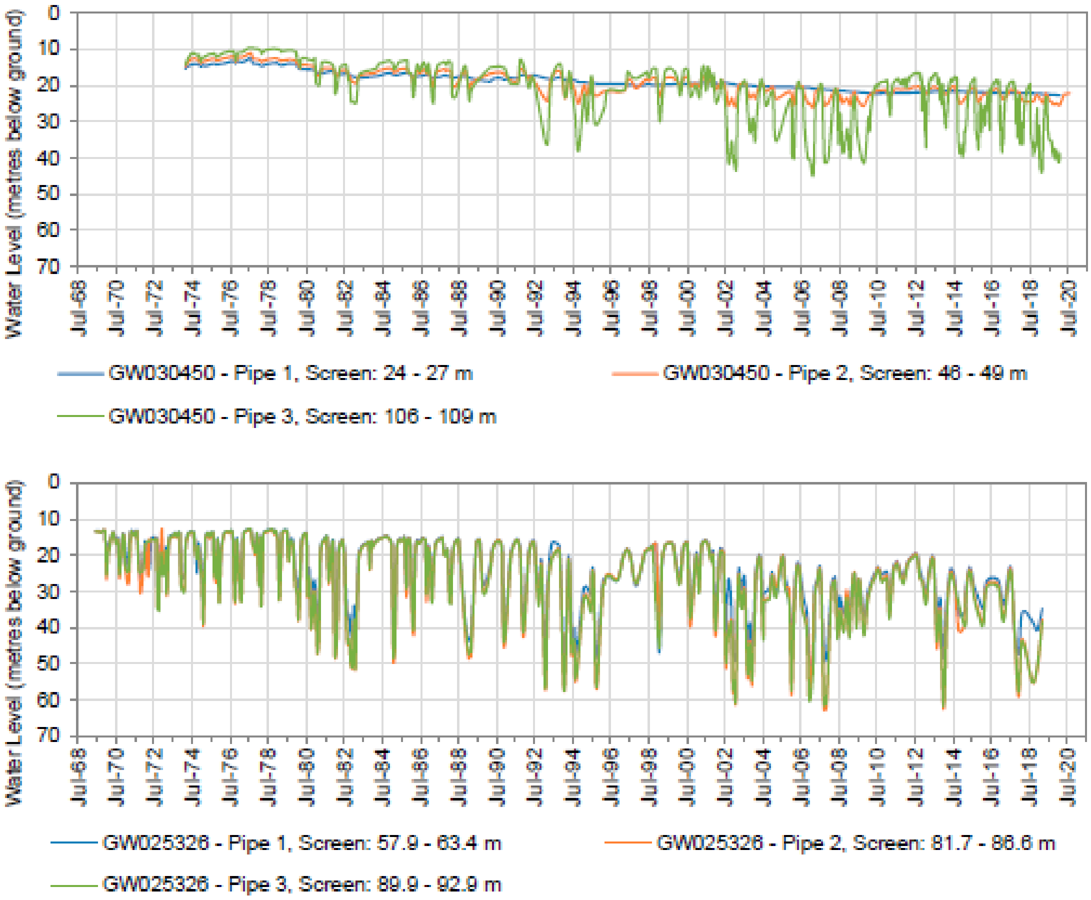


Figure 35 Hydrograph of monitoring bore GW030450 and GW025326 (Source: DPIE, 2020a)

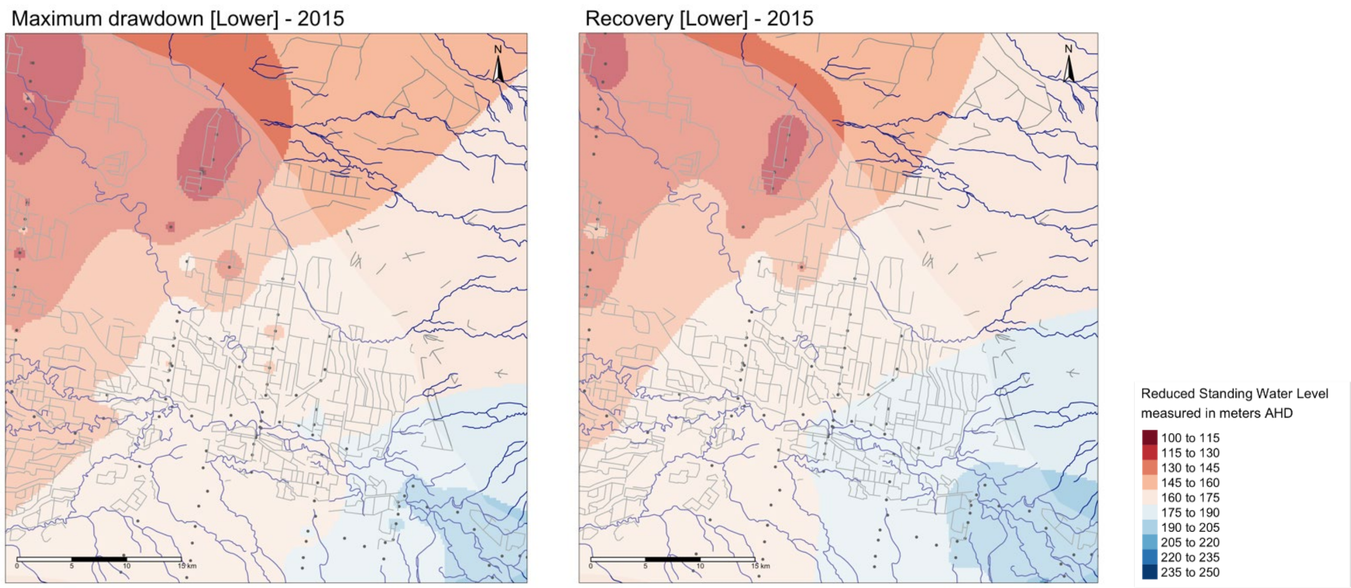


Figure 36 2015 maximum drawdown and recovery (reduced standing water level measured in meters above Australian Height Datum, AHD) in the lower aquifer. Inverse distance weighting was used to interpolate between borehole (black points) measurements. Canals (grey), rivers (dark blue) and Lower Namoi Groundwater Zone (shaded white) are also shown.

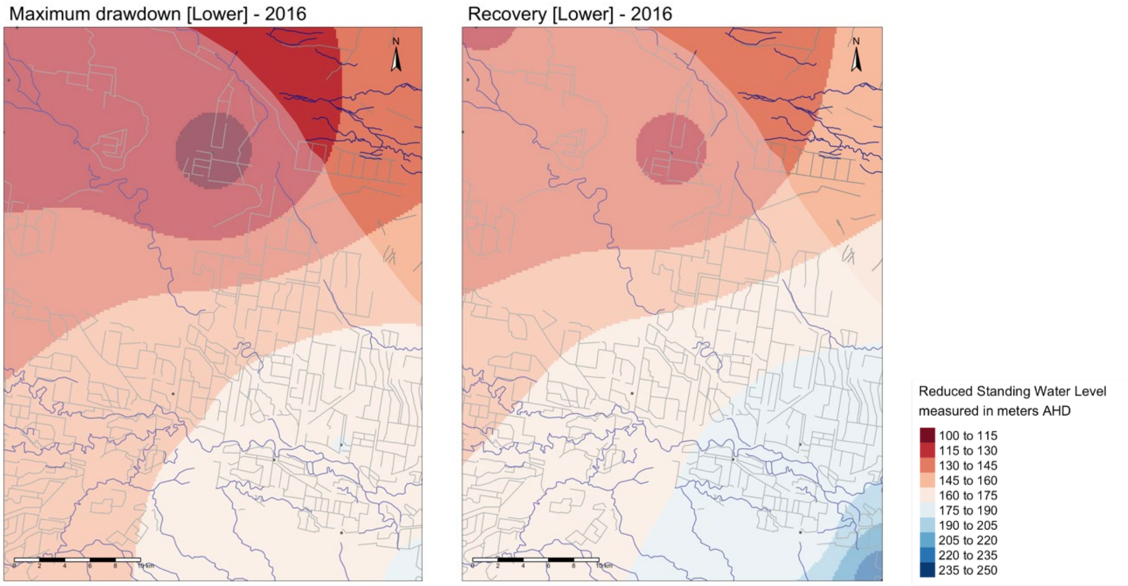


Figure 37 2016 maximum drawdown and recovery (reduced standing water level measured in meters above Australian Height Datum, AHD) in the lower aquifer. Inverse distance weighting was used to interpolate between borehole (black points) measurements (note few data points for this year). Canals (grey), rivers (dark blue) and Lower Namoi Groundwater Zone (shaded white) are also shown.

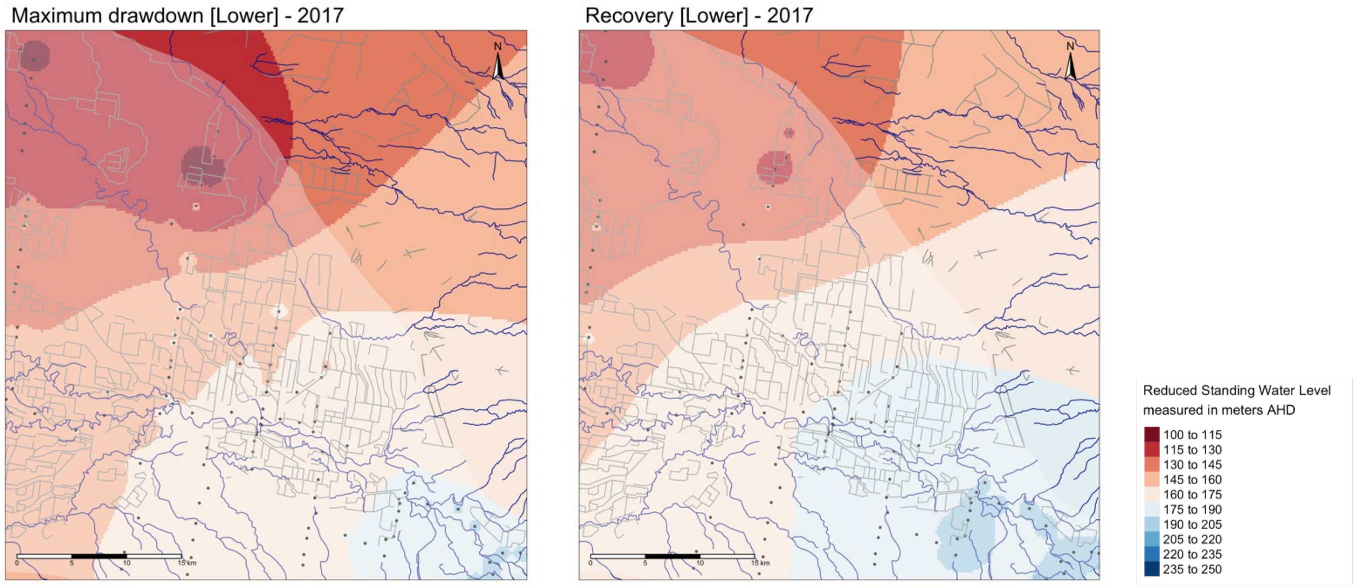


Figure 38 2017 maximum drawdown and recovery (reduced standing water level measured in meters above Australian Height Datum, AHD) in the lower aquifer. Inverse distance weighting was used to interpolate between borehole (black points) measurements. Canals (grey), rivers (dark blue) and Lower Namoi Groundwater Zone (shaded white) are also shown.

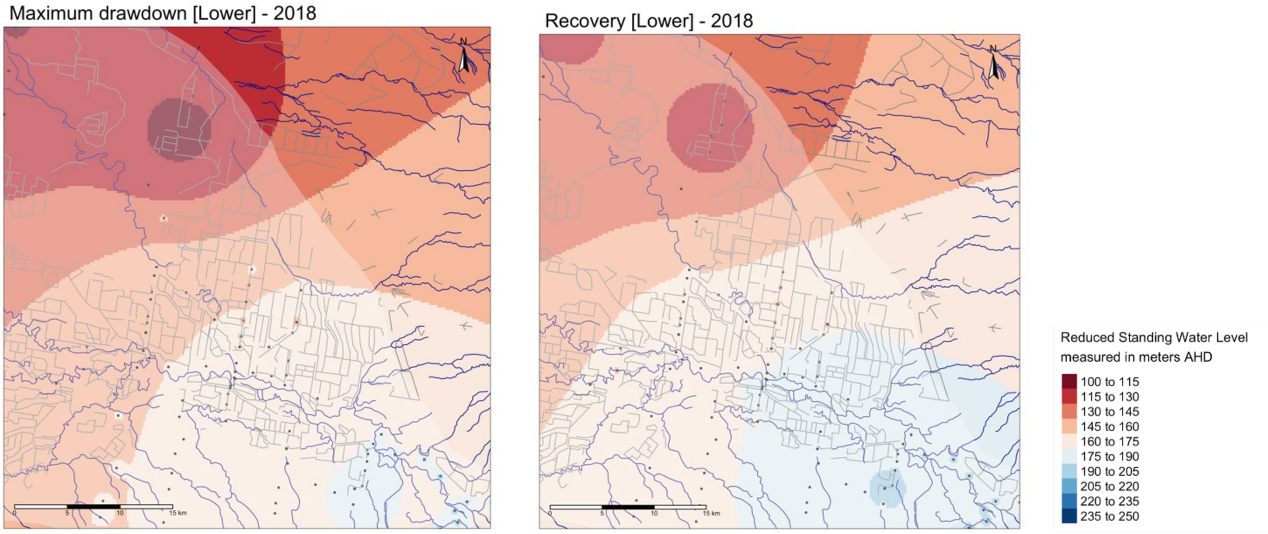


Figure 39 2018 maximum drawdown and recovery (reduced standing water level measured in meters above Australian Height Datum, AHD) in the lower aquifer. Inverse distance weighting was used to interpolate between borehole (black points) measurements. Canals (grey), rivers (dark blue) and Lower Namoi Groundwater Zone (shaded white) are also shown.

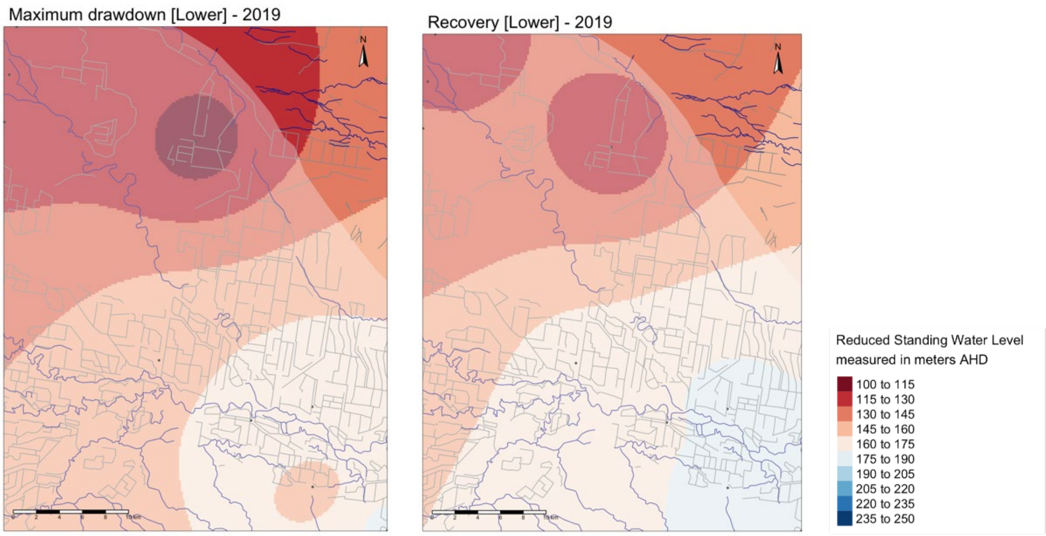


Figure 40 2019 maximum drawdown and recovery (reduced standing water level measured in meters above Australian Height Datum, AHD) in the lower aquifer. Inverse distance weighting was used to interpolate between borehole (black points) measurements (note the low number of data points). Canals (grey), rivers (dark blue) and Lower Namoi Groundwater Zone (shaded white) are also shown.

Groundwater responses to high rainfall events

A large flood event was reported at the end of 2000 (November) with additional high rainfall and associated flood events in late January/early February of 2001 [43]. This period is examined to identify groundwater response to this event.

Monthly rainfall at a nearby gauge to the AOI – Narrabri (Mollee), gauge number: 53026 – was analysed to confirm that the reported flooding was not solely due to large amounts of rainfall in the upper catchment. From the rainfall data (Figure 41), large amounts of rainfall were recorded at the gauge around the time of the reported flooding. This is suggestive that rainfall would be available to recharge the aquifer in the AOI.

[43] https://www.ses.nsw.gov.au/media/2552/the_summer_of_2000-2001.pdf

Next, the groundwater levels at monitoring bore in the AOI were plotted. First, the data was separated into two periods: one capturing a longer period before and after the reported flood (1999-01-01 - 2001-12-31) and one focused on the flood event (2000-06-01 - 2001-06-01). The data was separated by bore ID into upper and lower aquifer, based on a characterisation from DPIE. The mean RSWL for each bore was calculated for the two respective periods. The calculated mean RSWL was then subtracted from the measured bore levels to calculate the difference from the mean. This was done to be able to better visualise changes pre and post flood, and to make sure that the spread in RSWL between bores did not obscure any flood response. Results can be seen in Figure 42, Figure 43, Figure 44 and Figure 45.

In the lower aquifer seasonal trends are more obvious (Figure 43 and Figure 45). The lower aquifer is the aquifer used more heavily for irrigation and so seasonal trends that correspond to periods of high and lower extraction are expected. Trends in the upper aquifer are less obvious (Figure 42 and Figure 44). There are some bores in the upper aquifer that had a positive response post flood, however, there were other bores that had little response or where groundwater levels decreased (Figure 44). Further analysis would be needed to separate impact of pumping from recharge, noting that given the hydrogeological heterogeneity in the lower Namoi, MAR would require location-specific analysis of groundwater level response.

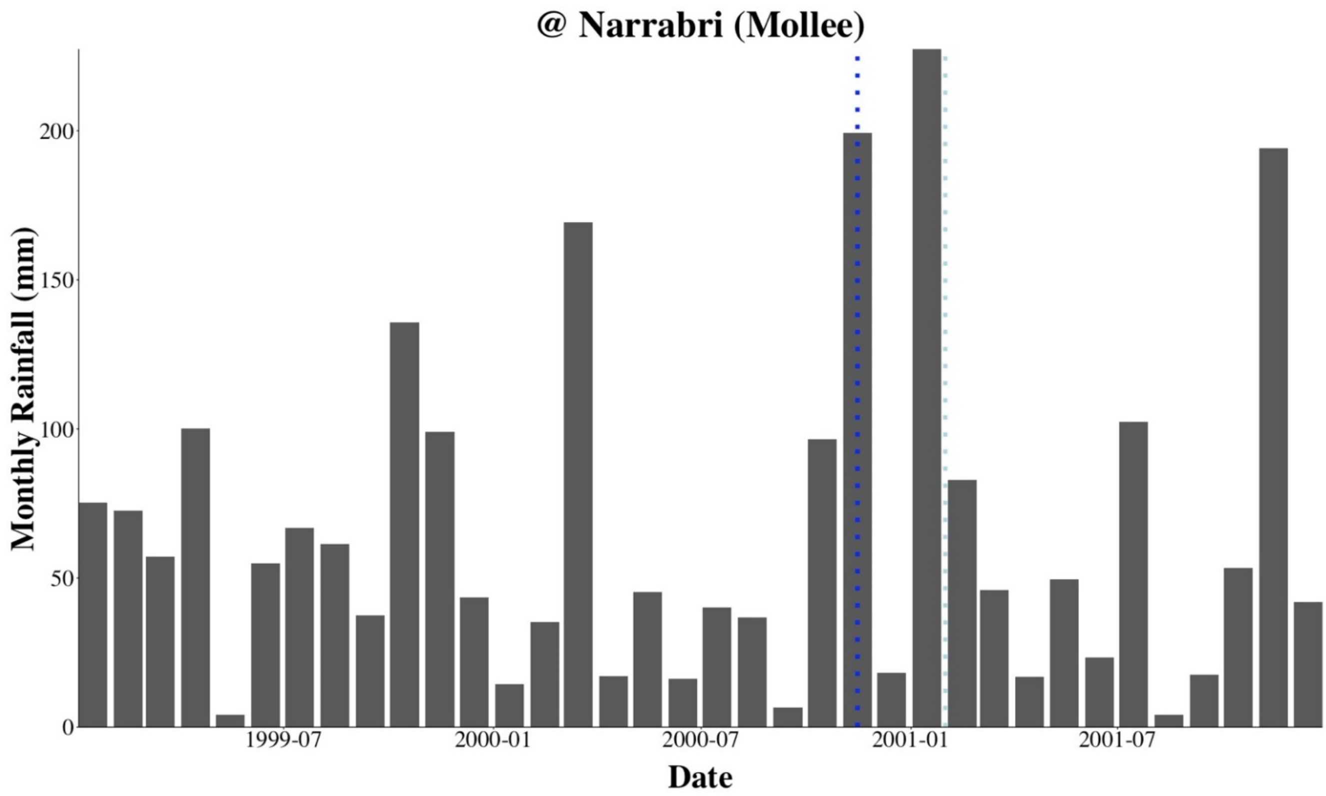


Figure 41 Monthly rainfall, as measured at Narrabri (Mollee), before, during and after the reported flood event. The dark blue dashed line highlights the date when the flood was reported to occur (mid-November, 2000-11-15) and the light blue dashed line highlights when additional flooding was reported to occur (late January/early February, 2001-01-31).

