TECHNICAL NOTE

Future-proofing hydrogeology by revising groundwater monitoring practice

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Abstract

Groundwater is an important global resource and its sustainable use faces major challenges. New methods and advances in computational science could lead to much improved understanding of groundwater processes and subsurface properties. A closer look at current groundwater monitoring practice reveals the need for updates with a special focus on the benefits of high-frequency and high-resolution datasets. To future-proof hydrogeology, this technical note raises awareness about the necessity for improvement, provides initial recommendations and advocates for the development of universal guidelines.

Keywords Groundwater monitoring · Equipment/field techniques · High resolution · High frequency · Guidelines

Novel approaches can tackle big challenges in hydrogeology

Our world faces many groundwater-related challenges (Alley 2002), for example over-extraction (e.g., Wada et al. 2010) and associated reduction in river base flow (e.g., de Graaf et al. 2019), land subsidence (e.g., Galloway and Burbey 2011), sea-water intrusion (e.g., Jiao and Post 2019) and deterioration of groundwater quality, due to arsenic (Rodriguez-Lado et al. 2013) or increasing nitrate concentrations (e.g. Hansen et al. 2017). This

is further exacerbated by groundwaters' slow response to anthropogenic and climatic impacts (i.e. long hydraulic memory; Cuthbert et al. 2019a) and competition for water for multiple purposes including domestic and stock supply, agriculture, thermal energy storage (e.g., Fleuchaus et al. 2018), resource mining and the environment (de Graaf et al. 2019).

Monitoring groundwater, for example by measuring heads, underpins virtually all groundwater flow and storage investigations (e.g., Rau et al. 2019) including the calibration of groundwater flow models (e.g., Hill and Tiedeman 2007) as well as ground-truth interpretations of large-scale indirect remote sensing or surface geophysical observations (e.g., Alley and Konikow 2015). Furthermore, groundwater monitoring is critical in times of unprecedented environmental change as the past is not necessarily a good predictor for the future. Monitoring is not only crucial to sustainable groundwater development (Gleeson et al. 2020), but also for mitigating groundwater-related disputes such as transboundary issues (Puri 2003) and conflicts that are anticipated to increase as a result of increasing demand and competition (Jarvis 2014).

Time series of groundwater levels provide insights into the pattern and dynamics of groundwater flow at local (e.g., McCallum et al. 2013), regional/subcontinental (e.g., Cuthbert et al. 2019b) and even the global scale (e.g., Fan et al. 2013). One of the biggest challenges for integrated water management is the lack of detailed knowledge of the distribution of subsurface hydrogeological properties at all scales (Bierkens 2015; Reinecke et al. 2019). Subsurface properties can be inferred by

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monitoring groundwater-level response to external stress—for example, the groundwater response to pumping has long been used to quantify important aquifer properties like hydraulic conductivity or storage coefficient (e.g., Kruseman and de Ridder 1990). However, 'active' aquifer testing, by applying an artificial hydraulic forcing (e.g. using an abstraction borehole), delivers localised results and requires substantial effort, which limits the number of locations that can be investigated in space and time (e.g., McMillan et al. 2019).

Decades of continuous head measurements are often required to capture changes in the balance of groundwater recharge and discharge fluxes (Cuthbert et al. 2019a) due to the delayed response of groundwater systems (Taylor and Alley 2001). However, heads also respond to natural forces on short (hours or days) timescales such as changes in stream stage (e.g., McCallum et al. 2013; Kelly et al. 2013); barometric fluctuations (Clark 1967; Rasmussen and Crawford 1997; Acworth et al. 2016); Earth, atmospheric and ocean tides (Bredehoeft 1967; Van Der Kamp and Gale 1983; Xue et al. 2016); rainfall loading at the surface (van der Kamp and Schmidt 2017); evapotranspiration by phreatophytes (e.g., Gribovszki et al. 2010); and earthquakes (e.g., Zhang et al. 2019).

High-frequency methods have been developed that exploit such natural variations—for example to calculate barometric response functions (BRF) that can be used to determine groundwater confinement (e.g., Rasmussen and Crawford 1997; Spane 2002). Further, groundwater response to Earth tides and atmospheric forcing can be used to determine confinement (Rahi and Halihan 2013; Acworth et al. 2017) as well as to quantify hydrogeomechanical properties—e.g. permeability, transmissivity, porosity, compressibility and even specific storage (e.g., Cutillo and Bredehoeft 2011). Recent research has illustrated that 1-mm instrument resolution is enough to capture and interpret the millimetres of variation in hydraulic head caused by atmospheric or Earth tide variations in confined systems (e.g., Acworth et al. 2016), known as Tidal Subsurface Analysis (TSA; McMillan et al. 2019). It is worth emphasising that such methods rely on high-resolution measurements where accuracy is secondary, as the sought information is in the relative changes.

