



**Chief Scientist
& Engineer**

Placement of monitoring equipment for water resources in NSW

NSW Chief Scientist & Engineer

June 2014



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Chief Scientist & Engineer

The Hon Michael Baird MP
Premier
Minister for Infrastructure
Minister for Western Sydney
Parliament House
SYDNEY NSW 2000

Dear Premier,

Placement of monitoring equipment for water resources in NSW

On 7 April 2014 the Minister for Resources and Energy wrote requesting that I provide advice on the “optimal location/placement of monitoring equipment to provide data to inform government and communities about water resources and the impact of Coal Seam Gas extraction, mining activities and irrigation on these resources”. The letter requested information to assist in prioritising locations for monitoring equipment.

After consulting with engineering and science experts in related fields, it was agreed early on that, in a mathematical sense, it is not possible formally to describe the optimal location/placement for monitoring equipment.

However, the Review found there is much that still can be done in a monitoring process sense to reduce uncertainty with regard to possible impacts from extractive activities on water resources. The fundamental approach needs to be one of ongoing data collection from appropriate sensors that is interpreted by a combination of experts and machines, using intelligent tools and models.

Accordingly, I recommend a process for harnessing the work that has been done to date and adding new sensors in high-risk areas; making data generally accessible; characterising NSW groundwater; and setting up a formal structure to assess impacts and reduce uncertainty. Using an independent expert technical committee would be a key part of this. Further, the Review suggests the Government consider setting up a new, independent statutory authority, possibly called the NSW Water Resources Impacts Commission, to oversee the process outlined in the Recommendation.

In presenting this report I wish to acknowledge the assistance of the experts and the Review team who worked hard to develop this report.

Yours sincerely,

Mary O’Kane
Chief Scientist & Engineer
30 June 2014

EXECUTIVE SUMMARY

This Review is a response to the request from the Minister for Resources and Energy for advice on the “optimal location/placement of monitoring equipment to provide data to inform government and communities about water resources and the impact of Coal Seam Gas extraction, mining activities and irrigation on these resources”. This Review is carried out as a subset of the wider Independent Review of Coal Seam Gas Activities in NSW.

The Review consulted experts from a range of disciplines including computer science, data science, geology and geophysics, and hydrology. It is agreed that, in a mathematical sense, this is an ill-posed and underconstrained problem and, as such, cannot be formally solved.

However much can be done to address the question. Essentially the problem is one of reducing/minimising spatial and temporal uncertainty with regard to the severity and impact of possible events that could occur as a result of activities such as mining, CSG extraction and irrigation. What is needed is a process to maximise information while minimising cost. Doing this comprehensively is difficult. Tackling it requires a well-designed and comprehensive long-term scientific and engineering effort.

The fundamental approach should be one of using a judicious combination of ongoing real-time collection of data from appropriate sensors (local and remote), on-ground observations, and other sampling techniques where automated measurement is not available. All these require joint interpretation by machines and human experts who have been supplied with appropriate, intelligent, modelling, data visualisation and analysis tools.

The overall formal process recommended by this Review can be described in summary as follows:

- Companies or organisations seeking to mine, extract CSG or irrigate as part of their initial and ongoing approvals processes should, in concert with the appropriate regulator, identify impacts to water resources, their pathways, their consequence and their likelihood, as well as the baseline conditions before activities start. Appropriate monitoring to detect these possible risks should then be implemented.
- Data from these monitors should be deposited (in as close to real time as possible) in the State Environment Data Repository and continuously interrogated by intelligent software looking for:
 - evidence of likely risks or even of discontinuities. The relevant companies or organisations would need to review the data and data analysis on a regular basis and provide a risk assessment report to government, especially highlighting any alerts or anomalies. They would also need to respond immediately to any significant alert
 - confirmation of predictions made in approved plans. If the impacts of activities significantly depart from those predicted and approved, the regulator and the company would be alerted.
- In a separate process, an expert committee should examine all data relevant to a region or a sedimentary basin on a frequent basis, using data from a range of sources (the companies’ monitoring data along with triangulation/cross-validation data such as that from satellites, reports from local councils, seismic data, etc.) to check for any other signs of problems in that region and, if any are found, recommend to government that appropriate action be taken with regard to the relevant actors.
- In parallel, government should construct and maintain a variety of models of each region and in particular one that seeks to address cumulative impact along the lines of that constructed in Queensland. These models should feed into the planning and approvals process.

- Also in parallel, government should commission formal characterisation of the groundwater of New South Wales.

These steps would not be independent but rather would mutually inform each other. The process would need to be overseen by an appropriate governance body. One way to do this would be to establish an expertise-based, independent statutory authority such as a commission (possibly called the NSW Water Resources Impacts Commission) that can bring together regulatory and technical oversight, research and development ability, and the necessary information and communication technology prowess.

There are already considerable amounts of water resource information for some locations in NSW across a range of topics – geology, hydrology, hydrogeology, ecology, mining plans – held by a range of parties, so bringing together what is already available would be an efficient first step.

It is important that the costs of such a process are borne by those companies wishing to extract resources and not by the community at large. It is also critical that the incentives with regard to each part of the process are such that it is in a proponent's best interest to work closely with the overall governance process.

This process will require considerable initial coordination of infrastructure and expertise but these are areas in which NSW (and, more generally Australia), given the sparse population managing a vast territory, has a history of excellence.

RECOMMENDATION

Recommendation

That Government establish a formal process consisting of five parallel but interacting steps. The five steps are:

- Companies or organisations seeking to mine, extract CSG or irrigate as part of their initial and ongoing approvals processes should, in concert with the appropriate regulator, identify impacts to water resources, their pathways, their consequence and their likelihood, as well as the baseline conditions before activities start. Appropriate monitoring to detect these possible risks should then be installed.
- Data from these monitors should be deposited (in as close to real time as possible) in the State Environment Data Repository and continuously interrogated by intelligent software looking for:
 - evidence of likely risks or even of discontinuities. The relevant companies or organisations would need to review the data and data analysis on a regular basis and provide a risk assessment report to government, especially highlighting any alerts or anomalies. They would also need to respond immediately to any significant alert.
 - confirmation of predictions made in approved plans. If the impacts of activities significantly depart from those predicted and approved, the regulator and the company would be alerted.
- In a separate process, an expert committee should examine all data relevant to a region or a sedimentary basin on a frequent basis, using data from a range of sources (the companies' monitoring data along with triangulation/cross-validation data such as that from satellites, reports from local councils, seismic data, etc.) to check for any other signs of problems in that region and, if any are found, recommend to government that appropriate action be taken with regard to the relevant actors.
- In parallel, government should construct and maintain a variety of models of each region and in particular one that seeks to address cumulative impact along the lines of that constructed in Queensland. These should feed into the planning and approvals process.
- Also in parallel, government should commission formal scientific characterisation of in New South Wales groundwater.

These steps would not be independent but rather would mutually inform each other. This process should be overseen by an appropriate governance body such as an expertise-based, independent statutory authority (possibly called the NSW Water Resources Impacts Commission) that can bring together regulatory and technical oversight, research and development ability, and the necessary information and communication technology prowess.

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1 INTRODUCTION: THE ISSUE AND CONTEXT

In April 2014, the Minister for Resources and Energy, the Hon Anthony Roberts MP, asked the Chief Scientist and Engineer to build on the work of the Independent Review of Coal Seam Gas Activities in NSW to look at monitoring. In particular, the Minister asked that the Review provide advice on “the optimal location/placement of monitoring equipment to provide data to inform government and communities about water resources and the impact of Coal Seam Gas extraction, mining activities and irrigation on these resources.” The Minister further asked for information as to prioritising monitoring locations. The Minister’s letter is at Appendix 1.

1.1 THE CONTEXT: THE INDEPENDENT REVIEW OF COAL SEAM GAS ACTIVITIES IN NSW

The Chief Scientist and Engineer is undertaking a significant body of work as part of the Independent Review of Coal Seam Gas Activities in NSW (CSG Review). The initial report of that review was released in July 2013. Among other recommendations, the report called for better monitoring of the activities and outputs from CSG operations and noted that such monitoring must be supported by sophisticated data management systems, specifically the establishment of a State environmental data repository. The Review will be finalised in 2014.

1.2 THE APPROACH OF THIS REVIEW

Over the course of the CSG Review, the Review team has consulted widely, including through written submissions as well as site visits, stakeholder meetings and workshops and through commissioning a range of background papers from independent experts. A clear message from this process has been the need for better monitoring and modelling to inform our understanding of the impacts of CSG, including measurement of background conditions prior to extraction activities (baseline monitoring), and the modelling and monitoring of cumulative impacts.

In both the initial report of the CSG Review in July 2013 (CSE, 2013) and the subsequent Sydney Water Catchment study (CSE, 2014), the Review noted that CSG is not alone in its impacts on water resources. A range of industries, including irrigated agriculture, mining and CSG, affect water resources by reducing the quantity of water available to competing uses, and/or by affecting the quality of water. These impacts are controversial particularly where there are competing uses of that water, such as nearby towns and communities or other industries, and where the impacts are such that they will have effects on local environments. Of particular concern to communities is the relatively short-term nature of many extractive industry projects, and the long-term effects they can have.

In approaching this topic, the Review has drawn from a range of sources by:

- consulting experts in computer science, data science, geology, geophysics and hydrology
- obtaining input from experts on characterising groundwater and on understanding uncertainty in impact models for extractive industries
- holding workshops, as part of the broader CSG Review, to characterise risks to surface water and groundwater related to CSG extraction (a separate report on this topic is forthcoming)
- reviewing background papers commissioned as part of the CSG Review
- reviewing submissions on water resources to the CSG Review
- examining other relevant scientific literature, government reports and policies.

The goal of a good monitoring system should be to detect impacts at an early stage, and to be coupled to modelling systems to predict impacts (especially ones that could be severe and/or irreversible). It should be able to identify early warning signs to help manage risks. A starting point for any monitoring system is to establish baseline conditions, so that the severity of impacts can be understood. As models built from the monitoring data become more and more accurate in their predictions, uncertainty will be reduced. Such a system requires both capabilities to take and analyse measurements and the expertise to interpret and use these analyses.

1.3 AN 'OPTIMAL' SYSTEM?

The Government has requested the 'optimal locations' for monitoring equipment within the State be determined. In a formal sense, an optimal solution can only be found for a well-defined mathematical problem. Specifically, this requires that the intrinsic value of a decision, for instance a set of locations for monitoring equipment, be formally quantified through the definition of an objective, or utility, function. This function must capture the expected benefits that may be realised in the future from taking a decision and in particular how the collected measurements will be used to reduce the chance that significant impacts will occur in the future. This in turn must quantify the measurements' ability to improve the knowledge base regarding how a specific water resource may respond to different development scenarios; the resource's existing background dynamics; and to provide early detection of potential adverse impacts, if they were to occur, allowing early mitigation actions to be implemented.

In addition to the quantification of benefits of new monitoring, the available resources for the construction of the monitoring system also need to be understood and quantified. For instance this will require an understanding of the available funding and the capital and operational costs of the monitoring.