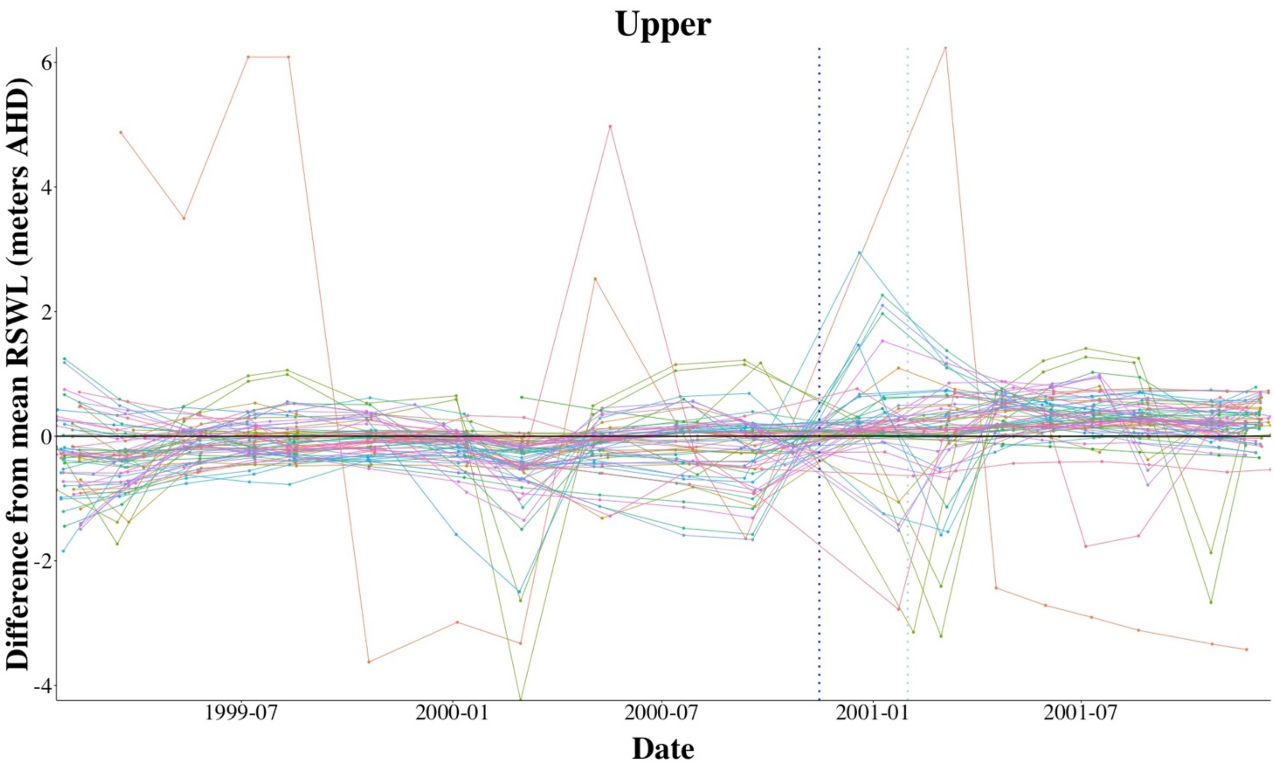


Figure 42 Difference between mean reduced standing water level (RSWL) measured in meters above Australian Height Datum (AHD) and measured RSWL (meters AHD). Bores are in the upper aquifer as defined in data from DPIE. The dark blue dashed line highlights the date when the flood was reported to occur (mid-November, 2000-11-15) and the light blue dashed line highlights when additional flooding was reported to occur (late January/early February, 2001-01-31).

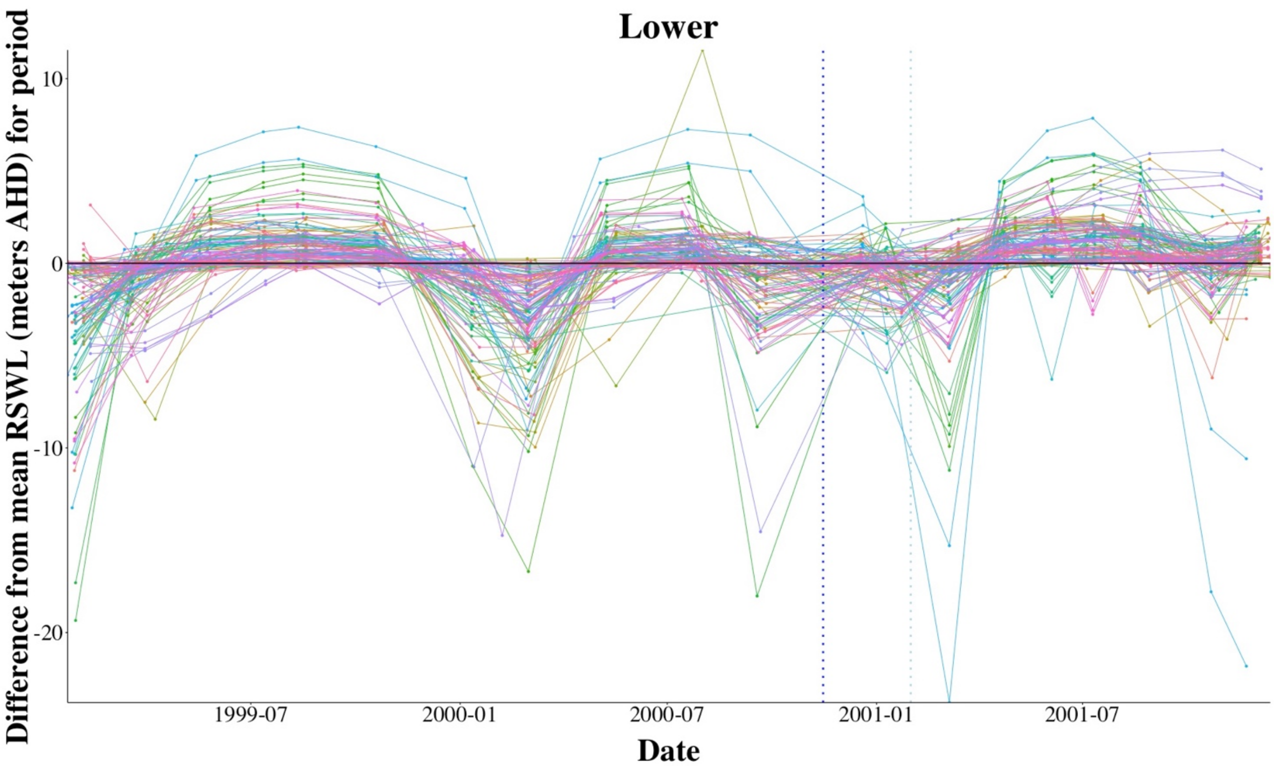


Figure 43 Difference between mean reduced standing water level (RSWL) measured in meters above Australian Height Datum (AHD) and measured RSWL (meters AHD). Bores are in the lower aquifer as defined in data from DPIE. The dark blue dashed line highlights the date when the flood was reported to occur (mid-November, 2000-11-15) and the light blue dashed line highlights when additional flooding was reported to occur (late January/early February, 2001-01-31).

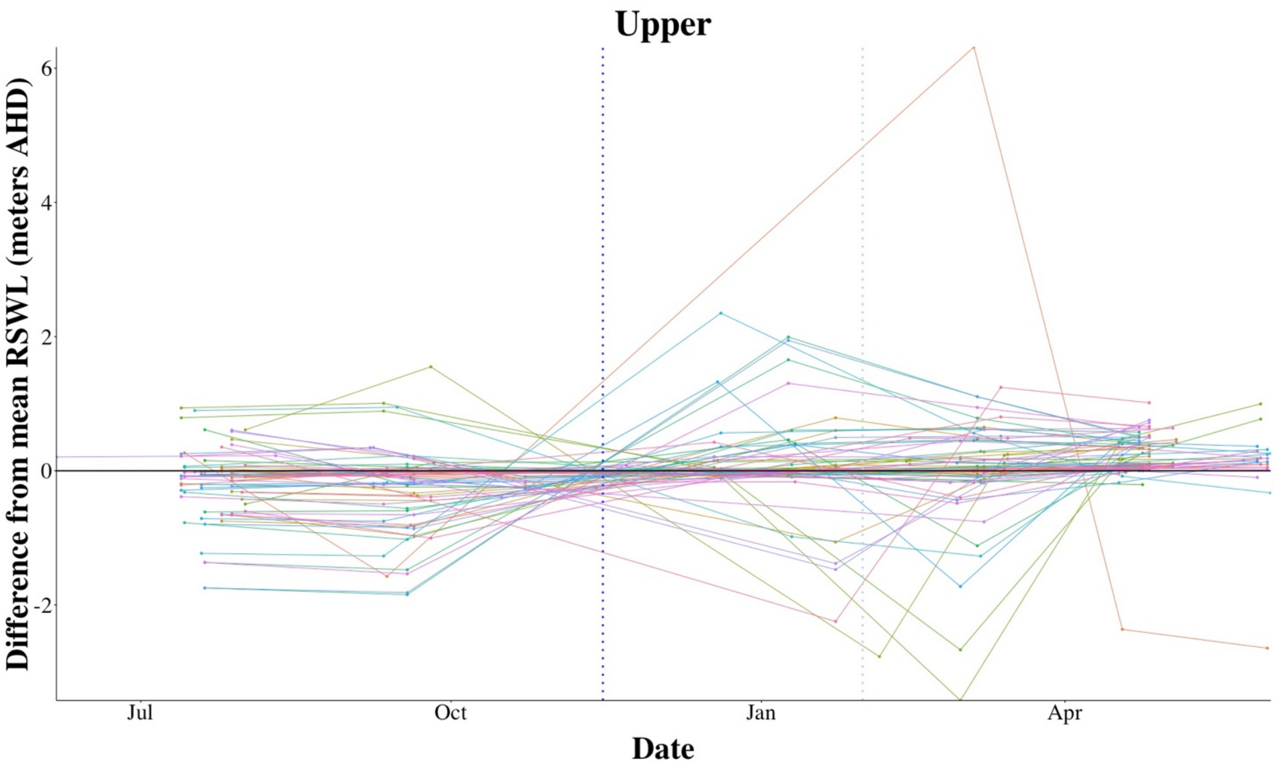


Figure 44 Difference between mean reduced standing water level (RSWL) measured in meters above Australian Height Datum (AHD) and measured RSWL (meters AHD). Bores are in the upper aquifer as defined in data from DPIE. The dark blue dashed line highlights the date when the flood was reported to occur (mid-November, 2000-11-15) and the light blue dashed line highlights when additional flooding was reported to occur (late January/early February, 2001-01-31).

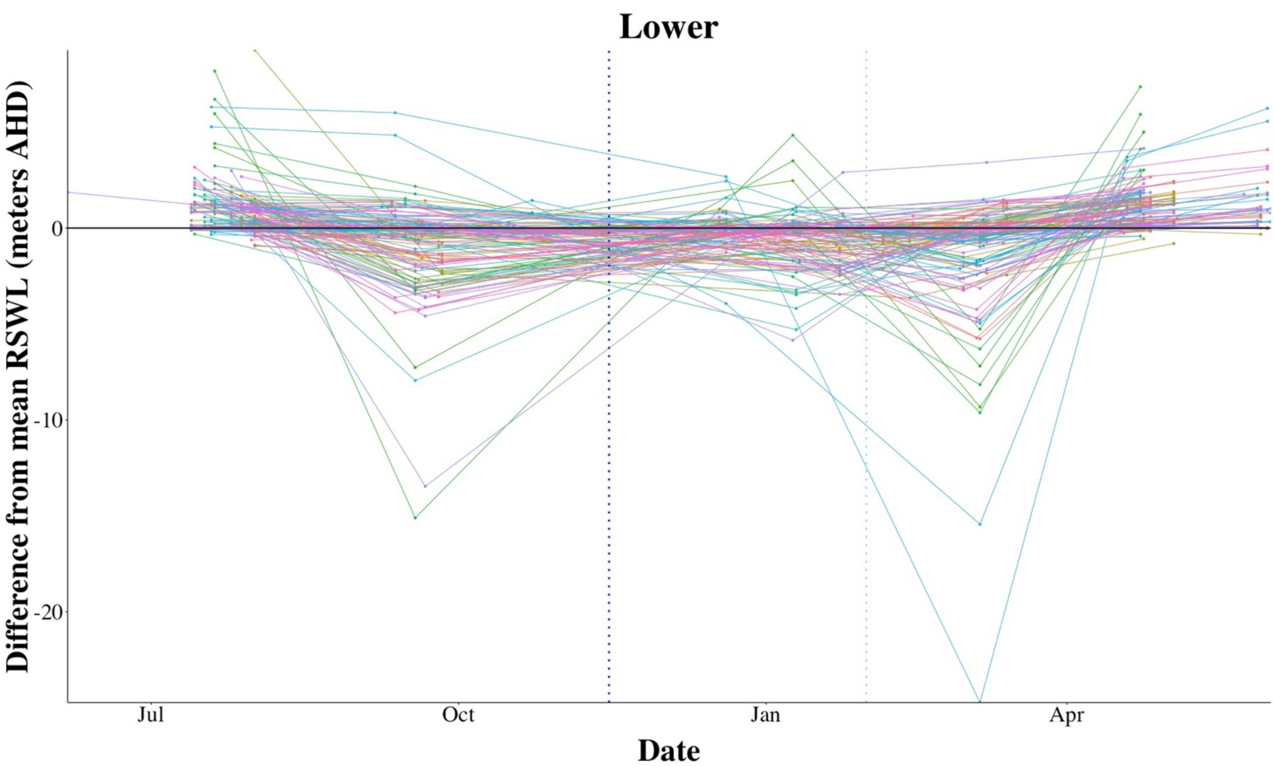


Figure 45 Difference between mean reduced standing water level (RSWL) measured in meters above Australian Height Datum (AHD) and measured RSWL (meters AHD). Bores are in the lower aquifer as defined by data provided by Catherine Barrett. The dark blue dashed line highlights the date when the flood was reported to occur (mid-November, 2000-11-15) and the light blue dashed line highlights when additional flooding was reported to occur (late January/early February, 2001-01-31).

5.3.4 Groundwater Salinity

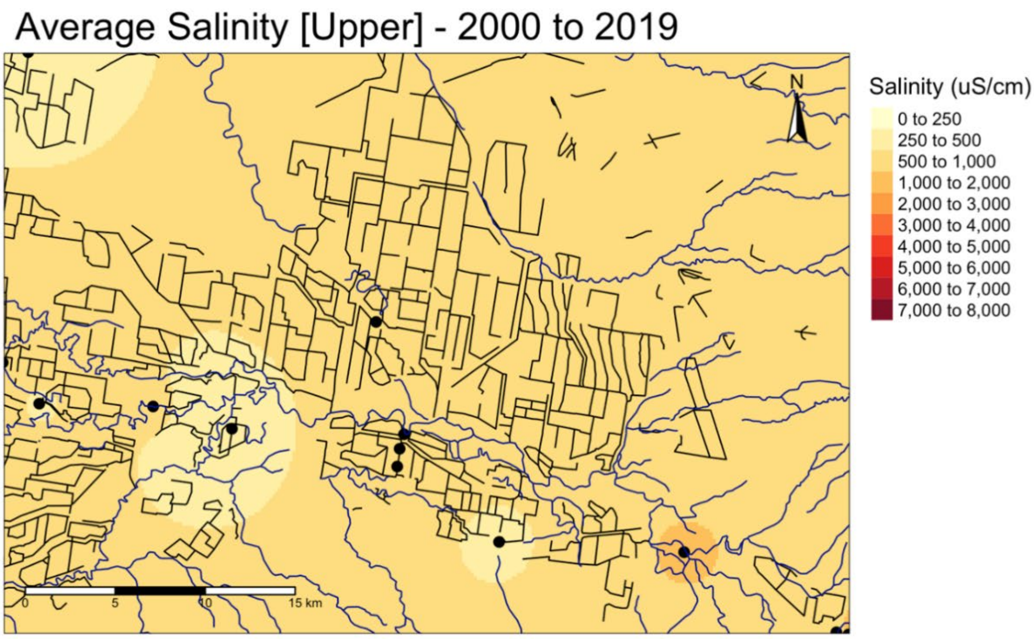
Groundwater salinity is seldom a problem in the Upper Namoi as a result of the high connection between the river and groundwater in the shallow aquifers of the region (Green et al., 2011). Water quality deteriorates west into the Lower Namoi region, where brackish and saline groundwater is more common, although this does seem to be less problematic northwest of Narrabri where this study is focused (see Figure 14). In the Namoi, areas of long-term decline in groundwater levels, where drawdowns are high during pumping season and/or where intense pumping occurs during drought are more likely to see increases in groundwater salinity (Badenhop and Timms, 2012). Variation in groundwater salinity over a short distance is common (Badenhop and Timms, 2012).

Using measurements of salinity at multiple bores, salinity was assessed (Figure 46). The aquifers were delineated based on the screen depth of the individual bore. Once again inverse distance weighting (Kollias et al., 1999, Kravchenko, 2003, Kravchenko and Bullock, 1999, Nalder and Wein, 1998, Schloeder et al., 2001) was used to interpolate between measurements, where unknown areas use surrounding points for prediction with closer points having more influence on the prediction. Some bores have many measurements (i.e., as monitoring bores) while others were only measured once, likely at time of drilling. All measurements for the years 2000 – 2019 were therefore used and the average salinity was calculated at each bore before interpolation.

Generally, salinity does not show any obvious trends in either aquifer in our AOI (Figure 46). It is possible that salinity may increase to the northwest in the lower aquifer, consistent with wider spatial trends in the Lower Namoi (see Figure 14), however, this cannot be confirmed. Salinity values in the upper and lower aquifer also appear similar (Figure 46).

Based on reported salinity tolerances of irrigated crops (NSW Department of Primary Industries, 2017), there should be no yield reduction with water salinity up to 5.1 dS/m (5,100 uS/cm) for cotton. Based on the available data salinities this high are basically absent in the region (Figure 46).

There is only one monitoring bore taking frequent measures of salinity in the region (GW273314.1.1) (Figure 47, Figure 48). This bore is likely in the deep aquifer based on its depth (depth = 195 m). The salinity at this bore has not changed substantially over the last several years, ranging from 291 to 319 uS/cm.