These approaches have the immense advantage that they are 'passive', i.e. they do not require artificially applied forcing (such as pumping), but rather rely on ubiquitous natural influences (e.g., Xue et al. 2016). Such analysis only requires time series of (1) borehole water levels (or pressure heads), (2) atmospheric pressure, and (3) calculated Earth tides (McMillan et al. 2019). Measuring and interpreting such head changes provides a huge treasure trove for wide-spread analysis of subsurface processes and properties (McMillan et al. 2019). Due to the number of observation boreholes relative to dedicated pump testing boreholes, this has the potential to significantly increase spatial knowledge of subsurface hydrogeological properties and hence the characterisation of heterogeneity. To ensure robust application, analysed datasets must adhere to minimum requirements

(outlined in section 'How can hydrogeology be future-proofed through improved groundwater monitoring and archiving practice?'). It is noted that while high time and measurement resolution may not be required for traditional hydrogeological approaches (e.g., large-scale models), this becomes significant when applying passive techniques. Importantly, results from the latter can inform traditional approaches and improve the quality of interpretation.

Computational advances have brought about methods which can digest large quantities of data to solve challenging problems, derive new understanding or forecast future scenarios, for example using artificial intelligence approaches such as deep learning (Shen 2018). Groundwater databases have become increasingly available in recent decades due to increased accessibility over the Internet and decreased computer storage costs. This, in combination with the widespread availability of open-source data analysis software, offers much potential for data-driven discovery (Bergen et al. 2019). The authors propose that these new approaches should increasingly be applied to the large volume of existing hydrogeological datasets, so that improved groundwater-system understanding with high-frequency datasets and large spatial coverage can be derived at low effort and cost.

Unfortunately, there are many obstacles to taking advantage of existing datasets such as accessibility, and limited provision of meta-data to assess their quality, as well as insufficient time or sensor resolution and dataset duration. This technical note calls for a more holistic approach for collecting, managing and disseminating groundwater head datasets, with an emphasis on those collected at high frequency. This is not intended to be a comprehensive review or blueprint for groundwater monitoring in general terms, but specifically to address how the benefits of new high-frequency methods can be fully exploited in the future.

Observations from current practice

Traditionally, groundwater level measurements are performed manually by using water level meters, i.e. measuring tapes with a water-sensitive tip at the end (Freeman et al. 2004). It is recognized that much critically important historical information is held in data bases where measurements have only been taken using measuring tapes (dip meters) to centimetric accuracy at intervals that may have only been monthly or less frequently. Automated water-level recorders have been used for decades, but only since the 1980s have advances in electronics enabled the construction of automated pressure and distance sensors that are small enough to fit inside smaller (25-mm diameter) monitoring boreholes (e.g., Rosenberry 1990), and in the 1990s, further development allowed the storage of large amounts of data in the same devices. Using these sensors, water-level changes inside boreholes are measured and stored at programmable time intervals providing time series of pressure that can be converted to hydraulic heads. For this conversion, manual water level measurements are

required to calibrate and check automated measurements (e.g., Rau et al. 2019).

The advent of automated measurement systems, in conjunction with data telemetry, enables increasingly comprehensive and cost-effective collection of groundwater data, even in remote locations (e.g., Rosenberry 1990; Post and von Asmuth 2013; Rau et al. 2019). Many countries such as the US Geological Survey (Freeman et al. 2004) or the Australian Government's Bureau of Meteorology (BoM 2019), have developed guidelines for groundwater monitoring. The Internet has facilitated accessibility, and well-curated groundwater data from various providers are available to researchers and the general public. Some good examples for open access databases are:

- The Global Groundwater Information System (GGIS) by the International Groundwater Resources Assessment Centre (IGRAC), which is financially supported by the Government of the Netherlands (IGRAC 2020).
- The National Ground-Water Monitoring Network (NGWMN) operated by the US Geological Survey (USGS 2020) provides groundwater monitoring data from more than 9,000 wells in the USA.
- The British Columbia Groundwater Wells and Aquifers application (Government of British Columbia 2020a), real-time hydrological data (Government of British Columbia 2020b) and the Provincial Groundwater Observation Well Network interactive map (Government of British Columbia 2020c) are examples of spatially displayed datasets for well location and real-time groundwater level data queries. Established in 1961, the Provincial Groundwater Observation Well Network program has been collecting hourly groundwater level readings reported to three decimal places for over 17 years.
- The National Groundwater Information System (NGIS) and its mapping interface the Australian Groundwater Explorer operated by the Australian Government's Bureau of Meteorology (BoM 2020) which contains information for 900,000 bores across the country and the National Collaborative Research Infrastructure Strategy (NCRIS) Groundwater Infrastructure Program (NCRIS 2020).

