PAPER

The 3D Water Atlas: a tool to facilitate and communicate new understanding of groundwater systems

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Abstract

Effective management of groundwater resources requires an understanding of the complexity of groundwater systems by the experts, and a certain level of understanding and trust in management by the community. Groundwater data sharing and visualisation systems are being used across the world to provide an insight into groundwater systems. The 3D Water Atlas of the Surat Basin, Queensland, Australia, provides a way of visualising and analysing hydrogeochemical information in a way that is accessible to a wide audience. It combines data on the location, construction, water chemistry and water levels of groundwater bores within the framework of a geological model and other spatial datasets. It is freely available on a single Web-based interactive three-dimensional (3D) platform. Visualisation tools such as line graphs of groundwater bore water levels, pie charts and animations of major ions, can be used to advance understanding of groundwater resources. For example, a general regional decline, but with local variability in Hutton Sandstone groundwater levels in the Surat Basin can be seen by using the 3D Water Atlas. The combination of groundwater data with filtering, analysis and visualisation tools in the 3D Water Atlas helps to communicate complex hydrogeological concepts. It can also assist with the management of groundwater resources by improving confidence in decision-making, as necessary information can be viewed together, in context. Although the 3D Water Atlas was produced for the Surat Basin, its design means that 3D Water Atlases for different regions can be produced easily.

Keywords Australia · Groundwater management · 3D visualisation · Quality control · Geographic information systems

Introduction

Management of groundwater resources can be a difficult task. It is a resource that goes largely unseen and is poorly understood

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by the community (Baldwin et al. 2012). The complexity of groundwater systems also makes it difficult for experts to fully appreciate the nature of the resource and to predict the effects of various groundwater users on the resource. There is increasing reliance, as well as unsustainable extraction of groundwater resources world wide (Konikow and Kendy 2005, Wada et al. 2010, Gleeson et al. 2012). The arrival of new groundwater users to a region such as the coal seam gas industry (CSG, also known as coal bed methane) in the Great Artesian Basin, Australia (Towler et al. 2016), also emphasises the need for improved and cumulative management systems and tools that enhance understanding of groundwater systems (Vink 2014). The management systems must also be accepted by groundwater users and the broader community (Howe et al. 2010; Vink 2017).

Effective management of complex systems such as groundwater requires at least a certain level of acceptance by stakeholders of the "management rules" and the process by which the rules are made (Lockwood et al. 2010). Much has been written about stakeholder acceptance, particularly in the context of social licence to operate (see Moffat et al. 2016 for a review) and governance (Bingham et al. 2005, Lockwood et al. 2010,

Hess 2007). Common elements in literature regarding stake-holder acceptance include enhancing trust through transparency and access to information, and the need for a shared understanding or mental model of the system being managed.

While trust is usually enhanced through access to information regarding how and why decisions are made (Lockwood et al. 2010), the provision of data through open data initiatives can also enhance trust by providing more information on which people can base decisions (O'Hara 2012). Work by Dando and Swift (2003) has shown that trust in data made available through transparency initiatives is improved through third party assurance of the data. Visualisation support has also been shown to help groups reach a shared understanding and achieve consensus in decision making related to spatial problems faster than if no visualisation support is given (Swaab et al. 2002). Bosch et al. (2003) argue that collaborative learning environments and information management systems are essential for integrating management and science. An opportunity therefore exists to improve groundwater management through the provision, visualisation and quality assurance of groundwater data.

A vast array of software and Web platforms exists that can be used to visualise groundwater information; however, many of them have been designed specifically to be used for groundwater modelling (e.g. MODFLOW) or they may rely on access to proprietary software such as the British Geological Survey's BGS GISGroundwater (Wang et al. 2016), that requires ArcGIS. Alternatively, many of the freely available platforms have been designed to display a wide range of, usually 2D spatial data, for example Australia's NationalMap (Australian Government 2018), and therefore are not particularly suited to displaying more complex groundwater data within a 3D geological context.

Over recent years platforms have been developed specifically to provide free groundwater data to the public. Most of them are Web-based 2D map services that allow users to view and interact with groundwater information within a particular jurisdiction. For example, the United States National Groundwater Monitoring Network (USGS Office of Water Information 2019), the Republic of Korea's National Groundwater Monitoring Network and Groundwater Quality Monitoring Network (Lee and Kwon 2016) and DINOloket in the Netherlands (Netherlands Organisation for Applied Scientific Research TNO 2019) offer information on the location of groundwater bores, groundwater levels and other associated information such as bore construction details at a country level. DINOloket also renders 2D cross sections and synthetic boreholes from geological models.

Other platforms provide the usual 2D maps with additional 3D extensions for viewing a subset of data. Canada's Groundwater Information Network (Boisvert and Brodaric 2011) provides a simple 2D viewer for groundwater borehole data, aquifer extents and geological information; it also provides an interactive 2D map with fewer datasets, which also display information like geological cross sections in 3D. In New Zealand, the SMART Aquifer Characterisation Programme (Klug and Kmoch 2014) provides similar information along with 3D views of surfaces from geological models from particular areas. The Australian Groundwater Explorer (Bureau of Meteorology 2019, Iwanaga et al. 2013) offers nationally consistent groundwater information along with interactive 3D visualisations of geological models for certain geological basins across Australia available as pdfs.

The Groundwater Visualisation System (GVS) produced by Cox et al. (2013) is a desktop product that allows 3D visualisation of groundwater data. Information generally available in 2D tools such as the location of groundwater bores, bore construction information, water level and water chemistry data can be displayed along with 3D data such as geological models. Data from multiple bores can be combined into charts and animations from independent simulations can be used to display forecast data. The Visualising Victoria's Groundwater portal has a 3D extension that provides a modified version of GVS that allows users to view the location and depth of groundwater bores along with a geological model in a 3D scene (Dahlhaus et al. 2016; Federation University Australia 2019). It is also one of the few groundwater information portals that allows users to visualise groundwater quality information in graphs.

In Queensland, the need for readily available, easily understood and expanded access to groundwater and geological data was realised when management of groundwater resources became of particular concern (Williams et al. 2012) due to the rapid expansion of the CSG industry in the Surat Basin, Australia. The economy of the Surat Basin, part of the Great Artesian Basin (GAB) is dominated by agriculture (Everingham et al. 2014), which is reliant on groundwater (Frontier Economics Pty. Ltd. 2016). The expansion of the CSG industry since 2006 (Towler et al. 2016) meant that an additional ~65,000 ML of groundwater was predicted to be extracted each year (OGIA 2016a), although this figure is expected to change as the industry matures (Underschultz et al. 2018). Concerns were also raised regarding the CSG industry having appropriate methods for the disposal of co-produced water in a way that would not negatively impact surface water systems, or change the water quality of aquifers if the co-produced water was reinjected (Williams et al. 2012; QWC 2012).

