PUTTING GROUNDWATER ON THE MAP:
A STATUS REPORT ON HYDROGEOLOGICAL MAPPING IN AUSTRALIA.

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Abstract:

From traditional indigenous symbology to the digital products of today, hydrogeological mapping has been an important tool for groundwater managers and users in Australia. Maps of varying styles and formats have been used to synthesise and interpret data from different sources, and to represent the understanding of groundwater systems. These range from nation-wide perspectives of groundwater availability, flow systems and salinity, to regional 1:250,000 scale maps in priority management areas, to more detailed and localised mapping.

Hydrogeological mapping in Australia has arrived at an important milestone in its evolution. Up until the 1990s, a typical map was hardcopy and depicted parameters such as aquifer yield, groundwater salinity or potentiometry, and focussed on the development of the available groundwater resource. Over the past decade there has been a major transition in terms of how and why hydrogeological maps are compiled. During this time, natural resource management has changed from a development focus to one of conservation and sustainability. In response, hydrogeological maps have diversified and either become more specialised, dealing with issues such as water quality protection or ecosystem dependencies, or have become more integrated, with groundwater information being combined with other data sets to deal with broader issues such as conjunctive use or dryland salinity.

At the same time, the digital revolution has made an irreversible impact on how hydrogeological maps are compiled and delivered. Nowadays, hydrogeological information is routinely being derived and stored in an array of different digital mechanisms such as geographical information systems, relational databases, groundwater flow models, image processors, statistical packages and surface interpolators, with techniques from the simple to the complex. The term “map” is being replaced by words such as dataset, coverage, surface, interpolation, contours, raster, array, or image. True 3-D visualisation tools are being applied to groundwater studies, with advances in computing capability making these tools more accessible. The nomenclature has changed from that of hydrogeological mapping to that of hydrogeological characterisation and visualisation.

The optimal way forward to get the most out of hydrogeological mapping will actually be a blend of the old with the new. We need to take advantage of the digital developments taking place both nationally and internationally – the growing functionality in data analysis and processing, the emerging data infrastructures designed to facilitate timely and cost effective information access, and the data standards to deliver consistency and productivity. However, there is also great benefit in revisiting the historical roots of mapping. There is a strong case for continuing the mapping of a core set of hydrogeological parameters such as aquifer yield, groundwater salinity and potentiometry, as these are flexible datasets that are used for a wide range of purposes, and in fact the foundation of much of the specialised mapping. In this way, a fundamental dataset such as depth to watertable can be made available for a wide variety of purposes such as understanding groundwater processes, determining resource access, defining vulnerability to contamination, targeting areas of ecosystem dependency and mapping salinity hazard. There is also a huge repository of historical mapping, not only as published hardcopy maps but also embedded in reports, journals, management plans and theses. Whenever these are converted into digital format, there should be a concerted effort to have the data made appropriately accessible within the infrastructures currently being constructed, using the standards available. Lastly, modern mapping can always benefit from the strong cartographic traditions established by previous mapping generations in terms of layout, symbology and colour design.

Key Words:

General hydrogeology, geographic information systems, hydrogeological maps, Australia

INTRODUCTION

Consumptive water use over about 80% of the Australian continent is significantly if not totally dependent on groundwater. Use of groundwater exceeds surface water in both Western Australia and the Northern Territory. Without groundwater, much of the nation’s pastoral industry, a significant proportion of agriculture and many mines would not be viable. The Great Artesian Basin, covering 1.7 million km^2 or one-fifth of Australia, is one of the world’s largest aquifers. Groundwater management is a significant and strategic issue. From traditional indigenous symbology to the digital products of today, hydrogeological mapping has been an important tool for groundwater managers and users in Australia. Maps of varying styles and formats have been used to synthesise and interpret data from different sources and to represent the understanding of groundwater systems.

AN HISTORICAL PERSPECTIVE

Stylised mapping showing the type and relative location of water supplies, combined with oral instruction, was of paramount importance for the survival of the traditional Aboriginal inhabitants of the Australian arid zone (Bayly 1999). These maps were portrayed in many forms, including decorated weapons or domestic implements, rock engravings, body paintings or sand drawings (Caruana 1989). The typical symbology consists of concentric circles representing the water supply (amongst other things like a camp or fire) and these are connected with lines, generally in the appropriate compass direction, but not to scale in terms of distance (Tindale 1974). These maps are placed into context by detailed narrative, with each water source named and described. Thomson (1962) gives an account of such a process that occurred at the end of his travels in 1957 with the Bindibu (=Pintupi) of the Great Sandy Desert, Western Australia:

> "Just before we left, the old men recited to me the names of more than fifty waters – wells, rockholes and claypans… in an area that the early explorers believed to be waterless… And on the eve of our going, Tjappanongo produced spear throwers, on the backs of which were designs deeply incised, more or less geometric in form. Sometimes with a stick, or with his finger, he would point to each well or rock hole in turn and recite its name, waiting for me to repeat it after him… I realised that here was the most important discovery of the expedition – that what Tjappanongo and the old men had shown me was really a map, highly conventionalised, like the works on a "message" or "letter" stick of the Aborigines, of the waters of the vast terrain over which the Bindibu hunted", refer Figure 1.