These examples summarize advances that testify to the giant steps that have been made during the last three decades. Nevertheless, practicalities often prevent data from achieving their full potential. Collectively, the authors have gained substantial field and data-interpretation experience while working for, and with, many academic institutions, consultancies and governing bodies around the world. In doing so, the authors have distilled the following observations:

- Groundwater levels are not routinely collected at high frequency, even for limited time periods, at long-term monitoring locations. Some monitoring is associated with a finite project period and there are few known groundwater monitoring sites at which strategic long-term high-frequency monitoring is conducted.
- The choice of an appropriate sampling frequency is difficult to make, usually due to a lack of knowledge about the dynamics of groundwater processes for a particular location. Further, the relationship between the internal clock in automated devices (which are prone to clock drift) and a common time base (e.g. time zone and daylight saving time setting) is often neglected which leads to post-processing confusion, for example spurious offsets between barometric pressure or ocean tides and groundwater records, which can thwart advanced interpretation of processes and properties when using high-frequency methods or when interpreting multiple data sets together.
- Using an established and accurate vertical reference for groundwater head records is crucial when interpreting multiple datasets. Practitioners often simply reference to ground level or the top of the borehole casing and neglect the accuracy of this information. Please refer to Rau et al. (2019) for a detailed discussion of this issue.
- In the trade-off between pressure transducer range (maximum limits) and resolution (smallest resolvable signals), practitioners seem to prefer maximizing range as it allows for greater versatility (less chance of failure due to over-pressurization and a wider range of deployments). In addition, some practitioners report and archive datasets rounded to the nearest centimetre thereby mistaking the limited absolute accuracy of manual measurements with the high relative accuracy of automated measurements. This leads to a loss of information content such as the often-subtle water level variations caused by Earth or atmospheric tide influences and prevents the immense benefit of their interpretation.
- Converting pressure time series from automated pressure transducers into hydraulic head records requires regular manual measurements (e.g., Freeman et al. 2004; Post and von Asmuth 2013). Systematic and regular borehole inspections are further required to ensure bore integrity and that the water level inside the well is a truthful representation of the pressure head in the aquifer. However, regular manual measurement of groundwater levels in spatially distributed monitoring bores is being deprioritised because it requires effort by a human operator and therefore has a significant financial cost. Because there are often little spatial and temporal overlap between manual and automated measurement, groundwater monitoring bores often have insufficient evaluation of automatically measured water levels.
- Data units vary across countries (e.g., metric or imperial) and are sometimes not explicitly stated within datasets. This can create confusion when converting between different unit systems.
- Hydraulic head measurements are rarely corrected for density effects, which is crucial in areas with brackish or

saline groundwater (Post and von Asmuth 2013). As part of standard practice, fluid electrical conductivity and temperature should always be measured as a proxy for density, and corrections to the head made, if required.

- Groundwater is monitored by many different stakeholders with varying objectives, including private companies. Datasets are often archived separately, have yet to make their way into accessible databases or are not made accessible, e.g. archived by government agencies or private companies. Obtaining information about monitoring locations as well as datasets therefore requires significant search, communication and quality assurance efforts.

- Auxiliary datasets are not commensurate with available water-level time series. For example, barometric pressure or rainfall records may be required to interpret datasets but may not be available at all or not at the required spatial or temporal resolution. Typically, such data are collected and maintained by different institutions, which again increases interpretation efforts.

- Perhaps because of a lack of market push, many standard pressure transducers do not measure to subcentimetre resolution (Rau et al. 2019). During procurement, affordability is all too often favoured over performance, even though low-end pressure transducers are known to have operational issues (e.g., resolution, accuracy, clock accuracy, longevity, etc.) that limit interpretability of the data they collect.

- Quality assurance (QA) and quality control (QC) procedures for data stored in databases are not always transparent and may lack meta-data descriptions, thus making it unclear for what purpose the data are suited.

- Groundwater monitoring is organised differently around the world. While the stakeholders can roughly be categorised into private, industry, government and research (Fig. 1), the responsibilities for and expectations of groundwater monitoring vary greatly. Consequently, defining a universally applicable best practice is a challenging task.