The 3D Water Atlas of the Surat Basin was developed by The University of Queensland to provide community members and groundwater managers access to groundwater data and visualisation tools to increase understanding of the resource. It was designed to bring together multiple lines of evidence and types of data for interpreting complex groundwater systems, allowing groundwater managers, researchers and CSG company staff to view relevant data in the one place,

and providing members of the community with access to the data. Priorities for the design of the 3D Water Atlas included that it be freely available through the Web, without any need to download special software or plug-ins, and that it provide a unified, quality-controlled database of water chemistry data with easy to understand visualisation tools (Hunter et al. 2016).

In this paper, the design and structure of the 3D Water Atlas, as well as tools and data visualisation options available, are described. The background, data and some specific tools are presented as a case study for the Surat Basin, with a focus on quality control of groundwater chemistry data and insights that can be gained through groundwater level data. The paper then compares the 3D Water Atlas to other similar groundwater visualisation tools and discusses how the 3D Water Atlas can provide new insights into the groundwater resources of the Surat Basin. Potential future improvements to the 3D Water Atlas are also discussed.

The 3D Water Atlas

Design of the Water Atlas

The 3D Water Atlas uses Cesium (Analytical Graphics Inc 2013), an open source Web-based platform based on common programming languages including HTML and JavaScript (Hunter et al. 2016), with a "ground-push" plug in (NICTA 2014) to visualise 3D sub-surface information. Data and information for the 3D Water Atlas is stored in a PostGreSQL database with PostGIS (PostGIS 2014) used to store and display spatial datasets. Figure 1 shows a high-level view of the 3D Water Atlas's system architecture. Two types of coding languages are used to implement the 3D Water Atlas—Cesium (the client code) creates the interactive features and visualisations, and the server code (implemented using PHP

and Python) performs database queries to retrieve information and does the processing required to create cross sections (Hunter et al. 2016). Groundwater bore data from different sources are mapped to a common data model based on the Queensland Groundwater Database (GWDB; DNRME 2018) and the Bore Baseline Assessment Database Data Dictionary (OGIA 2015) for water quality data. OGIA is a Queensland government entity that has regulatory responsibilities relating to groundwater impact assessment and management within the 3D Water Atlas geographic boundaries. Different modes of the 3D Water Atlas are available through different log-in options, allowing for certain data to be password protected, while other data can be made freely available. More detailed information on the system design and architecture of the 3D Water Atlas is available in Hunter et al. (2016).

Visualisation of data

The 3D Water Atlas displays data in a 3D scene. Groundwater bores from a bore dataset are shown as "sticks" against a map background (Fig. 2). Data including static geological model surfaces or groundwater flow model surfaces, a digital elevation model and 2D spatial data sets (e.g. surface geology, lot and plan boundaries) can be added to the scene. Bores can also be saved in a favourites list so that the user can go back to them, and metadata and a user manual are also available. Three viewing scenes are available, including the default 3D scene, a 2D bird's eye view scene and a Columbus (2.5) mode. The 3D static geological model surfaces in the 3D Water Atlas will usually have been defined from other data sources such as oil and gas exploration wells and seismic data.

The length of the stick shows the depth of a groundwater bore and bore casing information is displayed as blue collars on the stick. The user can view additional information about the bore in a pop-up, with tabs for different information about the bore such as stratigraphy, casing information, water
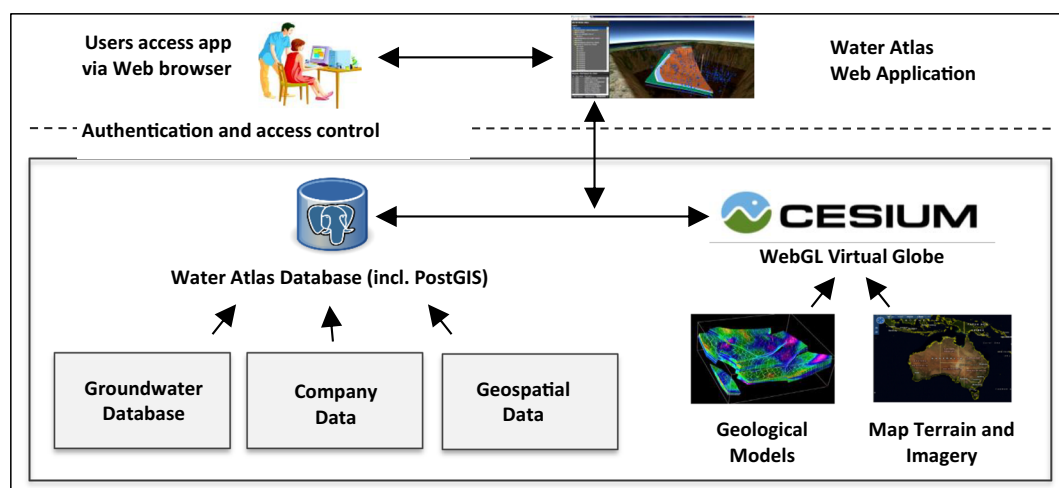