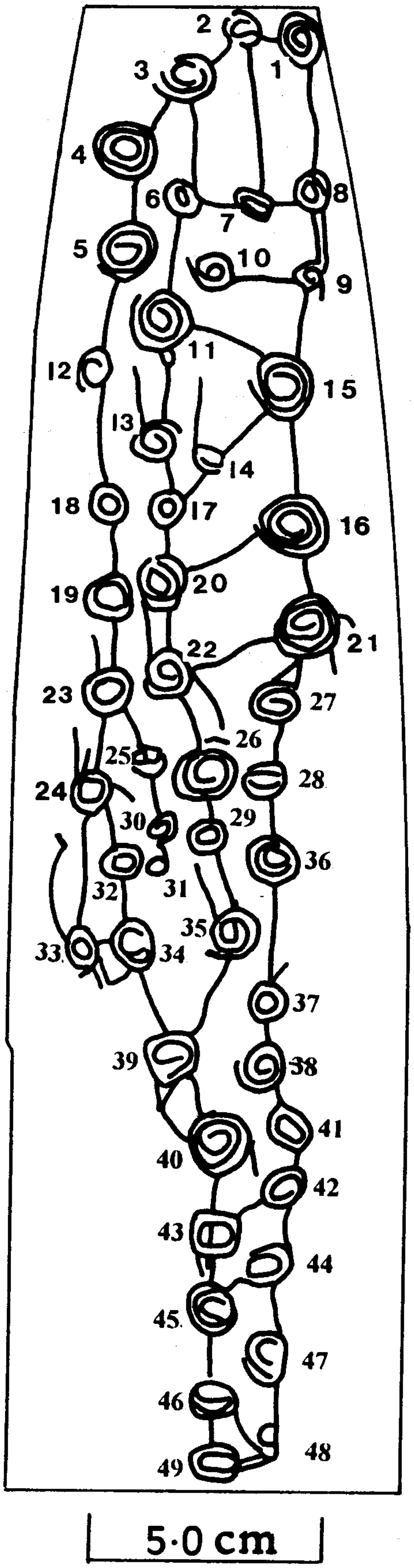
Williamson (2001) provides an account of the historical development of hydrogeology in post-colonial Australia. The first documented groundwater report in Australia is thought to be that by the Rev. W. B. Clarke dealing with investigations into providing a secure water supply for the Sydney colony (Clarke 1850). A bore drilled within the bounds of Darlinghurst Gaol targeting artesian groundwater at 500 feet was abandoned at 75 feet, owing to sabotage by the prison inmates who had to provide the motive power for the drilling rig.

The early publication of maps with groundwater information is linked to the development of the State geological surveys. Primed by the discovery of gold, these were first established in Victoria (1856) and then Queensland (1868), with the remaining States following from the 1870s onwards. In 1857, the Victorian Geological Surveyor provided a report to the State Legislative Assembly defining areas in the colony where flowing artesian supplies could be potentially sought (Selwyn 1857). Although focussed on mineral prospecting and mining, some of the early work of the geological surveys had relevance to hydrogeology. For example, Smythe (1869) reported the issue of dewatering the deep lead gold workings of the Victorian Majorca goldfield. Over time, locations of bores and wells were incorporated onto published geological maps, and groundwater data reported.

The development of the groundwater resources in the Great Artesian Basin provided the impetus for the first major regional mapping directed at groundwater conditions. Drilling in the basin rapidly expanded after the successful completion of a flowing artesian bore near Bourke, NSW in 1878. Concerns about water wastage and pressure declines quickly followed. A series of five Interstate Conferences on Artesian Water held between 1912 and 1928 give early examples of regional mapping of recharge areas, groundwater potentials, flow directions and temperature gradients (eg Interstate Conference on Artesian Water 1929). Early mapping of groundwater resources in other parts of Australia include the work of Jack (1912), Nye (1921), Kenney (1934) and Mulholland (1940), focussing on drier inland areas.

Exploratory drilling (and groundwater mapping) expanded from the post-war 1950s, with water resource development being the priority. Examples include regional groundwater investigations in the Flinders Ranges (O'Driscoll 1956), the upper Hunter Valley (Williamson 1958), the Murray Geological Basin (O'Driscoll 1960; Johns and Lawrence 1964), the Dumaresq River Valley (QIWSC 1965) and the Pilbara region (Davidson 1975). The formation of the Australian Water Resources Council in 1963 lead to the milestone publication of the first comprehensive nation-wide map of Australia's groundwater resources (AWRC 1965). This highlighted the significant information gaps and initiated greater government investment in hydrogeological research and investigations. This is reflected in improved national groundwater resource maps a decade later (AWRC 1975). These outlined the general availability and salinity of groundwater in the sedimentary basins, fractured rock provinces and unconsolidated sediments across the country.

The 1980's heralded the more routine release of hydrogeological maps as specific publications, rather than being incorporated into reports and journals. The 1:100,000 scale hydrogeological map of Western Port Basin (Lakey and Tickell 1980) is an early example. Compilations based on 1:250,000 mapsheets also commenced, such as for the BENDIGO (Tickell and Humphreys 1985), FORBES (Ross *et al* 1986) and the BALLARAT sheets (AGC 1986) in the east and the PERENJORI (McGowan 1987) sheet in the west. Meanwhile, the State-wide compilations of groundwater availability such as for South Australia (Shepherd 1982), Victoria (Nahm 1982) and Queensland (Laycock and Wecker 1971), formed the basis of an updated version of an Australia-wide hydrogeological map (Jacobson and Lau 1987; Lau *et al* 1987).



