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Low-Cost, Open Source Wireless Sensor Network for Real-Time, Scalable Groundwater Monitoring

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Abstract: Population growth, climate uncertainties, and unsustainable groundwater pumping challenge aquifer sustainability worldwide. Efficient and data-driven groundwater supply management is a necessity to maintain essential water-dependent functions. Currently, managers lack the cost-effective, scalable, and reliable groundwater monitoring systems needed to collect vital groundwater data. Existing automated groundwater monitoring systems tend to be cost-prohibitive, and manual methods lack the spatial or temporal resolution to sufficiently meet critical water modeling, management, and policy objectives. In this study, we developed a fully automated, open source, low cost wireless sensor network (LCSN) for real-time groundwater data acquisition, processing, and visualization in the South American Subbasin Groundwater Observatory (GWO), located in California, USA. We demonstrate the steps taken to create the GWO, including field, hardware, software, and data pipeline components so that it may be easily reproduced in new areas. We find that the GWO is comparable in cost to manual measurements at a weekly measurement frequency, and costs between three and four times less than comparable commercially available telemetry and dashboard systems, largely due to the use of free open source software to acquire, clean, store, and visualize data. The open source-powered GWO thus lowers the financial and technical barrier of entry for real-time groundwater monitoring, creating the potential for more informed water management worldwide, particularly in regions whose managers are restricted by the high capital costs of commercial monitoring systems.

Keywords: low cost sensor network; groundwater sustainability; open source; groundwater monitoring

1. Introduction

Groundwater is critical in many food production systems around the world as a supplement to intermittent, and historically much more thoroughly monitored, surface water supply [1] and, in some parts of the world, is the primary source of irrigation water [2]. Global groundwater extraction has reached alarming rates [3–5], and future threats to groundwater are anticipated from population growth [6], climate change [7,8], and natural climate variability [9]. Effective groundwater management depends heavily on information pertaining to changes in groundwater levels and storage. Quite commonly, however, the impacts of groundwater pumping or recharge operations are not well known until months or even years after these events due to limitations in data reporting (e.g., sampling wells with a water level meter by hand, or waiting to download data from a deployed sensor). This separation between cause (e.g., pumping) and effect (e.g., water level decline and storage loss) hinders sustainable groundwater management and motivates modern real-time monitoring (Figure 1c).

Groundwater levels are monitored with in situ networks in major aquifer systems including the North China Plain [10], the Great Plains Aquifer in the United States of America [11], and California's Central Valley [12], although the spatial and temporal frequency of the measurements and the technology deployed to measure them varies greatly. Monitoring wells provide direct in situ measures of the depth below land surface at which water is encountered. In situ groundwater level monitoring is used to estimate changes in aquifer storage [13], calibrate groundwater flow models [14,15], and provide groundwater users, decision-makers and regulatory agencies with up-to-date groundwater system information to facilitate water resource management and policy. Many technical approaches to measure groundwater levels exist, and they differ in cost, scalability, and the ability to answer specific scientific and management questions.

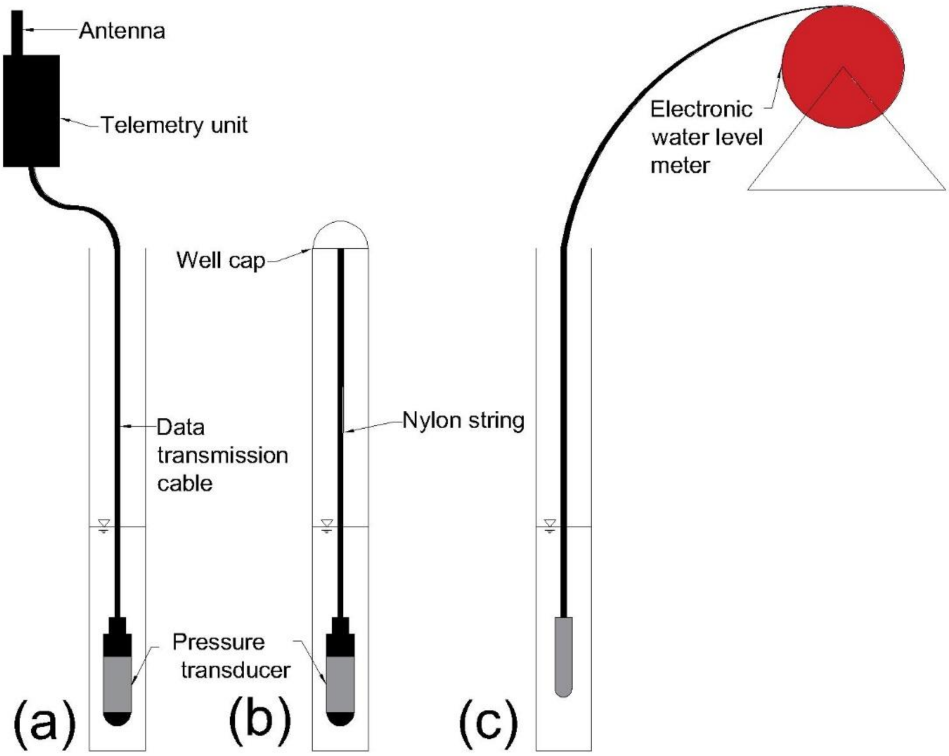

Figure 1. Three methods of groundwater level monitoring: (**a**) pressure transducers that remain deployed in a monitoring well and send continuous data via telemetry (**b**) pressure transducers that remain deployed in a monitoring well until the sensor is removed for manual data retrieval, and (**c**) manual water level meter measurements which provide a single data point per measurement event.