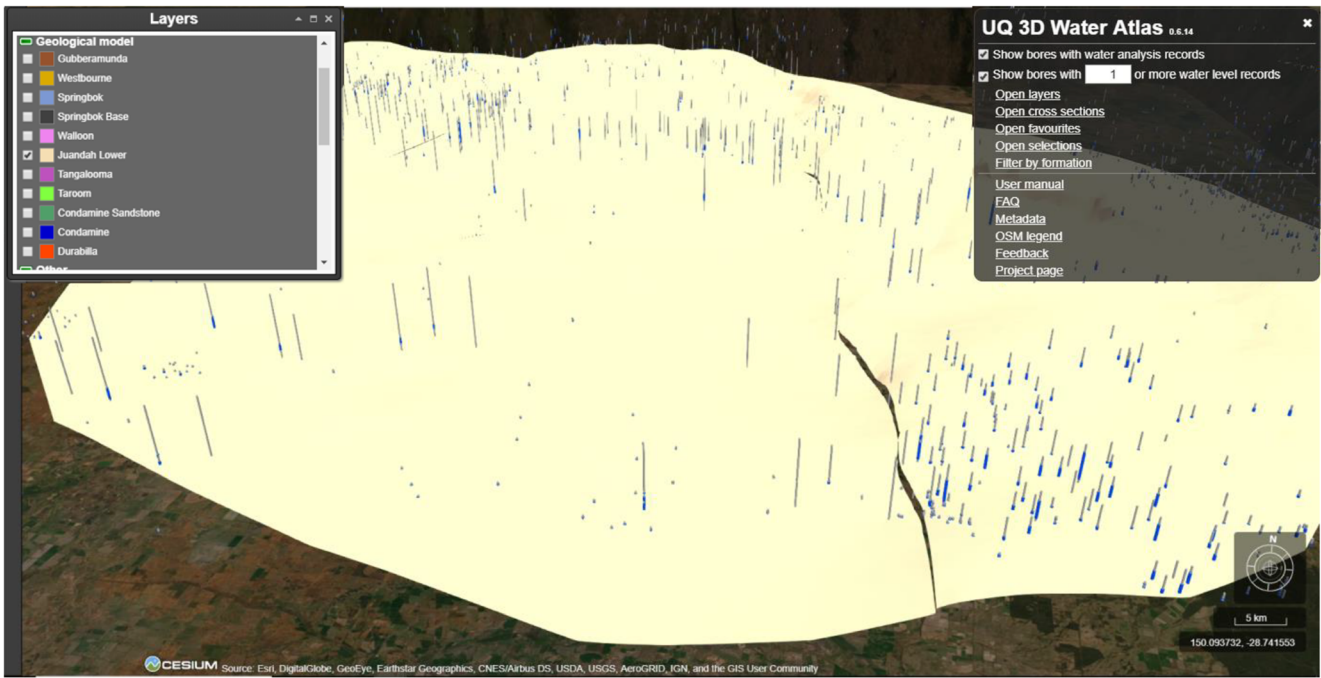**Fig. 1** Internal architecture of the 3D Water Atlas (Hunter et al. 2016)

Fig. 2 View of the 3D Water Atlas showing groundwater bores and a layer of the geological model

chemistry and water level data (Fig. 3). Each tab in the pop-up shows the data about the groundwater bore with diagrams to visualise the data—for example, a scatter plot allows the user to compare the concentration of major ions. If the bore has multiple water measurements, a line plot and an animation of water level measurements next to the bore stick allow the user to view temporal changes in water level. Piper and Stiff diagrams are also available for viewing water chemistry data.

One of the key difficulties in gaining value from the public groundwater databases is that key information regarding the source aquifer is often either missing or untrustworthy. Most groundwater bore records do not have enough petrophysical information, core or cuttings descriptions to confidently determine the formation in which the well is screened. Bore aquifer

assignments often only rely on the drillers' best estimate of the formation in which the bore was completed, made when the bore was drilled. To help address the uncertainty related to determining the source aquifer/s for a bore, the 3D Water Atlas includes a diagram that displays the casing and stratigraphy information next to a representation of the static geological model/groundwater flow model surface layers at the bore's location (Fig. 4).

The ability to view casing, stratigraphy and contributing aquifer data side by side and compare it with the static geological model can help the user to estimate the stratigraphic unit that matches the screened interval of a groundwater bore located within the 3D geological model domain and consider the accuracy of the bore's stratigraphic data. A critical

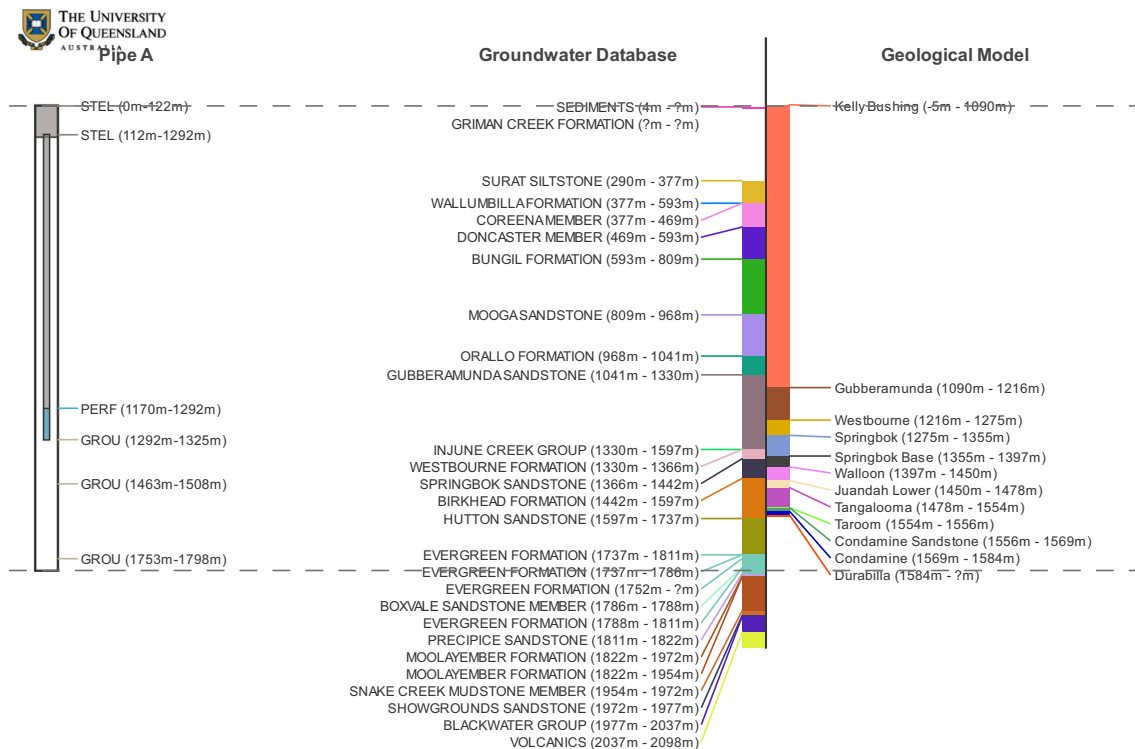**Fig. 3** Example of pop-up with groundwater bore information

Fig. 4 Diagram showing bore casing next to stratigraphy and geological model

assessment of the quality of the groundwater data can be conducted on the fly, without the original data source needing to be altered and without the user having to flick between multiple tables and compare depth ranges.