1. Labbi-labbi
2. Tananga
3. Liuwiringa
4. Kunnamannera
5. Maiyada-maiyada
6. Wirra-wirra
7. Kirindji
8. Kanandibaroo
9. Markodarindja
10. Kampanbarro
11. Wirrkaldjarra
12. Pinna
13. Luwano
14. Kira
15. Tjul'tjun'waridji
16. Dandju
17. Tildi
18. Wakilbi
19. Kuna
20. Pintinba
21. Yinindi
22. Yalbirrimanno
23. Tanda
24. Kurandal
25. Palta
26. Kura
27. Binbiyan
28. Tjipallalla
29. Yirabanda
30. Dangalli
31. Yappadarra
32. Timbabiddi
33. Yuldumallo
34. Kunagarri
35. Mukubanda
36. Mari-mari
37. Karruwildji
38. Wallabarrarba
39. Kiribarro
40. Yanna
41. Wangadjarro
42. Wornba
43. Tjimarri
44. Kunananno
45. Wirrarigulong
46. Danneriyono
47. Miltji-miltji
48. Papulba
49. Lola

Figure 1. A stylised map of the Western Australian water resources of the Bindibu (=Pintupi) as carved into the back of a spear thrower. Drawn by Bayly (1999) from a photograph of Thomson (1962).

Between 1989 and 1994 saw the publication of 26 maps at 1:250,000 scale forming the Murray Basin Hydrogeological Map Series (Evans 1992). This was a milestone in terms of setting a consistent map format and cartographic standard for a regional hydrogeological map series. It was also important in providing a basin-wide perspective that crossed State borders, that was followed by other examples in the Amadeus Basin (Lau 1992), the Darling River drainage basin (Evans *et al* 1995) and the Great Artesian Basin (Habermehl and Lau 1997). The application of geographical information systems (GIS) in hydrogeological mapping also gained momentum during the early 1990s.

A significant departure from the traditional role and format of hydrogeological maps occurred from about 1994 onwards. Maps started being published that were more than portrayals of the general characteristics of the groundwater system in terms of yield, salinity and potentiometry, but integrated with other information. The series of water resource development maps in the Northern Territory such as Tickell and Rajaratnam (1994), where groundwater and surface water information were combined on the mapface is typical of this trend. A more recent example is the integration of ecological data with groundwater data in the mapping of groundwater dependent ecosystems (Brodie *et al* 2002).

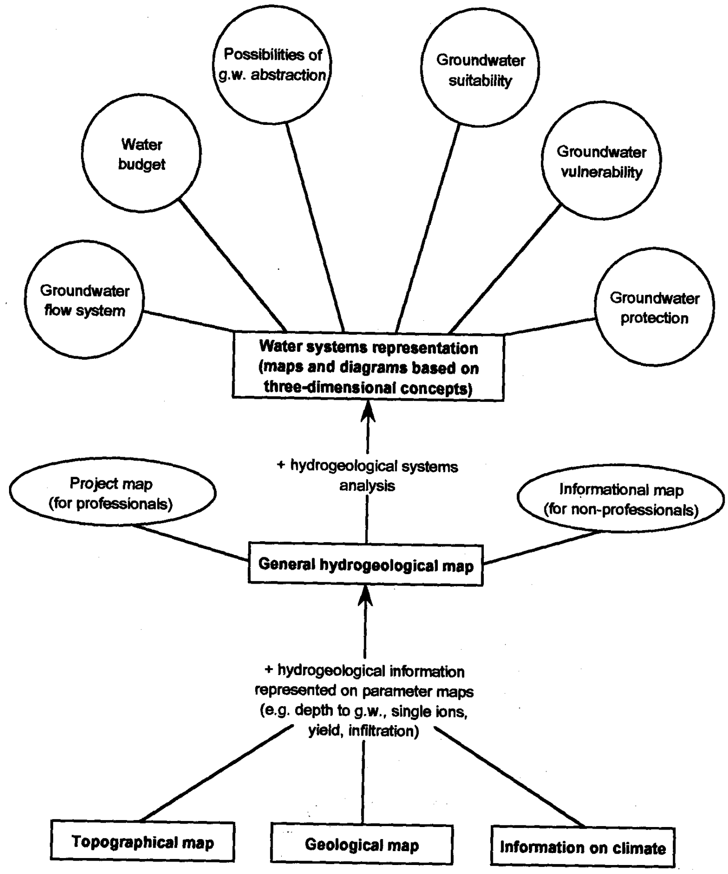


Figure 2. Evolution of hydrogeological maps (Struckmeier & Margat 1995)

Specialised mapping also became prevalent. For example, beneficial use maps of Victoria were produced on the basis of groundwater salinity thresholds (SKM 1996). Groundwater vulnerability mapping commenced in Western Australia (Appleyard 1993), New South Wales (such as Piscopo and Please 1997) and in Queensland (such as Stenson and Hansen 1998). Management of dryland salinity also gave recent impetus for compilation of hydrogeological data, indicating areas of shallow watertable or rising groundwater levels. One of the earliest dryland salinity hazard maps was one for the Northern Territory (Tickell and Tyson 1994), the most recent being the assessments completed for the National Land and Water Resources Audit (NLWRA 2001).