At present, information regarding these critical aspects is not fully available. Thus, the Review has focused first on the broader issue of understanding the risks posed by extractive industries on the State's water resources and the types of data currently collected. This will provide the framework for future quantitative analyses to be performed in the future regarding the optimal monitoring strategies.

It is also observed that it is not possible to provide more generic, or blanket, recommendation for locations of monitoring equipment in relation to the main extractive industries of CSG, mining, and irrigation, due to the inherent variability in different water resources that exist throughout the State. For instance, the characteristics of groundwater systems vary due to the inherent differences between local climatic drivers and the characteristics of the geological basins within which they reside. These cause risks that may be significant for one development in a particular location to be insignificant for a similar development in another location. This in turn leads to significant differences in monitoring requirements.

1.4 MONITORING WATER RESOURCES

Concerns over water resources can be characterised into concerns over the quality of water and concerns over its availability, or quantity. Water, occurring as either surface water or groundwater, can be monitored with a range of different techniques. Considerable advances towards automating these and towards improving modelling have been made in as is discussed in more detail in Chapter 3.

The two issues of quality and quantity are not always independent but in some cases have a causal link. For instance a reduction in water volume of surface water or groundwater can

affect quality through changed oxidation state, promotion of algal blooms, or change in sediment transport.

Water quality standards vary depending on the intended use of that water. For drinking water, the Australian Drinking Water Guidelines specify a range of physical and chemical properties that must be within acceptable standards. For environmental water, a more common set of guidelines is that produced by the Australian and New Zealand Environment and Conservation Council. It is possible to monitor physical and chemical factors not listed in these guidelines, but costs may be increased for those measurements that are not commonly done.

Monitoring for surface water quantity involves, for rivers, measuring flows at gauging stations and for lakes, measuring water levels against a known bathymetry (depth). To determine groundwater quantity, the water level (i.e. piezometric head; the combination of pressure head and elevation head) must be known, along with geological information (e.g. stratigraphy from wireline logs, geophysics, extent, porosity, and hydraulic conductivity of the aquifer and aquitards etc.). Also important to both surface water and groundwater monitoring, are related fluxes of water, e.g. precipitation, evapotranspiration, runoff, recharge, discharge (e.g. springs, baseflow).

To characterise fully water resource systems, further information is typically required including:

- satellite and aerial data to measure vertical and horizontal surface movement and displacement; salinity; bushfire; vegetation distribution, die off, or algal blooms
- geological and geomechanical measurements and modelling to inform the context of the surface water and groundwater
- local experience and knowledge which can provide insight into environmental changes
- geochemistry, isotopic fingerprinting, and other chemical characterisation techniques.

Visualisation of the basic and supplementary information can enable assessments of the system to give an understanding of the complexities of the resource, and allow for new impacts to be detected and thereby provide early warning of issues as they arise.

1.5 HOW THIS REPORT IS ORGANISED

Chapter 2 considers the question of whether we can currently assess the impacts of extractive industries on water resources in NSW. It examines who is currently measuring and monitoring water resources, why, and how the information is being interpreted and used to understand risk. It considers the issues with the current approach.

Chapters 3 and 4 discuss technological, policy, research and community developments that are occurring that will allow better understanding and measurement of impacts on water resources.

Chapter 5 gives the Review's recommendation and conclusions.

2 CURRENT IMPACT ASSESSMENT

2.1 ISSUES WITH IDENTIFYING AND MEASURING IMPACT

The Review began by considering whether the current monitoring of NSW water resources is capable of identifying irreversible or major consequence impacts.

NSW's water needs are growing at the same time as climate change and variability are shifting the distribution of rainfall and aquifer recharge in Australia (CSIRO, 2012). NSW is also increasingly relying on groundwater to meet its water needs: our use of groundwater has increased approximately five-fold since 1983 and this is proportionately higher than the increased use of surface water over the same period (Harrington & Cook, 2014). Thus, the use, fate and vulnerability of groundwater resources is a crucial environmental and economic issue.

Impacts on water resources, affecting quality and/or quantity, may have consequences for human and environmental health, or for agricultural productivity. As such, they are of concern to regulators and the community alike. Of greatest concern are irreversible impacts which may have major long-term consequences such as impacts that affect water resources that are particularly important to water-sensitive ecosystems (Eamus, Froend, Loomes, Hose, & Murray, 2006) or are for human use. These impacts may come from incidents that progress slowly, and are potentially difficult to observe in the early stages. The magnitude and trajectory of impacts, particularly those that occur over the long term and/or have long-term consequences, must generally be anticipated in order for preventative management actions to be taken. Similarly, a long-term observational framework must be established in order to detect impacts and monitor any mitigation.

Many water resources are already being monitored in NSW. Such monitoring is undertaken by various different entities for a number of different purposes and the data from this monitoring is not, at present, organised and accessible through a single authoritative source. This means that it is difficult to obtain a picture of what impacts may be occurring on a regional or basin scale, and to detect what may be long term, unexpected or cumulative impacts.

The current scale of effort to monitor water resources varies by location. In some cases, information is collected in quite fine detail, such as groundwater in alluvial sediments in the Namoi sub-catchment. In other locations there may be little, if any, information available. A particular focus of monitoring has been on monitoring extraction activities for adverse events or accidents. This monitoring is typically carried out at the local level and over short time frames (e.g. groundwater piezometric monitoring associated with a mine).

Much of the necessary contextual data for the building of models to understand impacts is also collected, but not necessarily for this purpose, and bringing it together to build such models has not often been done on appropriate spatial and temporal scales.

An important requirement for measuring impacts that may derive from extractive activities is the characterisation of baseline conditions at a point in time, with appropriate resolution that can be used as a reference state. Such baseline data is missing for many projects, and interpolation methods must be used to establish these. Without accurate baseline understanding, efforts to attribute impacts to activities can be fraught.

While the monitoring currently undertaken for NSW water resources works relatively well to identify many immediate and local impacts at the level of the project, it is impossible to assess reliably the type, location, source and magnitude of some impacts at the regional or basin level, or to assess those that are slow to develop but have a major impact once at full

scale. 'Sentinel' variables are rarely identified that can indicate a particular developing impact. The detection of certain subtle impacts may require long-term or wide-field observations to identify relative changes to a catchment, aquifer or ecosystem.

Difficulties can arise in part because not all the data that is currently collected is readily available, nor is it collected to a clear set of reporting and analytical standards. The purposes for which data are being collected are also diverse, which means that data may be limited in their re-use value. This also means that it is not, as yet, possible to detect impacts that are slow in developing, iterative or subtle, but may occur over wider temporal or spatial domains where they have significant consequences.

Where regional-scale monitoring is done, it may fail to detect local impacts, which can be significant in their effect. For example draw-down of an aquifer can cause net migration of water from nearby rivers and streambeds to aquifers resulting in the mobilisation and leaching of some metals (e.g. iron, trace arsenic) from the surrounding rocks and soils (Andersen, Rau, McCallum, & Acworth, 2011). While monitoring may be in place to observe changes in water table height regionally, unless appropriate monitoring of the mass balance of rivers and streams, and appropriate quality testing is undertaken, such impacts may not be observed or managed.

There is no single agency in NSW or nationally with the responsibility for collecting and interpreting all of this information. This can cause difficulty for those wishing to use the information in that it may be difficult to discover and access, and difficult to decide which source of information is authoritative. In addition, there is no current agency or organisation with responsibility for looking at the overall picture created by this data, developing a standard model or set of models, and assessing what the impacts to water resources may be on a long-term, regional or statewide basis.

2.2 WHO MEASURES WHAT

A range of NSW Government and private organisations are undertaking water monitoring for various purposes across the State. This is by no means an exhaustive list, but an attempt to survey the key monitoring efforts and where key datasets may lie.

2.2.1 NSW Government Agencies

NSW Government agencies are involved in a range of monitoring activities that aim to characterise underground and surface water resources. Figures 1 and 2 indicate current water monitoring sites as of 2012.

The NSW Office of Water (NOW) is responsible for the management of surface and groundwater policy and regulation. NOW's remit is water resources across the State; however its focus to date has been primarily the management of water for its sustainable use by different stakeholders, particularly irrigators and drinking water utilities, with monitoring focussed on gathering data to support these activities, including for management of Water Sharing Plans under the *Water Management Act 2000*. The majority of NOW's monitoring capabilities are for surface water and shallow groundwater (between 20 and 150m) (DPI, 2014e).

The information collected through the monitoring networks maintained by NOW includes:

-For groundwater:

- location, depth information
- manually monitored water level information
- water level data from bores with loggers
- drillers logs
- artesian flow summaries

- pump test records
 - licensing details (DPI, 2013a)
- For surface water:
- daily stream flow information
 - stream height data
 - groundwater level data
 - rainfall data
 - conductivity data
 - continuous water temperature data
 - turbidity data
 - air temperature data
 - pH data
 - wind data (DPI, 2014d)

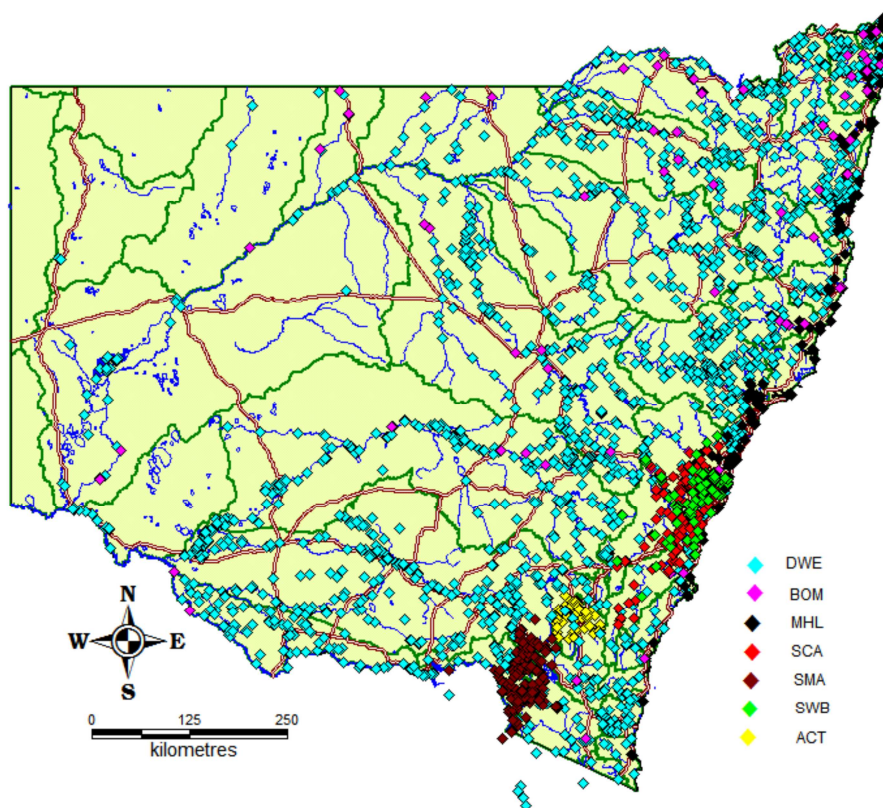


Figure 1: Surface water monitoring sites in NSW (Reproduced from DPI, 2012)