Data filtering tools allow the user to limit what bores are displayed in the 3D scene and in any selection made using the area selection tool—for example, tick boxes allow only bores with water chemistry and/or water level data to be displayed. A window also lets the user define how many water level measurements a bore needs for it to be displayed. Users can also filter bores according to whether they are likely to be sourcing water from a particular formation, making it easier to compare and apply visualisation tools to bores that are likely to be sourcing water from the same formation. Users can select bores within an area and view pie charts, Piper diagrams and summary statistics of the water samples and line charts of water levels from the bores in the area. Animations of pie charts showing changes in major ion composition over time are also available through the area selection tool for bores with multiple water chemistry analyses. Data from all the bores in the selected area can also be downloaded.
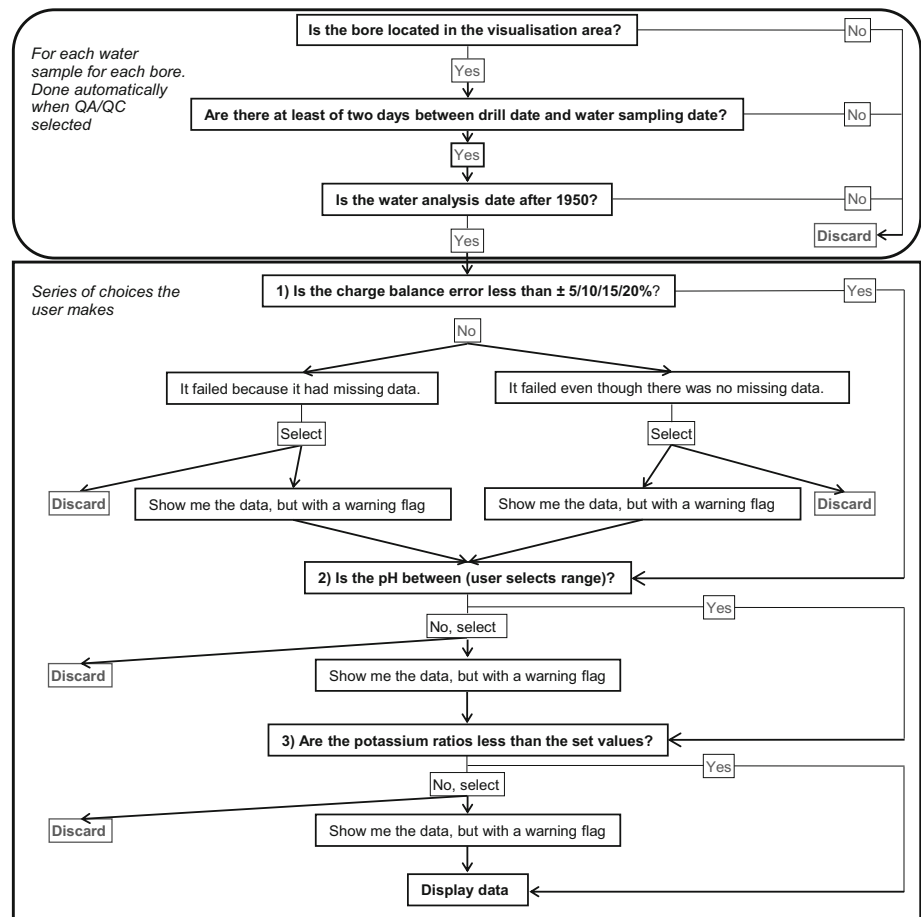
Users can create cross sections of the static geological or groundwater flow model surfaces. The cross sections can be a single straight line, or a "fence" cross section to capture bores or geological features of interest. Groundwater bores within 100 m of the cross section are displayed as small lines on the 2D cross section window to show their approximate location and depth to assist with geological correlations.

Data quality control

The Quality Assurance/Quality Control (QA/QC) procedure applied to groundwater chemistry data is informed by previous work (Grigorescu 2011; Hodgkinson and Grigorescu 2013) and standard geochemistry data quality control procedures (Hitchon and Brulotte 1994). The tool, which functions as a script running in the background, focuses on filtering out spurious water chemistry data caused by poor sampling methods or contamination of the sample due to drilling. It does this by requiring at least 2 days between drilling and sampling and filtering out samples with a high charge balance error (CBE) and high ratios of potassium to sodium, calcium and chloride. It accommodates varying threshold detection limits amongst laboratories, and available as technology improved, but sets cut-offs for data considered too old (pre 1950) to be comparable with newer sampling techniques (see Fig. 5 for an outline of the QA/QC procedure).

An interface for the tool allows certain users to customise steps in the QA/QC procedure, such as CBE percentage cut-offs. They can also decide whether data that fail the test are discarded or kept but flagged as potentially erroneous. If the user does not customise or turn off the QA/QC tool, the default values for each step in the procedure are applied. The default values can be changed to suit the water chemistry of a region for different versions of the 3D Water Atlas. Many water chemistry samples, particularly older samples fail the QA/QC procedure as they do not have records for some of the

Fig. 5 QA/QC procedure

For each water sample for each bore. Done automatically when QA/QC selected

Is the bore located in the visualisation area? — No

Are there at least of two days between drill date and water sampling date? — No

Is the water analysis date after 1950? — No

Discard

Series of choices the user makes

1) Is the charge balance error less than ± 5/10/15/20%? — Yes

No

It failed because it had missing data.

It failed even though there was no missing data.

Select

Select

Discard | Show me the data, but with a warning flag | Show me the data, but with a warning flag | Discard

2) Is the pH between (user selects range)? — Yes

No, select

Discard

Show me the data, but with a warning flag

3) Are the potassium ratios less than the set values? — Yes

No, select

Discard

Show me the data, but with a warning flag

Display data

major ions, usually potassium. An option to keep samples that failed the QA/QC because values for one of more of the major ions were missing was included so that the user could distinguish between failure because of a high CBE versus failure due to missing data.

Development of the 3D Water Atlas of the Surat Basin

### Data and specific design for Surat Basin

The current 3D Water Atlas covers an area in Queensland from Toowoomba in the east, to west of Roma, Monto in the north and south to the New South Wales border (Fig. 6). Groundwater bore information is sourced from the GWDB (DNRME 2018) and CSG companies. The registration, aquifer, facility role, casing, strata log, stratigraphy, water analysis and water level tables from the GWDB are displayed as tabs in the pop-up. The static geological model currently displayed in the atlas was produced at The University of Queensland using information from petroleum and coal exploration such as stratigraphic bores, petroleum well logs and seismic data and geological correlations from the Office of Groundwater Impact

Assessment (OGIA; Esterle et al. 2017). The 3D Water Atlas currently has surfaces taken from OGIA's 2016 regional groundwater flow model (OGIA 2016b). Additional 2D data such as petroleum lease boundaries, the Surat Cumulative Management Area, GAB Water Resource Management Zones, and cadastral data obtained from the Queensland Government can also be displayed.