There are two main drivers for maps from the 1990s becoming either more integrated with other datasets or more specialised. The first is that natural resource management made the fundamental transition from a development phase to a conservation one. In terms of groundwater, this is encapsulated in the *National Water Reform* framework (CoAG 1994) and its specific recommendations relating to groundwater (SLWRMC 1996). Groundwater use and resource potential have branched out into issues such as quality protection and sustainable yield and there is now a need to understand how groundwater interacts with other parts of the biophysical world such as surface water, ecosystems or salt stores. This created the demand for more specialised or integrated mapping. On the supply side, the other main driver is the digital revolution that has made it easier to address these new demands.

In summary, the history of hydrogeological mapping in Australia follows the classic evolutionary path as outlined by Struckmeier & Margat (1995), refer Figure 2. Some of the 19th century topographic or geological maps, notably from the State geological surveys were annotated with groundwater information such as location of bores and indications of water quality. These progressed to general hydrogeological maps *per se* describing groundwater conditions in combinations of availability, quality or potentiometry. Over the last decade, the more traditional mapping has been joined by mapping designed for specific purposes such as groundwater vulnerability, beneficial use or ecosystem dependency.

TOWARDS A NATIONAL COVERAGE

The compilation by Jacobson and Lau (1987) is still the most current Australian-wide perspective of hydrogeological parameters such as aquifer type, groundwater availability, salinity and regional flow directions in the traditional mapped form. Rather than presenting information in this way , as has been the trend in previous national water resource reviews, the recent National Land and Water Resources Audit (NLWRA) has taken a different approach. Out of this audit has come three significant national compilations of hydrogeological significance:

(i) Mapping of 538 groundwater management units and unincorporated areas, the former being the hydraulically connected groundwater systems that are defined and recognised by State/Territory agencies for management purposes, the latter being residual areas with low levels of groundwater development and corresponding management input. These have been aggregated into 69 groundwater provinces for reporting purposes. Information such as surface area, groundwater allocation and use, average salinity, depth to top of aquifer, and an estimate of sustainable yield has been compiled for each unit where available. This allowed a national analysis of where groundwater resources are overallocated or overused relative to sustainable yield estimates.

(ii) Mapping and categorisation of groundwater flow systems, based on recharge and flow behaviour and using attributes such as elevation, landscape form and geology (Coram *et al* 2000). Local, intermediate and regional groundwater flow systems were identified across a range of geological and geomorphological terranes (Figure 3). The mapping was aimed at how groundwater systems respond to changing recharge and for defining appropriate salinity management options.

(iii) Mapping of current and future dryland salinity hazard. These assessments were undertaken by State/Territory agencies using a combination of groundwater levels and trends, known salinity incidences, soil properties and topography.

These national coverages, with similar compilations for land use, vegetation and soils, are being made available from the Australian Natural Resources Atlas (http://audit.ea.gov.au/ANRA/).

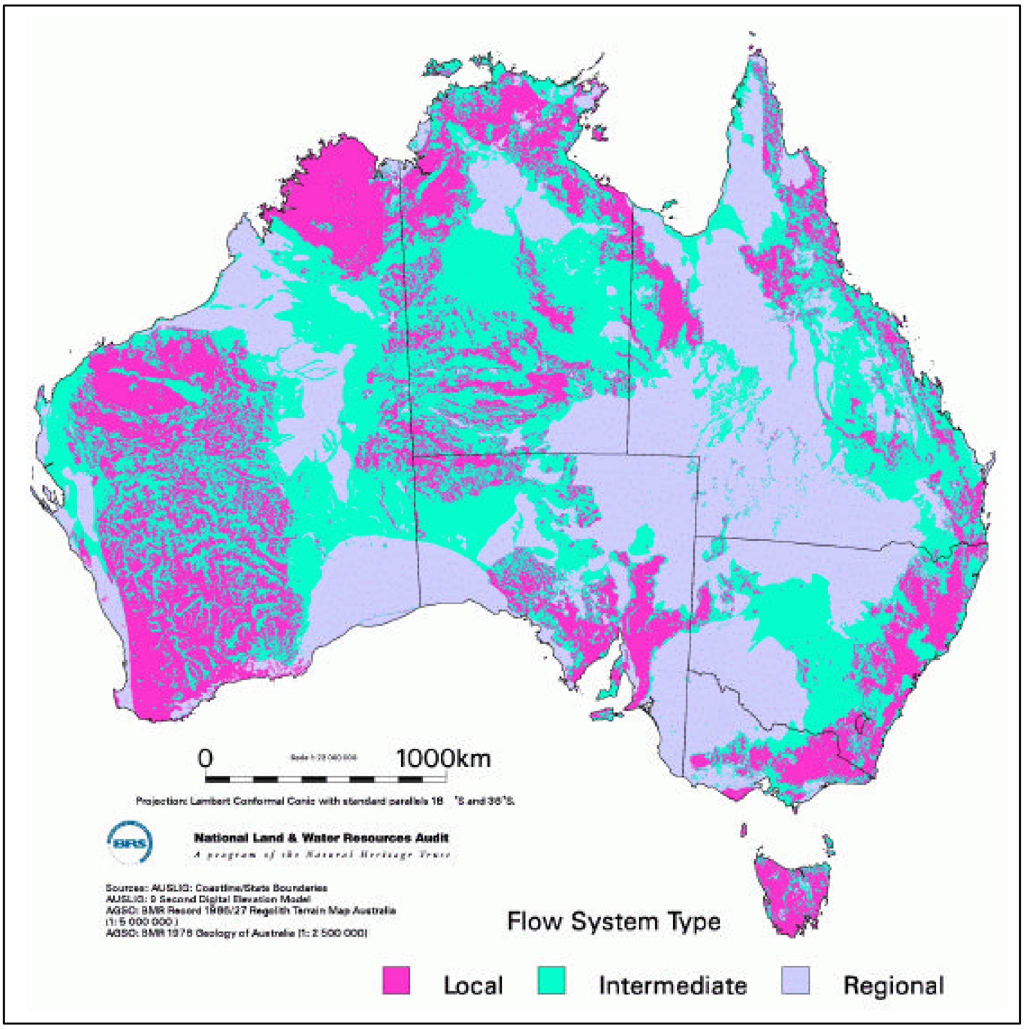


Figure 3 Summarised Australian groundwater flow systems contributing to salinity (Coram *et al* 2000)