Two widely used approaches to in situ groundwater level measurement via monitoring wells include sensors that remain deployed in the well [16] (Figure 1a,b) and water level meters [17] (Figure 1c). Water level meters are easy to use and provide an immediate single measurement performed at the wellhead at a specific point in time, whereas sensors deployed within a well may stay there for months or years, all the while collecting data at a specified temporal monitoring frequency, and recovered at a later date whereupon the data is downloaded for analysis. Compared to water level meters (Figure 1c), sensors (Figure 1a,b) are more costly and require more configuration, albeit with the advantage of their ability to collect more data. In the case of sensors that remain deployed in the well (Figure 1b), data access is delayed until the date at which the probe is retrieved.

Sensors installed in wells (Figure 1a,b) offer the advantage of measuring high frequency groundwater level time series data, which, in addition to revealing seasonal groundwater level trends, can also be used to answer more complex scientific questions such as the determination of unknown aquifer characteristics (e.g., hydraulic conductivity or storativity) [18](pp. 125–129), the influence of adjacent pumping wells, and changes in aquifer storage [13]. When sensors are connected to telemetry (Figure 1a), which use antennae to wirelessly transmit sensor data to a database, the need for in-person data access is eliminated, thus providing real-time, automated data streaming with minimal supervision. Although widely used in ecology [19], surface water hydrology [20,21], crop management [22,23], and energy economics [24,25] among other fields, telemetry applied to remote in situ groundwater sensing networks is limited, and notably reliant on proprietary, commercial applications. These networks remain costly to deploy, and thus remain unlikely to take hold worldwide, where inexpensive and reliable monitoring is needed to characterize causes (e.g., pumping) and effects (e.g., groundwater level decline) in heavily relied upon aquifers.

Low cost sensor networks (LCSNs) are constructed from affordable, telemetry-enabled sensors rising in use across various fields due to their low financial cost, ability to provide real-time data, and general ability to outperform traditional in situ measurements in terms of cost, scalability, and volume of obtained measurements (Figure 1a) [26]. However, sensor hardware is only half of a monitoring system—software is also needed to manage, clean, store, and visualize the data collected by sensors. Many commercial sensor network applications integrate real-time data streams with online analytics and visualizations to monitor human safety [26]. Thus, analytics and visualizations built with open source software provide one way to dramatically reduce LCSN cost. Free software for near real-time processing of geoscience data exists, but the source code is not available for individual user group hosting and modification (e.g., the data must pass through a research center hosted data portal) [27], and it is thus not truly open source, which hinders wide application to a variety of use cases. To the best of our knowledge, although it would have wide application worldwide, there is a lack of free and open source software to process, clean, and render groundwater data from LCSNs into web dashboards for groundwater research and management.

In this study, we demonstrate an open source and openly available regional scale LCSN for local groundwater management and modeling in the South American River Subbasin (Figure 2). We built a pilot Groundwater Observatory (GWO) as a foundation for eventual high density monitoring of the entire basin to assess ongoing research tracking the effectiveness of flood-based managed aquifer recharge in the region. The GWO streams real-time groundwater level data via telemetry to an online dashboard to facilitate scientific analysis and water management decision-making (Figure 3). Although designed for specific regional-scale scientific and management objectives, the GWO is transferrable to any locality and scalable to tens of thousands of monitoring units. We now describe the creation of this open source tool [28], review the technical aspects to consider when establishing a similar LCSN for groundwater monitoring, and explain our open source workflow and provide the source code. Lastly, we discuss how a monitoring framework leveraging free and open source software may lower the financial and technical barrier of entry to groundwater monitoring, thus leading more informed water management worldwide, especially where cellular networks are common but where the high capital costs of commercial systems currently inhibit monitoring and sustainable management.

An underlying tenet of this work is that most of the globe's major aquifer systems are not being managed sustainably [3,4] because of the lack of transparency about the state of those systems at any given time. Consequently, we submit that LCSNs will be transformative in the quest to convert groundwater management globally from a condition of abject neglect to a condition of functional sustainability.

2. Materials and Methods

The GWO is located in the South American River Subbasin (Figure 2), a semi-confined, alluvial aquifer system with documented incised valley fill [29], a geological feature of great interest for its ability to accommodate relatively rapid rates of managed aquifer recharge [30,31]. The site was first instrumented on 14 November 2017 with groundwater pressure transducers and telemetry (Appendix Figure A2). We now review the hardware, software and database components of the GWO that direct the flow of data through the LCSN (Figure 3).