How can hydrogeology be future-proofed through improved groundwater monitoring and archiving practice?

New methodological advances could bring about improved process understanding from old monitoring datasets, but the points listed previously illustrate some of the difficulties typically encountered with this. To remove these obstacles, there is a need for developing and adopting universal standard practice for the future, when the availability of new data processing and interpretation methods will add even further value to groundwater datasets. Figure 1 shows a conceptual summary of the workflow in groundwater monitoring highlighting the limitations in current practices and a pathway to future opportunities.

The authors call for an update of existing groundwater monitoring and archiving practice to accelerate process understanding at different spatial and temporal scales. More specifically, the following recommendations are proposed:

1. For a successful application of high-frequency methods, a dataset must fulfil the following criteria:
    a. The minimum required measurement resolution is 1-mm head equivalent, which is necessary to accurately capture the subtle influences from atmospheric pressure changes or Earth tides. Importantly, good instrument resolution is more important than the overall accuracy of the dataset as is usually the focus when calculating head gradients. Measurements must be curated, preserved and archived at their original resolution (at least millimetres or three significant digits).
    b. The minimum sampling frequency in cycles per day (cpd) depends on the desired analysis as follows:
        - Barometric response functions (BRFs): Like aquifer testing, the minimum sampling period will depend on the hydraulic diffusivity of the aquifer (faster response requires higher time resolution but shorter record duration). However, in most cases a sampling frequency of one per hour is enough to establish confinement or to correct heads for barometric and Earth tide influences under confined conditions. A minimum record duration of 5 days is recommended, to capture the response under low hydraulic diffusivity conditions.
        - Tidal Subsurface Analysis (TSA): The minimum sampling frequency must be larger than twice the *Nyquist* frequency required to capture the highest dominant Earth tide influence (S2 tidal component at 2 cpd). This would lead to sampling every 6 h (or at 4 cpd). However, to accurately establish the amplitude of the S2 tidal component at 2 cpd, it is recommended to double that frequency to sample every 3 h (or at 8 cpd). Similarly, the minimum record duration to confidently distinguish between the dominant Earth tide frequencies M2 (at 1.93227 cpd) and S2 (at 2.00 cpd) can be derived by applying the *Nyquist* theorem to the frequency difference between both components resulting in a minimum duration of 60 days.

    c. A good compromise allowing application of both approaches is to sample hourly for a minimum duration of 60 days.
2. Encourage manufacturers to update sensor resolution— for example, using an industry standard 16-bit analogue-to-digital-converter (ADC) microchip could theoretically
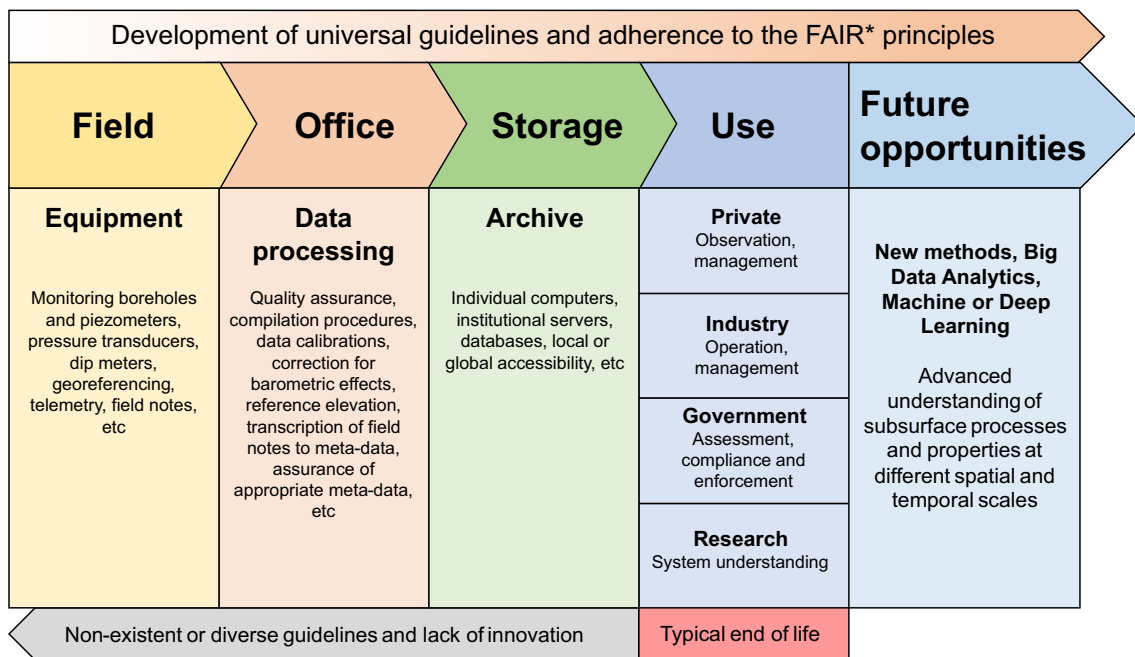
Field	Office	Storage	Use	Future opportunities
Equipment	**Data processing**	**Archive**	**Private** Observation, management	**New methods, Big Data Analytics, Machine or Deep Learning**
Monitoring boreholes and piezometers, pressure transducers, dip meters, georeferencing, telemetry, field notes, etc	Quality assurance, compilation procedures, data calibrations, correction for barometric effects, reference elevation, transcription of field notes to meta-data, assurance of appropriate meta-data, etc	Individual computers, institutional servers, databases, local or global accessibility, etc	**Industry** Operation, management	Advanced understanding of subsurface processes and properties at different spatial and temporal scales
			Government Assessment, compliance and enforcement	
			Research System understanding	