Figure 4 shows the extent of published hydrogeological maps at 1:250,000 scale or more detailed, across Australia. These are the printed maps that depict various combinations of the traditional hydrogeological parameters of groundwater availability, salinity and potentiometry. The recent mapping initiatives dealing with groundwater vulnerability, dryland salinity or beneficial use are not included. Nevertheless, the distribution is still an indication of some of the priority areas. In Western Australia, detailed mapping supports groundwater management in the Perth metropolitan area (eg Davidson, 1995), with 1:250,000 scale maps mostly in the south-west and Goldfield regions. The coverage in the Northern Territory consists of the water resources mapping undertaken in areas like the Western Victoria River District, Sturt Plateau, Alice Springs region and Arnhem Land. Much of this mapping was funded through the National Landcare Program/Natural Heritage Trust (Tickell *pers comm*). The maps of the Murray Basin Hydrogeological Map Series are a significant information resource for southeastern Australia. To update and extend this mapping, the Murray Darling Basin Commission is currently funding the mapping of hydrogeological datasets such as watertable elevation, depth to watertable, potentiometry of (semi-)confined aquifers, maximum drawdown and groundwater salinity across the entire Murray-Darling Basin (MDBC 2000). In Tasmania, hydrogeological mapping is focussed on key agricultural areas such as the Midlands, near Devonport and the Fingal and Coal River Valleys.

However, this perspective of the extent of hydrogeological mapping across Australia is by no means complete. The published hydrogeological map is only a small subset of a vast repository of mapping that has been undertaken, with hydrogeological maps embedded in journals, reports, unpublished consultancies, research theses or management plans. For example, the Queensland Department of Natural Resources and Mines (QDNRM) and its predecessors have undertaken extensive groundwater investigations and hydrogeological mapping of the fluviodeltaic sediments along the coast (such as the Don River and Burdekin Delta), the alluvial deposits of the major inland rivers (such as the Condamine and Warrego Rivers), and the fractured basalts of the Darling Downs and Atherton Tableland (Bedford *pers comm*).