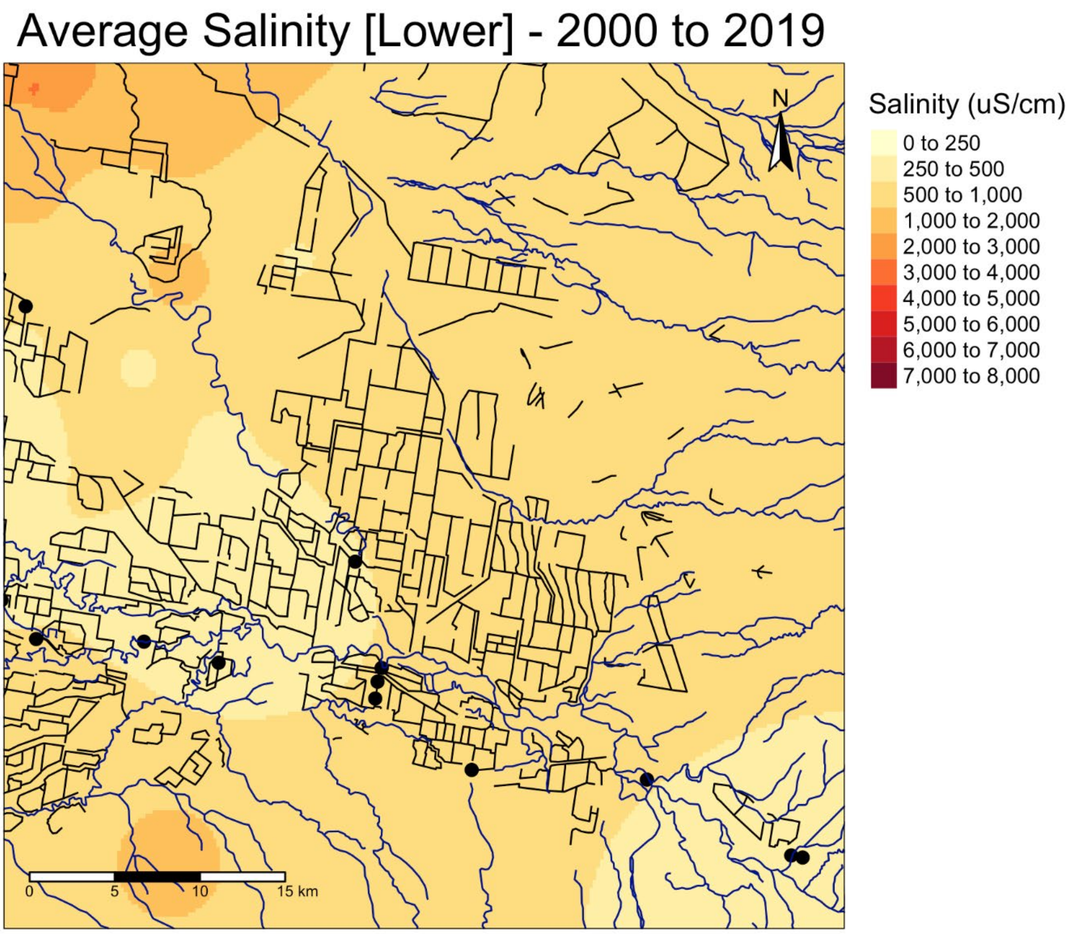


Figure 46 Salinity (uS/cm) in both upper and lower aquifer, where upper is delineated as having a screen depth less than 30 m. Inverse distance weighting was used to interpolate between borehole (black points) measurements (average of available data, with some bores having only single measurements). Canals (grey) and rivers (dark blue) are also shown.

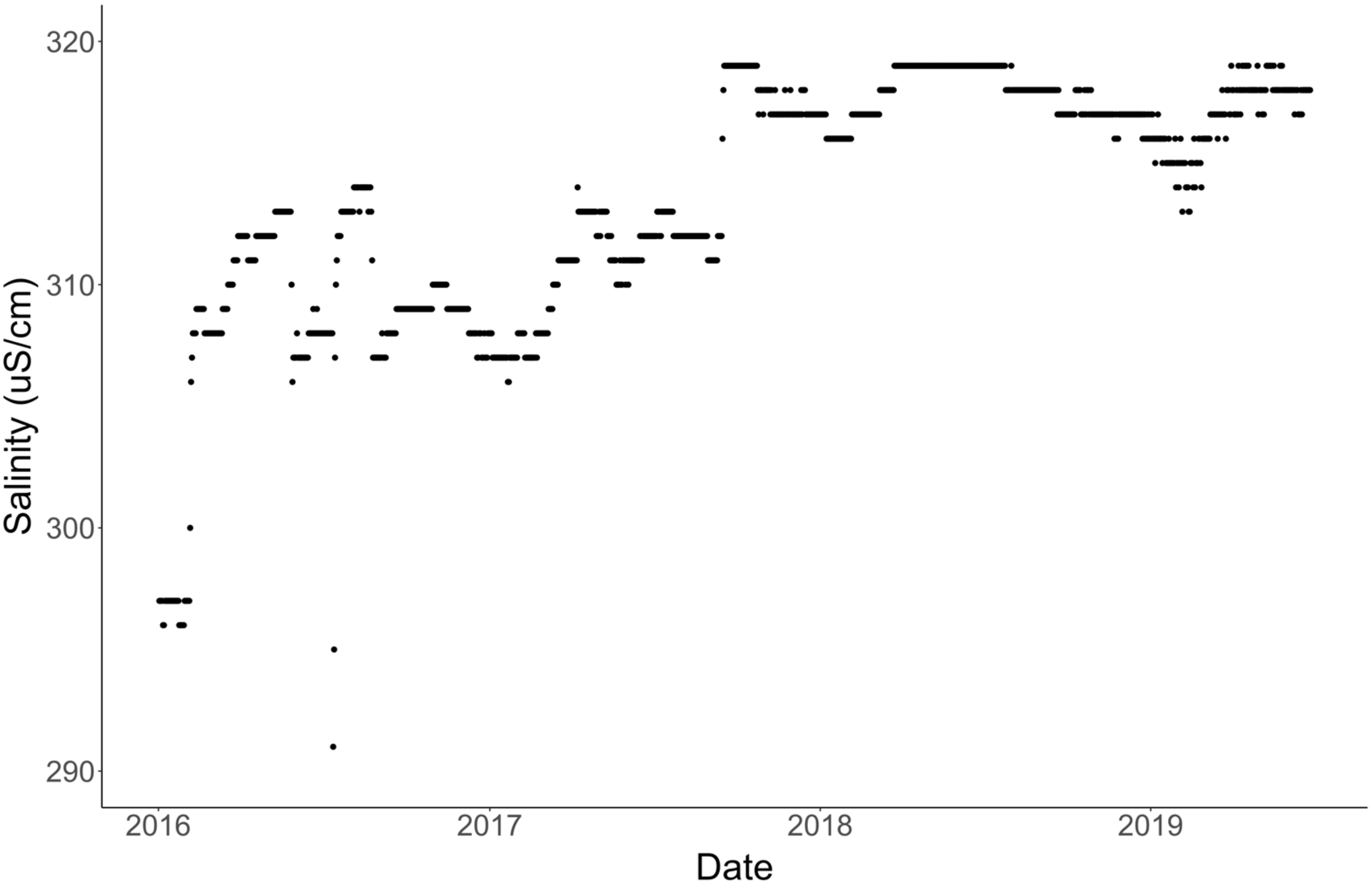


Figure 47 Salinity (uS/cm) as measured at bore GW273314.1.1 over recent years.

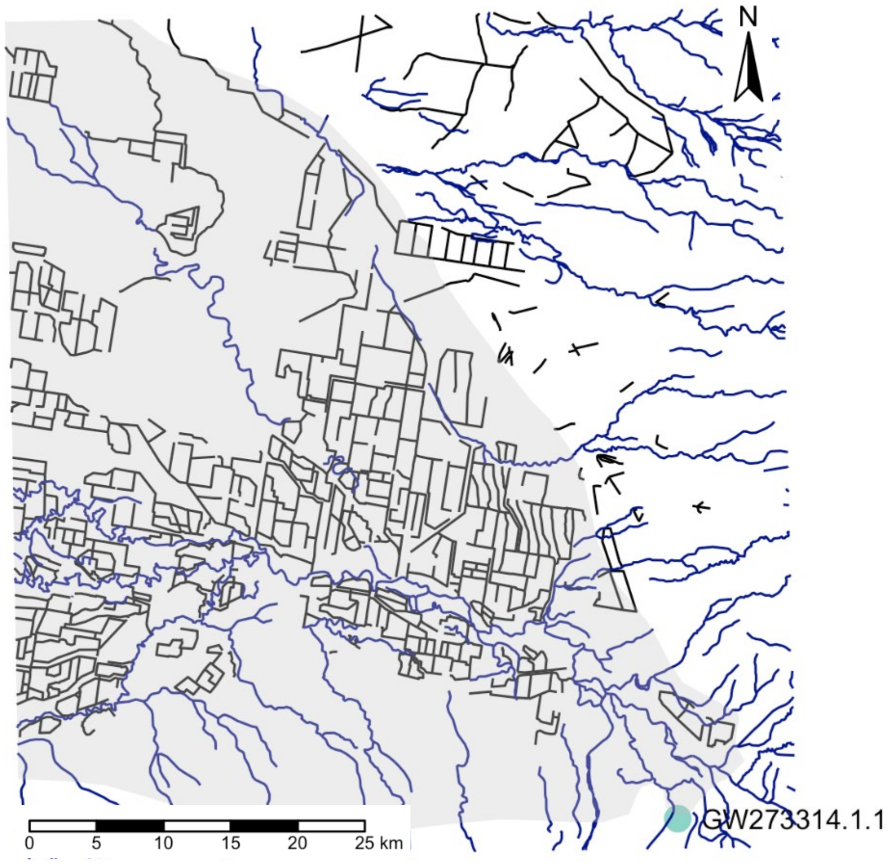


Figure 48 Location of monitoring bore with salinity timeseries (GW273314.1.1). Canals (grey), rivers (dark blue) and Lower Namoi Groundwater Zone (shaded white) are also shown.

5.3.5 Soils

Soils suitable for MAR

As infiltration-based MAR schemes can be limited by soil characteristics, it is important for these to be assessed. Sandy soil textures are often favored for infiltration-based MAR (Beganskas and Fisher, 2017, Smith and Pollock, 2012). This is due to the high permeability and infiltration rates of such soil types (Rahman et al., 2012, Russo et al., 2015), which would allow for quick infiltration of recharge water. As a suggested water source for MAR in the Namoi are supplementary entitlements, which are often only available for a short period of time, fast infiltration of MAR water would be important.

Injection MAR schemes are less dependent on soil type, as they do not rely on infiltration. Instead the characteristics of the target aquifer are more critical (Yuan et al., 2016). Semi-confined or confined aquifers are often suitable for injection wells (Yuan et al., 2016), while unconfined aquifers are better suited to infiltration basins.

Risks of soil salinization have been of historic concern in Australia, including the Namoi. Soils that are free-draining and therefore better suited to MAR are also likely to have lower accumulation of any salts from river water. River water would also be most likely to be recharged at times of higher flow and lower salinity. Infiltration would anyway be avoided in locations where the water table is already saline, avoiding risks of saline water table rise.

Soil characteristics of the Namoi

The reported presence of a clay layer on much of the alluvial deposits would hinder MAR water infiltration by reducing hydraulic connectivity (Fuentes and Vervoort, 2020). Higher recharge rates would be expected in the paleochannels that thread throughout the alluvial deposits (Fuentes and Vervoort, 2020, Wray, 2009). Given soil and aquifer heterogeneity, local investigation of suitability would be important.

Likely infiltration rates in many locations in the Lower Namoi are approximately 0.2 m/day (Arshad et al., 2014, Bouwer, 1999). Injection well recharge rates have been suggested to range from 0.5 – 8 ML/day per borehole, with past studies using the value of 2.2 ML/day (Arshad et al., 2014).

Soils characteristics of the Area of Interest

In the area of interest, preliminary suitability of soils for MAR was investigated using the Soil and Landscape Grid of Australia (https://www.clw.csiro.au/aclep/soillandscapegrid/), where national wide soil data is available for multiple attributes, including clay and sand percentage, at varying depth intervals (0 - 5 cm, 5 - 15 cm, 15 – 30 cm, 30 – 60 cm, 60 – 100 cm and 100 – 200 cm).

The sand % soil data shows a decrease in sand % with depth (Figure 49). There does appear to be a sandy corridor that runs north-west of the Namoi River, which is consistent at all depths (Figure 49).

Finer resolution confirmation is important. The sand % data from the Soil and Landscape Grid of Australia shows apparent areas of high sand % under farm dams, which is not mirrored in the areas directly adjacent to the dams (Figure 49, Figure 50). Although possible, this is unlikely since unlined dams would accumulate silt and clay over time, and farm operators would not look to build dams in sandy areas as this would lead to unnecessary losses. Local experience notes that dams in the region show very little leakage.

Salinisation

The accumulation of water-soluble salts in the soil is termed salinisation[44]. The accumulation of salts in the soil can have a detrimental effect on plant growth. High soil salinity can also have a negative impact on the water quality of underlying aquifers if the salts are mobilised during, for example, large recharge events, floods or periods of intense irrigation (Badenhop and Timms, 2012). Causes of salination include the presence of soluble salts, a perched water table, high evaporation rates, the use of saline water for irrigation and/or low annual rainfall (e.g., semi-arid climate).

[44] https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcs142p2_053151.pdf, accessed 8th November 2021

Salinisation has been highlighted as a possible threat to irrigation agriculture in the upper NSW catchments of the MDB (Triantafilis et al., 2004, Triantafilis et al., 2003). In upper parts of the Namoi catchment the presence of dryland salinity is established (Triantafilis et al., 2004). However, modelling efforts showed that salinisation risk in our AOI is low based on the water currently being used for irrigation in the area (Triantafilis et al., 2004). If irrigation in the area was to occur using saline water, the potential for salinisation increases and management protocols would likely have to be implemented to ensure cropping systems could continue as they do now (Triantafilis et al., 2004). The crops commonly used in rotation with cotton (e.g., wheat and legumes), are more susceptible to salinisation than cotton itself (Triantafilis et al., 2004). Cotton-based rotations that reduce subsoil structure, limiting drainage, have been shown to increase salinisation of the root zone in the Lower Namoi, even when irrigation water quality is reasonable (Weaver et al., 2013). Areas where prior stream channels are present have an overall lower risk of salt accumulation in the soil, however, if saline irrigation water from more brackish water sources were to be used for irrigation, contamination of local groundwater via deep drainage is possible (Triantafilis et al., 2004), as is a rising groundwater tables (Triantafilis et al., 2003).

The above studies, although not directly related to MAR, do provide some valuable insights into how MAR could operate and not increase salinisation risk in the area. The use of 'good' quality water for MAR, particularly MAR that involves infiltration whether through basins or in a AgMAR scheme, is imperative to limit soil salinisation. Also, monitoring groundwater levels and quality in the upper aquifer would assist in decreasing the likelihood of a perched saline water table. Schemes that involve AgMAR would also have to consider soil structure, both to ensure high infiltration rates are preserved and to limit salinisation.

5.3.6 Recharge

Previous studies have focused on understanding recharge that occurs via the river (Kelly et al., 2009) or have acknowledged that recharge from the river could be significant (Fuentes and Vervoort, 2020). Other studies have explored the magnitude of irrigation recharge (Ringrose-Voase and Nadelko, 2011). Recharge from rainfall is considered to be very small or negligible (Welsh et al., 2014).

River recharge

The streams on the alluvial plain flow across the top of the Narrabri Formation and an unsaturated zone can develop at points where the rivers are in direct hydraulic contact with the watertable; in this situation, surface water recharges the underlying aquifer as long as streamflow persists (Welsh et al., 2014).

Electrical imaging along the lower Namoi River suggests that river water, river recharge hosted in clay, and river recharge hosted in sands and gravels could be differentiated based on electrical conductivity (Kelly et al., 2009). That is to say that water quality (i.e., salinity) is not the major influence on electromagnetic (EM) data in this region (Kelly et al., 2009). This allowed for continuous sections of sand and gravels present beneath the river to be identified through low observed EC, suggestive of areas that are a hydraulic link between the river and underlying aquifers (Kelly et al., 2009). Piezometer data was explored to see if the impacts of floods were observable at depth (i.e., in the deeper Gunnedah formation) (Figure 51). From this there was evidence that flood waters migrate to the deeper semi-confined aquifer via recharge pathways beneath the Namoi River (Kelly et al., 2009). This was further expanded by looking at interpolated groundwater head data from pre- and post-flood to assess the broader impact of flood water moving down the river (Figure 52) (Kelly et al., 2009). Groundwater mounding near the river occurred in similar locations for flooding events in the past 50 years - to the north (Figure 52) (Kelly et al., 2009). This supports the notion that gravel and sand paleochannels extend to the north (Kelly et al., 2009).

A strategy suggested for where MAR in the region could be achieved is by building a weir between the old Wee Waa bridge and Wee Waa (Dr. Bryce Kelly, *pers. comm.* November 2020). Looking at past research (Iverach et al., 2017), Mollee's Weir works like a MAR system currently but this likely benefits those close to the river and not in the north western area of the Lower Namoi on the palaeochannel (Dr. Bryce Kelly, *pers. comm.* November 2020). As noted in Section 5.3.2, a Menyanthes model [45] could be built to better understand recharge during a flood event.

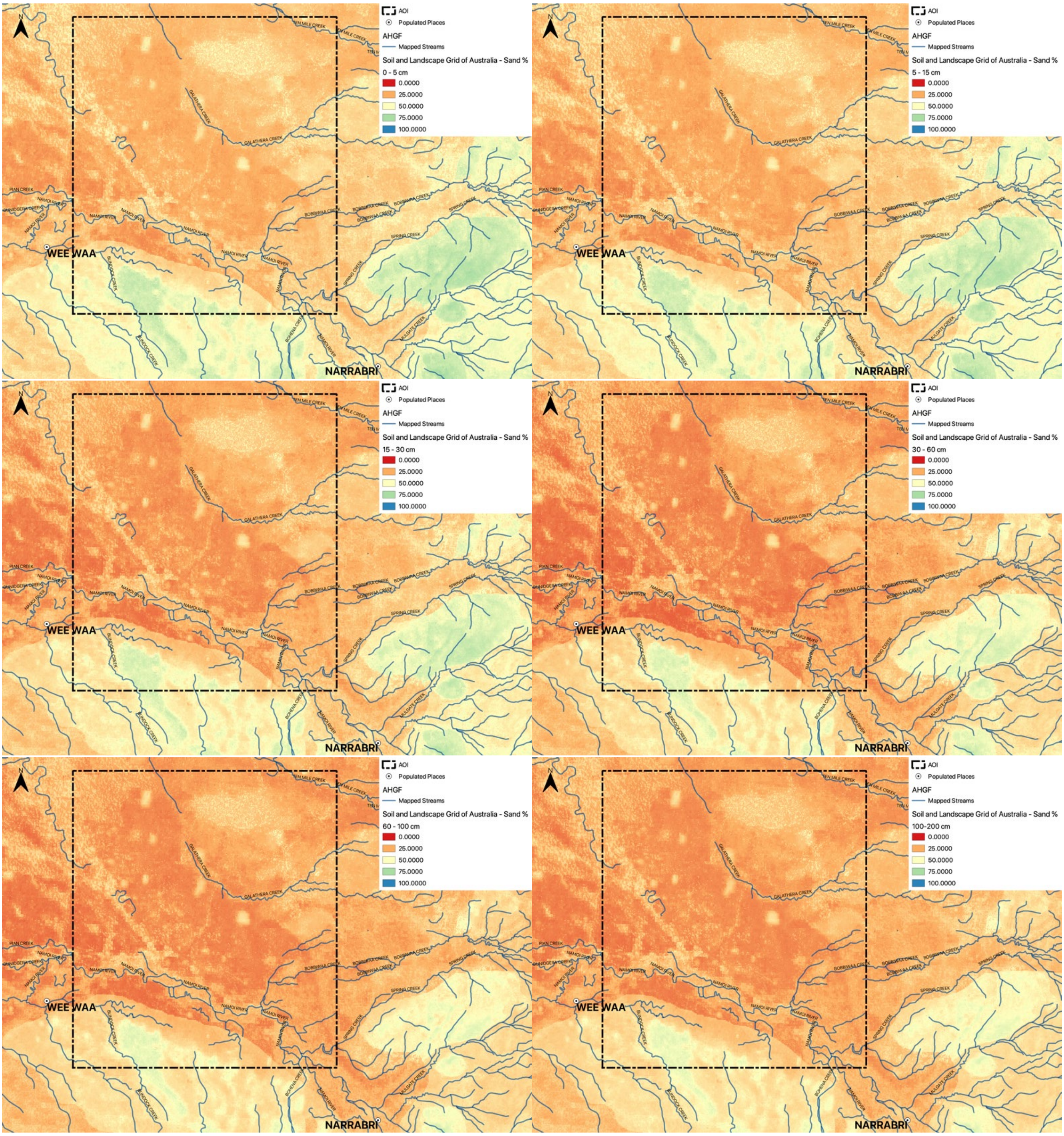


Figure 49 Sand % in the area of interest and surrounds at varying depths (0 - 5 cm, 5 - 15 cm, 15 – 30 cm, 30 – 60 cm, 60 – 100 cm and 100 – 200 cm). Data from: the Soil and Landscape Grid of Australia (https://www.clw.csiro.au/aclep/soilandlandscapegrid/) and the Australian Hydrological Geospatial Fabric (AHGF) (https://datasets.seed.nsw.gov.au/dataset/australian-hydrological-geospatial-fabric-geofabric).