DWE = NSW Office of Water, BOM = Bureau of Meteorology, MHL = Manly Hydraulics Laboratory; SCA = Sydney Catchment Authority, SMA = Snowy Mountains Engineering Corporation; SWB = Sydney Water Corporation, ACT = ActewAGL. Organisation names have changed since this diagram was created, not the location or ownership of the sites. (Reproduced from: (DPI, 2012)

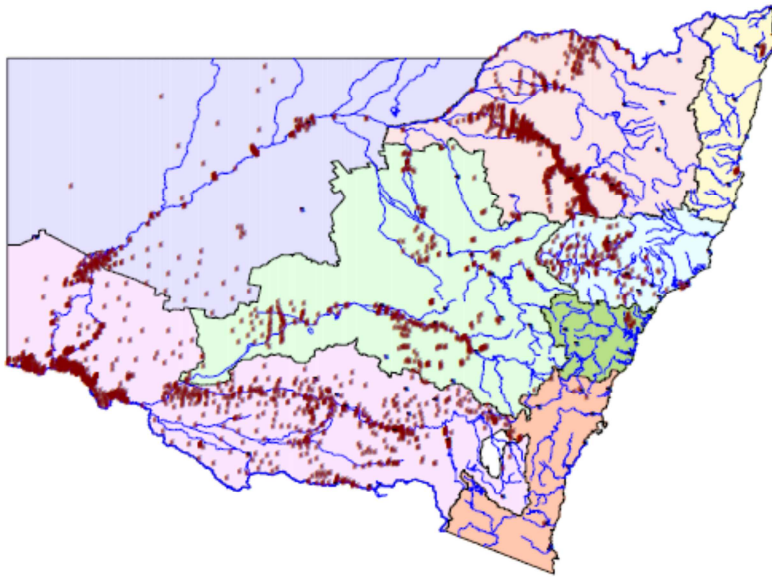


Figure 2: NSW Groundwater monitoring sites (Reproduced from DPI, 2012)

As of 2012, there were around 5,000 active manual-read groundwater installations (DPI, 2012). Figure 2 highlights that the distribution of these groundwater monitoring sites is concentrated in some basins while others have relatively few. NOW operates a Groundwater Data System, Hydstra GW, which maintains records about groundwater bore construction, lithological and aquifer details, groundwater levels, as well as detailed technical records including pumping tests, bore development and geological logs (DPI, 2013a). Since the introduction of the Aquifer Interference Policy in 2012 and the identification of a range of basins for CSG extraction, NOW is expanding its groundwater monitoring network, including the installation of deeper nested wells (between 100 and 1,000m) in the Gunnedah Basin and Hunter Valley (DPI, 2014e).

NOW estimated in 2013 that 46% of groundwater extraction is metered (DPI, 2013b). Telemetered data is transmitted to NOW's Hydrotel SCADA systems, while non-telemetered data is collected manually and used to maintain water accounts (DPI, 2009). Metering is used to measure extraction volumes sources and to ensure compliance under Water Sharing Plans. While not all small-yielding bores are metered, the high-yielding bores, particularly in the Murray-Darling Basin, are. Water licences are required for irrigators and other extractors to account for the water taken from groundwater and surface water through aquifer interference activities (DPI, 2014a).

The Office of Environment and Heritage (OEH) has a responsibility to help protect and monitor the health of NSW rivers, beaches, wetlands, groundwater systems, estuaries and other marine environments and the plants and animals that live in these habitats. In undertaking these responsibilities OEH works closely with the Manly Hydraulics Laboratory (MHL) and NOW. The MHL is a unit within NSW Public Works that provides services in the areas of water, sewer, stormwater, irrigation, coastal and environmental solutions including physical and numerical modelling investigations and delivery of extensive data collection programs (NSW Public Works, n.d.).

The Department of Primary Industries is involved in paddock-scale studies into salinity, nutrients and fertilisers (DPI, 2012). The Department also has invested in a range of water monitoring capabilities including automatic weather stations, stream gauging, climate and groundwater stations with data loggers, turbidity sensors, electrical conductivity, solar radiation sensors (DPI, 2012).

Table 1 gives the numbers and types of monitoring sites broken down by NSW government agency.

Table 1: Monitoring sites in NSW by NSW government agencies

Monitoring Sites					
	Surface Water	Groundwater	Water Quality	Meteorological	Total
NOW	2325	9043	1887	161	13366
MHL	237	0	23	72	287
DPI	48	5	41	31	125

NOW = NSW Office of Water; MHL = Manly Hydraulics Laboratory; DPI = Department of Primary Industries.
Source: (DPI, 2012)

The ability of the NOW monitoring system and those of other agencies to establish baseline conditions and to identify impacts is variable and dependent upon the location and types of monitoring available in the network. A large proportion of the monitoring equipment managed is not telemetered. Therefore, even if the right instruments were in the right location to detect an impact, it is uncertain whether the information would be detected, assessed and interpreted such that the cause of the impact could be determined in a timely way to enable intervention to stop the impact or minimise its scale.

Other NSW Government agencies collect information on the broader environment which is useful to understanding and characterising the systems in which the water resources are found. Examples of these are the Geological Survey of NSW and the Coal and Petroleum Geoscience group within the NSW Trade and Investment. These organisations contribute to understanding of groundwater and surface water through geological mapping and geophysical and geochemical surveys, including characterisation of cores, seismic surveys, and airborne magnetic surveys. This information may be collected through data submitted by licence holders, and information collected by service companies and analysed and mapped by staff.

2.2.2 Water utilities

Water utilities in metropolitan and regional NSW are responsible for a variety of activities including water storage, treatment, recycling and delivery of potable water, as well as waste water management, treatment and disposal including sewage and storm water. Monitoring of both drinking water supply and waste water is undertaken to ensure the protection of human health and environment from contamination, as well as monitoring of quantity and water availability. Water harvesting for potable supply is managed via licensing arrangements through the NSW Office of Water, and waste water management activities are undertaken through licencing by the Environmental Protection Authority.

In the Sydney region, Sydney Water has responsibility for the management of water supply to homes and businesses, with the requirement that it meets the Australian Drinking Water Guidelines (NHMRC & NRMCC, 2011). It also operates 23 sewage treatment systems, for which monitoring parameters include effluent quantity, quality (ammonia nitrogen, total nitrogen, total phosphorus, chlorine, faecal coliforms) and toxicity (Sydney Water, 2009).

The Sydney Catchment Authority monitors dams and water storages in drinking water catchments. SCA is involved in an environmental monitoring program looking at lake nitrification (DPI, 2012) and monitors raw water quantity and quality prior to delivery to Sydney Water. Further information on water monitoring in the Catchment is available in a separate report for the CSG Review (CSE, 2014).

Outside of Sydney, local governments and regional water utilities have responsibility for managing both wastewater and potable water, including filtration plants for drinking water, dams, and sewage treatment plants and have relevant monitoring and measurement systems to support these roles.

Hunter Water Corporation (HWC) provides potable water and waste water services to the lower Hunter region. HWC undertakes pollution monitoring as a requirement of its license with the EPA with monthly summary data reports made available online (Hunter Water, 2014). HWC is also involved in a groundwater monitoring program for Tomago Sands (DPI, 2012).

Table 2: Monitoring sites in NSW by water utility

Monitoring Sites					
Major Agency	Surface Water	Groundwater	Water Quality	Meteorological	Total
SWC*	350	0	0	25	25
SCA	134	0	115	167	416
HWC**	1	197	6	47	251
Sydney Water	5	0	179	99	363
Local Councils***	133	117	99	99	448

SWC = State Water Corporation; SCA = Sydney Catchment Authority; HWC = Hunter Water Corporation;

* SWC requires a number of river sites for river operations (these sites are funded by irrigators). NOW operates these sites and these numbers are included in the NOW totals in Table 1. SWC operates 20 major storages where a range of manual data is collected and some 280 weirs, many of which supply data via SCADA. At some storages, water quality is monitored, but not on a regular basis at this stage. All SWC data is stored on the NSW Office of Water Hydstra system.

**HWC – many sites undertake multiple tasks, i.e. groundwater, water quality and meteorology. Some double counting may have occurred.

***Includes 19 councils or shires monitoring sites

Source: (DPI, 2012)

2.2.3 Private companies

As part of approvals for major projects, NSW requires proponents of mining and CSG projects to undertake monitoring for baselines and impacts. The monitoring requirements are outlined through the licences and permits required through various agencies with conditions driven by the agency's remits and regulatory role. Table 3 summarises the main permits and licences required for mining and CSG companies, as well as irrigators, and the types of conditions within those that require monitoring.

The various NSW agencies differ in the level of detail of the required monitoring outlined in the various licences and permits. The EPA Environmental Protection Licences (EPL) tend to be more specific about monitoring requirements, including details about parameters like specific pollutants to be monitored and tested for and concentration limits; water, soil or air discharge points for monitoring; sampling methods and units of measurement; and frequency of monitoring, etc.

As planning approval is given with advice from other state agencies, consents and approvals tend to overlap with requirements outlined in the EPLs and/or petroleum licences and/or water licences provided by NOW. Development approvals also make reference to a variety of plans (e.g. environmental management plan, integrated land management plan, groundwater monitoring and modelling plan, etc.) that are required by the company to be developed in conjunction with relevant agencies. These plans typically require a monitoring component to be specified in order to meet set goals and limits. The Review looked at a sample of permits and licences to give an indication of the information required, set out in Table 3.

Table 3: Information required of private companies based on industry and licence/permit conditions

Note: To get a sense of the type of company monitoring required through various permits and licences the Review scanned a range of projects across different activity types and locations. Licences and conditions are prone to variations based on activity, location, and as policies change. As such, this information is by no means exhaustive and is based solely on the sources noted.