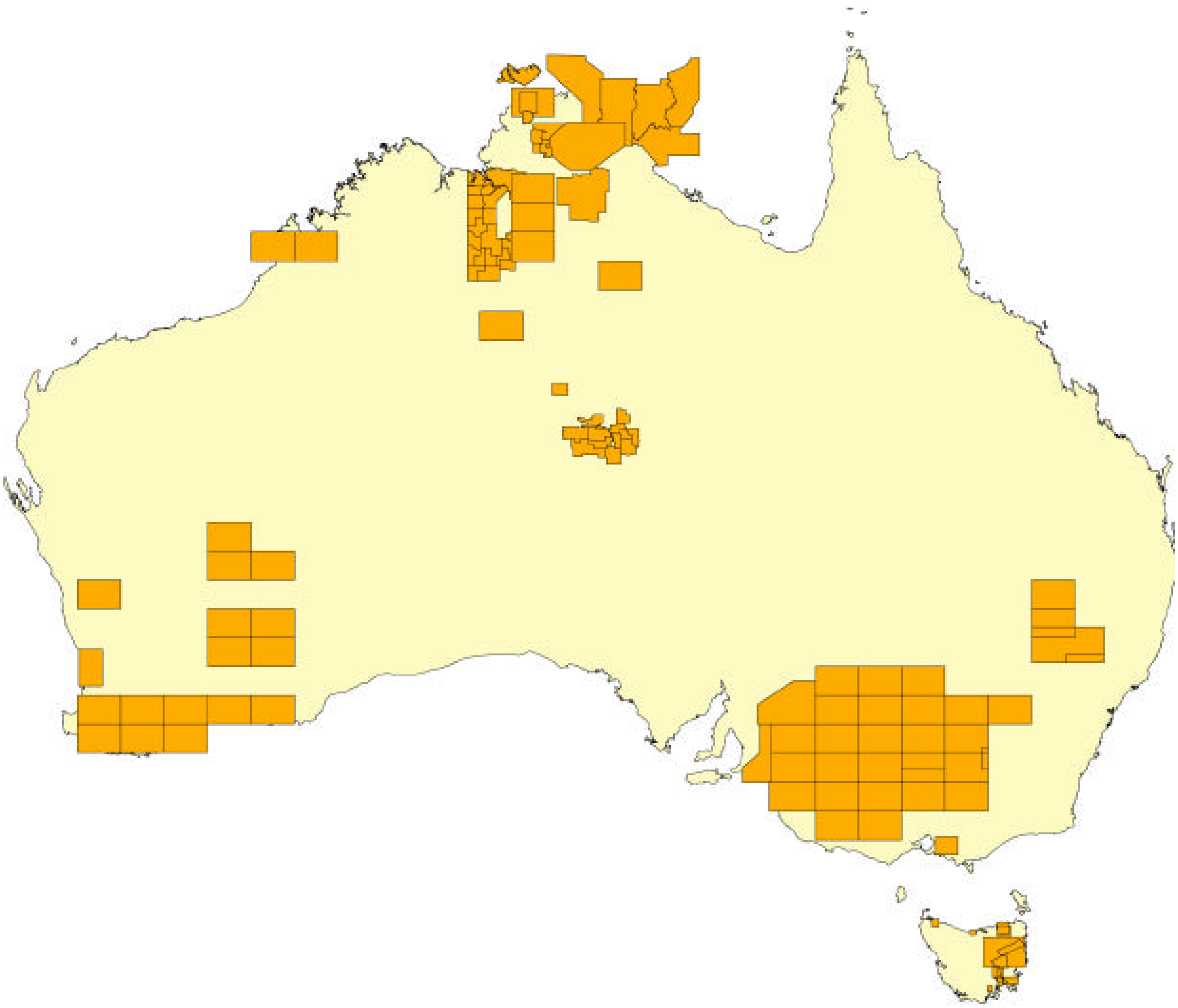


Figure 4 Extent of traditional published hydrogeological maps at 1:250,000 scale or more detailed

GOING DIGITAL

Hydrogeological mapping, like everything else, has been caught up in the digital revolution of the last decade or so. The first milestone was the replacement of manual map preparation with CAD/CAM techniques starting in the late 1980s. The 1:5,000,000 scale Hydrogeology of Australia (Jacobson & Lau, 1987) was the first major map compiled in this way. The advent of GIS revolutionised the concept of what was a hydrogeological map. Rather than be limited to a static paper medium, hydrogeological information could be presented and updated with a myriad of different datasets, in different styles and scales. GIS overcame the limitations of a single sheet map, particularly relating to the depiction of multi-aquifer information in layered sedimentary sequences. Over time, the use of GIS progressed from being a mapping and data presentation tool to its powerful capability in data analysis. Nowadays, hydrogeological information is routinely being derived and stored in an array of different digital mechanisms such as GIS, relational databases, groundwater flow models, image processors, statistical packages and surface interpolators, with techniques from the simple to the complex. The term “map” is being replaced by words such as data set, coverage, surface, interpolation, contours, raster, array, or image.

The advantages of this revolution are well known, in terms of greater flexibility, functionality and productivity. Many large mapping agencies now provide hardcopy maps as print-on-demand, perhaps tailored to the client, rather than a formal print run with all its inherent costs of publication and storage. The transfer of mapping in digital form rather than physical is expanding rapidly. The issue of information access is vexed. On the one hand, the digital revolution has significantly enhanced the timely and affordable access of groundwater information. The web sites of the State groundwater agencies are testimony to this trend. For example, the Perth Groundwater Atlas (http://www.wrc.wa.gov.au/infocentre/atlas/atlas_html/) is an interactive online resource for anyone interested in the groundwater conditions of the Perth metropolitan area. The WA Water and Rivers Commission also provides another similar service for state-wide hydrogeology in terms of regional mapping of aquifer type and salinity (http://www.wrc.wa.gov.au/hydrogeological_atlas). The linework for the 1:250,000 scale hydrogeological mapping is also available via http://www.walis.wa.gov.au/walis/content/wa_atlas_use.html. Images of hydrogeological maps have also been made available online such as in the Northern Territory (http://www.lpe.nt.gov.au/advis/water/ground/) and in Victoria (http://www.nre.vic.gov.au/web/root/Domino/vro/vrosite.nsf/pages/water-ground) On the other hand, data access can become complex and problematic – anyone that has attempted to import data from an obscure software package can testify to this. This is where the global effort in developing data standards comes into play.

KEEPING TO A STANDARD

With the explosion of hydrogeological mapping in all its variants in the last twenty years, there has been increased recognition for the need for standards. Mapping protocols allow users to readily compare one map with another, promote cost effective compilation, encourage best practice and reduce the risk of misinterpretation.

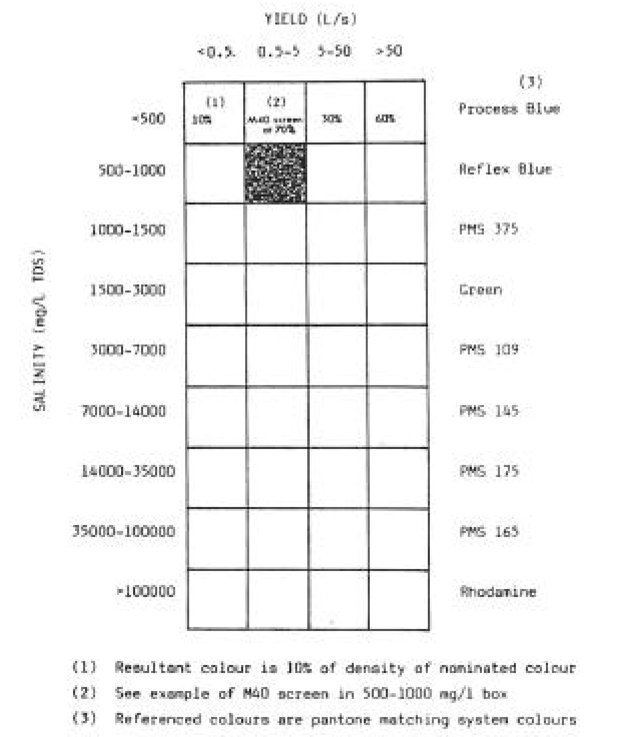


Figure 5. Salinity/yield matrix for hydrogeological maps (AWRC 1988)