[45] https://www.kwrwater.nl/en/tools-producten/menyanthes/, accessed 22 November 2021

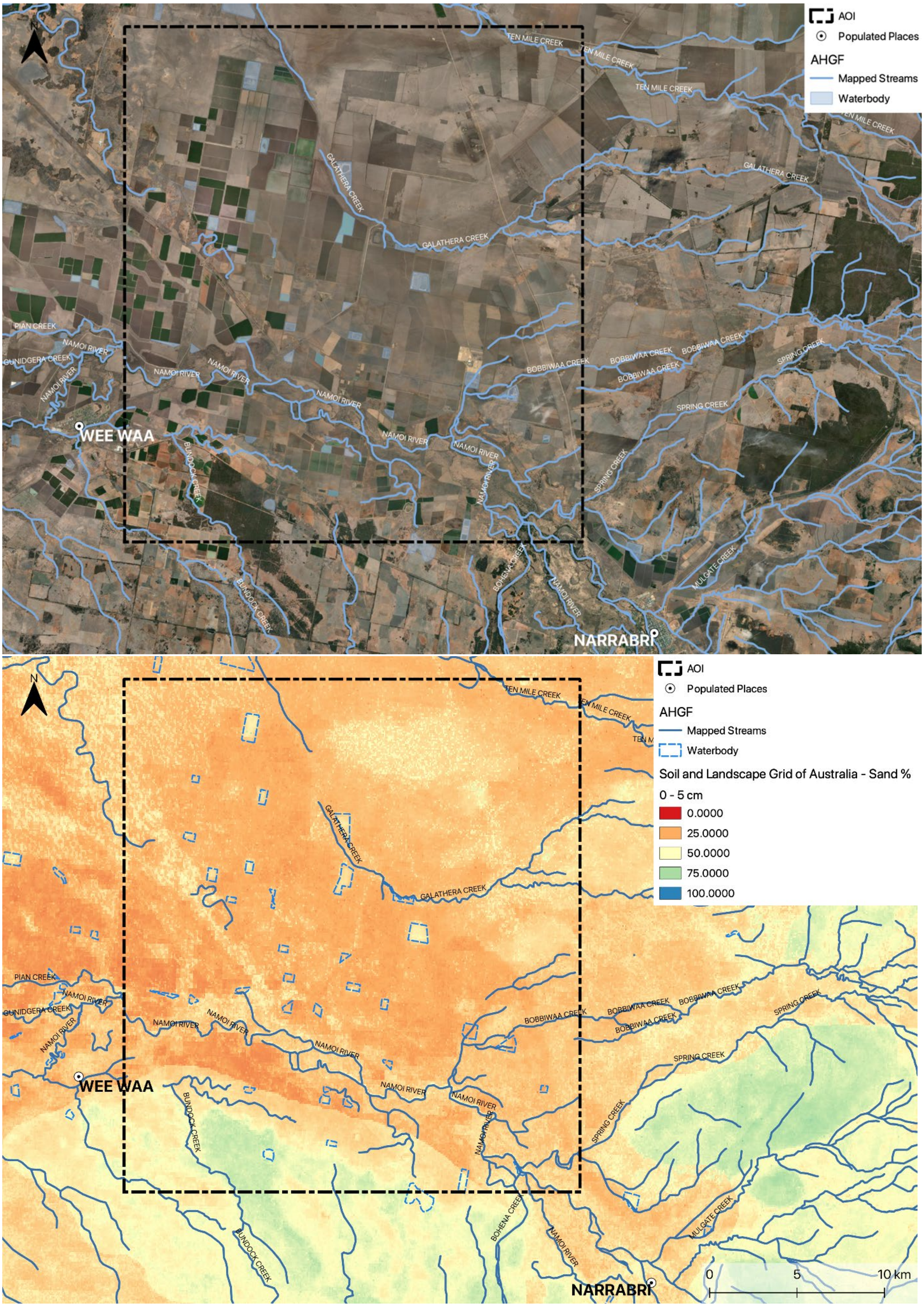


Figure 50 Mapped waterbodies (i.e., farm dams) highlighting one possible deficiency of the soil data: areas under dams are noticeably sandier than adjacent areas. Data from: the Soil and Landscape Grid of Australia (https://www.clw.csiro.au/aclep/soillandscapegrid/) and the Australian Hydrological Geospatial Fabric (AHGF) (https://datasets.seed.nsw.gov.au/dataset/australian-hydrological-geospatial-fabric-geofabric).

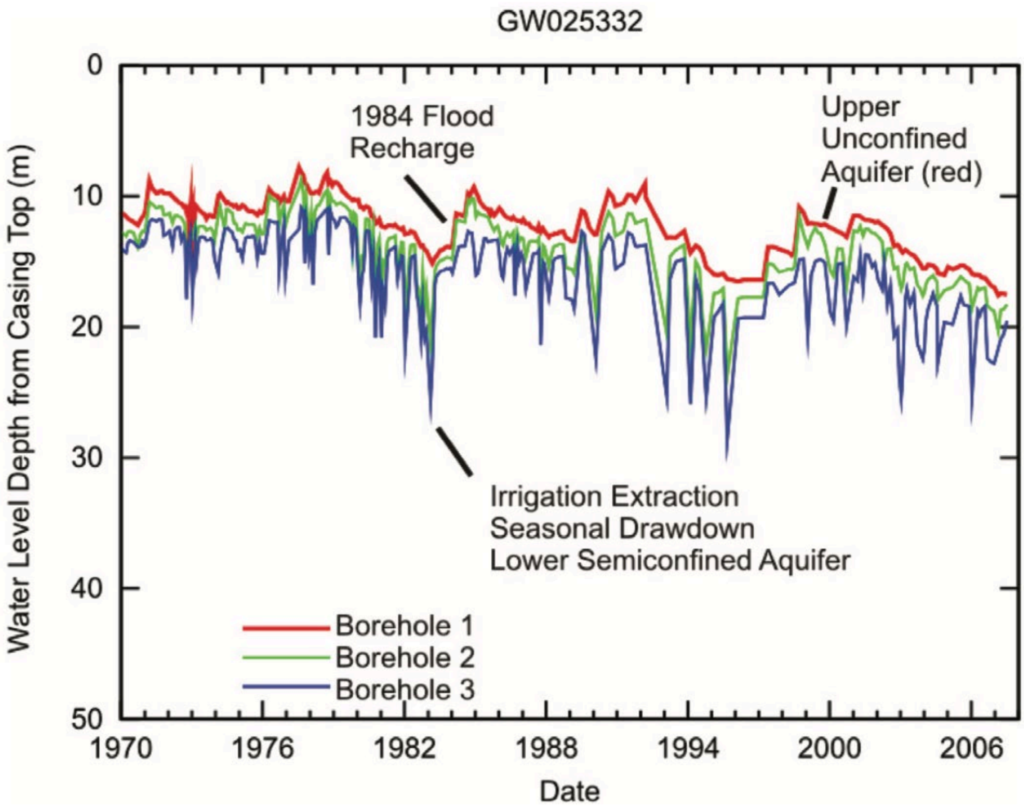


Figure 51 Groundwater monitoring borehole hydrographs. Borehole 1 is in the unconfined aquifer and is slotted from 17.7–21.4 m. The large rises in head observable in borehole 1 are due to recharge from flood water. Boreholes 2 and 3 are in the semi-confined aquifer. Borehole 2 is slotted from 38.1–41.1 m and borehole 3 is slotted from 50.9–55.5 m. Water used for irrigation is extracted from the semi-confined aquifer. Source: Kelly et al. (2009)

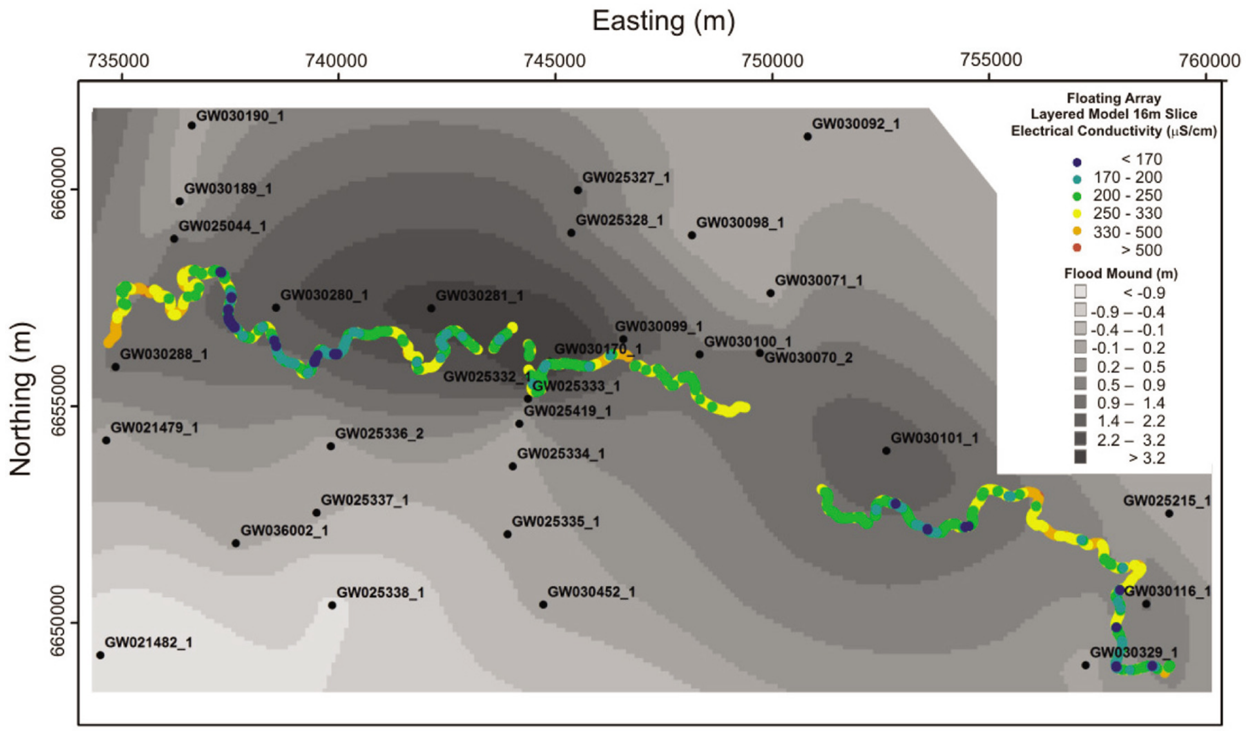


Figure 52 A map of the changes in borehole water levels resulting from the 1984 flood. Source: Kelly et al. (2009)

Paleochannels

Fuentes and Vervoort (2020) investigated the hydrographic behavior of wells in a small region surrounding the Lower Namoi River. All wells were assumed to be in the upper aquifer based on depth. Findings showed that wells closer the Namoi River and in the surrounding paleochannels displayed rapid peaks in groundwater level in response to recharge events, while these changes tend to smoothen in wells further from the river (Fuentes and Vervoort, 2020). Similar trends could be seen in the estimates of recharge at the well sites (Figure 53), where high recharge estimates occurred in the paleochannels surrounding the Namoi River (Fuentes and Vervoort, 2020). The high spatial variability of recharge estimates is also highlighted (Figure 53).

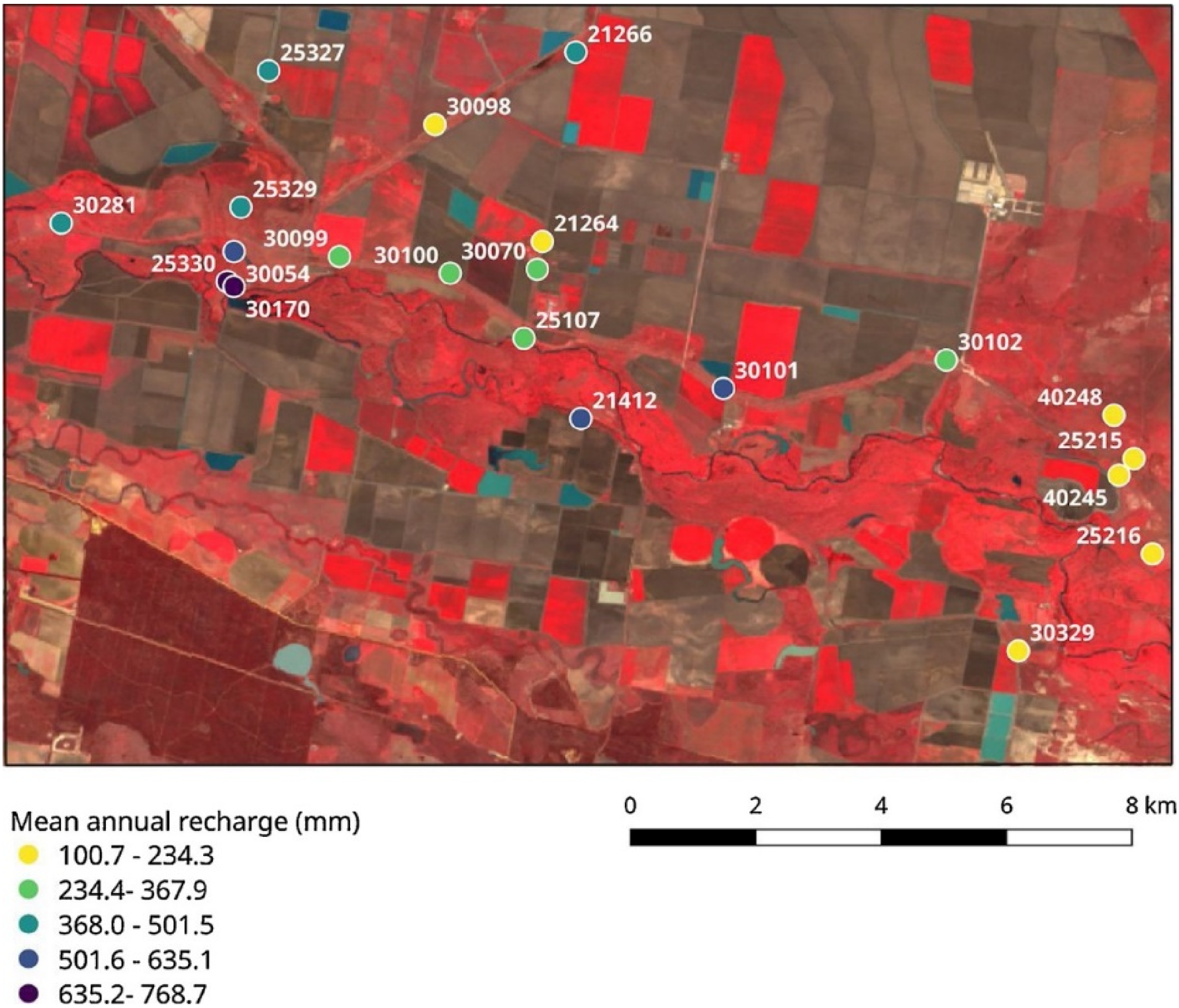


Figure 53 Mean recharge estimates for different labelled monitoring wells along the lower Namoi River. All wells are assumed to be located in the upper aquifer. Source: Fuentes and Vervoort (2020)

Due to groundwater extractions from the Gunnedah Formation, the Northern Namoi paleochannel (Figure 54) acts as a drain and there is significant downward leakage from the Narrabri formation (Herr et al., 2018).

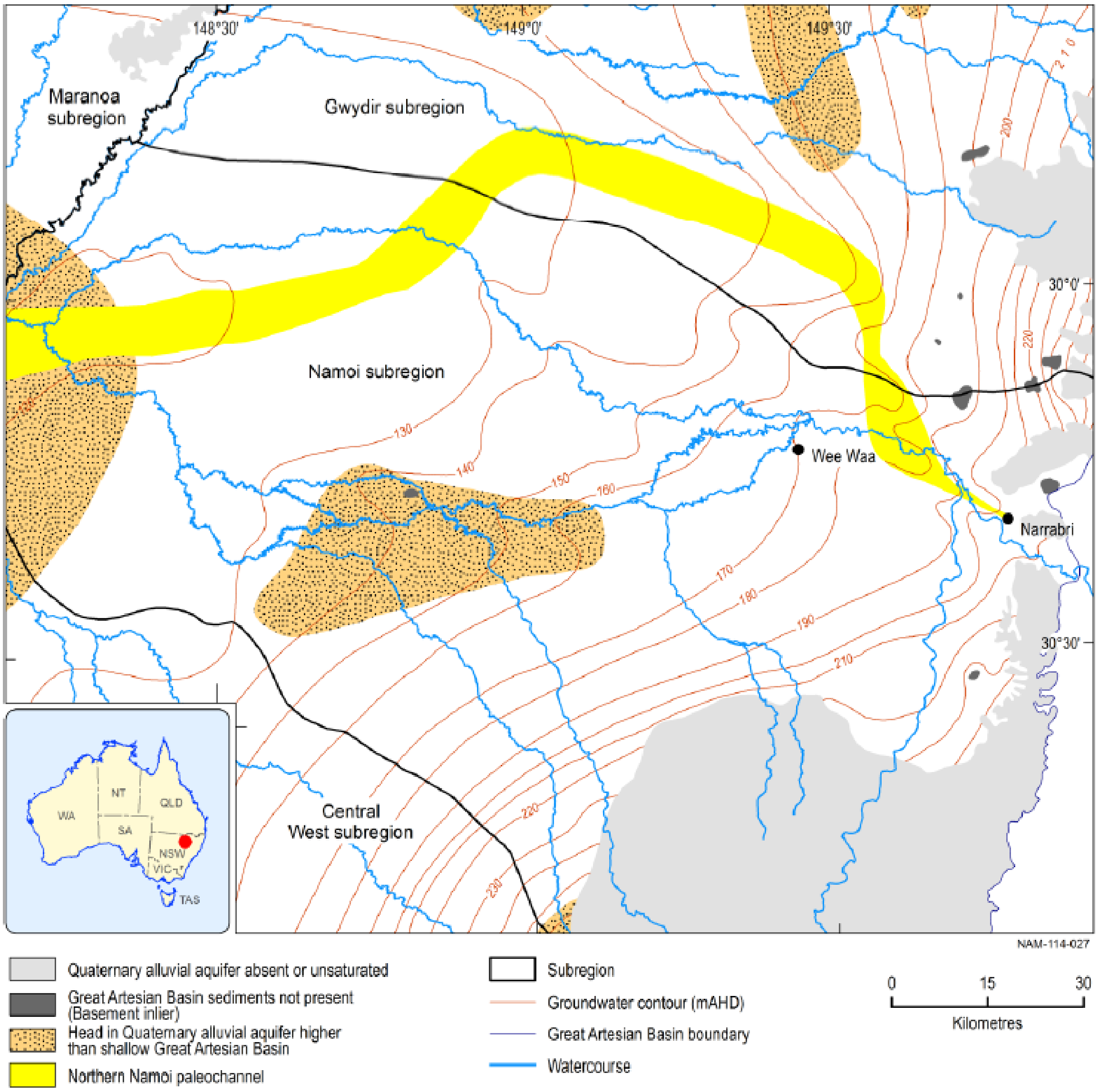


Figure 54 Northern Namoi paleochannel and water table (mAHD) in the Narrabri formation (SWS, 2011 in Herr et al., 2018)

Irrigation

Estimates of groundwater recharge of irrigation vary greatly and it is uncertain whether this water 'migrates laterally, returns to the surface water flows or moves downwards to recharge deeper aquifers' (Welsh et al., 2014). Ringrose-Voase and Nadelko (2011) identified that this recharge under cotton grown on soils in the Namoi can be significant and can occur in two forms. Matrix drainage occurs when water inputs exceed ET losses and the soil profile is filled to capacity. By-pass drainage occurs as quick downward flow through macropores thus bypassing the soil profile which can be in water deficit (Ringrose-Voase and Nadelko, 2011). This form of recharge can be dominant form of recharge during the irrigation season with implications for reducing drainage losses and for the efficient leaching of salt from the soil profile (Ringrose-Voase and Nadelko, 2011).

5.3.7 Implications for the design, planning and implementation of MAR strategies

Managing recharge

There are many different strategies used to implement MAR. Infiltration basins are a popular choice when the target aquifer is both shallow and non-saline and the soils in the area are sandy with high infiltration rates (Beganskas and Fisher, 2017, Rahman et al., 2012, Russo et al., 2015, Vanderzalm et al., 2018, Dillon, 2005). Infiltration could also occur via natural features such as paleochannels and losing stream reaches (Fuentes and Vervoort, 2020). The efficiency of infiltration ponds may decrease over time due to clogging by sediments present in the water to be recharged (Hutchison et al., 2013), which decreases soil conductivity. There are methods to limit clogging including the use of wetting and drying cycles (Hutchison et al., 2013, Vanderzalm et al., 2015) and the use of settling ponds to reduce suspended soils in recharge water (Arshad et al., 2014, Beganskas and Fisher, 2017). MAR via channel seepage works the same way as infiltration basins except that already established channels are used rather than specifically constructing basins. Injection wells are often used when the target aquifer is deep (i.e., not directly below the surface) and semi-confined or confined (Yuan et al., 2016, Dillon, 2005). Once again clogging can be a potential issue, but the use of settling ponds (Arshad et al., 2014) and back washing of the well can limit this (Barnett et al., 2000). Further details on infiltration and injection based MAR schemes can be found in Guillaume et al. (2020), the Murrumbidgee case study report prepared for this project.