2.1. Hardware, Water Level Measurement, and Data Correction

The GWO uses Solinst Leveloggers [16] as pressure transducers (Figure 3a) and Solinst LevelSenders as telemetry [32] (Figure 3b) to transmit collected data over a cellular network. However, other pressure transducer and telemetry units are available from several companies ranging in adaptability and cost (e.g., In Situ TROLL Link 201, Campbell Scientific CR300). The telemetry units require sufficient cellular service to send data across a cellular network (Figure 3c) to the local server which hosts a free and open source SQLite database (Figure 3d). To determine which monitoring wells to instrument and which cellular network to use, we tested the cellular reception of two different networks and chose the one with greater signal strength across the monitoring wells in our site. Since telemetry is installed within the metal wellhead housing, the antennae of some telemetry units were mounted directly to the steel housing to improve cellular reception and hence reporting consistency (Appendix Figure A1).

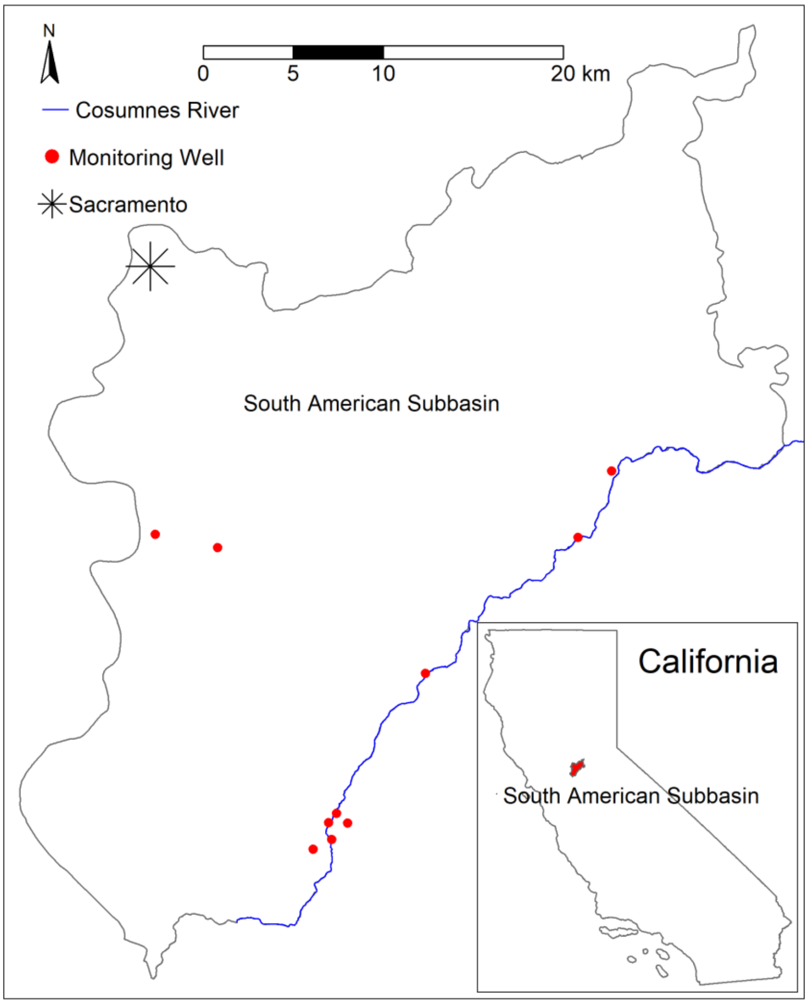

Figure 2. The Groundwater Observatory (GWO) network in the South American River Subbasin in central California, USA. The red polygon in the inset map indicates the range of the subbasin, and the red dots in the map show monitoring well locations outfitted with telemetry.

Next, raw data collected by the sensors was corrected for barometric pressure and cable length to compute a groundwater elevation at each site. Suspended sensors measure the pressure of the overlying water column in the well and calculate the height of water corresponding to the measured hydrostatic pressure. Raw data recorded by suspended sensors like the ones in our study are influenced by natural variations in atmospheric barometric pressure: an increase in barometric pressure imparts a downward force on the water level in the well, and a decrease in barometric pressure has the opposite effect. To remove the influence of barometric pressure in the recorded water level, we measured barometric pressure with a separate pressure transducer (i.e., Solinst Barologgers [16]) placed in the atmosphere within 32 kilometers of the transducers suspended in wells [16]. The barometrically corrected groundwater level above the sensor in a well $z_c(\mathrm{t})$ (L) at time t, is the difference between the measured groundwater level above the sensor, z_m (L), and the atmospheric pressure z_a (L) (Figure 3a):

$$z_c(\mathrm{t}) = z_m(\mathrm{t}) - z_a(\mathrm{t}), \tag{1}$$

The greatest distance between the barometric pressure transducer, and any well in the GWO is less than 27 kilometers, thus we observe little variance in barometric pressure across the monitoring region and a single barometric pressure transducer is sufficient for all monitoring wells [16].

Next, we use a water level meter to measure the depth to water, d (L) at a monitoring site at t = 0. The effective cable length, l at t = 0, $l(0)$ (L) (Figure 1a) is the sum of z_c from (1) at t = 0 and d at t = 0:

$$l(0) = z_c(0) + d(0), \tag{2}$$

Subsequent effective cable length measurements (l) should occur every six months to ensure the pressure transducers are properly recording data. According to Solinst, Leveloggers can experience some drift in measurement over an extended period of time; therefore, it is best practice to verify data with a manual measurement [16].