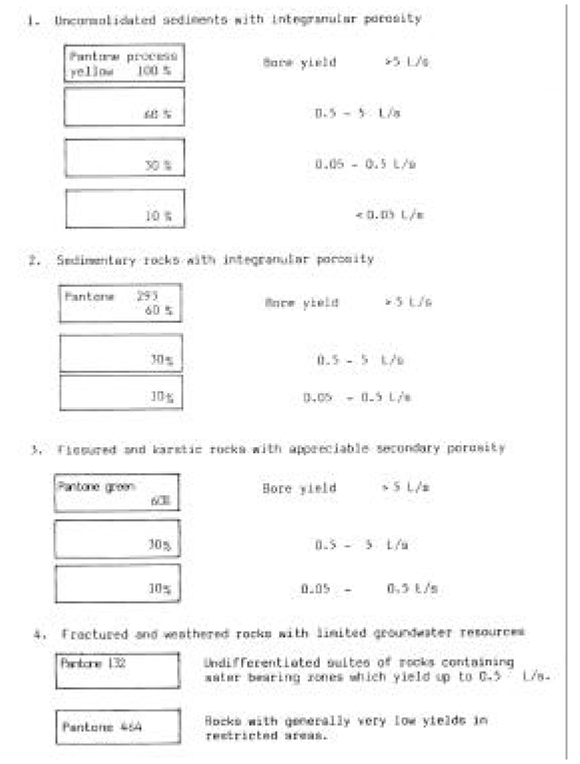


Figure 6. Modified aquifer type - yield classification (AWRC 1988)

International groundwater mapping standards were first addressed by a draft legend published by UNESCO (1963). This was used initially for 1:500,000 scale hydrogeological mapping of Europe and subject to a number or revisions (UNESCO 1970; UNESCO 1983). In 1988, a working group supported by the Australian Water Resources Groundwater Committee defined Australian guidelines for the preparation of hydrogeological maps (AWRC 1988). Instead of using the colour fill to represent aquifer types and yield as on the International Legend (UNESCO 1983), the committee reserved map colours for the combination of groundwater salinity and aquifer yield (Figure 5). This recognised that in Australia, groundwater salinity was highly variable and generally the dominant factor in defining the usefulness of the water. The groundwater salinity (mg/L) categories are defined by thresholds for different potential water uses such as drinking, irrigation and livestock. The aquifer yield (L/s) is interpreted as the most likely pumping rate obtainable from a bore located in an optimum location in the aquifer. Where the aquifer type classification was to be used, the committee recommended a modified version of the UNESCO standard (Figure 6). This allowed surficial alluvial and coastal plain aquifers to be differentiated from aquifers in sedimentary basins. Recommendations were also made on the map symbols, lines and ornaments to be used on the hydrogeological map.

In 1995, the IAH Commission for Hydrogeological Maps published guidelines for the preparation of hydrogeological maps (Struckmeier & Margat 1995). The scope of the guide book is broad, as it describes the concepts, components, characteristics, types, justification and evolution of hydrogeological maps, the basic information required for their compilation, general cartographic principles of representation and scale, and the techniques for preparation and publication. Also included is the standard international hydrogeological legend, as well as ornaments based on lithology. Symbology for point (eg springs, wells), line (eg flow, divides, contours, streams) and polygon features (eg. area of artesian flow, groundwater seepage, lakes) is also provided. A similar guidebook has been published by the IAH Commission for Groundwater Protection, dealing with groundwater vulnerability (Vrba & Zaporozec 1994).

With increasing emphasis on digital products in the last decade, there has been a transition from cartographic standards to data standards. In 1999, an intergovernmental working group under the direction of the National Groundwater Committee, released national guidelines for the transfer of basic groundwater data (NGC 1999, http://www.brs.gov.au/land&water/groundwater/). These are designed to facilitate the efficient transfer of the groundwater data commonly collected in the field, such as water levels, pumping rates, geological and geophysical logging, water chemistry and construction details of bores. These standards are highly relevant to the compilation of hydrogeological maps and include:

(i) A *data model* that describes data and how it is organised.
(ii) A collection of *attribute domains* that define the possible values of parameters. There are comprehensive lists of codes and their description for a wide variety of parameters such as chemical analytes, lithologies, minerals, colour and construction material.
(iii) *Data conventions* that are the rules about how data is represented. The classic quandary is whether standing water levels above the measuring point (eg artesian heads) should be reported as positive or negative values.
(iv) Standard *units of measurement* defined for many parameters that are measured eg metres for depth, degrees Celsius for temperature. Multiplication factors have been compiled to provide consistency in how data is converted from other units of measurement.
(v) The incorporation of *data quality indicators* with the dataset, to judge its appropriateness and how it should be analysed. The data model allows the opportunity for basic field measurements to be accompanied with information such as the instrument used, the nominal error margins, any correction factors etc.
(vi) Guidelines about how to define the *data source*, so that the user can investigate the data further.