A MAR method applicable in the Namoi not discussed in Guillaume et al. (2020) is agricultural managed aquifer recharge (Ag-MAR). Ag-MAR can employ many MAR techniques including canal seepage, off-season field irrigation and field flooding/spreading for infiltration, and is based on the idea that significant aquifer recharge occurs from agricultural land naturally (Niswonger et al., 2017, Ghasemizade et al., 2019, Ganot and Dahlke, 2021, Waterhouse et al., 2021, Kourakos et al., 2019, Murphy et al., 2021). Ag-MAR is an example of conjunctive use of surface and groundwater (Niswonger et al., 2017). Periods of excess surface water (i.e., flood) have been highlighted as particularly suitable for Ag-MAR (Niswonger et al., 2017, Murphy et al., 2021). Ag-MAR has most potential in agricultural basins and can increase sustainable yield in the target aquifer (Niswonger et al., 2017, Ghasemizade et al., 2019). Improved ecosystem services can also be a consequence of Ag-MAR (Niswonger et al., 2017). Benefits of Ag-MAR over other MAR methods includes the reduced need for specific infrastructure to support MAR, the likelihood of infrastructure to deliver water already being established and the likely placement of agricultural areas near rivers and other water sources (Niswonger et al., 2017, Kourakos et al., 2019). Ag-MAR can also be scheduled to occur only when crops are not being grown (off-season), meaning that Ag-MAR may not complete with other land uses (Niswonger et al., 2017, Ghasemizade et al., 2019, Ganot and Dahlke, 2021). Ag-MAR has its challenges including the need for farmers to gain knowledge on Ag-MAR, possible water-logging and possible aquifer contamination (Niswonger et al., 2017, Ghasemizade et al., 2019, Ganot and Dahlke, 2021, Waterhouse et al., 2021, Murphy et al., 2021). Like other MAR schemes, recovery of water recharged through Ag-MAR would require changes to water policy (Niswonger et al., 2017). Ag-MAR as a concept is relatively new, with pilots having occurred in California and recent modelling studies (Ghasemizade et al., 2019, Niswonger et al., 2017, Ganot and Dahlke, 2021, Harter, 2015, Waterhouse et al., 2021, Kourakos et al., 2019).

Recovery efficiency

Recovery rates in the AOI, and the Lower Namoi more generally, should not be a barrier to the extraction of MAR water due to the prominent use of groundwater currently. Bore yields in the Gunnedah and Cubbaroo Formations, which are currently tapped into for irrigation purposes, produce yields up to 250 L/sec (Arshad et al., 2014). Given that local watercourses are losing (i.e. recharge groundwater) rather than gaining (i.e. receiving groundwater), the primary loss of recharged water in the AOI would be through increased lateral flow to the west, though the extent of this loss would require site-specific analyses of flow paths to gain confidence in assignment of any right to recover recharged water. Given the productivity of groundwater in the AOI, MAR would be expected to support groundwater levels in the long term. The volume of water to be recovered across all groundwater users would likely be the primary constraint on recovery of recharged water, and would vary over time depending on the state of the groundwater system prior to its drawdown in dry years; active management of groundwater storage would help maximise its benefits.

Monitoring design to manage effects

The NSW Office of Water already monitoring groundwater levels at over 600 sites in the catchment, with monitoring beginning as early as the 1970s (Green et al., 2011). There are over 15,000 bores scattered throughout the Namoi catchment (Green et al., 2011) which could support further monitoring. Bores in the AOI and surrounds are shown in Figure 55. Given the heterogeneity of the aquifer, local investigation of soils and aquifers will likely be necessary both in planning of MAR and monitoring of aquifer responses.

Monitoring information has been used in groundwater model development for the Lower Namoi, which are used to estimate groundwater recharge and predict groundwater level responses (Green et al., 2011).

5.4 Financial viability

5.4.1 Cost-benefit analysis of MAR and surface storage options under uncertainty

In a series of papers (Arshad et al., 2013, Arshad et al., 2014), Arshad and colleagues investigated the irrigation related costs and benefits over a 50-year timeframe for a hypothetical irrigation enterprise in the Lower Namoi for three different water storage and management options: on-farm surface storage (the base case), infiltration-based MAR, and injection-based Aquifer Storage and Recovery (ASR). Arshad et al. (2014) recognised that while some studies, including Arshad et al. (2013), had found that MAR options could be financially competitive or superior to surface storage options, these studies had not explored the impact of the inherent uncertainty on the cost-benefits analyses.

The studies assumed that water availability was constrained such that <20% of the available land was irrigated. The cropping pattern under all was irrigated cotton Bt (*Bacillus thuringiensis*) and faba bean (*Vicia faba* L) as the summer and winter rotations on irrigated land with winter wheat, chick pea and faba bean carried out on marginal lands and on paddocks that are not cultivated by irrigation water. It was assumed that all required irrigation infrastructure, such as surface storage and irrigation water delivery network, existed and covered the entire irrigation land area. Annual water availability was set at 1350 ML based on recent (at the time) irrigation water allocations in the Lower Namoi. Farm economic data was adopted from available literature (Table 6).

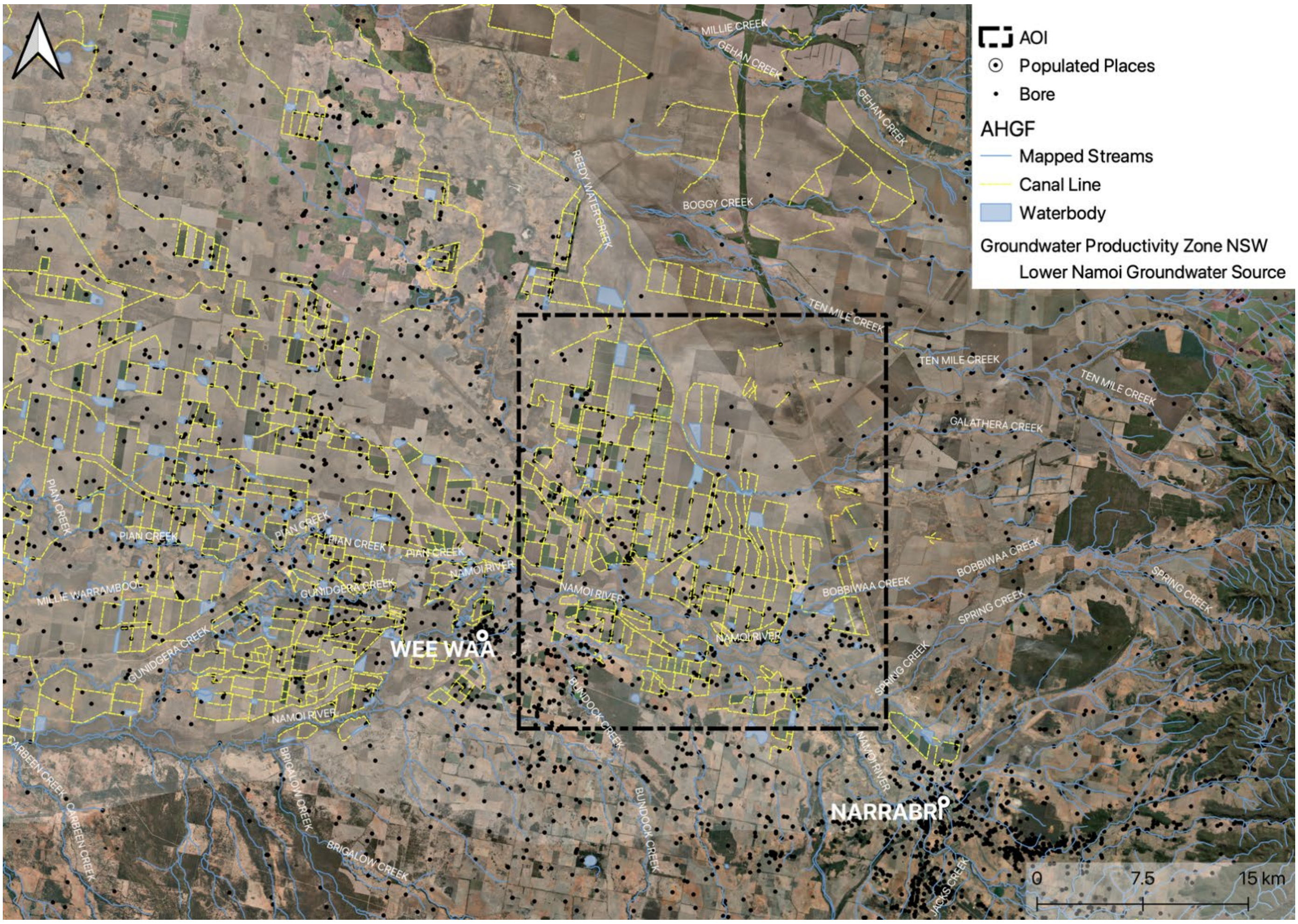


Figure 55 Bores in the region. Bore data is from the National Groundwater Information System (NGIS) (http://www.bom.gov.au/water/groundwater/ngis/). Stream, canals and dams are also shown (Australian Hydrological Geospatial Fabric (AHGF) (https://datasets.seed.nsw.gov.au/dataset/australian-hydrological-geospatial-fabric-geofabric)).

Table 6 Gross margins and net farm income, irrigated and dryland (Arshad et al., 2013) [46]

Crop	Irrigation Water Use ML/ha	Yield *bales/ha Tonnes/ha	Price *$/bale $/Tonne	Gross Value *$/bale $/Tonne	Variable Cost $/ha	Gross Margin $/ha	Gross Margin $/ML	Net Income $/ML #$/ha	Net Contribution in Farm Income %
Irrigated Cotton (Bt)	7.9	9.5*	538*	5,111*	2,505	2,606	326	207	57
Irrigated Faba Bean	2.7	5.0	348	1,740	565	1,175	435	277	28
Dryland, Wheat and Faba Bean		1.6	296	474	225	249		158#	15

Data Source: Powel and Scott, 2011 and DPI, NSW 2013

* *Cotton, price is in $/bale including both lint and seed*
\# *net income for dryland is in $/ha*

Levelised costs were used to estimate the cost of aquifer storage of 200 ML of flood water and recovery over 50 years with a 7% discount rate. Net present value (NPV) of farm benefits were estimated using an NPV function over

[46] NSW Department of Primary Industries (2013). Summer crop gross margin budgets: Irrigated northern summer crop gross margins. DPI, NSW; Powell, J. & Scott, F. (2011). A representative irrigated farming system in the Lower Namoi Valley of NSW: An economic analysis. Economic Research Report.

50 years with a 7% interest rate. The results of the cost-benefit analysis (summarised in Table 7) suggested that aquifer storage would be financially viable to implement in the lower Namoi with infiltration systems targeting the alluvial aquifers, although injection-based systems into the deeper confined aquifers in areas with low infiltration rates was not financially competitive (Arshad et al., 2014). Arshad et al. (2013) noted that while constructing a new temporary storage for floodwater might be prohibitively expensive, the majority of farms in the lower Namoi have farm dams which could act as temporary storage.

Table 7 Summary of cost-benefit analysis of water storage options on the hypothetical farm (Arshad et al., 2013). NPV = Net present value

	On Farm Surface Storage	Infiltration-based MAR	Injection

Costs [1]	• Opportunity cost of lost water in evaporation and the forgone farm benefits
	  ○ Estimated for each crop as the $/ML x the assumed annual evaporative loss (35%)
	  ○ 207 $/ML and 277 $/ML for cotton and faba bean respectively
	• Maintenance cost of the existing farm infrastructure
	  ○ Excluded from analysis as they were considered to be incidental and minimal
		• Cost of new infrastructure and additional costs to store the water underground
		• Cost of pumping water during recovery
			• Capital cost of well drilling and its construction
			• Cost of water treatment
			• Annual cost of maintenance
			• Cost of pumping water during recovery

Total annual cost [2]	22.5 $/ML	122.7 $/ML	247.7 $/ML
NPV [2]	$454,000	$502,000	$164,000

[1] *Source:* Arshad et al. (2013); [2] *Source:* Arshad et al. (2014)

Arshad et al. (2014) explored the uncertainty around the cost-effectiveness of MAR. They did this by systematically searching for conditions where the requirements for MAR may not be met and which could lead to potential failure. Cross-over points (thresholds) were defined that correspond to the values of variables at which the net present value (NPV) from MAR and surface storage become equal. At the cross-over point, a decision maker might be indifferent to selecting an option from the two, at least based on financial returns. Arshad et al. (2014) argue that the benefits of this cross-over approach are that it can:

1. determine minimum hydrogeological and cost requirements under which MAR can be worthwhile,
2. improve confidence in decision making for MAR investment, by enabling the assessment of conditions that are unfavourable to MAR compared to surface water storage, and
3. substantially lower the cost of geophysical and hydrogeological investigations by targeting only areas that satisfy the minimum requirements, as MAR investigations and trials are shown to be time and resource expensive.

The methodological underpinning of this analysis (using a different case study) is described in further detail in (Guillaume et al., 2016).

The break-even analysis of cross-over points involved finding values of variables that will provide exactly the same financial returns from the two compared options. The single variable cross-over points represent the minimum requirements for MAR to be preferred to surface water storage, assuming that the values of other variables remain fixed. Two variables can interact in a way that they can increase, decrease or balance the effect of each other on the resulting advantage of MAR over surface storage. These are shown in

Table 8 where an NA indicates no cross-over point exists between the two options.

Table 8 Single variable cross-over points in three scenarios, for which the preferred option may change from basin infiltration to surface storage or injection-based aquifer storage and recovery (ASR), or from surface storage to ASR.

No.	Variable (Unit)	Best Guess (Modelled) Value	Cross-Over Point		
			Surface Storage and Basin Infiltration	Surface Storage and ASR	Basin Infiltration and ASR
1	Pumping cost ($/ML)	35	53.63	NA	NA
2	Surface evaporation rate (%)	40	34	74	NA
3	Basin capital cost ($/ML)	363	466.69	NA	1,085.55
4	Basin infiltration rate (m/day)	0.2	0.16	NA	0.07
5	Basin maintenance rate (% of capital cost)	10	15	NA	NA
6	MAR loss rate (% of target storage volume)	5	11	NA	NA
7	ASR water treatment cost ($/ML)	150	NA	13.25	NA
8	ASR maintenance rate (% of capital cost)	0.07	NA	NA	NA
9	Price of cotton ($/bale)	538	475.64	1,155.22	NA
10	Price of faba bean ($/tonne)	348	229.52	NA	NA
11	Discount rate (%)	7	13	NA	NA
12	Lifespan of surface storage (Year)	30	48.16	5.57	NA
13	Lifespan of basin infiltration (Year)	30	23.51	NA	6.69
14	Lifespan ASR (Year)	20	NA	NA	NA

Looking at the difference between the best guess and the cross-over point values highlights the variables of most concern regarding the financial viability of MAR. This is shown in Table 9 using basin-scale infiltration and surface storage where several variables are close to the point of greatest concern. It is unlikely that all variables would change from best guess and result in the worst case and so Arshad et al. (2014) analysed groups of variables to assess whether or not the generated scenario is possible, and if so what mitigation options might be implemented and what adaptation actions might need to be taken. The analyses indicated that MAR using basin infiltration can be financially superior to surface storage in the Lower Namoi for a suitable site that has a high infiltration rate, low loss rates and achieved other minimum requirements.

5.4.2 Implications of the scenarios to the business case for MAR

The *MAR for low loss water storage* scenario (see Section 4.2) relies on a farm-specific assessment of evapotranspiration and other losses compared to MAR, and while the crossover analysis presented in Section 5.4.1 suggests that may be worthwhile, the effect of operations and high soil and geological heterogeneity means that the business case will be location specific. Preliminary discussions suggest that farmers will require individual support to make this assessment (see Section 5.6.3).

The *Moving water north* scenario (see Section 4.3) relies on collaboration between farmers. The business case rests on how costs and benefits of a scheme would be distributed spatially. Most benefits of alleviating drawdown would likely be indirect in the form of reduced pressure on groundwater levels further from the recharge point, which means that there is likely to be substantial uncertainty and a high level of trust is required.

The *River recharge as MAR* third scenario (see Section 4.4) alters river operations which involves substantial policy change and likely requires a higher degree of impact assessment. This means it is not currently appropriate to comment on the business case for this scenario.

Table 9 Cross-over point of greatest concern with basin infiltration vs. surface storage, using a subset of variables (Arshad et al., 2014). The colour of the text in the implication column indicates a change that favours MAR (blue), plays against MAR (red) or is neutral (black)

Variable	Minimum Bound	Maximum Bound	Best Guess	Point of Greatest Concern	Change from Best Guess	Implication of change in variable for the relative *viability of MAR*	Mitigation or adaptation options
Pumping cost ($/ML)	6.25	225	35	37.22	2.22	Historical trend of increasing price is a concern.	Adoption of renewable energy sources
Surface evaporation rate (%)	10	100	40	40	0	Expected to increase with a drying climate.	N/A
Basin capital cost ($/ML)	100	3,000	363	393.82	30.82	Cost will increase if an investment is delayed.	Managing and sharing investigation and capital costs
Basin infiltration rate (m/day)	0.01	2	0.2	0.2	0	A function of several variables including water quality. Any decrease will be of concern.	Focusing on areas with high infiltration rate (including exceeding 0.2 m/day)
Basin maintenance rate (% of capital cost)	1.0	40	10	10	0	Any increase will be of concern.	Selecting sites based on soil properties, locking in maintenance plan
MAR loss rate (% of target storage volume)	0	85	5	6	1	Recovery needs to remain high.	Minimise losses, advocate for policy to allow close to full recovery
Price of cotton ($/bale)	50	1500	538	532.30	−5.70	Value of saved water needs to remain high.	Ensure MAR is operated to provide water when it is of high value
Price of faba bean ($/tonne)	50	1400	348	344.52	−3.48		
Discount rate (%)	1	50	7	8	−1	Discount rates of more than 7% will make MAR financially un-attractive.	Seek to lock-in future benefits and delay short term costs
Lifespan of surface storage (Year)	2	50	30	30.23	0.23	Unless other concerns are managed, even small improvements in surface storage lifetime can tip the balance.	Ensure that other factors are mitigated to maximise benefits of MAR
Lifespan of basin infiltration (Year)	2	50	30	29.67	−0.33	Any decrease will be of concern.	Site selection should account for lifespan

5.5 Environmental considerations

This section introduces the environmental assets in the catchment which are targeted by environmental watering (Section 5.5.1), illustrates the importance of flows in the Namoi for the downstream Barwon-Darling system (Section 5.5.2), highlights the relationship between supplementary flows and environmental flows (Section 5.5.3) and summarises the rules in the WSP aimed at managing water quality risk and protecting groundwater dependent ecosystems (Section 5.5.4).

5.5.1 Environmental assets and watering

The Namoi catchment is characterised by a primary channel with a network of anabranches, small tributaries, and thousands of wetlands (natural and artificial) across the floodplain. While there are no extensive wetland complexes, these floodplain networks support a wide variety of waterbirds, fish, vegetation and other biota. The Sustainable Rivers Audit 2 (released in 2012) reported the overall ecosystem health of the Namoi River valley as poor and the fish community as very poor. Despite the large presence of alien fish species and elevated sediment loads in rivers, there are a number of threatened aquatic fauna known to occur in the in the Namoi, particularly between Gunnedah and Narrabri. The Namoi catchment wetlands and rivers also support important Aboriginal cultural heritage values for the Kamilaroi (Gomeroi) people.

While there are no extensive wetland complexes, areas downstream of the Narrabri contain many small lagoons, wetlands, anabranches and floodplain wetlands. The Namoi Long-Term Water Plan (DPIE, 2020b, DPIE, 2020c), developed as required under the Murray–Darling Basin Plan, is intended for water managers to use “to guide and inform their actions to support the ongoing health of rivers and wetlands for the benefit of plants, animals and people” [47]. 36 planning units have been defined under the Plan, the relevant one for the AOI being PU2 (Boggabri to Wee Waa; Figure 56). The Commonwealth Environmental Water Office (CEWO) holds ***general security*** entitlements for the Upper Namoi and Lower Namoi (Table 10) for environmental watering of the assets focusing on in-channel and off-channel assets. The priority environmental assets and values in this area are shown in Table 10. The main CEWO environmental objectives are to support both longitudinal connectivity, including with the Lower Namoi floodplain and the Barwon River, and lateral connectivity between the river and floodplain. These demands are subject to water availability, antecedent conditions, and environmental demands. The native fish objectives for PU2 and environmental watering requirements for the Namoi River at Mollee (gauge 419039), which is at the eastern edge of this study’s AOI, are shown in Table 12 and respectively.