We measure an elevation datum, z_d, (L) (i.e., the top of the well casing), and use it along with the barometrically corrected groundwater level above the sensor in a well $z_c(\mathrm{t})$ from (1) and $l(0)$ from Equation (2) to compute the final groundwater elevation, $h(\mathrm{t})$, which may then be mapped or directly compared to other wells in the region [18](pp. 98–100). The barometrically adjusted groundwater elevation is:

$$h(\mathrm{t}) = z_d - l(0) + z_c(\mathrm{t}), \tag{3}$$

As mentioned before, the effective cable length may change over time, thus Equation (3) is always calculated with the most up-to-date cable length.

2.2. Software and Databases

Software, which is now available free and on an open source basis, was developed to retrieve, clean, store, and visualize data from sensors. All of the code used to perform these functions is available for use and modification on GitHub [28].

2.2.1. Data Retrieval and Cleaning

Once data is transmitted from the telemetry (Figure 3b,c) to the local structured query language (SQL) database (Figure 3d), custom software scripts written in R [33] runs every 24 hours (Figure 3e) to correct the groundwater level data according to Equations (1)–(3). SQL is a modern, free, open source database language optimized for storing tabular data, and is appropriate for the data storage needs of a groundwater monitoring network, where observations consist of a table of: monitoring well identification numbers, date and time stamps, and corrected groundwater levels. Although we use R to connect to SQL, retrieve data, and clean data, other open source implementations are possible, notably in Python [34]. Moreover, although we perform data retrieval and cleaning on local computers (Figure 3d,e), these steps may also be moved to the cloud for a fully cloud-based workflow.

2.2.2. Data Storage

Data is retrieved and cleaned every day, but a copy of the data is saved once every 7 days to protect against unexpected data loss or network failure, and to reduce the amount of storage used for data backup. Regular and automated data backup is important, and snapshots of the data can be accessed at any time if unexpected errors occur that require the recovery of older data. The cleaned data is saved to a separate cloud-based SQL database (Figure 3f), so that it is easily available for the next step (data visualization).

2.2.3. Data Visualization

Once data has been retrieved and cleaned, it is visualized for users. When a user navigates to the online dashboard (Figure 3g), the application reads the corrected groundwater levels from the SQL database (Figure 3d), in addition to a configuration file containing location data for each of the monitoring wells. It then renders these data for the user to visualize, interact with, and download. Dashboards are easy to use for non-technical users, but also help technical users (e.g., researchers) by automatically handling routine tasks like data download, cleaning, preparation, and visualization, thus freeing the researcher to rapidly move towards analyzing and interpreting the data or incorporating it into models.

2.2.4. Web Dashboard Design

The web dashboard (Figure 3g) is written in Shiny [35], an open source software library that extends the R programming language to build custom, interactive dashboards, also called Shiny applications. A Shiny application consists of two main components: a server and a user interface. The server is not seen by the user—it defines the computations that happen when a user interacts with a particular component defined in the user interface (e.g., display a particular line plot, convert the units from feet to meters, start a data download). Shiny apps allow R programmers to flexibly add and subtract various user interface components and define arbitrarily complex server logic linking user interface components to various actions. Thus, our framework, by nature of being open source, may be modified and customized as new visualization and reporting needs arise. The Shiny framework is a powerful open source tool for building dashboards to visualize, explore, and access groundwater monitoring data from a LCSN.

3. Results

The GWO LSCN monitors groundwater levels in real-time over a critical portion of the South American River Subbasin, which may accommodate flood-based managed aquifer recharge [29,30]. Aside from occasional visits to change batteries, the installed groundwater pressure transducers and telemetry are fully automated, as is the open source data pipeline which processes sensor data and visualizes it on the web dashboard (Figure 4). A fully automated data collection platform such as the GWO permits operators to focus less on data management and more on analysis.