Agency/licence or consent	Mining (Coal and Minerals)	CSG	Irrigation
Environmental Protection Authority (EPA) Environmental Protection Licence (EPL) (1)	<ul style="list-style-type: none"> ground vibration and overpressure level from blasting - monitoring and limits specified air emissions monitoring at specified discharge points (dust disposition network; total suspended solids (TSS) network); pollutants specified in EPL discharge to water bodies quality and concentration monitoring (e.g. dams) – conductivity, pH, TSS, quality (range of pollutants), discharge amounts as specified in EPL ambient conditions, weather and wet weather monitoring water management plan and associated groundwater and surface water quality monitoring noise monitoring location of monitoring/discharge points specified in EPL units of measurement, frequency and sampling methods specified in EPL; loads and concentration limits specified 	<ul style="list-style-type: none"> air emissions monitoring at specified discharge points (e.g. stacks, flares); not to exceed load and concentration limits of pollutants specified in EPL water and/or land quality monitoring at points, typically quality sampling (grab samples) of groundwater for range of pollutants produced water storage dam (if applicable) monitoring for range of pollutants and levels as specified in EPL soil and water management plan noise monitoring location of monitoring/discharge points specified in EPL units of measurement, frequency and sampling methods specified in EPL 	<ul style="list-style-type: none"> monitoring of water and/or land in relation to herbicide/pesticide/etc. application – discharge point quality and concentration monitoring and environmental monitoring – pollutants specified in EPL; notification and action levels specified in EPL chemical control plan and chemical contingency plan including enhanced monitoring if limits are exceeding ambient conditions and weather monitoring, if applicable wet weather monitoring as specified measurement of chemicals used location of monitoring/discharge points specified in EPL units of measurement, timing and/or frequency, and sampling methods specified in EPL
NSW Trade & Investment <ul style="list-style-type: none"> Division of Resources and Energy Office of Coal Seam Gas for CSG projects Petroleum and Mining Licences or Titles (3)	<ul style="list-style-type: none"> mining operations plan subsidence management plan environmental management plan, as applicable Groundwater monitoring and modelling plan including 2 years baseline data (developed by company with NOW) (condition of exploration licence) produced water management plan (if produce >3 megalitres/yr across licence area) (developed by company with NOW and EPA) 	<ul style="list-style-type: none"> groundwater monitoring and modelling plan including 2 years baseline data (developed by company with NOW) (condition of PEL) produced water management plan (if produce >3 megalitres/yr across licence area) (developed by company with NOW and EPA) well logs and well monitoring to ensure drilling and bores do not cause specified conditions 	Not applicable
Department of Primary Industries	<ul style="list-style-type: none"> groundwater management plan, if applicable, prepared with NOW 	<ul style="list-style-type: none"> groundwater management plan prepared with NOW 	<ul style="list-style-type: none"> install monitoring bores as required by NOW; record groundwater levels

Office of Water (NOW) Water access licence (2)	<ul style="list-style-type: none"> install monitoring bores as required by NOW; record groundwater levels as applicable metering for groundwater extraction quantity as required; maintain records of volumes pumped and transported water quality testing as applicable 	<ul style="list-style-type: none"> install monitoring bores as required by NOW; record groundwater levels as applicable metering for groundwater extraction quantity as required; maintain records of volumes pumped and transported water quality testing as applicable 	as applicable <ul style="list-style-type: none"> metering for groundwater and/or surface water extraction quantities water quality testing; monitor environmental flow releases on river health, as applicable
Department of Planning and Environment Development Consents or Project Approvals Note: Development Consents overlap with other licences; many water access licences for small quantities do not have monitoring or metering requirements	<ul style="list-style-type: none"> environmental management strategy (including cumulative impacts) and environmental monitoring program (overarching) integrated land management plan blasting limits (overpressure and ground vibration) and blast management plan air quality management systems or monitoring programs; limits specified for dust, PM, etc. metrological monitoring water management plan or borefields management measures (site water balance, surface water management plan, groundwater management plan) biodiversity management plan and/or offset management plan light management plan radiation management plan erosion and sediment control measures heritage management plan rehabilitation management plan flora and fauna management plan landscape and re-vegetation management plan noise management plan (4) 	<ul style="list-style-type: none"> environmental management strategy including baseline data and monitoring program (details case by case) water management plan (site water balance, surface water management plan, groundwater management plan) (or soil and water management plan) drilling and fracking management plan and associated monitoring (developed case-by-case by company with DPI) well-testing and flaring management plan air quality and greenhouse gas management plan noise management plan erosion and sediment control plan vegetation clearing and rehabilitation management plan biodiversity offset and/or management plan including monitoring requirements (developed in conjunction with OEH) production operations plan approvals can specific monitoring required, including monitoring points, concentration and load limits of pollutants, frequency of sampling, sampling method, etc. (5) 	soil and water management plan which includes: <ul style="list-style-type: none"> an erosion and sediment control plan; the acid sulfate soil management plan submitted as part of the EA; and a groundwater management plan environmental management strategy wastewater irrigation management and monitoring plan construction environmental management plan (6)

Source notes:

(1) EPL licences sourced – Mining - Hillgrove Mines Pty Ltd, Bulga Coal Management Pty Ltd, Maules Creek Coal Pty Ltd, Xstrata Mount Owen Pty Ltd, Cobar Consolidated Resources Pty Ltd; CSG - Santos NSW (Eastern) Pty Ltd Narrabri, Metgasco Ltd Casino; Irrigation Corporations - Murray Irrigation Ltd, Murrumbidgee Irrigation Ltd; Coleambally Irrigation Co-operative Ltd via <http://www.epa.nsw.gov.au/prpoeoapp/>
(2) Water licences sourced – Mining and CSG – AGL Groundwater Management Plan for Camden Gas Project via <http://agl.com.au>; Irrigation corporations – Coleambally Irrigation Cooperative Limited Approval Number 40CA401473 via <http://www.water.nsw.gov.au/Water-licensing/Corporate-licences/Irrigation-corporations/Irrigation-corporations/default.aspx>; (3) Licences sourced – Mining - CCL713 Muswellbrook Coal Company; CCL703 Metropolitan Collieries Pty Ltd, AUTH432 Endeavour Coal Pty Ltd.; CSG - PEL 16 Metgasco; PEL 238 Santos (recently renewed licences with updated conditions) via <http://commonground.nsw.gov.au/> and <http://digsopen.minerals.nsw.gov.au/>
(4) Consents or approvals sourced – Mining - Cobbara Coal Project – open cut mine Project approval 10-0001, Snapper Mineral Sands Project Project approval 06-0168; CSG - Apex Gas Exploration Project – Project Approval 07_0103, Camden Gas Project DA No. 15-1-2002-I; Irrigation - McWilliam's Winery Proposed Winery Expansion Project Approval 09_0177, Project Approval 06-0141 Turf farm via <http://majorprojects.planning.nsw.gov.au/>

It is difficult to determine the full extent of private monitoring across the State. Given the licence requirements, the majority of information on water resources impacts is collected by project proponents. However, many of these companies rely on consulting firms to undertake the work related to environmental impact assessment and impact management plans on their behalf. When information is submitted to government it is often in the form of a summary report, and the raw data may be held either by the project proponent itself or by a sub-contractor. The consulting firms which often undertake this work keep their own databases, which may be particularly rich sources of information.

Private companies, such as proponent firms or their sub-contracted consultants, are responsible for developing their own modelling for groundwater and using these models to assess impacts and the response of the system to extraction and related activities. Companies choose modelling to address their needs in terms of the location, the characteristics of the data available and the questions to be answered.

As an industry, irrigation is regulated quite differently to mining and petroleum extraction. State irrigation corporations are private companies holding bulk water entitlements on behalf of their shareholders, generally thousands of individual water users. These often undertake monitoring – an example of the extensive monitoring network managed by three State irrigation corporations is in Table 4 (DPI, 2014c).

Table 4: Monitoring sites in NSW by irrigation corporations

Irrigator	Monitoring Sites				Total
	Surface Water	Groundwater	Water Quality	Meteorological	
Murrumbidgee Irrigation	16	900	27	7	950
Murray Irrigation	6	1449	0	0	1455
Coleambally Irrigation	6	809	56	0	871

Source: (DPI, 2012)

The proclivity for extractive industry firms to share data with each other is mixed at best. This can mean that the various models developed by companies have not incorporated information on nearby connected water or other data, and thus may be lacking in their predictive strength. A lack of an agreed set of standard models for groundwater in NSW basins means that it is not a simple task to compare between companies and models and determine relative impacts and outcomes. This contrasts with the situation in Queensland where the Office of Groundwater Impact Assessment maintains an authoritative model for the Surat Basin (see Chapter 2.3).

2.3 INTERPRETING IMPACTS

Key to the activity of interpreting signals (outputs from monitoring) to identify impacts (and subsequently managing the risk event), is both human and machine intelligence. The data need to be collected, analysed, visualised and compared, critiqued and stress-tested. These assessments are made more powerful if there is a set of pre-extraction/pre-industry baseline data and information, collected over a period of time, to demonstrate the range of conditions prior to mining, CSG or irrigation activity commencing.

Modelling is a key part of interpreting impacts. Models can predict impacts and can be used to attribute impacts to specific activities. Models can be refined over time, with more information as it becomes available. At present, modelling is undertaken for disparate purposes and no single authoritative model (or set of models) of water resources across a basin or region is in place for NSW.

By contrast, in Queensland, the Office of Groundwater Impact Assessment (OGIA) has developed a 19-layer hydrogeological model to help understand the impacts of multiple CSG projects on groundwater in the Surat Cumulative Management Area. The Office is also

responsible for designing, coordinating and directing an integrated, regional-based monitoring program to develop the data to feed into the model. It has authority to direct licence holders to undertake monitoring and their approach enables data sharing from and to petroleum title holders. Under Queensland's *Water Act 2000*, the model is to be reviewed and updated regularly, with the first review scheduled for 2015 (CSE, 2014).

The first step in building similar models for NSW is to resolve the data that is currently collected such that it can be used for modelling. This will involve discovering where the data are held, understanding what standards they were or are being collected to, and solving any interoperability issues. Consolidating and providing open access to the large amount of data held privately would be a major step forward. Once this had been completed, it may be possible to predict or estimate risk conditions for those locations or characteristics for which there is a lack of information. It will also be possible to prioritise the placement of monitoring to address those missing areas or characteristics.

2.4 BUILDING AN UNDERSTANDING OF RISK

A common approach to predicting and managing impacts is to undertake a risk assessment at the planning stage of a project, as well as when planning individual activities, to identify hazards, the likelihood of a hazardous event, and the consequences of the event occurring. Where hazards are understood as something that could cause harm, risk is defined as the likelihood of that harm occurring and the scale of the consequence of that harm. This assessment approach also allows operators and governments to identify control methods that may reduce the likelihood or consequence of the hazard and thus reduce its risk.

One of the control measures typically used in a risk management approach is monitoring. Monitoring can be employed to provide signals when triggers and early warning signs for impacts have been observed. Ideally, this monitoring allows operators and governments to detect critical impacts and to alter or cease activity accordingly. In practice a risk assessment is often used in the first place to decide what to monitor with that risk assessment also used to interpret the results of the monitoring undertaken; with the outcomes of the monitoring of impacts providing an indication of how accurate the risk assessment was in terms of likelihood and consequence.

For a new industry, such as CSG, a starting point would be to understand the process of extraction such that an initial risk assessment can be completed. This itself must be an iterative process – as more is known about the process and as experience grows in the types of impacts that do occur, the identification and rating of risks will become more accurate. Monitoring is a key part of this process, as results are reported back to refine the risk assessment and the management of the CSG well in an adaptive management approach.

Monitoring results can also be used to understand the trajectory and magnitude of impacts – the impact pathway. This requires expertise, and an ability to meld several sources of data together, from the local-scale monitoring results for particular water bodies, to the regional, basin or even national-scale monitoring that may come from tools such as remote sensing. As this iterative process continues, uncertainty as to the likelihood and consequence of each risk occurring can be reduced.

The process of using expertise along with monitoring to assess risks and impacts is key to obtaining an overall picture of impacts on water resources, whether at the State or the regional level. This is something that is currently missing from the approaches taken by individual government agencies and other organisations.