5.5.2 Flows into the Barwon River system

There is a growing awareness of the importance of connecting flows across the northern Basin, to support habitat, water quality, native fish and other aquatic species in the Barwon-Darling and its tributary systems, including the Namoi River. Depending on flow conditions in the Barwon and Namoi rivers and weir drownouts, native fish can move between these catchments, supporting native fish populations. Connection can provide opportunities for fish dispersal, increasing genetic diversity and recruitment.

The Namoi River connects with the Barwon-Darling near Walgett and is considered to have a high level of connectivity to the Barwon–Darling whereas the Macquarie-Castlereagh is considered to have a low to medium level of connectivity depending on local catchment conditions. A small flow of 100–150 ML/day at Wee Waa is needed to provide connection between the Namoi and Barwon rivers. This action is dependent on the Barwon River flowing high enough to back up from Walgett weir (11A) and drown out the Walgett town weir on the Namoi River, so will ideally occur when Barwon River flows are over 4000 ML/day at Dangar Bridge.

[47] https://www.environment.nsw.gov.au/topics/water/water-for-the-environment/planning-and-reporting/long-term-water-plans/namoi, accessed 22 September 2021

When using flood water for MAR it would be important to show that flood regimes in the region would not be **further** altered. Rules around the take of supplementary flows account for requirements of downstream environs, including the Barwon-Darling. Progress towards the licencing of floodwater harvesting aims to bring this type of take into alignment with other types and manage downstream impacts.

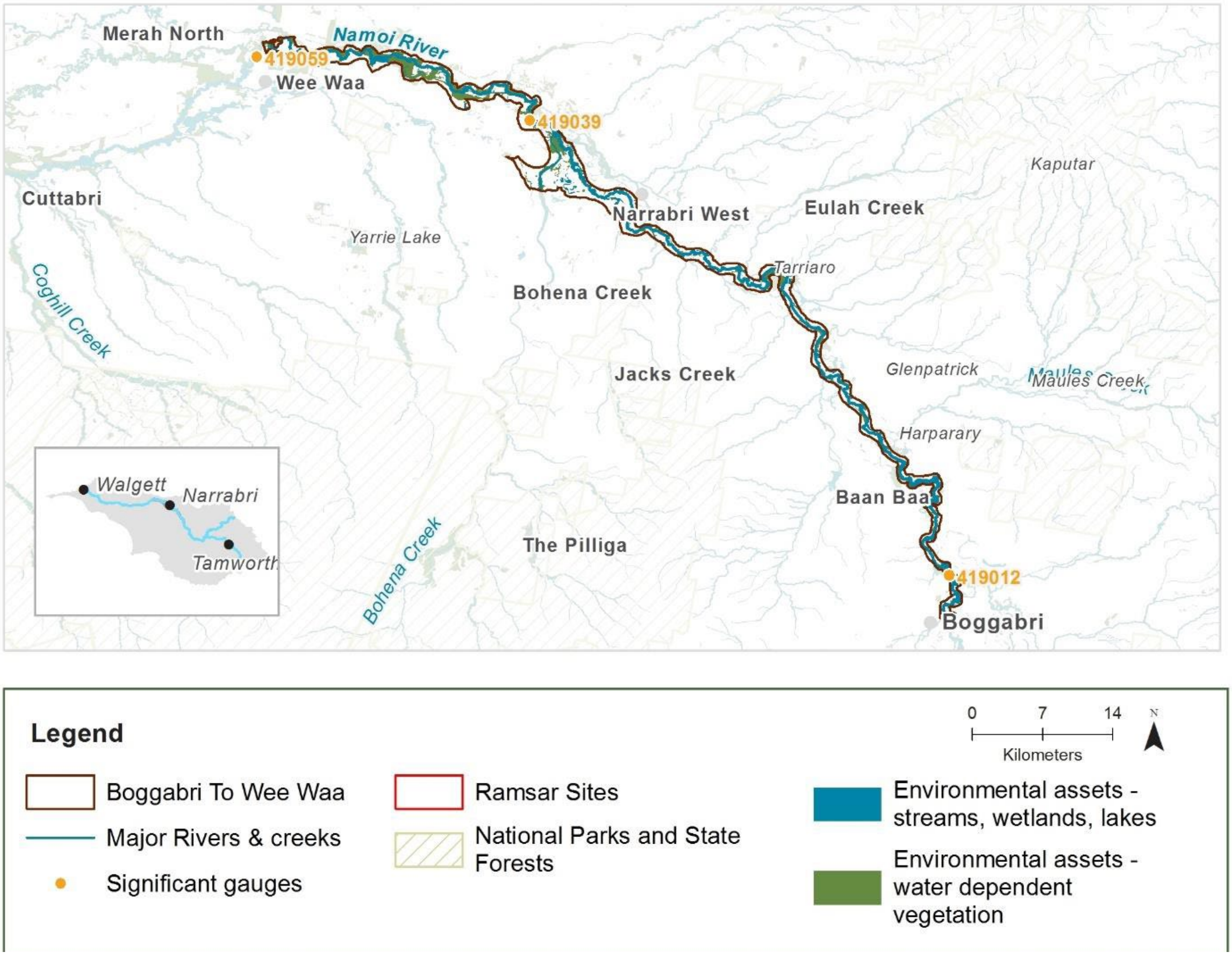


Figure 56 Planning unit 2, Boggabri to Wee Waa (Source: DPIE, 2020c)

Table 10 Commonwealth environmental water holdings (CEWO) in the Namoi catchment at 31 May 2021 (Source: http://www.environment.gov.au/water/cewo/about/water-holdings, accessed 22 September 2021)

Location	Security	Registered entitlements (ML)	Long Term Average Annual Yield (ML)	Carryover from 2020-21 (ML)	New allocations in 2021-22 (ML)	Net trade (ML)	Available water transferred for delivery or delivered directly in 2021-22 (ML)	Estimated current Commonwealth water account balance (ML)
Upper Namoi	General	105	79	12,918	1,433	0	0	14,351
Lower Namoi		13,548	10,202			0		
Peel		1,257	263	0	842	0	0	842
	Total	14,910	10,543	12,918	2,275	0	0	15,193

Table 11 Priority environmental assets and values (Source: DPIE, 2020c)

Rivers, creeks, wetlands & their associated floodplains & water-dependent native vegetation, including (but not limited to): • The Namoi River & its instream habitat & fringing vegetation communities • Barbers Lagoon, a 22 km anabranch of the Namoi River near Boggabri. Deep pools at downstream end that can serve as an aquatic drought refuge • River red gum corridor between Mollee Weir & Gunidgera Weir. Small lagoons that need overbank flooding • Large numbers of lagoons (most are small & require overbank flooding) • The Namoi demonstration reach is located between Boggabri & Narrabri. The inundated floodplain provides a fish nursery habitat, particularly golden & silver perch that spawn in response to flooding. Habitat restoration has taken place in this area • Other creeks and lagoons including: Barra Creek, Bibbla Creek, Black Gully, Bullawa Creek, Gurleigh Lagoon, Jack's Creek, Lochharba Lagoons, Sandy Creek, Sheep Station Creek, Tulla Mullen Creek and Yarrol Gully.	
Native fish	Unspecked hardyhead, carp gudgeon, spangled perch, Murray–Darling rainbowfish, bony herring, Australian smelt, golden perch, murray cod, freshwater catfish, flathead galaxias, olive perchlet, purple-spotted gudgeon, silver perch
Birds	48 water-dependent bird species recorded, including: royal spoonbill, Australian painted snipe, marsh sandpiper, Latham's snipe, sharp-tailed sandpiper, eastern great egret
Native vegetation	12 water-dependent plant community types, including: river red gum woodland, coolibah woodland, wetland sedgeland
Registered cultural assets	Burials, grinding grooves, modified trees, waterholes

Table 12 Native fish objectives for the Narrabri to Wee Waa planning unit (PU2) defined in (Source: DPIE, 2020c)

Objectives
1. **NF1:** No loss of native fish species: unspecked hardyhead, carp gudgeon, Murray-Darling rainbowfish, bony herring, Australian smelt, spangled perch, golden perch, silver perch, Murray cod, freshwater catfish, purple-spotted gudgeon, olive perchlet, flat-headed galaxias 2. **NF2:** Increase the distribution and abundance of short to moderate-lived generalist native fish species: Australian smelt, carp gudgeon, bony herring, Murray-Darling rainbowfish, unspecked hardyhead 3. **NF3:** Increase the distribution and abundance of short to moderate-lived floodplain specialist native fish species: olive perchlet, Flat-headed Galaxias, purple-spotted gudgeon 4. **NF4:** Improve native fish population structure for moderate to long-lived flow pulse specialist native fish species: golden perch, silver perch, spangled perch 5. **NF5:** Improve native fish population structure for moderate to long-lived riverine specialist native fish species: Murray cod, freshwater catfish, purple-spotted gudgeon, olive perchlet 6. **NF6:** A 25% increase in abundance of mature (harvestable sized) golden perch and Murray cod 7. **EF3:** Provide movement and dispersal opportunities within and between catchments for water-dependent biota to complete lifecycles: golden perch, silver perch, Murray cod, freshwater catfish

5.5.3 Effect of supplementary water capture on environmental flow delivery

CEWO or the NSW government do not hold supplementary licences for environmental water. About 36 GL of entitlements exist in the AOI (see Table 3). Past literature has suggested that the use of supplementary water could be used for MAR without compromising environmental flow and ecological requirements and the ecological role of floods in the river systems (Arshad et al., 2012). The specific rules around the take of supplementary flows are intended to manage such impacts (see Section 5.7.2).

5.5.4 *Water Sharing Plan for the Namoi Alluvial Groundwater Sources Order* 2020

The WSP has the broad environmental objective "to protect the condition of the groundwater sources and their groundwater-dependent ecosystems over the term of this Plan" [48]. The specific objectives listed under Part 2 (9) of the plan are (a) to protect the extent and condition of high priority groundwater-dependent ecosystems (GDE), (b) to contribute to the maintenance of salinity levels (total dissolved solids) within water quality target ranges that support high priority groundwater-dependent ecosystems and (c) to contribute to the prevention of groundwater extraction induced structural damage to the aquifers in the system [49]. The performance indicators used to measure the success of the strategies for the environmental objectives pertaining to GDE are the extent and recorded condition of high priority groundwater-dependent ecosystems, the recorded condition of target populations of high priority groundwater-dependent native vegetation, the recorded values of salinity levels (total dissolved solids) and recorded values of groundwater levels [50]. Water quality and GDE considerations are briefly discussed below.

Water quality risks

As highlighted in Section 5.6.2 (page 67), there were some concerns from irrigators regarding the potential risk that MAR could pose to groundwater (Rawluk et al., 2013). That said, all groundwater sources are subject to the NSW Aquifer Interference Policy (NSW AIP; see page 71 for more detail). Potential MAR schemes in the Namoi catchment that involved injection would certainly require an aquifer access license and a groundwater use license (see Section 5.7.4), and demonstrate that minimal impact considerations can be met [51,52]. The injection of 'river' water into deep aquifers or low salinity shallow aquifers might not pose a serious risk to groundwater quality, although it is important to note that the potential for geochemical reactions has not been examined in this report.

The Lower Namoi Groundwater Source is one of the priority locations for maintaining salinity levels under the WSP for the Namoi Alluvial Groundwater Sources. Water quality target ranges for the groundwater sources will be defined by the Water Quality Management Plan: GW14 of the Namoi Alluvium Water Resource Plan. The latest NSW Namoi Alluvium WRP was submitted to the MDBA on April 2020, and withdrawn March 2021 pending resubmission [53]

Groundwater dependent ecosystems

The GDE identified in the *WSP for the Namoi Alluvial Groundwater Sources 2020* are groundwater dependent vegetation associated with the river channels. Setback rules have been applied in the Lower Namoi for new water supply works. Works must take place 100 metres from a river if the work will take water for basic landholder rights only and 200 metres from a river for all other groundwater works, and 200 m from any high priority groundwater-dependent ecosystem defined in Figure 57 [54].

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[48] https://legislation.nsw.gov.au/view/whole/html/inforce/current/sl-2020-0346, accessed 28 September 2021

[49] https://legislation.nsw.gov.au/view/whole/html/inforce/current/sl-2020-0346, accessed 28 September 2021

[50] https://legislation.nsw.gov.au/view/whole/html/inforce/current/sl-2020-0346, accessed 28 September 2021

[51] The situation regarding infiltration-based systems is less clear although it could be argued that in the context of a shallow aquifer where infiltration might increase the risk of waterlogging, and salinization, this would constitute interference and there is a need to address the risk of deleterious environmental and other impacts.

[52] Note that the Aquifer Interference Approvals mechanism has not yet been activated (see Section 5.7.1, page 51)

[53] https://www.industry.nsw.gov.au/water/plans-programs/water-resource-plans/drafts, accessed 28 September 2021

[54] https://legislation.nsw.gov.au/view/whole/html/inforce/current/sl-2020-0346, accessed 28 September 2021

Table 13 Environmental watering requirements for gauge 419039, the Namoi River at Mollee (Source: DPIE, 2020c)

Flow category & EWR code		Flow rate / volume	Timing	Duration	Frequency (Long term average – LTA)	Maximum inter-event period	Additional requirements & comments
Cease-to-flow	CF1	0 ML/d	In line with historical low flow season, typically all seasons at this gauge	Typically CtF events should be around 7 days. CtF should not persist for longer than 29 days	Should occur in no more than 17% of years	N/A	
Very-low flow	VF1	> 10 ML/d	Any time	343 days minimum (or 191 days minimum in very dry years)	Annually	29 days	
Baseflow	BF1	> 200 ML/d	Any time	267 days minimum (or 88 days minimum in very dry years)	Annually	120 days	
	BF2	> 200 ML/d	Sept to Mar	154 days minimum (or 37 days minimum in very dry years)	5–10 years in 10 (75% LTA)	2 years	
Small fresh	SF1	> 500 ML/d	Oct to Apr (but can occur any time)	10 days minimum	Annually	1 year	
	SF2	500–6000 ML/d	Sept to Apr	14 days minimum	5–10 years in 10 (75% LTA)	2 years	
Large fresh	LF1	> 6000 ML/d	July to Sept (but can occur any time)	5 days minimum	5–10 years in 10 (75% LTA)	2 years	
	LF2	> 6000 ML/d	Oct to Apr	5 days minimum	3–5 years in 10 (40% LTA)	4 years	
Bankfull	BK1	> 18,750 ML/d	Oct to Apr	2 days minimum (ideally > 10 days[9])	4.5 years in 10 (45% LTA)	4 years	
	BK2	> 18,750 ML/d	Sept to Feb (but can occur any time)	5 days minimum	3–5 years in 10 (40% LTA)	5 years	
Small overbank	OB1	> 21,750 ML/d	Sep to Apr	2 days minimum (ideally > 10 days[9])	4–5 years in 10 (40% LTA)	4 years	
	OB2	> 21,750 ML/d		3 days minimum		5 years	
			Sept to Feb (but can occur any time)		3–5 years in 10 (40% LTA)		
Large overbank	OB3	> 25,000 ML/d	Aug to Feb (but can occur any time)	2 days minimum 1-2 months inundation for regeneration; 5-7 months for maintenance	3–10 years in 10 (50% LTA)	5 years	River red gum forest
	OB4	> 40,000 ML/d	Aug to Feb (but can occur any time)	1 days minimum 1–4 months (habitat inundated)	3-5 years in 10 (40% LTA)	5 years	Coolibah woodland (PCT 39) and river red gum woodland

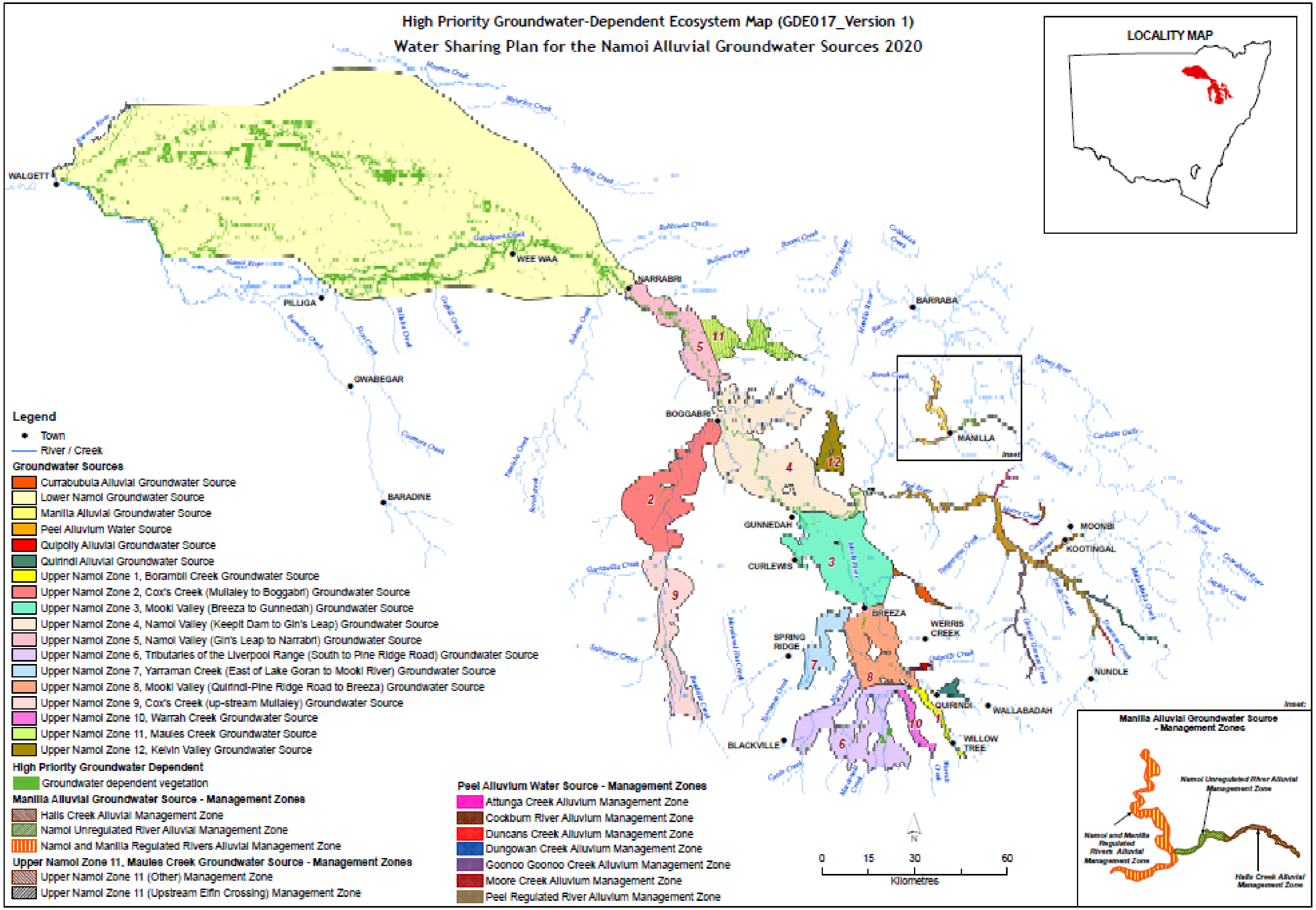

Figure 57 High priority GDE map from the WSP for the Namoi Alluvial Groundwater Sources (https://legislation.nsw.gov.au/view/html/inforce/current/sl-2020-0346/maps, accessed 16 September 2021)

5.6 Social acceptability

5.6.1 Conjunctive use of surface water and groundwater

Conjunctive water use is happening in the Namoi Valley; of the 13 farms in the AOI, one farm has only surface water entitlements and two have only aquifer licences. The other ten farms do have both surface water and groundwater entitlements, with the latter ranging between 0.3% and 30% of the volume of 1 ML shares of surface water entitlements (Figure 58).