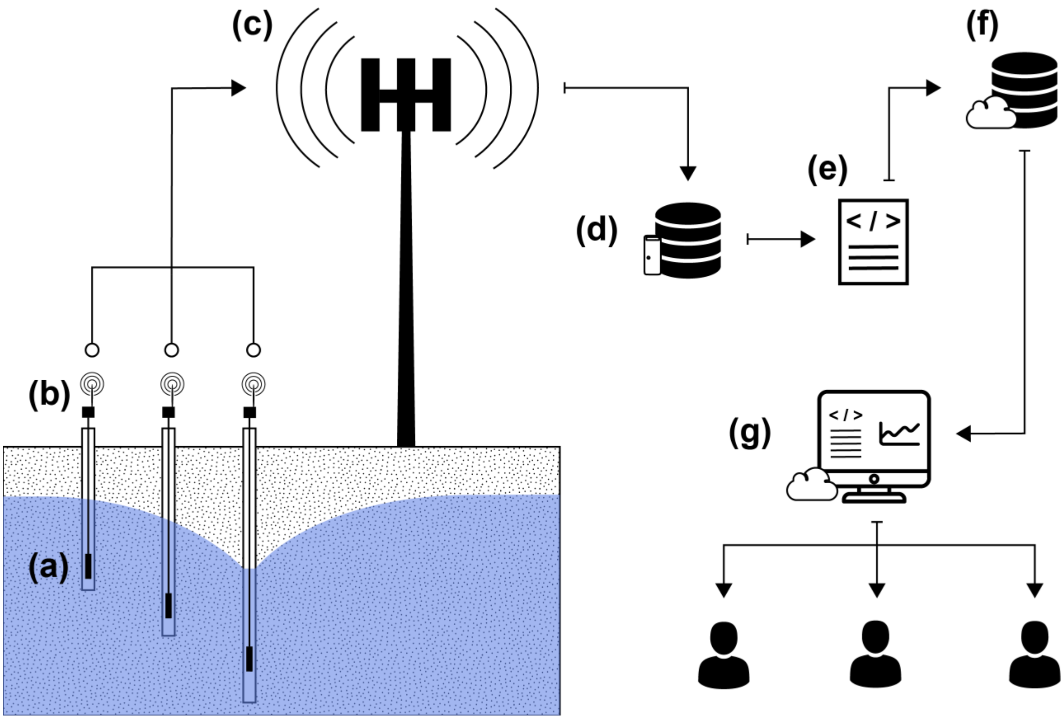

Figure 3. Each component of the GWO, labeled along the direction of data flow, (a) through (g). (**a**) Deployed sensors in monitoring wells collect groundwater level data at a specified monitoring frequency, (**b**) telemetry units located outside of the well housing send data at a specified reporting frequency, (**c**) cellular network that receives data sent via telemetry and forwards to the local server, (**d**) SQL database on local server, (**e**) local data processing scripts that automatically run on a task scheduler and push clean data to the cloud database, (**f**) cloud database for data backup and storage, (**g**) server that reads clean data from the cloud database and hosts the Shiny web dashboard.

The GWO online dashboard provides hydrographs of historical data (prior to telemetry installation) and recently collected data (post telemetry installation). On the main page (Figure 4), well locations are displayed as points on an interactive map. Hovering the cursor over a well on the map displays the well name and spatial coordinates, although this information is configurable by the programmer. Users may select a well by clicking it on the map, or by selecting it by name from a drop-down menu. When selected, the well's hydrograph is displayed. Hovering the cursor over the hydrograph shows the groundwater level over time. Sliders on the bottom of the hydrograph allow the user to zoom in on specific date ranges, which may be useful, for example, to examine recharge events due to precipitation or flooding.

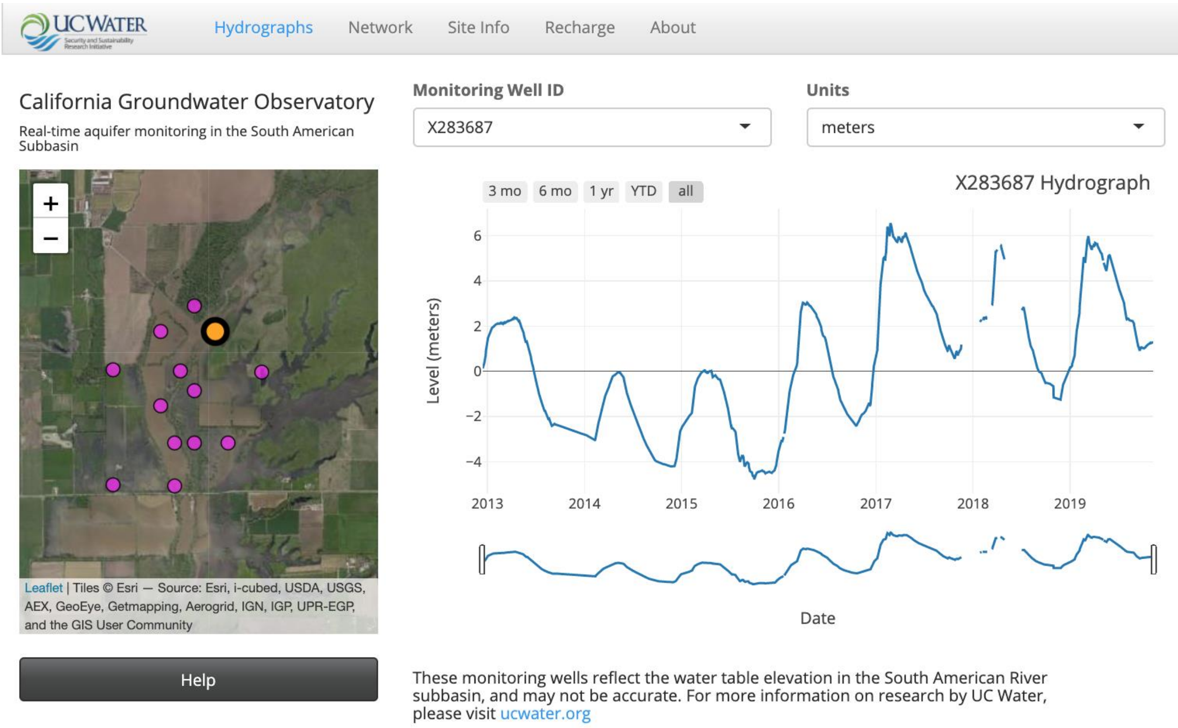

Figure 4. Main page of the online dashboard for the GWO. A single monitoring well is selected (yellow dot) from all wells (pink) on the map (left), and the selected well's hydrograph is displayed (right).