The ability to view groundwater information with a static geological model and apply a quality control filter to water chemistry data are particularly useful tools as they could help to deal with some of the inherent problems with data held in historical databases such as the GWDB (DNRME 2018). Queensland's GWDB contains information about registered groundwater bores dating back to 1900 and the quality of recorded information on the bore's construction, stratigraphy at the location and water chemistry is highly variable.

The 3D Water Atlas currently has three different modes, with some data and visualisation tools requiring log-in access. A "public" mode, with no log-in requirement allows access to all publicly available data and visualisation and data filtering tools that do not require specialist knowledge to interpret, such as pie charts and line graphs. An "expert user" mode is available to people such as scientific researchers through Australian Access Federation (AAF) login that provides

Fig. 6 Area covered by the 3D Water Atlas of the Surat Basin
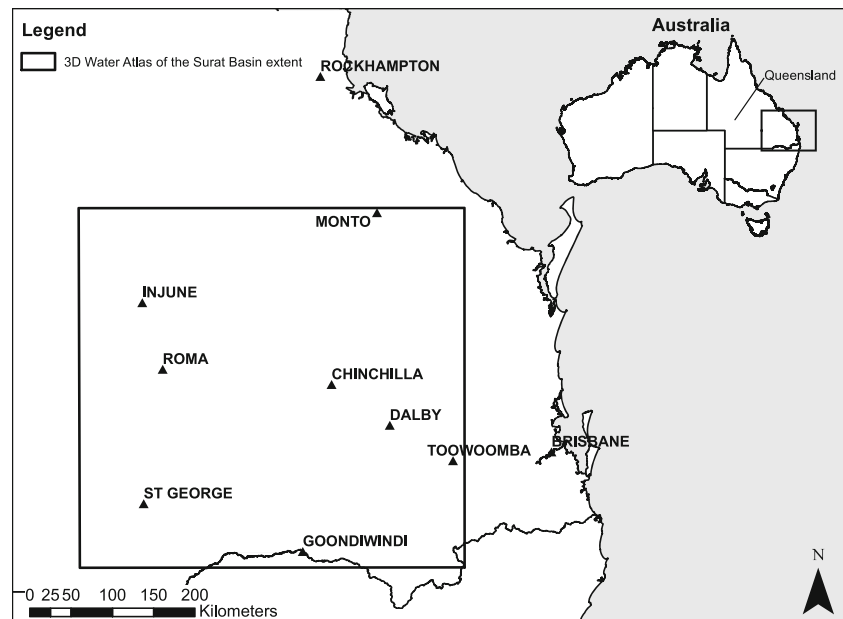
access to publicly available data and additional visualisation and data filtering tools including customisation of the QA/QC tool and Piper and Stiff diagrams for visualising water chemistry data. An "organisation" mode is available to participating CSG companies who provided data for the project and OGIA. The organisation mode is accessed through an organisation specific password and provides access to all publicly available data, all tools and organisation specific data (e.g. additional water chemistry analyses or parameters that the company collected). Participating CSG companies have access to their company's data and OGIA has access to all data due to the provisions of the Water Act 2000 (Qld) under which it operates.

QA/QC tool and its application to water chemistry data

The current groundwater chemistry data loaded into the 3D Water Atlas includes chemistry data available in the GWDB as well as baseline water quality assessments conducted by CSG companies according to requirements under the Water Act 2000 (Qld). There are few bores with multiple groundwater chemistry measurements, so trends are not currently discernible. Changes to groundwater chemistry may become evident as more water chemistry data becomes available through new monitoring schemes—for example through Groundwater Net, a monitoring scheme run by landholders or the continued monitoring conducted under the Water Act 2000 (Qld).

Of the 32,544 bores and CSG wells displayed in the Water Atlas of the Surat Basin, 11,987 have water level samples and 21,982 have water chemistry samples. Sampling date accounts for 2,992 bores failing the QA/QC, either because they were taken before 1950 (111) or because the water sample was taken within 2 days of drilling. Many bores fail at the step requiring that the sample be taken at least 2 days after the drilled date because of data entry errors, where the water sample date has been recorded as being taken before the drilled date.

Table 1 shows how many samples fail the QA/QC procedure and the difference between the chosen values and the default values (the strictest option) for the various steps where customisation is available. When the default QA/QC procedure is applied to the water chemistry samples, 44% of the

Table 1 Number of samples that fail the QA/QC procedure with different values set for the steps. Where the charge balance error (CBE), pH and potassium ratios have been changed, the other QA/QC steps have been kept at the default values

QA/QC steps	No. of failed samples	Difference in failure rate between default QA/QC values
CBE ±5% (default QA/QC)	9,667	–
Missing values not discarded	9,286	381
pH 3–12	9,641	26
Failed potassium ratio bores not discarded	9,660	7
CBE ±10%	9,302	365
CBE ±15%	9,237	652
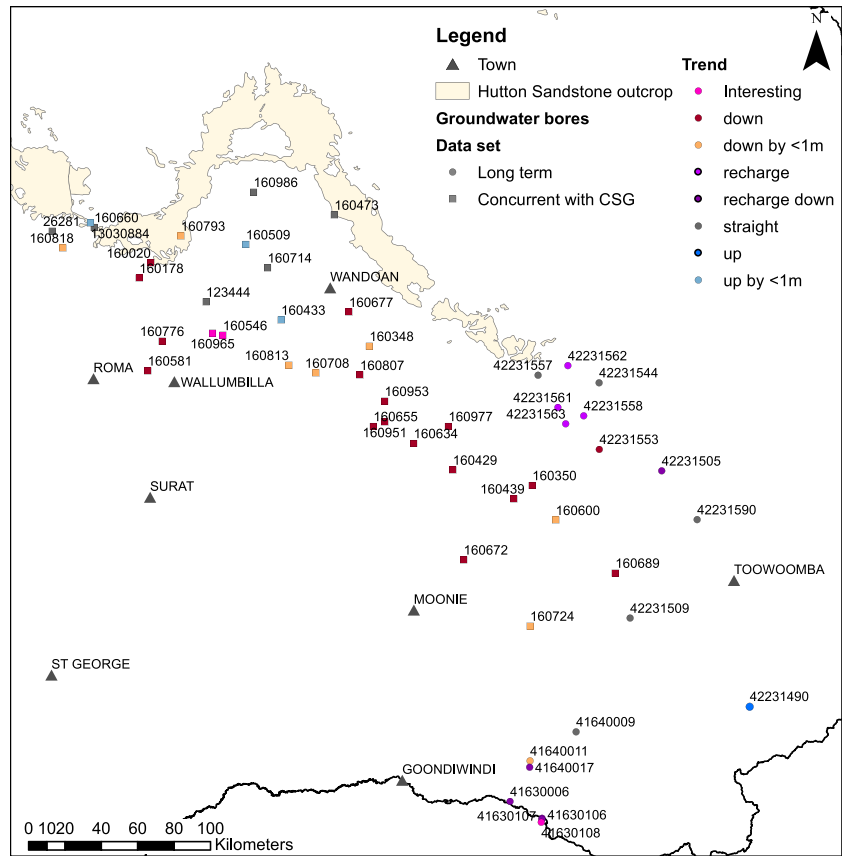
samples pass, with the majority failing because of CBE. Almost the same number of samples are filtered out by the default QA/QC option because they are missing a value for a major anion or cation (381 samples) as are filtered out because the CBE is between ±5 and ±10% (365 samples), while nearly double get filtered out because the CBE is between ±10 and ±15%. Few samples are filtered out at the pH range (26) and potassium ratio (7) stages of the QA/QC filter.