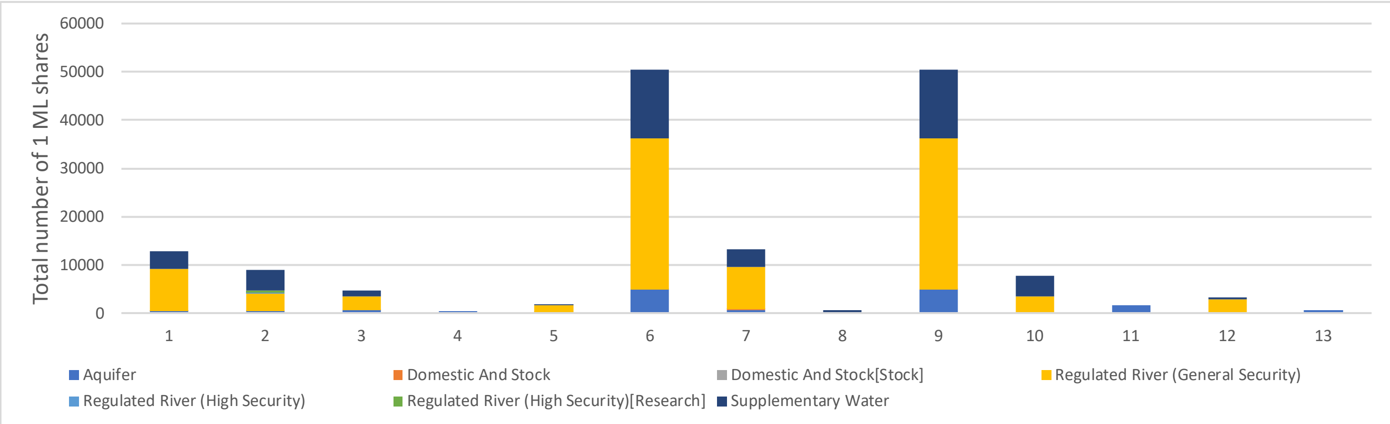

Figure 58 Total number of 1 ML shares, disaggregated by water allocation type, for each of the 13 farms in the AOI (Data source: https://waterregister.waternsw.com.au/water-register-frame, 16 September 2021)

5.6.2 Past social research into MAR and groundwater management

Local interest in Managed Aquifer Recharge

Sharp and Curtis (2012) and Rawluk et al. (2013) investigated the acceptability of using flood water for MAR (termed Aquifer Storage and Recovery [ASR] in their study) to groundwater irrigators in the Namoi (Table 14). Most of the 210 useable responses to the Namoi survey agreed that ASR has merit although some research informants were concerned about the impact of recharge on groundwater quality and the possibility that ASR would be another intervention that would lead to over-exploitation of a scarce resource. The irrigator survey indicated that respondents would be open to investing further in WUE measures if public funds were used to develop ASR infrastructure (Table 15).

Table 14 Proportion of respondents supporting MAR in the Namoi in 2011 (Source: Rawluk et al., 2013)

	In favour of MAR	Not in favour of MAR	
Survey item exploring social acceptability of MAR in Namoi	(Agreed/Strongly Agreed)	(Disagreed/Strongly Disagreed)	Unsure
Aquifer storage and recovery (MAR) appears to be a good idea	$n = 135$	$n = 18$	$n = 51$
	66.2%	8.8%	25%

Some quotes from the study (Rawluk et al., 2013):

> *[It is] about time someone promoted artificial recharge, farmers in our area have been trying to convince the government departments to develop the process for years.*

> *We require much more explanation before this can be considered. It is rare that these processes occur without loss of entitlement and asset and an increase in taxes on the water user.*
>
> *Aquifers are ancient pristine water sources and should NOT be contaminated with flood flows or coal seam gas.*

There was a trend (although not statistically significant) for MAR supporters to be operating larger properties, have larger areas laid out for irrigation, own larger groundwater entitlements, and spend more time in on-property work. Supporters of MAR were significantly more likely to have entered the water market to purchase permanent or temporary water in the past five years and intend to purchase temporary water in the future. MAR supporters were significantly more likely to agree that collective management of groundwater at the local scale would ensure operating rules are appropriate to local conditions and environmental circumstances. Survey respondents who opposed or were unsure about MAR tended to place greater importance on environmental conservation.

Table 15 Views about ASR in the Namoi catchment expressed in the 2011 Namoi groundwater management survey

Topic: Aquifer storage and recovery	n	Strongly Disagree	Disagree	Unsure	Agree	Strongly Agree	N/A	Mean score*
I am interested in learning more about the interception of large floods to implement ASR in my WSP area.	205	2%	5%	9%	55%	25%	4%	3.98
If public funds were used to develop the infrastructure for ASR based on intercepting large floods, I would be prepared to invest in technology to improve the water-use efficiency on my farm.	205	4%	8%	25%	41%	17%	5%	3.61
I would be prepared to invest, along with others, **without** public funding to develop ASR based on intercepting large floods in my water sharing plan (WSP) area.	204	9%	26%	35%	21%	6%	3%	2.89

*Responses were rated on a scale from 1, 'Strongly Disagree' to 5, 'Strongly Agree'. 'Not applicable' was a separate response option.

A cautionary note is that this survey is several years old; since this period groundwater extraction limits have reduced and irrigators, communities and the environment, have suffered through a serious drought. The question then is how opinions might have changed over time.

Collective management of groundwater

Sharp and Curtis (2012) asked groundwater licence holders in the Namoi Valley for their views on collective management of groundwater, that is the 'management of groundwater resources by water users' as an alternative form of groundwater governance (Table 16). There was general support from the 210 survey respondents with 69% agreeing that collective management of groundwater at the local scale would ensure operating rules are appropriate to local conditions and environmental circumstances. The role of the Government to 'umpire' collective management was broadly acknowledged, with 61% of respondents signalling the Government should oversee operating rules that were developed with landholder input. The results of Sharp and Curtis (2012) highlighted that respondents who had 'pro-conservation values and beliefs, and altruistic values and beliefs' were more favourable towards collective management than older licence-holders or those who had managed their enterprise for longer. Their study also highlighted the importance for the implementation of collective management to have "the strong support of practitioners on-the-ground whom licence-holders find more trustworthy than the agency itself".

Table 16 Views about collective management of groundwater from the 2011 Namoi groundwater management survey of Sharp and Curtis (2012). Respondents were asked to rate how much they agreed with the statements on a Likert scale of 1-5 from Strongly Disagree to Strongly Agree. Not Applicable was a separate response option.

Topic: Collective management of groundwater	n	Strongly disagree	Disagree	Unsure	Agree	Strongly agree	N/A	Mean score*
If governments and water users agreed to the collective management of groundwater at the local scale, that would ensure operating rules are appropriate to local conditions and environmental circumstances.	206	2%	5%	24%	51%	18%	0%	3.76
As part of collective management at a local scale, it would be desirable to have Government oversee operating rules developed with landholder input.	207	5%	12%	23%	51%	10%	0%	3.48

*Responses were rated on a scale from 1, 'Strongly Disagree' to 5, 'Strongly Agree'. 'Not applicable' was a separate response option.

5.6.3 Preliminary feedback on MAR scenarios

Project team resources available for this (the third and final) case study, COVID-19 travel restrictions, and the November-December floods constrained the extent of local engagement with irrigators and local stakeholders in the Lower Namoi region. This section summarises preliminary feedback on the MAR scenarios presented in Section 4 from a Lower Namoi irrigator [I1], an academic with expertise in the hydrogeology of the Namoi catchment [H1] and NSW DPIE water policy [WP1] staff.

MAR context and purpose

There is interest in MAR to support the agricultural industry despite the considerable uncertainties associated with demonstrating the 'business case' for individual farmers or enterprises to change current operational water management approaches and invest in developing MAR schemes [I1]. The potential for MAR to support towns was noted as potentially more critical than for agricultural purpose given the number of small and 'fairly ineffective' weirs and where calls for innovative local solutions are needed to address the deficiencies of the many small weirs along the Darling system and its tributaries that are intended to service the water demands of towns [I1]. For agriculture, a critical challenge would be making decisions around the efficiency of recharging surface water, that is, are land managers better off making the most of their water while they can or trying to elongate access during dry times [I1]? This is likely a farm-specific calculation. MAR would need to be considered in the light of all other aspects of water management in the Lower Namoi region, including floodplain harvesting and will need a water accounting system to be developed for MAR to happen [I1, WP1].

Source of water

[I1] noted that the typical sequence of water used by irrigators [55] in the region are on-farm water sources then general security if available and, when other sources are not available, groundwater [56]. They noted that if an irrigator has general security water available they tend to make best use of it as soon as possible; they did not know of anyone they thought would use general security licences for MAR as the analysis needed to demonstrate the benefit of 'propping up the least-used and most reliable' water source [groundwater] would be prohibitive. [57] The take of supplementary water is so sporadic that when an event is announced [I1] noted that licence holders order as much

[55] Irrigators, as referred to by [I1] is assumed in the context of the Lower Namoi to cover producers of irrigated cotton or other irrigated annual crops.

[56] For this irrigator's enterprise, if conditions are such that their only source of water is groundwater, then the operations of the enterprise are scaled back to 'subsistence' farming with the aim of keeping infrastructure operations and core workers employed. They are very conscious of how much pumping occurs in the dry season and do not want to 'bugger up' the aquifer.

[57] Since reductions in entitlements happened, restrictions on groundwater extractions have not needed to be enforced. Although groundwater use got close to the compliance trigger for the long-term average annual extraction limit (LTAAEL) in the Lower Namoi, this limit has not been breached (see Figure 22).

water as they can get and store it in on-farm dams. They felt that as the water is used in the following weeks and months, the losses due to evaporation were not a sufficient reason to use supplementary flows as the water source for MAR. A similar argument was made for water sourced from floodplain harvesting.

The most promising source of water for MAR was seen by [I1] and [H1] as interventions to enhance recharge during large flood events where the water spreads extensively across the landscape and can inundate the land surface for extended periods of time. The challenge for MAR, noted by [I1], is that most of the country in the AOI consists of heavy black soils and on-farm storages do not leak. Interventions to enhance recharge might need to identify areas of land with high infiltration and/or excavate the top layer (~10-15 m) to reach more permeable soils.

Feedback on MAR scenarios

MAR for low loss storage: Whilst MAR is often proposed as a means for reducing evaporative losses (See Section 5.2.4), [I1] did not think that this scenario would be desirable to most farmers in the AOI; rather individual farms will continue to order surface water and put it into on-farm water storages for use as soon as possible. This person felt that quite a specific analysis would be needed to demonstrate the benefit of ordered water being recharged and recovered later and that this analysis would be beyond the capacity of most farmers without assistance.

Moving water north: Of the three scenarios, [I1] felt that this was the most needed option but that there are substantial complexities that would need to be overcome. There are reportedly restrictions to lateral groundwater flow that limits the effect of river recharge [I1, H1]. Moving water through the existing channel infrastructure would be possible but this might mean that water is moved onto and through someone's dryland enterprise at a time when they do not want it. Regional drawdown (see Figure 36 to Figure 40) is of concern to [I1] but they noted that this is now in an area that is not intensively farmed with a shift from irrigated farming to dryland agriculture or livestock. [H1] felt that recharging the northern region was the most challenging scenario to achieve and wondered about the cost required to implement the scheme in relation to the number of people who would benefit from the scheme.

River recharge as MAR: The hydrogeological context for this scenario reflects the current reality that river recharge is naturally recharging the alluvial aquifers of the Lower Namoi. Mollee's Weir was identified by [H1] as a nice 'MAR' system on the Namoi and that the 'best way to do MAR in the region would be to build a weir mid-way between the old Wee Waa bridge and Wee Waa'. [I1] thought that Mollee's Weir was a huge part of the natural recharge that supported extractions in the area they operate. The implication for the *River Recharge as MAR* scenario (Section 4.4) is the challenge around the potential to control or further enhance river recharge to achieve desired outcomes.

Knowledge building and strategic planning

Part of the uncertainty around the potential of MAR in the AOI stems from remaining knowledge gaps on the implications of the highly heterogenous hydrogeology and its implications for groundwater response to MAR.

At both the irrigator enterprise and institutional levels, in-house capacity for strategic water planning and investing in recharge and groundwater monitoring has been identified as a constraint to MAR. For irrigator enterprises, the ever-increasing financial and time resources needed to comply with water regulatory requirements has been compounded by large increases in the price of water. For [I1] this meant that non-essential activities that had been conducted in the past, including groundwater monitoring, have been scaled back. In terms of institutional support for strategic water planning, the CRDC was noted as the closest to an organisation that could support cotton producers in the region, together with the Australian Cotton Research Institute (ACRI) with whom [I1] interacted primarily in relation to agronomic work. Water specific matters such as studies needed to comply with NSW water management and accounting requirements (e.g. around floodplain harvesting) need to be outsourced to consultants, raising the prospect of equity issues for small operators interested in MAR. A water institution equivalent to the well-trusted ACRI, that drew on support from the advocacy role played by Namoi Water, was seen as desirable by [I1] to support the operational water management of irrigators into the future .

5.7 Governance arrangements

This section summarises the NSW Aquifer Interference Policy (AIP) and the Australian Guidelines for Water Recycling: Managed Aquifer Recharge (NRMMC et al., 2009) in Section 5.7.1; more detail on these is given in (Guillaume et al., 2020). This is followed by a summary of relevant rules within the WSP covering our AOI (Section 5.7.2), the NSW Floodplain Harvesting Policy (Section 5.7.3) and the recently released NSW Water Strategy (Section 5.7.4).

5.7.1 Summary of relevant material from Milestone 4.1 report (Murrumbidgee Case Study)

Much of the policy context and governance arrangements considered in the Murrumbidgee case study (Guillaume et al., 2020) is relevant to the Namoi case study. The key points from that case study were that

1. The absence of MAR policies in NSW was an opportunity to ensure rules play to the strengths of MAR while minimising associated risks.
2. Pilots for recharge and monitoring can already go ahead with current regulatory frameworks, and are needed to build confidence and expertise.

This section summarises relevant content from the Milestone 4.1 report (Guillaume et al., 2020) which can be accessed from the CRDC website for further detail [58]. Ross (2019) reviewed existing policies, legislation and regulations that impact on the implementation of MAR operations, with special reference to cotton growing areas in New South Wales and Queensland.

Access to surface water for recharge operations

In NSW, this access is determined by applicable water allocation regulations, notably under the Water Management Act (2000) and the Water Management Amendment Act (2018). Water recharge to aquifers becomes part of the consumptive pool and subject to aquifer extraction limits set in water plans. No specific rights are granted to recharged water. The MDBA's provision for avoiding double counting has not yet been implemented in state policy.

The NSW Aquifer Interference Policy (AIP)

Although the focus of the policy is primarily on mining activities, there is specific mentions of injection works used to transmit water into an aquifer. In areas covered by a WSP, approved aquifer interference activities (which would include MAR) require an aquifer access licence and a groundwater use licence for a share of the consumptive pool. The Aquifer Interference Activities approvals mechanism is not currently active [59] but would assist MAR policy by being able to regulate the volume, timing and quality of water recharged into an aquifer (A. Goulstone *pers. comm.* 23 September 2021). In water sources where water sharing plans do not yet apply, an aquifer interference activity (if the mechanism were enabled) would be required to hold a water licence under Part 5 of the Water Act 1912. Under the NSW AIP proponents of aquifer interference activities would need to demonstrate that they can obtain the necessary licences and ensure that minimal impact considerations can be met or propose remedial actions. Proponents are encouraged to take a risk management approach to assess the potential impacts of aquifer interference activities, with the level of detail proportion to a combination of the likelihood of impacts occurring on water resources uses and dependent ecosystems, and potential consequences of these impacts.

Infiltration schemes are not explicitly mentioned in the AIP. Infiltration could be classed as an activity that interferes with aquifers, for example in the situation of a shallow aquifer where infiltration might increase the risk of

[58] This report is available from http://www.insidecotton.com/xmlui/handle/1/4874 (accessed 23 September 2021)
[59] https://www.industry.nsw.gov.au/water/science/groundwater/aquifer-interference-activities, accessed 24 September 2021

waterlogging. However, infiltration into an aquifer that has substantial drawdown and where the recharge volumes have limited effect might not be considered interference.

The Australian Guidelines for Water Recycling: Managed Aquifer Recharge

The Australian Guidelines for Water Recycling: Managed Aquifer Recharge (NRMMC et al., 2009) provide recommendations to minimise the effect on *water quality, human and environmental health* as a result of a new MAR project. The guidelines detail entry-level assessments that should be undertaken to prior to a MAR project being undertaken, namely a viability assessment and an assessment of the degree of difficulty associated with the project. How this report addresses the components of the viability assessment is outlined in Table 17. The Namoi MAR scenarios presents varying degrees of difficulty for MAR, based on the attributes in Table 18, from farm-scale *MAR for evaporation reduction* (Section 4.2) to the more complex sub-regional MAR to alleviate drawdown (*Moving water north;* Section 4.3) and *River recharge as MAR* (Section 4.4).

5.7.2 Water Sharing Plans (WSP) covering the AOI

The WSP in force that cover areas in the Namoi Valley are listed in Table 19. This subsection summarises key rules for the WAL in the *Upper Namoi and Lower Namoi Regulated River Water Sources 2016* and *Water Sharing Plan for the Namoi and Peel Unregulated Rivers Water Sources 2012* that might be used as sources of water for MAR.

General security

In any one year, the water allocated general security licences will never exceed 1 ML/share (i.e. 100% of entitlement) [60]. A continuous accounting method for general security, such that any remaining water in an allocation account at the end of the water year is carried over. A maximum of 2.0 ML/share of a licence can be held in an account at any one time. In terms of use limits, the maximum volume that may be taken or traded out in

- any 12-month period beginning 1 October is equal to 1.25 ML/share plus any assignment (e.g. allocation trading) into the account during the same period [61].
- any 3 consecutive years beginning 1 October is equal to 3 ML/share plus any assignment (e.g. allocation trading) into the account during the same period.

Carryover may be restricted under very dry conditions; this occurred on 1 July 2019 where carryover was fully suspended in Lower Namoi and partially suspended (25%) in Upper Namoi until 25 February 2020 (the date of repealment) [62]. The volume of suspended carryover held in in a drought holding account will be returned to users when storage volumes improve. The rules around access of general security water suggest this is not likely to be a desirable or financially viable source of water for MAR.

[60] https://waterinsights.waternsw.com.au/11986-lower-namoi-regulated-river/rules, accessed 16 September 2021
[61] https://waterinsights.waternsw.com.au/11986-lower-namoi-regulated-river/rules, accessed 16 September 2021
[62] https://www.industry.nsw.gov.au/__data/assets/pdf_file/0003/272154/imposing-restrictions-on-carryover-water-in-regulated-rivers.pdf, accessed 16 September 2021

Table 17 Mapping the content of this report against the viability assessment components recommended by the Australian Guidelines for Water Recycling: Managed Aquifer Recharge entry-level viability assessment and this report (NRMMC, EPHC & NHMRC, 2009).

Attribute from the Guidelines	Notes from Guidelines	Assessed in this report	Comments
Is there a sufficient demand for water?	The ongoing volumetric demand for recovered water should be sufficient to warrant investment in the proposed project; if this is not the case, there needs to be a clearly defined environmental benefit. Either one of these criteria is essential for managed aquifer recharge. Projects involving recharge of partially treated water where recovery is incidental do not qualify as managed aquifer recharge	Yes in 5.1.2 and 5.1.3	
Is there an adequate source of water available for allocation to recharge?	Entitlement to water to be used for recharge needs to be secured. Mean annual volume of recharge should exceed mean annual demand, with sufficient excess to build up a buffer storage to meet reliability and quality requirements. In an already over allocated catchment, an entitlement to surface water is unlikely to be available.	Yes in 5.2.1 to 5.2.5	
Is there a suitable aquifer for storage and recovery of the required volume?	Presence of a suitable aquifer is critical for managed aquifer recharge. Such an aquifer needs to have an adequate rate of recharge and sufficient storage capacity; it also needs to be capable of retaining the water where it can be recovered. Low salinity and marginally brackish aquifers are preferred, to maximise the volume of recovered water that is fit for use after fresh recharge water mixes with ambient groundwater. Regional maps showing the potential of aquifers as storages for managed aquifer recharge have been developed for some urban and rural areas, and are available from water resources managers in the local jurisdiction. In over allocated aquifers, water managers may have additional constraints on the proportion of recharge that may be recovered.	Yes in 5.3.2 and 5.3.3	
Is there sufficient space available for capture and treatment of the water?	For stormwater recharge systems (either open space or dams), wetlands, ponds or basins are needed to detain sufficient water to achieve the target volume of recharge. Similarly, space needs to be available for whatever treatment process, if any, is subsequently determined to be required. For recycled water from a sewage treatment plant, generally no additional detention storage will be required at the recharge facility.	Yes in 5.3.1 and 5.3.5	
Is there a capability to design, construct and operate a MAR project?	Knowledge of hydrogeology and water-quality management is vital for the successful design, construction and operation of managed aquifer recharge projects. Also necessary for some projects are geotechnical know-how, and expertise in water storage and treatment design, water sensitive urban design, hydrology, monitoring and reporting. ***Proponents who do not have these skills are encouraged to gain access to them before proceeding with Stage 2 investigations.*** The number of consultants experienced in investigations and design of managed aquifer recharge projects is growing.		Development of capacity and skills is a key component of the proposed scenarios, as is the incremental development of local and subregional hydrogeology and groundwater response to recharge. Expertise from across Australia would need to be accessed and leveraged with the aim of building local expertise.