Well hydrographs for the entire network (Figure 5) are displayed on a tab entitled "Network" and show the full range of historical data, dating back to 14 December 2012, including data collected with sensors prior to telemetry instrumentation. At the scale of the network, seasonal variations in groundwater level (i.e., winter recharge and summer drawdown) are visible, as are the impact of pumping wells, which appear as rapid oscillations in water level in some wells on the right-hand side of Figure 5. The red trend line represents the smoothed average groundwater level of all monitoring wells in the GWO. Declining average groundwater level during the 2012–2016 California drought are visible, consistent with similar trends statewide [36], due to increased pumping and decreased recharge from surface water. Moreover, groundwater levels increase during the exceptionally wet winter of 2017 [36].

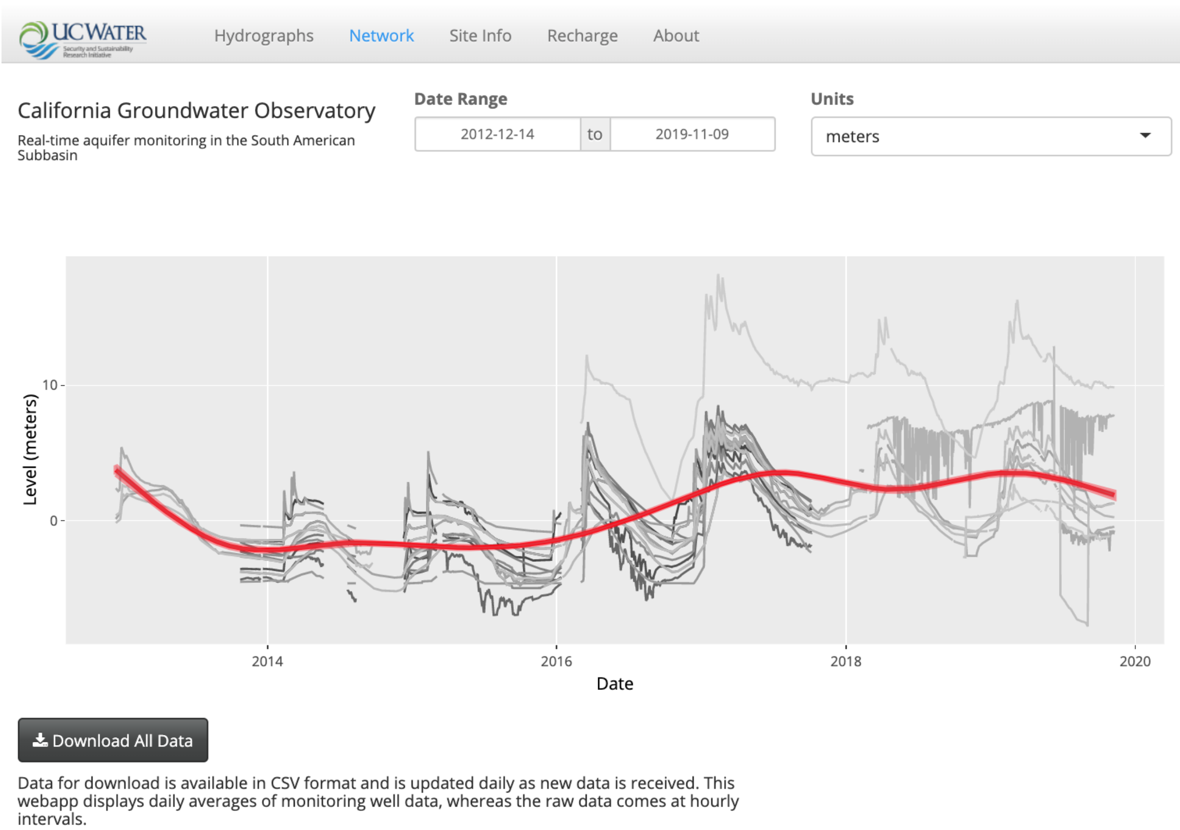

Figure 5. The network tab of the GWO shows all monitoring well data, and allows for a more complete picture of the system state. A button is provided for data download.

A data download button on the "Network" tab (Figure 5) allows any user to download the most current and complete dataset from the SQL server (Figure 3f) as a comma-separated-value (CSV) file. Additional tabs on the dashboard provide users with information on the site, the research, the research team, and resources for creating a similar dashboard (e.g., a technical field manual and online code repository).

4. Discussion

4.1. Comparison with Other Groundwater Level Measurement Methods

The GWO approach has several benefits over traditional water level meter measurements but may not be appropriate or cost-effective for every monitoring project. We will now discuss the benefits of the GWO with an example from our research on flood-based managed aquifer recharge and contrast this example with examples of cases when a GWO may not be necessary.