The proportion of samples that fail the QA/QC procedure indicates the importance of applying it to the data, particularly in the free publicly accessible mode, as it ensures that spurious data are not included in statistical analysis or data visualisations available to members of the community. As the tool is built into the 3D Water Atlas, new data that is added

can automatically be controlled for quality, rather than relying on a person to do the quality control prior to up-load, thus streamlining the process of adding new data. The rejected data can however be extracted and interrogated if required.

Case study: Hutton Sandstone groundwater levels

The ability to view transient groundwater level data either for individual bores of for multiple bores in an area allows users to quickly identify trends or areas worthy of further analysis to enhance understanding of the groundwater system. To demonstrate this, a case study of water levels in the Hutton Sandstone of the Surat Basin in Queensland is presented. Groundwater bores that sourced water only from the Hutton

Fig. 8 Examples of declining water levels in bores (locations by number in Fig. 7)
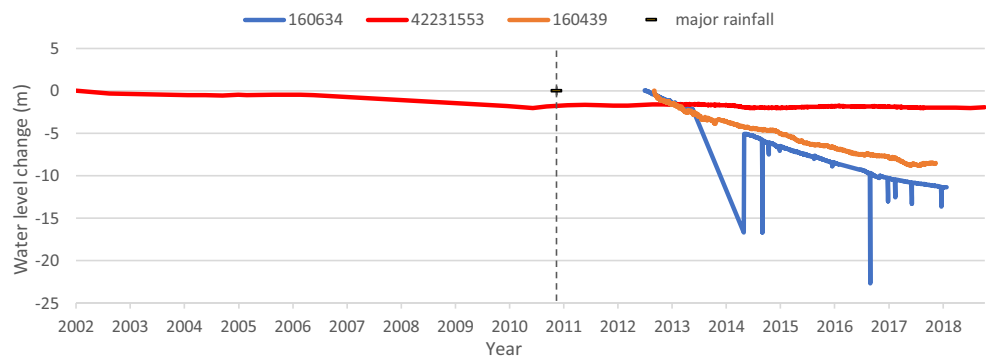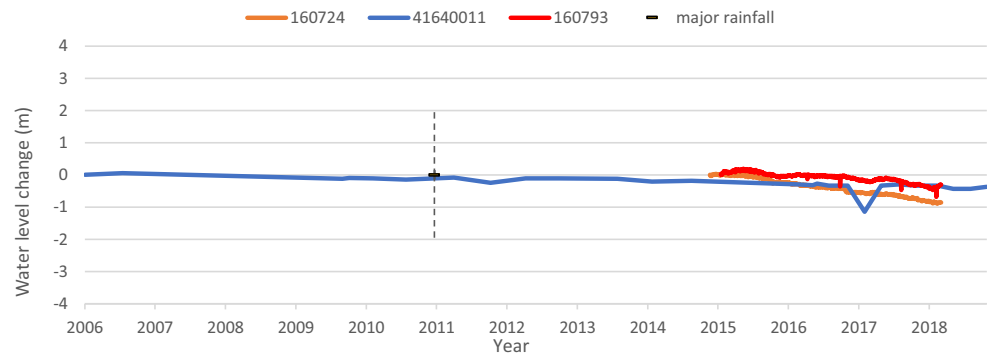
Fig. 9 Examples of declining water levels under 1 m

Sandstone and with multiple water level measurements were selected for this analysis using a cross check of the screened interval with the OGIA aquifer attribution data.

Two sets of groundwater bores were chosen. One set consisted mostly of government groundwater monitoring bores that had multiple groundwater level measurements over time, starting at around 2002, at least a decade before any significant CSG development in the region (Long term data). The other set consisted of monitoring bores installed by CSG companies under the Water Act 2000 (Qld) for reporting in the Underground Water Impact Report (e.g. OGIA 2016a), with most groundwater measurements starting between 2012 and 2015 (concurrent with CSG development data). These two sets were chosen as they contained bores with water level measurements taken at sufficient frequency and over a consistent period to be comparable with each other.

For the ease of visualising the results in the context of a technical journal article, the data are presented in a 2D map and graphs of water level time series data from bores with representative or interesting water level curves. Figure 7 shows the location of the bores in the two datasets with the bores colour coded according to the general trend visible in the bore's water level time series data and the symbol representing the data set from which the bore came (long term or concurrent with CSG). Figures 8, 9, 10, 11, 12, 13, and 14 show the time series graphs of water level changes for the representative or interesting bores (also see Figs. 1 and 2 of the electronic supplementary material (ESM) for examples of graphs produced by the 3D Water Atlas). The y-axis of the

graph shows the change in water level from the initial measurement so that the change in water level over time can be seen and compared more easily.

Spatial variation in water level changes can be seen from Fig. 7, although a general long-term regional decline in water levels is evident. The extent of the decline varies, with some declines over 10 m over the last 6 years (Fig. 8), while other areas have a decline under 1 m over the last 12 years (Fig. 9) and in other areas the water levels remain constant (Fig. 10). Areas of localised recharge can also be seen, particularly associated with significant rainfall events such as in late 2010/ early 2011 regional floods (indicated as 1 January 2011 in the graphs). In some areas, particularly closer to where the Hutton Sandstone outcrops, water levels appear to remain steady after recharge (Fig. 11). Further south, water levels declined after the recharge event (Fig. 12). A few bores had gradually increasing water levels, but only one with water levels increasing more than 1 m over the time that water levels were measured (Fig. 13).