2.5 SUMMARY

There are a range of organisations collecting data on water resources for various purposes across NSW. Some, like operators under licence, are required to identify or interpret impacts on water resources from their activities. However, the efforts across organisations, both public and private, are uncoordinated, and data sharing is limited.

While some risks, particularly at the local project level, are managed reasonably well, there are gaps in overall risk identification and data management that lead to inefficiencies, lack of trust and transparency. Without coordination of existing monitoring efforts and a specific focus on identifying and monitoring for the risks associated with multiple extractive industries on a water resource, there is currently no assurance that impacts are being comprehensively detected.

Knowing where to put new water monitors and knowing what type of monitor is needed requires, as a vital first step, a more systematic approach to identifying and managing risk and impacts on water resources from multiple industries (present and future).

Until a more systematic approach to identifying and managing risk and impacts on water resources from multiple industries (present and future) is developed, determining an ideal placement of monitoring is improbable.

3 TECHNOLOGY DEVELOPMENTS

Identifying and understanding the impacts on water resources from extractive industries requires an iterative process, using data and expertise to undertake risk assessments and modelling, with continual monitoring and analysis to calibrate models and reduce uncertainty. In this chapter, the Review considers some of the major recent technological developments that bear on this problem. These developments underpin the ability of the Government to manage the impacts of extractive industries on water resources.

The capability to characterise impacts and to measure, detect and minimise them is being improved by a range of recent scientific advances. Rapidly developing scientific tools and methods are improving experts' abilities to characterise complex systems, including underground systems and their interaction with surface systems.

3.1 MONITORING

3.1.1 Developments in monitoring and related equipment

Traditional measurement and monitoring techniques such as borehole data have been enhanced by combining them with new technologies which allow for logging and telemetering of data as they are collected. Data which previously needed to be manually entered into databases are now often accessible remotely and can be viewed in near real time. For example, the Victorian Government operates a groundwater information system incorporating automated data gathering from the State Observation Bore Network including a set of visualisation capabilities for groundwater and geological data (Federation University Australia, 2014).

Monitoring equipment is also becoming smaller, cheaper and more robust. It often also comes with local signal-processing capability. The availability of new, lightweight, automated and inexpensive cameras and sensors means that monitoring with these could easily be incorporated into extraction site management protocols, with appropriate picture processing and analysis software. A growing number of sensors can now be coupled to data loggers and/or telemetering systems, allowing for near-real-time detection of changes in groundwater systems. Spills and burst pipes or valves such as occurred at the Pilliga Forest CSG site could be detected and addressed through camera detection with these systems.

There are also advantages to real-time monitoring of groundwater properties as some physicochemical properties of groundwater change quickly once the water is removed and exposed to the atmosphere and surface temperature and pressure (Sundaram, Feitz, de Caritat, Plazinska, Brodie, Coram, & Ransley, 2009). Properties with very labile characteristics include temperature, pH, dissolved oxygen, and redox potential. Though electrodes for measuring conductivity, pH, oxygen, redox potential, and other properties are becoming smaller, cheaper, more robust, and less power-hungry, these sensors require calibration from time to time to correct for instrument drift and other errors using standard solutions (Sundaram et al., 2009). However back-to-base, self-calibration systems are becoming available to address this issue.

Groundwater quantity, quality, and flows can be monitored using the following classes of potentially-automated sensors, among others:

- piezometers – these provide fundamental measurements of hydraulic pressure, a central constraint on subsurface water inventory
- temperature loggers – the temperature of groundwater and of groundwater-fed surface water bodies can provide important information on groundwater flow. The heat carried by groundwater can trace flow within aquifers, through fractures, and

ground-surface water interactions (Anderson, 2005; Rau, Andersen, McCallum, Roshan, & Acworth, 2014). Improvements in sensor and logger technology have increased the application of heat in groundwater to testing and constraining groundwater models and in detecting connectivity

- electrical conductivity (EC) meters – these provide a measure of total dissolved salts, or salinity, of subsurface water, and provide a constraint on the usage of the water. The ionic composition of water influences its electrical conductivity, so any automated metering needs to be accompanied by laboratory or field measurement of the water's ionic composition. Though sodium (Na^+) and chloride (Cl^-) are the main ions controlling groundwater EC, carbonates, sulphates, magnesium, calcium, potassium, and others can also influence EC
- pH meters – these measure the acidity of groundwater, another crucial quality measure of suitability for intended usage, its propensity to carry in dissolved form possibly harmful chemicals, and of biogeochemical processes occurring in the aquifer (e.g. organic matter breakdown)
- dissolved oxygen – optodes for monitoring dissolved oxygen provide another measure of groundwater quality, and of biogeochemical processes affecting the water
- redox potential (Eh) – sensor systems for measuring Eh provide data on the oxidising versus reducing conditions in groundwater; this property can be a measure of solubility of different metal ions (iron, manganese, etc.) in water as well its corrosivity to metal pipes, valves, and pump components.

Emerging technologies are also beginning to provide the capabilities for automated sensing of groundwater quality and of exchange with surface waters through detection of gases such as methane, dissolved constituents such as nitrate, and radioactive tracers such as radon (Dulaiova, Camilli, Henderson, & Charette, 2010).

3.1.2 Remote sensing

A challenge to the management of groundwater is assessing the inventories, locations, residence times and flows within aquifers at catchment and basin scales and over seasonal to decadal timescales. New remote sensing (satellite or airborne) and in-situ technologies are providing opportunities for the monitoring and detection of groundwater and impacts upon it. Remote sensing products provide the potential to detect and assess surface water height (through altimetry), soil moisture, vegetation, and groundwater (van Dijk & Renzullo, 2011). Satellite remote sensing systems may also allow impacts on groundwater-dependent ecosystems (BOM, 2014a) and artesian springs (surface manifestations of groundwater aquifers) to be detected (CSIRO, 2012; Miles, White, & Scholz, 2012).

The “GRACE” (Gravity Recovery and Climate Experiment) satellite system works by detecting gravity changes under its flight paths, essentially “weighing” the Earth beneath it. Changes in gravity fields are often due to changes in the mass inventory of groundwater, thus GRACE data can be used to estimate changes in total integrated water storage over time. GRACE has been used to detect the continent-scale addition of water beneath the Australian continent during the 2010-11 La Niña event (Fasullo, Boening, Landerer, & Nerem, 2013), inter-annual changes in subsurface water storage (Ahmed, Sultan, Wahr, & Yan, 2014) as well as seasonal changes in groundwater storage at basin-scale (Tregoning, McCluskey, van Dijk, Crosbie, & Peña-Arancibia, 2012). One limitation of GRACE is its current spatial resolution of hundreds of kilometres, however a successor mission is aiming at higher resolution. An inherent constraint is that although GRACE can be used to estimate total water storage beneath the surface it cannot pinpoint at what depth the groundwater occurs.

Remote sensing systems like GRACE must be augmented by ‘ground truth’ or in-situ observations to account for uncertainties due to soil moisture and biomass.

Subsurface water flows can also be detected through their effects on magnetic and electrical fields at Earth's surface, a set of methods known as magnetotellurics. The application of magnetotellurics to groundwater flows is just beginning in Australia but has great potential to detect changes to groundwater flows at basin scale (Peacock, Thiel, Reid, & Heinson, 2012), and an effort to apply magnetotelluric technology to groundwater was recently the recipient of an innovation prize from the Australian Government (Jones, 2013).

Changes in groundwater can also be associated with vertical surface ground movements and remote sensing, and remote sensing tools like synthetic aperture radar are necessary fully to constrain subsurface water budgets (Ng, Ge, Zhang, Chang, Li, Rizos, & Omura, 2011). These also need to be "ground-truthed" with automated and on-ground geodetic observations (e.g. automated GPS).

Changes in seismicity are also often associated with the manipulation of the subsurface fluid reservoir, by removal and/or injection (Keranen, Savage, Abers, & Cochran, 2013; van der Elst, Savage, Keranen, & Abers, 2013). Networks of geophysical instruments need to be installed and maintained to assess long-term baselines, assess risk, and detect impacts to seismicity and its effect on groundwater (AuScope, 2012).

Sensor system data sets, though invaluable, must be considered in the context of the usually complex geological settings of the shallow subsurface catchment-level and deeper basin-scale structures hosting groundwater resources. Efforts to incorporate the long time-scale geological and climatic history of basins, and their structures are underway (Kelly, Timms, Ralph, Giambastiani, Comunian, McCallum, Andersen, Blakers, Acworth, & Baker, 2014), and these studies need to be applied to all basins in which extractive activities are considered.

3.2 DATA TECHNOLOGIES

The increased storage capabilities and computational power that has been developed over the past decades has meant that large data sets can be archived, interrogated, and visualised more easily than previously. In particular, technology for the efficient storage, organisation and interrogation of data has developed significantly over the recent years and is most evident in internet-based companies, such as Google. However, the underlying technologies have spread to major industries, including the mining and petroleum industries due to the value that can be extracted from the data.

Data only have value if they can be interrogated without ambiguity. To achieve this, data standards are required that explicitly specify what the data are, how they were collected and how they should be interpreted. For the geosciences there have been several recent developments in data standards. For instance CoalLog was specifically developed to ensure that borehole data can be collected, stored and transferred in a standardised fashion within the Australian coal industry. In addition AuScope has built on open standards for data storage and distribution where possible. In the hydrology domain, the Bureau of Meteorology has developed standards for the storage and transfer of weather and surface water data. However, more can be done in the area of groundwater systems, in particular standardising the data collection and reporting procedures performed by industry proponents undertaking aquifer pump tests, core sample tests, or direct pressure measurements to allow it to be integrated more readily with other data sets.

Another benefit of increased computational power is that modelling which previously would not have been possible, is now feasible, and at finer spatial and temporal resolutions. Models are increasingly able to incorporate large data sets, leading to decreased uncertainty. In addition, new approaches such as machine learning are increasing the sophistication of models and improving the accuracy of data-driven models (Mathews, 2014).

The rapid development of such tools over recent years has, in some cases, led to more cost-effective collection and interpretation of data. Data can be collected remotely and with better accuracy and precision. Although uncertainty will continue to play a role, the tools are helping experts in various fields to get a better handle on the uncertainty they are dealing with. It is a challenge to keep abreast of, and adopt in a timely manner, these rapidly changing developments.

Both agile systems and expertise are required to embrace and capitalise on the benefits these tools can provide toward visualising the groundwater and surface water systems and picking up anomalies in data that could identify the impacts we aim to manage.

3.3 MODELLING

3.3.1 Geological

Traditionally, the geology for an area has been visualised in terms of plan-view maps and cross-sections. Increasingly, there is a move towards creating 3D geological models for visualisation and interpretation of geological data¹. For example, the British Geological Survey is in the process of constructing an accurate geospatial model of the arrangement of sediments and rocks for the entire subsurface of the United Kingdom (British Geological Survey, 2014). Similar models for each sedimentary basin in NSW would be a considerable step forward.