An LSCN like the GWO may be necessary for some sites that are hard to reach, or that become nearly impossible to reach, for example, during periods of inundation. In our study site, flood-based managed aquifer recharge has been proposed as a partial solution to groundwater overdraft [37,38]. Floodplain restoration may benefit both aquifer storage projects [31] and salmon habitats that depend on groundwater baseflow during the fall spawning season [39]. Thus, to assess the impact of floodplain restoration on groundwater levels, we required high frequency (i.e., 15-minute interval) groundwater level measurements over a large spatial area (~ 600 km^2), particularly near the river aquifer interface (Figure 2). Many of the measurements critical to this study occurred during extreme precipitation events, which made field visitation either extremely challenging, dangerous, or infeasible when flooding prevented site access. Hence, a LCSN approach was taken to overcome the limitations of in-person measurement via water level meters. During the winter, when rainfall and flood events were frequent, the GWO allowed us to access and analyze the groundwater response for each distinct flood event in near real-time, without needing to coordinate in-person visits to the site to obtain measurements during inclement weather. Lastly, the web dashboard component of the GWO allowed us to easily provide real-time data to stakeholders on whose private land we established sensors in the network.

A GWO may offer advantages compared to traditional water level meters in research and management that tracks rapidly changing hydrology (e.g., flooding), or that depends on real-time data (e.g., implementing groundwater markets, optimizing irrigation schedules). For instance, a GWO may be used to monitor shallow water levels in real-time, and inform irrigation schedules to avoid waterlogging and shallow soil salinization [40,41]. Additionally, a regional-scale GWO could provide the real-time data critical to inform water transfers in a modern groundwater market [42].

A GWO may not always be a practical, due to the cost of installing and maintaining sensors, or research and management objectives that do not require high-frequency data. For such applications, traditional measurement methods via water level meters may be sufficient. For example, sampling ambient groundwater levels before or after a growing season is easily accomplished with water level meters. However, as the spatial scale of a monitoring network grows, it becomes increasingly difficult to manually sample across the network within a short time frame (to ensure temporal consistency between individual measurements). The state of California's official ambient groundwater level monitoring program is an example of a large monitoring network that, due to its size, takes several months to fully sample with water level meters [43]. For a monitoring network of this size, a LCSN may be an appropriate investment that automatically collects data at exactly the same time across thousands of sites without the need for human intervention other than network maintenance. Such measurements could also help constrain groundwater budgets in the regional scale hydrologic models of the Central Valley [14,15], and assist in implementing California's landmark Sustainable Groundwater Management Act [44].

LCSNs are more difficult to establish, and in some cases, can be more costly than traditional hand-based monitoring programs, which may challenge project longevity. A survey of Fall 2017 American Geophysical Union Meeting participants found that participants expected scientist-led LCSNs to stop after the end of a research project due to funding constraints [45]. Therefore, we emphasize that free and open source software may extend the lifetime of LCSN projects, shifting the primary cost towards the occasional maintenance of sensors.

Additional benefits of LCSNs over deployed sensors without telemetry include real-time feedback of issues impacting the deployed hardware, thus allowing for maintenance and intervention sooner than the scheduled time period of data retrieval. This helps to prevent data loss and ensure network reliability. The telemetry may also be used to increase the recording rate at the beginning of key hydrologic events (e.g., a major recharge event, or a pump test) to better capture high resolution data around these events.

4.2. Cost Comparison to Groundwater Level Measurement Methods

LCSNs are inexpensive because they depend on low cost hardware, free and open source software, and minimal work hours for installation and maintenance. Simple hardware can ease installation and prevent labor costs from entering the thousand dollar range per unit due to the high billable hours for professional work. Additionally, the hardware should be appropriately robust for the task of groundwater measurement, but not excessively so because purchasing the most expensive model of battery, datalogger, antenna and sensor can increase cost from a thousand dollars to several thousand per unit. Importantly, LSCNs easily scale to arbitrary temporal ranges because one can increase measurement frequency without increased costs (Table 1), thus they are increasingly cost-effective for higher frequency data.

Table 1. Cost comparison of manual measurements and the Groundwater Observatory (GWO).

Monitoring Time Scale	Annualized Cost ($)	
	Manual measurement [1]	GWO
Daily	$8400–33,600	$981
Weekly	$1200–4800	$981
Monthly	$300–1200	$981
Biannual	$50–200	$981

[1] Approximate cost to visit a well and measure the water level with an electric probe.

On the other hand, manual water level measurements have linearly increasing costs corresponding to the temporal frequency, because each additional measurement requires additional technician work hours. Although the cost for manual measurements is uncertain due to the variance in technician wage, water wells, distances between wells and equipment used, there is evidence that, at a desired weekly measurement frequency, an LSCN may be more economical. We estimate a $25-100 cost per manual measurement assuming 1–2 h of travel time, 10–15 min spent measuring each well, and a $25–50 hourly wage. At a desired sub-weekly (e.g., daily or hourly) monitoring frequency, LCSNs are more economical than manual measurements (Table 1). Next, we compare our LSCN to a commercial monitoring system (Max Stevenson, Personal Communication 2 December 2020) (Table 2), which, like the LCSN, is telemetry based and scales to arbitrarily fine time scales.

Table 2. Telemetry system costs for a commercial system and the Groundwater Observatory (GWO) (Max Stevenson, Personal Communication 2 December 2020). Values are based on a lifespan of commercial system of 5–20 years, and a GWO lifespan of 10 years. Average annual costs are provided in the last row of the table.