Bores with water level changes that were interesting (particularly in that there were dramatic changes not seen in other bores) included bores 160,546 (Reedy Creek MB3-H) and 160,965 (Reedy Creek INJ3-H; Fig. 14). Further investigation into these bores show that they were drilled for managed aquifer recharge trials, and the CSG company responsible for collecting water level data from them (APLNG/Origin) attributes the changes in water level to "hydraulic testing, with temporary local groundwater extraction and re-injection trials" (Origin 2017). Investigation of groundwater bores also
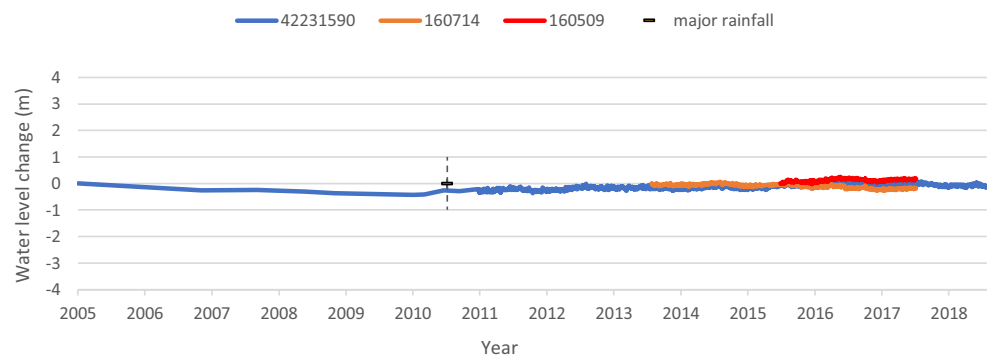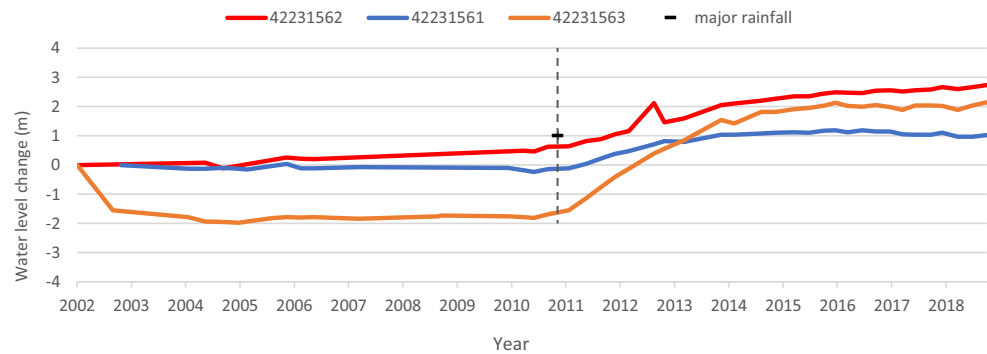
Fig. 10 Examples of relatively steady water levels

Fig. 11 Example of increasing water levels, probably from recharge after a major rainfall event

explains other water level measurements. For example, the intermittent sharp decline and then return to trend water levels in bore 160,634 (Fig. 8) may be attributed to water quality sampling events (Origin 2017).

Discussion

The 3D Water Atlas's ability to display groundwater bore data in context with a geological model along with graphs of groundwater chemistry, water level data and animations means that in many instances it can take the place of multiple specialist software, such as Petrel, ArcGIS and Geochemist's Workbench. While it does not have the same functionality of all the specialist software combined, the ability to visualise groundwater bore data in a 3D context with other relevant information can assist with assessing the quality of groundwater data. It can also enhance understanding of groundwater systems, and help to create a shared mental model of the groundwater system, particularly for members of the community who do not have access to, or knowledge of how to use the specialist software.

The 3D Water Atlas is also different to most other groundwater visualisation portals as its initial or default setting is to display data in 3D. All data can be accessed within the 3D scene, allowing for subsurface visualisation and interaction with data on a basin-wide scale while bore data can be interrogated within its geological context. It also has more features for visualising groundwater chemistry data; only the 2D

version of Visualising Victoria's Groundwater provides graphs or visualisations (Piper and Stiff diagrams) of groundwater chemistry data (Federation University Australia 2019). Other groundwater visualisation systems that do have 3D capability such as Canada's GIN (Boisvert and Brodaric 2011), New Zealand's SMART Aquifer Characterisation Programme (Klug and Kmoch 2014) and the Australian Groundwater Explorer (Bureau of Meteorology 2019, Iwanaga et al. 2013) display a subset of data in a special 3D window or pdf download and do not have the same level of data interactivity. Versions of the GVS provide similar 3D visualisation of groundwater and geological data to the 3D Water Atlas and is it based on open source software (Cox et al. 2013); however, a free version with all these capabilities is not currently available to the public.

Displaying data in 3D does have disadvantages. People can sometimes find it difficult to judge the size, position and depth of objects in a 3D visualisation (Young 1996). In the 3D Water Atlas, a map is draped across the bottom of the underground visualisation ("ground push") area; however, the groundwater bores are tied to an invisible surface, rather than the underlying map. This can make it difficult to judge the location of the bores in relation to the map when navigating in 3D mode. In the 2D mode, bores are tied to the map. 3D visualisation also requires a lot of memory and an Internet connection with enough speed to load and visualise the data over a reasonable period.

Previous research has however demonstrated the usefulness of 3D groundwater visualisation tools for groundwater