An area of potential weakness in groundwater modelling in Australia at present is its representation of the geological settings of the groundwater systems. In contrast to models of petroleum reservoirs, models of aquifers are typically constructed using less data and often have fewer geological realisations of the available data. Of significance is the fact that little fracture network mapping is done. These fracture networks, however, are often the key to how the water moves in groundwater systems. Realisations of the geological models that underlie model predictions for water resources need to reflect these realities (Ward & Kelly, 2013).

Hydrological modelling typically models parts of the hydrological cycle: rainfall-runoff, overland-flow routing, sub-surface flow (i.e. groundwater models). Given the improved computing power available, advances within each of these model groups are continuously occurring in both research developments and in commercially-available software.

A further notable advance is that surface water and groundwater are increasingly being modelled together, reflecting the fact that they are a single water resource. This is being done in surface water models which better account for losses to or gains from groundwater, groundwater models which better account for exchanges with surface water, and a new generation of models which model surface water and groundwater as a coupled unit.

¹ Various packages have been developed for this purpose:

- EarthVision: www.dg.com
- Roxar: <http://www2.emersonprocess.com/en-US/brands/roxar/reservoirmanagement/Pages/ReservoirManagementSoftware.aspx>
- GoCAD: <http://www.pdgm.com/products/gocad/>
- Petrel: <http://www.software.slb.com/products/platform/pages/petrel-geology-modeling-software.aspx>
- Leapfrog3D: <http://www.leapfrog3d.com/>
- MOVE: <http://www.mve.com/>
- Vulcan3D: <http://www.maptek.com/products/vulcan/>
- Micromine: <http://www.micromine.com>
- FracSIS: <http://www.rpmglobal.com/mining-software/data-visualisation-fracsis>

Another significant step forward has been that, for the first time, software packages such as MIKE SHE (DHI, 2011) have allowed whole-of-hydrological cycle modelling to be attempted. However hydrological modelling is a complex task with inherent uncertainties (Poeter, 2007) and current whole-of-hydrological cycle models need to be examined with care by experts. Nevertheless, there are areas where improvements can be made. Two recent studies illustrate a trajectory towards best practice. One of these is the 'Namoi Water Study'; the other is the modelling work done by the Queensland referred to in Section 2.3 above.

In 2010 a study was commissioned to look at the possible impacts of coal mining and gas extraction on the water resources. The 'Namoi Water Study' was contracted to Schlumberger Water Services. The Namoi Catchment is a significant agricultural area in Australia and has one of the most intensively-developed water resources in the land. In addition to pressure from agriculture, there are also current and predicted pressures placed on the water resources from mining and CSG. A key output from the study was the development of two numerical models: a hydrologic model (i.e. rainfall-runoff model) and a groundwater flow model. The hydrologic and groundwater models were for two different, though overlapping, sub-areas of the Catchment. Seven scenarios covering various configurations of mining and CSG activity were then tested using these two models, with an eighth conceptual scenario added after the initial report. The models were used to assess the risk associated with coal mining and CSG development within the Catchment, and allowed for consideration of best and worst-case scenarios. Having at a minimum both a hydrologic and groundwater flow model for each studied area represents good practice.

3.3.2 Data-Driven Methods

In contrast to models based on physical assumptions which are theoretically capable of reproducing the natural processes that are believed to occur within a system, statistical data-driven methods instead attempt to capture the spatial and/or temporal evolution of the system directly from the measured system responses. These are applicable when sufficient historical monitoring data has been collected under conditions similar to those for which predictions are required. For the prediction of impacts to the availability and quality of water caused by the significant increase in extractions, or the physical modifications of the environment, it is unlikely that these methods will be of benefit. However, they are likely to be of significant benefit in the modelling and identification of the background or baseline conditions of a water resource. Such a data-driven modelling approach may enable a statistical characterisation of the natural dynamics of the system such that any significant change or anomaly can be readily detected through automated means. Although these methods will be unlikely to identify the cause of the change, they can provide a starting point for a more directed investigation by a human expert.

At present the NSW Office of Water (NOW) is drawing on expertise at National ICT Australia (NICTA) to use data-driven methods to model some of the State's water resources.

3.4 SUMMARY

A key risk from extractive activities is the potential to degrade the quality and quantity of water resources. The capabilities to characterise the environmental context of these activities, and to detect and quantify their impacts is being improved by recent technological advances. Rapidly developing tools and methods are improving experts' abilities to characterise complex geological and hydrogeological systems on which waters resources depend, including underground systems and their interaction with surface systems. These tools are important in that their increasing sophistication and accuracy helps measure and reduce uncertainty in predictions and provide better visualisation of the systems under examination. By utilising these developments, Government could provide a solid knowledge base from which policymakers can make timely decisions and more effectively manage the state's water resources.

4 POLICY DEVELOPMENTS, RESEARCH, AND COMMUNITY INITIATIVES

In addition to the technological developments considered in the previous chapter, there are also developments in policies pertaining to water resources as the Federal and State Governments have increased efforts to understand and manage the impacts of extractive industries. In this chapter, the Review considers some of the major recent policy, research and community initiatives affecting water resources.

4.1 POLICY DEVELOPMENTS

As water, particularly groundwater, has become a critical resource of contention in the Australian community, governments have moved to create a research and information infrastructure to support policy decisions in these areas.

4.1.1 NSW Government

The Aquifer Interference Policy (AIP) represents a move towards addressing water quantity and quality issues at a regional scale. The AIP was released by the NSW Government in September 2012 and is managed by NOW. It aims to ensure that all water taken from groundwater sources is accounted for; that impacts are adequately assessed against minimal impact considerations (for the water table, water pressures and water quality); and measures exist for the event that impacts are greater than those predicted. Under the AIP, thresholds are set so that cumulative impacts from a number of activities are considered.

As proponents seeking approval under the *Mining Act 1992* or the *Petroleum (Onshore) Act 1991* are generally required to prepare a Groundwater Monitoring and Modelling Plan in consultation with NOW, in February 2014 NOW released an information sheet to inform proponents about how the plans tie-in with the requirements of the AIP. These plans are to be used to ensure there is sufficient groundwater data to assess future operations and will require two years baseline data prior to submitting applications for future mining (DPI, 2014b).

Water Sharing Plans, established under the *Water Management Act 2000* (see Chapter 2.2.1) also attempt to balance sustainable yield for water sources with dependent ecosystems and communities. These are still being introduced for some regions.

4.1.2 Commonwealth Government

The Council of Australian Government's National Water Initiative, in 2004, began building a national-scale picture of Australia's water resources. This established the National Water Commission, due to conclude this year, which has been responsible for reporting on the implementation of the initiative.

The *Water Act 2007*, prompted by the millennial drought, gave the Commonwealth management of the Murray-Darling Basin and matters of national interest in relation to water and water information. It centralised responsibility for national water information in the Bureau of Meteorology (BOM). Under this Act, the BOM is responsible for the collection, management and dissemination of national water information, including setting data standards and issuing national water accounts. The Water Data Transfer Format, water information standards and water accounting standards developed by the BOM are a result of this. A few years later, the National Plan for Environmental Information initiative also established the BOM as the central coordinating authority for environmental information. The National Environmental Information Infrastructure, currently under development, is a result of this initiative, with a reference architecture for this recently released (BOM, 2014b).

In implementing its water information responsibilities, the BOM has introduced a range of new products and services including annual national water accounts, water resources assessments, tracking of reservoir storages and seasonal stream flow forecasts. The Modernisation and Extension of Hydrologic Monitoring Systems Program also delivered assistance to State organisations to update their water information systems and their ability to disseminate that information. Most products released to date are primarily directed at surface water; products addressing groundwater have taken longer to produce, with the National Groundwater Information System due for release in late 2014. Already released is the Atlas of Groundwater Dependent Ecosystems which identifies ecosystems that, due to their dependence on groundwater, could be used as sentinels to signal changes.

As the national meteorological agency, BOM also collects extensive weather data, which is key to understanding water resources.

Geoscience Australia (GA) has also taken an interest in groundwater, for example in a demonstrator monitoring project on the Macleay Coastal Sands Aquifer. GA holds many remote sensing datasets that can be used to understand water resources on a regional or State level. GA also provides hydrogeological expertise and advice to governments across jurisdictions and carries out a significant body of work on the groundwater of the Great Artesian Basin for the Department of the Environment (Geoscience Australia, 2014).

The Murray Darling Basin Authority (MDBA) was established under the *Water Act 2007*. As an expertise-based agency, the MDBA harvests water information from the States to monitor the water resources of the Basin, undertakes research on the same, as well as advising the Commonwealth Minister for the Environment on sustainable extraction limits. From 2019, the MDBA will also be responsible for setting sustainable diversion limits for groundwater within the Basin. The Commonwealth Environmental Water Holder is an office that was created under the same Act to purchase environmental water in the Basin. Some monitoring to detect the effect of these environmental flows is undertaken by this office as a result (Department of the Environment, n.d.).

In 2012, amendments to the *Environment Protection and Biodiversity Conservation Act 1999* established the Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining Development to provide scientific advice on the impact of these developments on water resources. Under this committee's auspices, bioregional assessments and other research priorities have been progressed through collaboration between the Department of Environment, BOM, CSIRO and GA. Several of NSW's sedimentary basins are being studied.

The bioregional assessments analyse the ecology, hydrology, geology, hydrogeology of each bioregion, and assess the potential impacts on water resources from coal seam gas and large coal mining projects. Each assessment will bring together relevant scientific information to create a range of products including contextual information (e.g. register of water dependent assets), model data analysis, impact analysis, and risk analysis. A data register will also be produced for each Bioregional Assessment, which lists and describes the datasets used (Australian Government, n.d.-a). A methodology for these assessments has been developed and several context statement publications have recently been released on the Namoi sub-catchment, Gloucester Basin and the Clarence-Moreton basin (Australian Government, n.d.-b; Barrett, Couch, Metcalfe, Lytton, Adhikary, & Schmidt, 2013).

4.2 RESEARCH INITIATIVES

Federal and State government research funding has also been directed to understanding water resources, including groundwater. Examples of this investment include several water-related Cooperative Research Centres (CRCs) that have been in operation over the years.

Investment in national research infrastructure facilities such as AuScope (funded by the National Collaborative Infrastructure Scheme) and the Australian Geophysical Observing System, funded mainly by the Education Investment Fund, also provide research capabilities readily applicable to studying water impacts, through access to physical, data, modelling, and visualisation resources. The Super Science Initiative has also funded a Groundwater Data Portal, managed by the University of New South Wales, through which access is available to groundwater information from several bores in NSW and other States, including at Wellington and Namoi (UNSW, 2014).

The AuScope Subsurface Observatory program is set up to provide infrastructure allowing additional experimentation to take place in and around existing boreholes, including re-entry of blocked holes and support for maintaining access to boreholes for research purposes following the completion of commercial objectives. This program will also provide a facility for physical-properties logging of core samples. The Geospatial Observatory provides the ability to detect ground movements, such as subsidence. The AuScope Earth Sounding Network provides capability for seismic arrays suitable for detections of artificial sources, ambient noise, local earthquake sources, and induced seismicity, such as that associated for example with geothermal stimulation tests. The Earth Imaging capabilities in AuScope include access to magnetotelluric profiling (see Chapter 3).