Table 18 The Australian Guidelines for Water Recycling: Managed Aquifer Recharge entry-level degree of difficulty assessment: attributes to consider.

Attribute from the guidelines
Does source water meet the water-quality requirements for the environmental value of ambient groundwater?
Does source water meet the water-quality requirements for the environmental values of the intended end uses of the water on recovery?
Does source water have low quality; for example: total suspended solids >10 mg/L, total organic carbon >10 mg/L, total nitrogen >10 mg/L? Also, is the soil or aquifer free of macropores?
Does ambient groundwater meet the water- quality requirements for the environmental values of intended end uses of water on recovery?
Is either drinking water supply, or protection of aquatic ecosystems with high conservation or ecological values, an environmental value of the target aquifer?
Does the salinity of native groundwater exceed either of the following: (a) 10 000 mg/L, (b) the salinity criterion for uses of recovered water?
Is redox status, pH, temperature, nutrient status and ionic strength of groundwater similar to that of source water?
Are there other groundwater users, groundwater-connected ecosystems or a property boundary within 100–1000 m of the MAR site?
Is the aquifer: (a) confined and not artesian?, (b) unconfined, with a water table deeper than 4 m in rural areas or 8 m in urban areas?
Is the aquifer unconfined, with an intended use of recovered water that includes drinking water supplies?
Is the aquifer composed of fractured rock or karstic media, or known to contain reactive minerals?
Has another project in the same aquifer with similar source water been operating successfully for at least 12 months?
Does the proponent have experience with operating managed aquifer recharge sites with the same or higher degree of difficult, or with water treatment or water supply operations involving a structured approach to water-quality risk management?
Does the proposed project require development approval? Is it in a built-up area; built on public, flood-prone or steep land; or close to a property boundary? Does it contain open water storages or engineering structures; or is it likely to cause public health or safety issues (e.g. falling or drowning), nuisance from noise, dust, odour or insects (during construction or operation), or adverse environmental impacts (e.g. from waste products of treatment processes)?

Supplementary flows

The taking of supplementary water in the Lower Namoi is covered by Clause 48 in the *Upper Namoi and Lower Namoi Regulated River Water Sources 2016*. Extractions can only be made from uncontrolled flows that are in excess of the replenishment requirements (clause 59) and extractions will be restricted (in part or in full) if outflows from this Source are needed to meet the requirements for flows into the Barwon-Darling system. Rules around the take of supplementary flows are intended to ensure that they do not jeopardise critical environmental needs, basic rights holders, or any other of the higher priority WAL types. Subclause (11) prescribes that "the volume of water that may be made available for extraction under supplementary water access licences in the Lower Namoi Regulated River Water Source during each supplementary water event", after 30 June 2019 should not exceed 10% of the supplementary event volume between 1 July and 31 October and 50% of the supplementary event between 1 November and 30 June. This remains the same in the draft WSP submitted to the MDBA [63]. What has changed are the flow threshold used to define supplementary flows (Table 20 and Table 21).

Unregulated river

The access and trading rules for the Spring and Bobbiwaa Creeks water source, under the *Namoi and Peel Unregulated River Water Sources 2020*, are summarised in Table 22.

[63] https://www.industry.nsw.gov.au/__data/assets/pdf_file/0017/315422/final-wsp-upper-namoi-and-lower-namoi-regulated-river-water-sources-2020.pdf, accessed 24 September 2021

Table 19 In force WSP covering areas of the Namoi Valley

Water Sharing Plans in force in the Namoi Valley	Considered in Section 5.1 or 5.2 in relation to the AOI
Namoi Alluvial Groundwater Sources 2020 • *Legislation:* https://www.legislation.nsw.gov.au/view/html/inforce/current/sl-2020-0346 • *Rule summary sheets:* https://www.industry.nsw.gov.au/__data/assets/pdf_file/0011/312968/namoi-alluvial-groundwater-sources-2020-rule-summary-sheets.pdf	Yes – see Section 5.1.2
Namoi and Peel Unregulated River Water Sources 2012 • *Legislation:* https://www.legislation.nsw.gov.au/view/html/inforce/current/sl-2012-0493 • *Rule summary sheets:* https://www.industry.nsw.gov.au/__data/assets/pdf_file/0004/329278/namoi-and-peel-unregulated-river-rss.pdf • *Background document:* https://www.industry.nsw.gov.au/__data/assets/pdf_file/0006/166875/peel-valley-background.pdf	Yes – see Section 5.2.2
Namoi Great Artesian Basin Groundwater Sources 2020 • *Legislation:* https://www.legislation.nsw.gov.au/view/html/inforce/current/sl-2020-0354 • *Rule summary sheets:* https://www.industry.nsw.gov.au/__data/assets/pdf_file/0018/312732/nsw-gab-groundwater-sources-2020-rule-summary-sheets.pdf	No
Namoi Great Artesian Basin Shallow Groundwater Sources 2020 • *Legislation:* https://www.legislation.nsw.gov.au/view/html/inforce/current/sl-2020-0347 • *Rule summary sheets:* https://www.industry.nsw.gov.au/__data/assets/pdf_file/0003/312798/nsw-gab-shallow-groundwater-source-2020-rule-summary-sheet.pdf	
NSW Murray-Darlin Basin Porous Rock Groundwater Source 2020 • *Legislation:* https://www.legislation.nsw.gov.au/view/html/inforce/current/sl-2020-0348 • *Rule summary sheets:* https://www.industry.nsw.gov.au/__data/assets/pdf_file/0005/312737/nsw-mdb-fractured-rock-groundwater-sources-2020-rule-summary-sheets.pdf	No
Peel Regulated River Water Sources 2016 • *Legislation:* https://www.legislation.nsw.gov.au/view/html/inforce/current/sl-2010-0134 • *Rule summary sheets:* https://www.industry.nsw.gov.au/__data/assets/pdf_file/0004/325867/peel-regulated-river-rule-summary-sheet.pdf	No
Upper Namoi and Lower Namoi Regulated River Water Sources 2016 [1] • *Legislation:* https://www.legislation.nsw.gov.au/#/view/regulation/2015/631	Yes – see Sections 5.1.1 and 5.2.2

[1] The draft WSP for the *Upper Namoi and Lower Namoi Regulated River Water Sources 2020* has been submitted to the MDBA pending commencement https://www.industry.nsw.gov.au/water/plans-programs/water-resource-plans/drafts/namoi-surface

Table 20 Supplementary water event start and finish flows for downstream of the Namoi River at Narrabri (Source: Water Sharing Plan for Water Sharing Plan for the Upper Namoi and Lower Namoi Regulated River Water Sources 2016)

Total water allocations (ML)	Period	Supplementary water event start flow (ML/day)	Supplementary water finish start flow (ML/day)	Flow reference points
≤90,000	1 July to 31 August	2000	1000	Namoi River at Mollee (419039)
		2000	1000	Namoi River at downstream Gunidgera Weir (419059)
		2000	1000	Namoi River at downstream Weeta Weir (419068)
	1 September to 30 June	500	500	Namoi River at Mollee (419039)
		500	500	Namoi River at downstream Gunidgera Weir (419059)
		500	500	Namoi River at downstream Weeta Weir (419068)
>90,000	1 July to 31 August	6000	4000	Namoi River at Mollee (419039)
		2130	2130	Namoi River at downstream Gunidgera Weir (419059)
		2130	2130	Namoi River at downstream Weeta Weir (419068)
	1 September to 31 December	5000	3000	Namoi River at Mollee (419039)
		4000	2500	Namoi River at downstream Gunidgera Weir (419059)
		3000	2000	Namoi River at downstream Weeta Weir (419068)
	1 January to 31 January	4000	2000	Namoi River at Mollee (419039)
		3000	2000	Namoi River at downstream Gunidgera Weir (419059)
		2000	1500	Namoi River at downstream Weeta Weir (419068)
	1 February to 31 July	2000	1000	Namoi River at Mollee (419039)
		2000	1000	Namoi River at downstream Gunidgera Weir (419059)
		1500	1000	Namoi River at downstream Weeta Weir (419068)

Table 21 Supplementary water event start and finish flows for downstream of the Namoi River at Narrabri (Source: Water Sharing Plan for Water Sharing Plan for the Upper Namoi and Lower Namoi Regulated River Water Sources 2021 submitted to the MDBA)

Total water allocations (ML)	Period	Supplementary water event start flow (ML/day)	Supplementary water finish start flow (ML/day)	Flow reference points
≤90,000	All year	500	500	Namoi River at Mollee (419039)
		500	500	Namoi River at downstream Gunidgera Weir (419059)
		500	500	Namoi River at downstream Weeta Weir (419068)
>90,000	1 August to 31 December	5000	3000	Namoi River at Mollee (419039)
		4000	2500	Namoi River at downstream Gunidgera Weir (419059)
		3000	2000	Namoi River at downstream Weeta Weir (419068)
	1 January to 31 January	4000	2000	Namoi River at Mollee (419039)
		3000	2000	Namoi River at downstream Gunidgera Weir (419059)
		2000	2000	Namoi River at downstream Weeta Weir (419068)
	1 February to 31 July	2000	1000	Namoi River at Mollee (419039)
		2000	1000	Namoi River at downstream Gunidgera Weir (419059)
		1500	1000	Namoi River at downstream Weeta Weir (419068)

Table 22 Access rules for rivers and creeks and trading rules for the Spring and Bobbiwaa Creeks unregulated WAL.

Access rules for rivers and creeks	
Cease to pump	Pumping is not permitted from natural pools when the water level in the pool is lower than its full capacity.
Reference point	Individual natural pool
Trading rules	
Into water source	Allows trade of additional water entitlement into the Water Source from a water source with higher ecological value. Trades not permitted into natural off-river pools. The cap on entitlement is 1681 ML and the entitlement at time of assessment is 981 ML
Within water source	Permitted

5.7.3 NSW Floodplain Harvesting Policy

The NSW Government has developed the NSW Floodplain Harvesting Policy [64] in order to support a fairer system of floodplain access for water users and to improve flows for the environment and downstream communities [65]. However, the implementation dates for the policy are unclear as amendments to the Water Management (General) Regulation 2018 [66] that relate to floodplain harvesting were disallowed in early 2021.

Estimates of volumes across northern NSW and Queensland in the early 2010's were considered to be of poor reliability as they were based on models that were not fit-for-purpose (see Section 5.2.3). However, the volume of water taken via floodplain harvesting is considered to have grown to a level that is not sustainable. The policy needs to be fully implemented so as to provide an enforceable legal framework that prevents further growth and, in areas where harvested volumes exceed legal limit, provide a mechanism to reduce take to below the limit [67].

The intent of the policy is to bring floodplain harvesting into the alignment with the regulation of take of water from other sources. That is water will be taken in *"accordance with the individual licensed volumes and legal limits prescribed in the Murray–Darling Basin Plan 2012 and NSW water-sharing plans"* [68]. Critical to ensuring that accurate measurements of floodplain harvesting can be made is the requirement that landholders install minimum-standard telemetry-enabled metering devices fitted with tamper-evident seals.

Any MAR policy will need to align with the NSW Floodplain Harvesting Policy, particularly where water taken from floodplain harvesting is recharged by irrigators for later recovery. The accurate measurements of water captured in on-farm storages will need to be matched with the same standard of accounting of the water that is used directly for irrigation or that is recharged.

5.7.4 NSW Water Strategy

The NSW Government has recently published *"a 20-year, state-wide strategy to improve the security, reliability and quality of the state's water resources over the coming decades"* (DPIE, 2021). MAR is mentioned under Priority 6 (*Support resilient, prosperous and liveable cities and towns*) as an option that NSW Government is investigating for improving town water security and perhaps the agricultural sector. The specific action (6.8) pertaining to MAR is shown in Table 23.

[64] https://www.industry.nsw.gov.au/water/plans-programs/healthy-floodplains-project/nsw-floodplain-harvesting-policy, accessed 28 September 2021

[65] https://www.industry.nsw.gov.au/water/plans-programs/healthy-floodplains-project/improvement-program-for-floodplain-harvesting-measurement-and-compliance/about, accessed 28 September 2021

[66] https://www.industry.nsw.gov.au/water/plans-programs/healthy-floodplains-project/about/legislative-amendments, a

[67] https://www.industry.nsw.gov.au/water/plans-programs/healthy-floodplains-project/faqs, accessed 28 September 2021

[68] https://www.industry.nsw.gov.au/water/plans-programs/healthy-floodplains-project/improvement-program-for-floodplain-harvesting-measurement-and-compliance/about, accessed 28 September 2021

The maturity of water policy in NSW poses somewhat of a challenge for developing and enacting new policies and the DPIE is currently scoping issues that need to be addressed in the development of the policy. These include (A. Goulstone. *pers. comm*. 23 September 2021):

- *Options to licence the extraction of MAR water:* through the aquifer access WAL currently prescribed in (e.g.) the Namoi Alluvial Groundwater Sources 2020 Plan, OR through creation of a new licence type that is separate from 'native' water
- *Links to aquifer interference approvals:* this mechanism in the *Water Management Act 2000* is yet to be commenced but will assist MAR policy by being able to regulate the volume, timing and quality of water recharged into an aquifer
- *Water accounting changes:* Accounting is currently based on annual Available Water Determinations (AWD) and water allocation but accounting for MAR will need to consider longer time periods. This is again related to distinguishing between native or MAR water and needs to consider implications for ability to trade
- *How and when to apply decay factors reflecting the inability to recover all recharged water*
- *Maximum aquifer storage volumes*
- *Timing of recharge and recovery:* management of issues relating to waterlogging risks and the recovery of water in periods of high demand for groundwater
- *Water quality considerations:* management of the health of the receiving water source and establishment of monitoring requirements and governance arrangement
- *Metering and monitoring:* determining accepted methods for obtaining accurate information on volumes recharged into an aquifer, particularly for infiltration-based system
- *Establishing priority of access:* water access is currently prioritized between users (e.g. environment, critical human needs, basic landholder rights, licence holders). The priority of recovering MAR in relation to other access/use types needs to be established, both in 'normal' conditions and during extreme events
- *Impacts on surface water users:* in water sources where surface water allocations are not fully utilized, consideration needs to be given to the risk of MAR leading to a growth in surface water take to a level that exceeded a Sustainable Diversion Limit (SDL) or Long Term Average Annual Extraction Limit (LTAAEL) result in reduced AWDs for water access licence holders
- *Identifying legislative changes:* Amendments that may be needed to Acts, water sharing plans and/or the Aquifer Interference Policy
- *Fees and charges:* determining the amount and equity of fees and charges that would apply to MAR users
- *System changes:* working with WaterNSW (NSW's bulk water supplier and river operator) in relation to licensing requirements, processes and procedures.

The intent of the NSW government is that options for implementing a managed aquifer recharge framework in NSW will be analysed in 2021-21 ready for consultation with stakeholders and the community in 2022-23 (refer to NSW Water Strategy Implementation Plan, 2021).

Table 23 Investigation into MAR as part of the NSW Water Strategy (DPIE, 2021).

Action 6.8 Investigate and enable managed aquifer recharge
The Government will develop a policy that sets out the framework for MAR in NSW and identify where it is technically and economically viable. We will: • identify and implement the legislative changes, accounting, assessment and approval processes that are needed to enable MAR to be implemented • provide guidance on where MAR could be a feasible option given the scientific and engineering challenges and potential environmental implications, particularly for those locations where supplies are vulnerable or where demand is high compared to supply • collaborate with research institutions to ensure we have the latest scientific information available to government, the wider community and industries.

6. Synthesis

The Lower Namoi was selected as a third and last case study for the project as a region where MAR has long been discussed but has not yet advanced, with a highly developed irrigated agriculture industry where cotton is an important irrigated crop. Given the previous work on MAR in the catchment, and in exploring opportunities to move MAR forward towards field investigations, this case study experiments with initiating discussion from an operational, site specific perspective on MAR. It focused on an area of previously mapped high MAR suitability between Narrabri and Wee Waa in the east of the Lower Namoi groundwater source. The broad approach taken was to draw on evidence from a holistic feasibility assessment to scope the most promising opportunities ("scenarios") for MAR. The feasibility assessment facilitated the identification and evaluation of three MAR scenarios:

- *MAR for low loss water storage:* deliberate recharge and infiltration to increase water available in aquifer and reduce evaporative losses
- *Moving water north:* moving water through existing channel infrastructure for recharge targeted at drawdown areas (north of Wee Waa)
- *River recharge as MAR:* a transformative shift in water governance and river operations that emphasises active collective management of surface water to recharge aquifers

Each scenario is backed up by evidence from analyses against each of the seven criteria for the feasibility of MAR.

6.1 Key learnings

There continues to be opportunities for MAR in the Namoi valley, and with the NSW Water Strategy delivered in August 2021 there is some impetus for change. However, given the developed nature of the AOI, and the mature policy framework for water management, gains from optimising the *status q*uo through the use of MAR innovations are unlikely to provide new water, but rather to provide greater control over where and when water is available.

Technical feasibility: The established irrigation industry in the Lower Namoi, with its intricate channel infrastructure and many on-farm dams, provides both opportunities and challenges for MAR. The canal system could work to transport water to MAR sites and dams could be used as temporary storages/sedimentation ponds. This, however, would require a significant change in current practice that would require a strong business case to establish the benefits to irrigators for such a change, and cooperation between landholders to minimise unwanted impacts.

Aquifers in the region are heavily used for irrigation which has resulted in substantial drawdowns, suggesting there is space in the aquifers for recharged water. However, the most effective way to recharge these aquifers in the area of interest is less certain. River recharge is a major contributor but its management represents a transformative change for the region. Paleochannels are known to exist in the region but high system heterogeneity highlights the need for local knowledge to target suitable locations.

Financial viability: Past studies have suggested that infiltration-based MAR schemes could be financially competitive with surface storage options in the Lower Namoi. Factors such as (expected) increases in surface evaporation rates increase the viability of MAR. As reiterated in the scenarios developed here, further development of the business case for MAR requires further quantification of current system losses and discussion of management and governance arrangements for sharing of costs, benefits and regulation of MAR.

Governance arrangements: There is not yet a MAR specific policy in NSW, although the NSW Government recently published the NSW Water Strategy which includes plans to analyse options for implementing a managed aquifer recharge framework in NSW for consultation with stakeholders and the community. The use of MAR pilots, which can go ahead under current regulations, is critical to inform policy as well as technical expertise. Current policy indirectly associated with MAR includes the Aquifer Interference Policy, while the published Australian Guidelines for Water Recycling: Managed Aquifer Recharge can already inform future MAR policy and associated assessments.

6.2 Enabling environment for MAR

Stemming from this case study, the general recommendations for CRDC, State government, landholders and/or other parties are to:

- Build a culture of and capacity for understanding groundwater dynamics at farm scale, and infiltration and recharge at field and channel scale.
- Invest in pilot studies of MAR that develop regulatory and farm management understanding of recharge consistent with water accounting requirements.
- Engage in the development of the policy framework for MAR within the NSW strategy to ensure that water sharing plan, pilot project, and collective management options remain possible in future.
- Explore the range of possible paradigms for managing aquifers as reservoirs to minimise impacts and maximise benefits

A staged approach to operationalising and implementing these recommendations should target initial no-regret actions that minimise initial investment and provide value regardless of which management paradigm and MAR innovation are later pursued. In principle, as the value of water increases, telemetry and automation have the potential to dramatically increase understanding of an irrigation system, provide savings through condition-based or predictive asset maintenance, and in the process yield high resolution understanding of infiltration and evaporation. Similarly, increasing farm data availability increases the benefits of information sharing and greater involvement of farmers and other emerging data holders in regulatory review and development processes. Investing in precision agriculture water management could therefore lay the groundwork for MAR in future.

All scenarios developed for the Namoi case study rely on the establishment of organisational structures and research and development support that will gradually increase local to subregional hydrogeological understanding. They place an emphasis on enhancing the ability of irrigators to evaluate the costs and benefits (in relation to the farm water balance and enterprise resilience) of proposed changes to their operational water management. There is a need for multi-stakeholder efforts to experiment with new regulatory frameworks and policy innovation niches that support sustainable irrigation industries. These are changes that would also be desirable more widely to improve capacity for whole-of-system water management in NSW and Australia. MAR is an ideal case to develop this improvement in governance but would also benefit from investments in improvements through other pathways, including through greater cooperation in operational water delivery or regional system efficiency improvement mechanisms.

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