Hydrogeological mapping is also party to the national (and global) standards and initiatives being developed for spatial data in general. In terms of consistent spatial positioning, the Intergovernmental Committee on Surveying and Mapping (ICSM) in 1994 adopted a new coordinate system for Australia, called the Geocentric Datum of Australia (GDA, http://www.anzlic.org.au/icsm/gda). This allows global compatibility for geographical coordinates and the direct linkage with the Global Positioning System (GPS), following the trend in positioning, navigation and information systems being related to a global (rather than a regional) Earth model. The earth-centred nature of GDA differs from its predecessor, the Australian Geodetic Datum (AGD) that was adopted to fit the Australian region. The Map Grid of Australia (MGA94) is the Universal Transverse Mercator (UTM) projection of the GDA latitudes and longitudes. As such, these grid coordinates supersede the Australian Map Grid (AMG) coordinates. There is a displacement of about 200m across Australia in a northeast direction, between coordinates of points using the old and new standard.

There are now also national guidelines for metadata – how information such as source, scale and availability of a spatial data set is reported (ANZLIC 2001, http://www.anzlic.org.au/asdi/metaelem.htm). Metadata is critical in terms of finding what data is available, how it was produced and whether it is suitable for your purposes. It is a fundamental part of data storage and management. The metadata guidelines form the foundation for the Australian Spatial Data Directory (ASDD, http://www.auslig.gov.au/asdd/) established to improve access to currently about 28,000 spatial data sets across Australia. The directory is a component of the Australian Spatial Data Infrastructure (ASDI, http://www.anzlic.org.au/asdi/asdimain.htm), aimed at providing consistent and timely access to spatial data that is collected and maintained by a wide range of organisations. The ASDI is part of a spectrum of data infrastructures that span from a State perspective (such as the CANRI initiative in New South Wales, http://www.canri.nsw.gov.au/) to an international one (the Global Spatial Data Infrastructure, http://www.gsdi.org/).

The growth of GIS applications and routine use of digital spatial data has resulted in global initiatives dealing with standards in the field of digital geographical information. The International Organization for Standardization (ISO) formed a technical committee (ISO/TC 211, http://www.isotc211.org/) in 1994 to define such standards. There are cooperative links between this work and that done by the Open GIS Consortium http://www.opengis.org in developing specifications that support open access to geographical information and geospatial processes. The United Nations has also established a working group dealing with geographic information (UNGIWG, http://als.unep.org/ungiwg/).

MAPPING IN FOUR DIMENSIONS

Groundwater systems operate in four dimensions made up of 3-D space plus time. Up until recently, our representation of groundwater systems has been essentially two-dimensional, either as static planimetric maps or cross sections. This has severely limited our ability to portray subsurface complexity and groundwater dynamics. Since the mid 1990s there has been significant growth in the development of multi-dimensional visualisation tools in groundwater studies, with advances in computing capability making these tools more accessible.

Groundwater modelling is a significant driver of this trend with many pre/post-processor software packages now offering an array of visualisation tools. These allow borehole data to be located in space, dynamic processes such as contamination plumes or cones of depression to be animated, surfaces such as isoconcentrations or isopotentials rendered and multiple slices oriented along any axis. The nomenclature has changed from that of hydrogeological mapping to that of hydrogeological characterisation and visualisation.

CONCLUSIONS

Hydrogeological maps, from traditional indigenous symbology to the digital products of today, have been important to groundwater managers and users in Australia. Maps of varying styles, scales and formats have been used to synthesise and interpret data from different sources and to represent the understanding of groundwater systems. These range from nation-wide perspectives of groundwater availability, flow systems and salinity, to regional 1:250,000 scale maps in priority management areas, to more detailed and localised mapping.

Hydrogeological mapping in Australia has arrived at a significant milestone in its evolution. Initially, the ‘old world’ hardcopy mapping of parameters such as aquifer yield, groundwater salinity and potentiometry focused on development of the groundwater resource. Mapping in the ‘new world’ since the 1990s has become much more diverse, reflecting the transition from a development paradigm to a resource conservation one, as well as the impacts of the digital revolution.

An optimal way forward to get the most out of hydrogeological mapping will actually be a blend of the old with the new. We need to take advantage of the digital developments taking place both nationally and internationally – the growing functionality in data analysis and processing, the available data infrastructures designed to facilitate timely and cost effective information access, and the data standards to deliver consistency and productivity. In this way, hydrogeological mapping can continue to branch out from its traditional roots, both in terms of increasing specialisation in the groundwater arena (eg. vulnerability, protection, environmental requirements) and also integration with other disciplines to resolve broader natural resource management issues (eg dryland salinity, acid sulphate soils, conjunctive use).

However, there is also great benefit in revisiting the historical development of mapping. There is a strong case for continued mapping of the core set of hydrogeological parameters such as aquifer yield, groundwater salinity and potentiometry, as these are flexible datasets that are used for a wide range of purposes, and in fact the foundation of much of the specialised mapping. In this way, a fundamental dataset such as depth to watertable can be made available for a wide variety of purposes such as understanding groundwater processes, determining resource access, defining vulnerability to contamination, targeting areas of ecosystem dependency and mapping salinity hazard. There is also a huge repository of historical mapping, not only published hardcopy maps but also embedded in reports, journals, management plans and theses. Whenever these are converted into digital format, there should be a concerted effort to have the data made appropriately accessible within the data infrastructures currently being constructed, using the standards available. Lastly, modern mapping can always benefit from the strong cartographic traditions established by previous mapping generations in terms of layout, symbology and colour design.

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