The National Centre for Groundwater Research and Training (NCGRT) was established in 2009 as a Centre of Excellence co-funded by the Australian Research Council and the National Water Commission. The NCGRT, with several NSW-based partners has undertaken a wide spectrum of fundamental research into areas such as hydrodynamics and modelling of complex groundwater systems, incorporation of geological structure into groundwater modelling, groundwater interactions, and comprehensive characterisation of aquitards and aquifers.

As well as the research capabilities held in current and past CRCs and other centres, a number of new CRC bids and related initiatives in relevant fields are also in the development stage. For instance, the Sedimentary Basin Management Initiative is a proposed consortium, the development of which is being led by the University of Melbourne, to address issue of multiple basin uses (subsurface and surface) and their impacts from a geoscience, technical, socio-economic and regulatory perspective.

Many other research organisations and groups collect and synthesise information about water resources – those discussed here are a small sample of what is available within the research community. The challenge lies in accessing and resolving the data such that it can usefully be harnessed in a monitoring system and/or used to support modelling.

4.3 COMMUNITY COLLECTORS

In recent years, there has been considerable interest in citizen science initiatives that can incorporate the information collected by individuals or community groups into larger databases. The US Environment Protection Agency has been using volunteer collectors of water quality information for over a decade (US EPA, 2014). Successful examples of such programs in Australia tend to be based on biodiversity observations and include Climatewatch, which asks users to enter observations of certain climate indicator species, or the Atlas of Living Australia, which has several tools to allow volunteer observation records to be incorporated. In Victoria, the Department of Environment and Primary Industries supports the Waterwatch program which has been operating for 20 years. This program uses community volunteers to monitor waterways and has recently moved to centralise data collection and improve data confidence (Waterwatch Victoria, 2014).

Individuals and groups with a long history of collecting information and working in an environment develop a sophisticated understanding of the response of a region or location to

different weather and climate patterns, this insight would be very powerful if harnessed and used in this enterprise. Sources of historical data, from traditional ecological knowledge to landholders and others who may have been collecting information such as rainfall for years can be very important to harness when building models, particularly when baseline data is missing. Community environmental groups and individuals are also important observers of impact, and their observations and reporting of accidents and spillages have been key to many compliance investigations in the coal seam gas industry.

Concerns over the use of citizen science traditionally centre around questions of accuracy and bias in data. The advantage of new, 'big data' developments and the use of intelligent data tools is that such mistakes and biases can be identified and often corrected. For water information, cheap and accurate instrumentation will be fundamental to ensuring community members can participate. Finding a way to harvest the data collected by the community through citizen-science initiatives makes smart use of this rich source of information.

4.4 SUMMARY

Many of the initiatives described above are large scale (national or multi-state) or site specific. But, within their varying scopes, they all contain features that are important for characterising NSW surface and groundwater systems.

The initiatives offer a wealth of information, expertise, and frameworks that could be drawn upon. Through harnessing these, NSW would be well positioned to characterise various key groundwater and surface water systems, as well as to develop better understanding of baseline conditions and impacts.

The first steps in doing this are to harness local expertise, undertake a stocktake of what data are available and coordinate access to the data from various collection activities. One mechanism to do this through could be an independent, expertise-based statutory authority which could leverage the efforts of other initiatives to keep NSW at the cutting edge of developments in this area which could leverage the efforts of other initiatives to keep NSW at the cutting edge of developments in this area.

5 CONCLUSION AND RECOMMENDATION

5.1 CONCLUSION

Significant effort has been expended and progress made in understanding and managing impacts from extractive industries on water resources. Current monitoring systems, where they do exist, focus mainly on surface water quantity, as this has been a source of concern to various stakeholders for some time. Surface water quality monitoring is less common, except where water is used for drinking, and can be harder to automate or to measure remotely.

For groundwater, the use of which has increased markedly in NSW in the past couple of decades, both in absolute terms and as a proportion of water used, there is much less information available and much less monitoring in place. There is even less known for groundwater at depths of more than 100m, that is, beyond the shallow aquifers most often accessed for irrigation and drinking purposes. Both quantity and quality information is poorly collected, but quality even more so. This dearth of information confounds attempts to understand surface water systems as well, given the sometimes significant role played by groundwater in moderating and driving water flow.

As interest in, and demand for, groundwater has increased, efforts by researchers and governments to understand this resource have also increased. This has resulted in pockets of good information and good understanding, but these are distributed both topically and spatially. A first step in seeking to understand fully the water resources of NSW and the potential and extant impacts on these by various extractive industries is to harness the information available across these initiatives.

Government and research data provides only part of the picture, however, and must be combined with the detailed information that project proponents are collecting under the terms of their licenses, permits and other regulatory instruments. Once this information is assembled, it will be possible to begin to assess risk at a regional or basin scale better, as well as to determine where further monitoring and research effort is needed.

Bringing this information together in digital form, in a single data repository, would allow the innovations of 'big data' to be used, such as intelligent software tools that could trawl through the data looking for unexpected events, and for subtle patterns that might indicate impacts that are not yet clearly discernible in other ways. It would also allow relatively cheap, ongoing assessment of the accuracy of predictions made in plans submitted by proponents and approved by regulators, allowing both an improvement in future accuracy and a way for regulators to ensure approval conditions are being met.

Machine tools allow a cheap and ongoing form of impact surveillance, but must be supplemented by expert analyses to ensure a full picture of impact, across NSW, is obtained. These would need to incorporate data from a multitude of sources to cross-check results of monitoring, to create new models and to produce reports. Reports could be prepared regularly on a region basis and on a statewide basis and would be key planning tools to help assess the likely impact of proposed developments in a region. This will require ongoing expert involvement, and the Government could consider setting up a new, independent statutory authority to assist with this.

Creating models for each region, especially models that seek to address cumulative impacts, is a way both to understand and to predict impacts and to attribute them to particular activities. This should lead to a way to assign costs, via existing mechanisms such as

licences, permits, titles, and so on, which will allow the overheads of these efforts to be ameliorated.

Finally, with a State-wide increased demand for groundwater that shows little sign of abating, it is imperative that groundwater is formally characterised. A more complete understanding of groundwater requires a thorough and comprehensive assessment of current groundwater inventories as well as the quality and recharge times of aquifers in NSW and adjoining regions in Victoria, Queensland, and South Australia. Long-term studies of the natural baselines and variability of aquifers, their water inventories, and the sedimentary basins hosting them are needed. In most basins, the condition of pore spaces hosting water has been at least partially affected by past use and climatic variability and this history needs to be taken into account in estimating or reconstructing baseline conditions.

5.2 RECOMMENDATION

That Government establish a formal process consisting of five parallel but interacting steps. The five steps are:

- Companies or organisations seeking to mine, extract CSG or irrigate as part of their initial and ongoing approvals processes should, in concert with the appropriate regulator, identify impacts to water resources, their pathways, their consequence and their likelihood, as well as the baseline conditions before activities start. Appropriate monitoring to detect these possible risks should then be installed.
- Data from these monitors should be deposited (in as close to real time as possible) in the State Environment Data Repository and continuously interrogated by intelligent software looking for:
 - evidence of likely risks or even of discontinuities. The relevant companies or organisations would need to review the data and data analysis on a regular basis and provide a risk assessment report to government, especially highlighting any alerts or anomalies. They would also need to respond immediately to any significant alert.
 - confirmation of predictions made in approved plans. If the impacts of activities significantly depart from those predicted and approved, the regulator and the company would be alerted.
- In a separate process, an expert committee should examine all data relevant to a region or a sedimentary basin on a frequent basis, using data from a range of sources (the companies' monitoring data along with triangulation/cross-validation data such as that from satellites, reports from local councils, seismic data, etc.) to check for any other signs of problems in that region and, if any are found, recommend to government that appropriate action be taken with regard to the relevant actors.
- In parallel, government should construct and maintain a variety of models of each region and in particular one that seeks to address cumulative impact along the lines of that constructed in Queensland. These should feed into the planning and approvals process.
- Also in parallel, government should commission formal scientific characterisation of in New South Wales groundwater.

These steps would not be independent but rather would mutually inform each other. This process should be overseen by an appropriate governance body such as an expertise-based, independent statutory authority (possibly called the NSW Water Resources Impacts Commission) that can bring together regulatory and technical oversight, research and development ability, and the necessary information and communication technology prowess.

REFERENCES

- Ahmed, Mohamed, Sultan, Mohamed, Wahr, John, & Yan, Eugene. (2014). The use of GRACE data to monitor natural and anthropogenic induced variations in water availability across Africa. *Earth-Science Reviews*. doi: 10.1016/j.earscirev.2014.05.009
- Andersen, M., Rau, G., McCallum, A., & Acworth, I. (2011). *Redox Processes and Arsenic Release in the Streambed of a Semi-arid Losing Stream*. Paper presented at the American Geophysical Union, Fall Meeting 2011.
- Anderson, Mary P. (2005). Heat as a Ground Water Tracer. *Ground Water*, 43(6), 951-968. doi: 10.1111/j.1745-6584.2005.00052.x
- AuScope. (2012, 5 September). Earth Sounding Network. Retrieved 25 June, 2014, from http://www.auscope.org.au/site/earth_sounding_network.php
- Australian Government. (n.d.-a). Bioregional Assessments - Products Summary. Retrieved 24 June, 2014, from <http://www.bioregionalassessments.gov.au/products-summary.shtml>
- Australian Government. (n.d.-b). Bioregional Assessments - Welcome. Retrieved 18 June, 2014, from www.bioregionalassessments.gov.au
- Barrett, D.J., Couch, C.A., Metcalfe, D.J., Lytton, L., Adhikary, D.P., & Schmidt, R.K. (2013). Methodology for bioregional assessments of the impacts of coal seam gas and coal mining development on water resources (pp. 75). Canberra: Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining Development.
- BOM. (2014a). About the Groundwater Dependent Ecosystems Atlas. Retrieved 26 June, 2014, from <http://www.bom.gov.au/water/groundwater/gde/index.shtml>
- BOM. (2014b). *National Environmental Information Infrastructure: Reference Architecture*. (Environmental Information Programme Publication Series document no. 4). Canberra, Australia: Retrieved from http://www.bom.gov.au/environment/doc/NEII_Reference_Architecture.pdf.
- British Geological Survey. (2014). National Geological Model. Retrieved 25 June, 2014, from <http://www.bgs.ac.uk/research/UKGeology/nationalgeologicalmodel/home.html>
- CSE. (2013). *Initial Report on the Independent Review of Coal Seam Gas Activities in NSW*. NSW Chief Scientist & Engineer Retrieved from <http://www.chiefscientist.nsw.gov.au/coal-seam-gas-review/initial-report-july-2013>.
- CSE. (2014). *On measuring the cumulative impacts of activities which impact ground and surface water in the Sydney Water Catchment*. NSW Chief Scientist & Engineer Retrieved from http://www.chiefscientist.nsw.gov.au/_data/assets/pdf_file/0007/44485/140530_SC_A-Report-Final-Combined.pdf.
- CSIRO. (2012). *State of the Climate*. Retrieved from <http://www.csiro.au/en/Outcomes/Climate/Understanding/State-of-the-Climates-2012.aspx>.
- Department of the Environment. (n.d.). Commonwealth Environmental Water Office. Retrieved 27 June, 2014, from <http://www.environment.gov.au/topics/water/commonwealth-environmental-water-office/about-office>
- DHI. (2011). MIKE SHE - integrated catchment modelling. Retrieved 27 June, 2014, from <http://www.mikebydhi.com/Products/WaterResources/MIKESHE.aspx>
- DPI. (2009). *NSW strategic water information and monitoring plan final report*. NSW Department of Primary Industries, Office of Water. Retrieved from <http://waterinfo.nsw.gov.au/about/swimp.shtml>.
- DPI. (2012). *New South Wales Strategic Water Information and Monitoring Plan*. NSW Department of Primary Industries, Office of Water. Retrieved from <http://waterinfo.nsw.gov.au/about/swimp.shtml>.