Fig. 12 Example of increasing then declining water levels
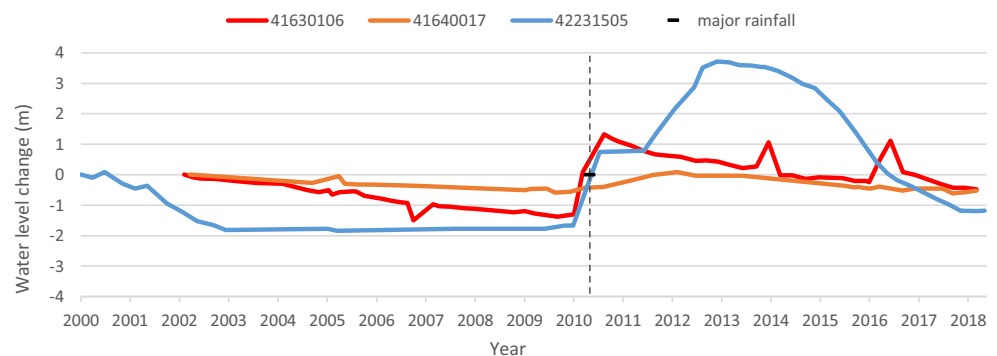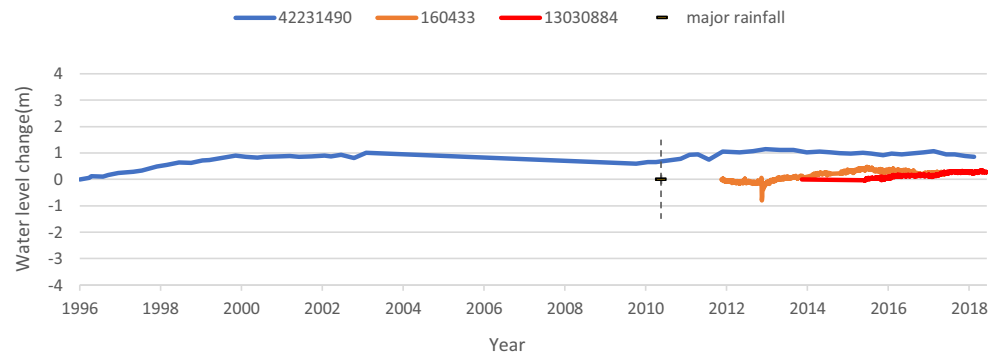
Fig. 13 Example of bores with increasing water levels

management (Tan et al. 2012, Baldwin et al. 2012). The strengths of 3D groundwater visualisation tools lie in their ability to educate or increase the understanding of groundwater systems, particularly for lay members of the community (Tan et al. 2012). Members of the community also often view Groundwater models produced by management agencies as "black boxes" based on unreliable data (Baldwin et al. 2012). The ability to view and explore the data that goes into groundwater models via the 3D Water Atlas can therefore increase community confidence in groundwater modelling and any management decisions based on the modelling results. It also demonstrates the increasing need for platforms that bring together multiples forms of data to provide a new understanding of groundwater systems, to elucidate possible management interventions and allow management decisions to become visible.

The steps at which the water chemistry samples fail the QA/QC procedure provide insight into the quality of the water chemistry data. Most samples were filtered out because the water sample date was entered as being before the drill date, or due to charge balance error. Advances in understanding the water chemistry of the Surat Basin, and likely the GAB more generally, may be limited by errors in data entry and sampling technique errors. Management interventions that focus on better collection and entry of data are likely to have a big impact on the quality of water chemistry data, thereby improving the quality and confidence in management decisions related to groundwater quality in the GAB.

By viewing bore water level information in a spatial context, the 3D Water Atlas easily shows the spatial and temporal changes in a groundwater resource. Management interventions such as managed aquifer recharge trials (MAR), and groundwater sampling events are also visible. As more data become available, the animations and regional visualisation tools will also make it easier to view temporal and cumulative impacts on groundwater in the Surat Basin. For example, it would be possible to see if re-injected water in the MAR trials also had an effect on water chemistry. Importantly, long-term trends can help establish contributions that may be causing depletion of groundwater resources, a key area of concern for management of the Surat Basin and the GAB in general.

The 3D Water Atlas is therefore able to increase a user's understanding of groundwater systems as well as contribute to transparency and trust in groundwater management, as management actions are visible in the data. The different modes of access, where some data and tools are available to certain groups but not others, does however reduce data transparency and therefore has the potential to undermine trust in groundwater management of the Surat Basin.

In areas of new resource developments that impact water resources, the ability of the 3D Water Atlas to be quickly adapted to a new region can be valuable in assisting regulatory requirements for the granting of exploration and development permits. The 3D Water Atlas can be used to provide a consistent, QA/QC'd data set and visualisation tool to proponents and government enabling rigorous analysis and presentation

Fig. 14 Interesting bores: water level changes due to local extraction and injection testing
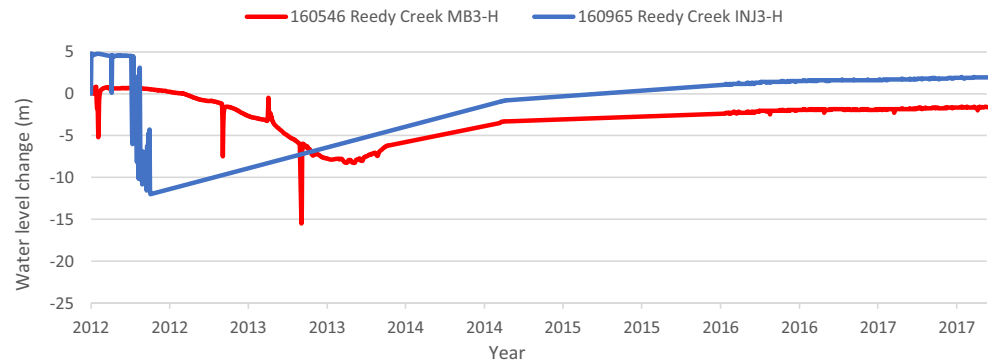
of both local and cumulative impacts on ground or surface water systems (Howe et al. 2010; Vink 2017).

The architecture of the 3D Water Atlas makes it highly customisable. A basic 3D Water Atlas can be easily implemented for any area with a groundwater bore database and a geological model as most software programmers would have the skills necessary to develop and work with it. Developing a 3D Water Atlas does however require substantial time from software engineers as wells as people with knowledge of the data being used for it to be implemented properly. Like other visualisation systems, it also requires continued input from software engineers to maintain the platform to ensure it remains compatible with new web-browsers, and changes to database formatting.

There are some potential future developments for the 3D Water Atlas that would improve its ability to help manage groundwater resources. A capability for live data updates from official data web portals, rather than requiring the data to be manually uploaded would greatly improve data currency as well as reduce the staff time required for maintenance. Changing the common data model to something like GroundWaterML2, an international standard for the exchange of groundwater data (Brodaric et al. 2018) would also make it easier for the 3D Water Atlas to incorporate data from jurisdictions outside of Queensland and be extensible internationally.

Conclusion

The 3D Water Atlas is distinct from other groundwater visualisation systems as it allows users to visualise all the incorporated data within a 3D scene and provides quality control and multiple visualisation options for groundwater chemistry data in a freely accessible platform that does not require any downloads or specialist software. It is therefore well placed to play a role in more integrated systems of governance that involve community consultation and require a shared understating of the system being managed. It can also help to improve groundwater management by increasing trust through the provision of data in a readily understandable, quality-controlled format that allows users to see the results of management decisions in the data. Although the 3D Water Atlas was created for the Surat Basin, the software implementation system means that it can be adapted and used in other groundwater systems, providing a new tool for groundwater management.

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