Fig. 1 General overview of the groundwater-monitoring and data-archiving workflow. The development of new universal guidelines and adherence to the *FAIR principles (findable, accessible, interoperable, and reusable; Wilkinson et al. 2016) for groundwater data is needed to gain maximum benefit of recent methodological advances and future opportunities

deliver a 0.7-mm resolution with a measurement range of 50 m. This would allow the same device to capture large drawdowns as well as subtle changes caused by Earth tides and atmospheric pressure changes.

3. Regular field trips usually dedicated to manual water-level measurements, monitoring infrastructure and instrument maintenance should include the task to coordinate the relocation of the generally limited number of automated monitoring devices around a catchment (or monitoring jurisdiction) so that records satisfying the minimal requirements for high-frequency methods (hourly sampling frequency with 60-day duration) can be established for each location. The resulting datasets should be analysed, and the results would lead to a much better decision about which locations to focus the limited resources on for strategic long-term monitoring.

4. Increase the availability of measurements and meta-data (Taylor and Alley 2001), especially for government-funded groundwater monitoring efforts, by migrating discrete datasets into centralized and publicly available data-storage infrastructure.

5. A requirement to provide readily available, standardized meta-data information about instrumentation used, i.e. sensor details, sensing types (vented/nonvented), brand, range, resolution, calibration records, an assessment of the measurement errors and data units.

6. Regular synchronisation of the internal clocks of automated devices (and records of observed clock drift for recorded time-series) and conversion to a generic time

reference. The authors recommend Coordinated Universal Time (UTC) as a time base to allow for cross-referencing with other influences on groundwater heads archived elsewhere such as gravity (Earth tides) or seismic activity (earthquakes).

7. Implementation of the FAIR principles (findable, accessible, interoperable, and reusable) when archiving datasets (Wilkinson et al. 2016). This includes providing data access via standardised application programming interfaces (APIs) to circumvent onerous download and formatting issues.

8. The need for full appreciation of the difficulty and skill requirements for accurate head measurements (including installations, calibration, conversion and standard interpretation) and with that, the provision of appropriately trained technical staff.

Recent advances in open-source software development facilitate the widespread use of sophisticated analysis techniques (e.g., Bakker and Schaars 2019). Further, the capabilities of cloud-based big data analysis (Hayley 2017) such as deep or machine learning are rapidly progressing (Shen 2018; Bergen et al. 2019) and will inevitably play a major role in the discipline of hydrogeology. Such developments will, without doubt, lead to improved knowledge of groundwater system functioning, deliver much increased spatiotemporal understanding of subsurface resources and therefore also progress sustainable groundwater management efforts. However, newly developed methods will always rely on, and benefit from, high-resolution and quality assured time-series data from accessible sources. The authors

believe that implementing these recommendations would help to future-proof hydrogeology by ensuring that currently acquired datasets enable maximum benefit in future interpretations.

The foregoing views and recommendations are reinforced by the recent publication of a special issue of *Hydrological Sciences Journal* called "Hydrological data: opportunities and barriers", which focuses on hydrometeorology and river basin data (Cudennec et al. 2020). International initiatives focusing on innovation and data sharing in hydrology more broadly have also emerged, like the World Meteorological Organisation's HydroHub (WMO 2020). It is imperative that the hydrogeological community is represented within these initiatives as they can be instrumental in driving forward the changes envisaged in this article. A good start would be the coordinated development of groundwater monitoring guidelines and data requirements by an international community of experts.

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