- DPI. (2013a). *NSW Ground Water Data Pinneena GW User Guide*. NSW Department of Primary Industries, Office of Water. Retrieved from http://waterinfo.nsw.gov.au/pinneena/Pinneena_Manual_GW.pdf.
- DPI. (2013b). *NSW metering implementation plan*. NSW Department of Primary Industries, Office of Water. Retrieved from <http://www.water.nsw.gov.au/Water-licensing/Metering/Metering-in-NSW>.
- DPI. (2014a, 2 June). *Aquifer Interference Policy*. Retrieved 24 June, 2014, from <http://www.water.nsw.gov.au/Water-management/Law-and-policy/Key-policies/Aquifer-interference>
- DPI. (2014b). *Groundwater Monitoring and Modelling Plans - Information for prospective mining and petroleum exploration activities*. NSW Department of Primary Industries, Office of Water. Retrieved from <http://www.water.nsw.gov.au/Water-management/Law-and-policy/Key-policies/Aquifer-interference/Aquifer-interference>.
- DPI. (2014c, 17 June). *Irrigation Corporations*. Retrieved 27 June, 2014, from <http://www.water.nsw.gov.au/Water-licensing/Corporate-licences/Irrigation-corporations/default.aspx>
- DPI. (2014d). *Pinneena 10.2 Continuous monitoring - users guide*. New South Wales surface water data archive. NSW Department of Primary Industries, Office of Water. Retrieved from http://waterinfo.nsw.gov.au/pinneena/Pinneena_Manual_CM.pdf.
- DPI. (2014e, 2 June). *Regulation and monitoring*. Retrieved 18 June, 2014, from <http://www.water.nsw.gov.au/Water-management/Groundwater/Water-and-coal-seam-gas/Regulation-and-monitoring/default.aspx>
- Dulaiova, Henrieta, Camilli, Richard, Henderson, Paul B., & Charette, Matthew A. (2010). Coupled radon, methane and nitrate sensors for large-scale assessment of groundwater discharge and non-point source pollution to coastal waters. *Journal of Environmental Radioactivity*, 101(7), 553-563. doi: 10.1016/j.jenvrad.2009.12.004
- Eamus, D., Froend, R., Loomes, R., Hose, G., & Murray, B. (2006). A functional methodology for determining the groundwater regime needed to maintain the health of groundwater-dependent vegetation. *Australian Journal of Botany*, 54(2), 97-114. doi: 10.1071/BT05031
- Fasullo, John T., Boening, Carmen, Landerer, Felix W., & Nerem, R. Steven. (2013). Australia's unique influence on global sea level in 2010–2011. *Geophysical Research Letters*, 40(16), 4368-4373. doi: 10.1002/grl.50834
- Federation University Australia. (2014). The Victorian Water Measurement Information System (WMIS). *Visualising Victoria's Groundwater*. Retrieved 27 June, 2014, from http://www.vvq.org.au/cb_pages/wmis.php
- Geoscience Australia. (2014, 8 May). Great Artesian Basin Water Resource Assessment. Retrieved 20 June, 2014, from <http://www.ga.gov.au/groundwater/great-artesian-basin-water-resource-assessment.html>
- Harrington, Nikki, & Cook, Peter. (2014). *Groundwater in Australia* (pp. 40). Australia: National Centre for Groundwater Research and Training.
- Hunter Water. (2014). Hunter Water - Home Page. Retrieved 30 June, 2014, from <http://www.hunterwater.com.au/>
- Jones, Cheryl. (2013). The Australian Innovation Challenge: Minerals and Energy Winner: Stephan Thiel. *The Australian*. <http://www.theaustralian.com.au/innovationchallenge/minerals-and-energy-winner-stephan-thiel/story-fn9dkrp5-1226771361779>
- Kelly, B. F. J., Timms, W., Ralph, T. J., Giambastiani, B. M. S., Comunian, A., McCallum, A. M., Andersen, M. S., Blakers, R. S., Acworth, R. I., & Baker, A. (2014). A reassessment of the Lower Namoi Catchment aquifer architecture and hydraulic connectivity with reference to climate drivers. *Australian Journal of Earth Sciences*, 61(3), 501-511. doi: 10.1080/08120099.2014.900647
- Keranen, Katie M., Savage, Heather M., Abers, Geoffrey A., & Cochran, Elizabeth S. (2013). Potentially induced earthquakes in Oklahoma, USA: Links between wastewater

- injection and the 2011 Mw 5.7 earthquake sequence. *Geology*, 41(6), 699-702. doi: 10.1130/g34045.1
- Mathews, George (2014, 10 June). [Meeting with OCSE discussing the barriers to the mainstream use of quantitative techniques on uncertainty and risk analysis in the groundwater industry].
- Miles, C., White, M., & Scholz, G. (2012). *Assessment of the impacts of future climate and groundwater development on Great Artesian Basin springs: A technical report to the Australian Government from the CSIRO Great Artesian Basin Water Resource Assessment*. Australia: CSIRO Water for a Healthy Country Flagship Retrieved from <http://www.csiro.au/~media/CSIROau/Flagships/Water%20for%20a%20Healthy%20Country%20Flagship/WaterResourceAssessment/GABWRA/GABWRA-TechnicalReport-GABSprings.ashx>.
- Ng, Alex Hay-Man, Ge, Linlin, Zhang, Kui, Chang, Hsing-Chung, Li, Xiaojing, Rizos, Chris, & Omura, Makoto. (2011). Deformation mapping in three dimensions for underground mining using InSAR – Southern highland coalfield in New South Wales, Australia. *International Journal of Remote Sensing*, 32(22), 7227-7256. doi: 10.1080/01431161.2010.519741
- NHMRC, & NRMCC. (2011). *Australian Drinking Water Guidelines 6 National Water Quality Management Strategy*. (Version 2.0 updated December 2013). Canberra: Commonwealth of Australia, National Health and Medical Research Council, National Resource Management Ministerial Council. Retrieved from http://www.nhmrc.gov.au/files_nhmrc/publications/attachments/eh52_aust_drinking_water_guidelines_update_131216.pdf.
- NSW Public Works. (n.d.). Public Works - Manly Hydraulic Laboratory. Retrieved 27 June, 2014, from www.mhl.nsw.gov.au
- Peacock, J. R., Thiel, S., Reid, P., & Heinson, G. (2012). Magnetotelluric monitoring of a fluid injection: Example from an enhanced geothermal system. *Geophysical Research Letters*, 39(18), L18403. doi: 10.1029/2012GL053080
- Poeter, E. (2007). All Models are Wrong, How Do We Know Which are Useful? *Ground Water*, 45(4), 390-391. doi: 10.1111/j.1745-6584.2007.00350.x
- Rau, Gabriel C., Andersen, Martin S., McCallum, Andrew M., Roshan, Hamid, & Acworth, R. Ian. (2014). Heat as a tracer to quantify water flow in near-surface sediments. *Earth-Science Reviews*, 129, 40-58. doi: 10.1016/j.earscirev.2013.10.015
- Sundaram, B., Feitz, A., de Caritat, P., Plazinska, A., Brodie, R., Coram, J., & Ransley, T. (2009). *Groundwater Sampling and Analysis – A Field Guide*. Canberra: Australian Government, Geoscience Australia. Retrieved from http://www.ga.gov.au/image_cache/GA15501.pdf.
- Sydney Water. (2009). *Sewage Treatment System Impact Monitoring Program* (2010 Update). Sydney Water. Retrieved from http://www.sydneywater.com.au/web/groups/publicwebcontent/documents/document/zgrf/mdq1/~edisp/dd_045379.pdf.
- Tregoning, P., McCluskey, S., van Dijk, A. I. J. M., Crosbie, R. S., & Peña-Arancibia, J. L. (2012). Assessment of GRACE satellites for groundwater estimation in Australia *Waterlines Report Series* (pp. 83). Canberra: National Water Commission.
- UNSW. (2014, 11 June). Connected Waters Initiative. Retrieved 24 June, 2014, from www.connectedwaters.unsw.edu.au/groundwater-eif/super-science-groundwater-database
- US EPA. (2014, 5 May). Water. Retrieved 14 June, 2014, from <http://www.epa.gov/region2/citizenscience/water.html>
- van der Elst, Nicholas J., Savage, Heather M., Keranen, Katie M., & Abers, Geoffrey A. (2013). Enhanced Remote Earthquake Triggering at Fluid-Injection Sites in the Midwestern United States. *Science*, 341(6142), 164-167. doi: 10.1126/science.1238948

- van Dijk, A. I. J. M., & Renzullo, L. J. (2011). Water resource monitoring systems and the role of satellite observations. *Hydrol. Earth Syst. Sci.*, 15(1), 39-55. doi: 10.5194/hess-15-39-2011
- Ward, C R, & Kelly, B F J. (2013). Background Paper on New South Wales Geology: With a focus on basins containing coal seam gas resources. Report commissioned for the independent review of coal seam gas activities in NSW by the NSW Chief Scientist & Engineer: UNSW Global Pty Ltd.
- Waterwatch Victoria. (2014). Data Confidence. Retrieved 25 June, 2014, from <http://www.vic.waterwatch.org.au/monitoring-and-data/152/>

APPENDIX 1: LETTER FROM THE MINISTER



INWA/14197

The Hon Anthony Roberts MP
Minister for Resources and Energy
Special Minister of State

MOC14/1416

07 APR 2014

Professor Mary O'Kane
NSW Chief Scientist and Engineer
GPO Box 5477
SYDNEY NSW 2001

Dear Professor O'Kane

In the context of considering the State's multiple uses of groundwater resources and the need for sustainable use of such resources, I am writing to request that you provide advice to me on the optimal location/placement of monitoring equipment to provide data to inform government and communities about water resources and the impact of Coal Seam Gas extraction, mining activities and irrigation on these resources.

It would also be useful to include information that may assist in prioritising locations.

If you agree, I would ask that you provide your advice to both the Premier, the Hon Barry O'Farrell MP, Minister Katrina Hodgkinson, and myself, by 30 June 2014.

Yours sincerely

Anthony Roberts MP
Minister for Resources and Energy
Special Minister of State