Cost area	Commercial Cost	GWO Cost
Hardware	$1250–6500	$1645
Installation and well owner agreement	$200–1500	$60
Radio or data fees	$0–480	$180
Maintenance and calibration	$1200–1600	$40
Database server (approximate)	$0–100	$391
Data analysis, reporting, public access	$800	$150
total average annual cost (hardware amortized over life)	$3330–4050	$981

The annual radio or data fees start at no cost for an ethernet or radio connection, to higher costs for proprietary radio and cell modems. The installation cost for ethernet connections is thus higher as more initial work is required than for a cellular modem. The annual maintenance and calibration cost is higher for the commercial cost as water agencies may require a fine accuracy due to regulation, whereas the GWO is designed to serve the local parties who may only need a biannual check up on logger reporting accuracy. The database server has no cost for a proprietary monitoring company, but for wells managed directly by the water agency there is a small annual cost of around $100. The data analysis, reporting and public access cost comes from a total of $20,000 per year for 25 wells for the water agency. On the other hand, the GWO built with free, open source software has no annual cost but rather a maintenance cost of $1500 for the 10 wells operated, which could be scaled at little additional cost.

We compare these two systems in terms of average annual cost, though it should be noted that the upfront hardware and installation costs of a commercial system may be up to four times higher than an LSCN. In addition to saving on software costs, we also reduced costs by choosing relatively inexpensive hardware compared to the commercial system, and scheduling annual maintenance twice a year instead of every month.

4.3. Limitations

A key component of this study involved building strategic partnerships with local well owners and agencies who allowed us to instrument their wells. We installed five telemetry units on a site where our institution had a long-standing relationship with the landowners. In some regions, stakeholder involvement to gain approval of using a well for a GWO may pose a greater challenge than physical limitations such as cellular reception. We found that access to monitoring sites was easier to obtain from stakeholders who already had a connection to water management and saw no negative effects for their well. Financial support for a LCSN was more likely from stakeholders if a web dashboard component was available to help inform specific management objectives.

Despite initial challenges in acquiring access to wells for the network, once the GWO was established and the web interface demonstrated, we received requests from both private well owners and from consultants monitoring contaminant plumes in the region to add their wells to the GWO. This leads us to believe that the value proposition of a GWO can produce sufficient community interest to drive future expansion of monitoring efforts. Some well owners may always prefer to keep their well status confidential, but our success in gaining financial support for groundwater level monitoring from multiple interest groups after having a dashboard in place indicates the potential for a crowdsourced LCSN model to continue GWO development and maintenance.

4.4. Technical Considerations

Groundwater elevation in an aquifer cannot be directly measured. What is measured is the equilibrium water level in a monitoring well casing adjacent to the aquifer material [18] (pp. 93–94). Improperly screened wells in the aquifer may lead to an inaccurate representation of the groundwater level. A high-density monitoring network may reduce uncertainty introduced by groundwater level measurement where well completion data are unavailable, as long as it includes properly screened wells.

When establishing an LCSN, one should consider if real-time data is necessary, and at what temporal frequency the data is required. Data transmission depletes batteries which leads to increased site maintenance. Thus, financial resources may be conserved by only transmitting data at a weekly or monthly interval, though these gains in battery performance must be weighed against the loss of real-time data and information on network performance (e.g., if the network is down and requires repair, it will only be apparent during transmission).

Hardware and software requirements in establishing an LCSN are significantly greater than using water level meters, or deploying and recovering sensors, but pay for themselves at a weekly sampling frequency, and save money at sub-weekly measurements (Table 1). Cellular reception at monitoring sites needs to be evaluated, and antennae may need to be installed alongside telemetry to improve transmission in areas with poor reception (Appendix Figure A1). Although we have written our open source code to be as portable as possible to new projects, a skilled programmer is important to connect the code to servers, databases, and the web dashboard.

4.5. LCSN Expansion and Extensibility

A general framework for an LCSN allows it to be easily replicated and applied to many cases [46]. In this study we created a general framework for a groundwater LCSN with an open source data pipeline and dashboard to permit the expansion of collected data and extensibility to other areas. Theoretically, a water manager with a moderate knowledge of the R programming language could copy the framework provided here and adjust the input files to start a GWO after installing groundwater sensors and telemetry equipment. Moreover, since the solution we provide is open source, the source code may be customized to add or subtract features from the data cleaning, storage, and dashboard components of the GWO. Commercial systems typically do not provide this level of flexibility and control.

LCSNs consist of sensors and telemetry, but multiple sensors collecting different types of data may be connected to a single telemetry unit. Although we do not demonstrate it with the GWO, one may add sensors to LCSNs to monitor data such as electrical conductivity, soil moisture, precipitation, and evapotranspiration. A website with stream stage, precipitation, and evapotranspiration data coupled with groundwater elevation could provide an all-in-one source for basin-level water management decisions [23]. Thus, the strategic siting of sensors in LCSNs should take into consideration which additional environmental variables need to be measured, so that sites are chosen that maximize access to these data. In California, where our GWO is located, we see the potential for LSCNs to aid in the implementation of monitoring programs required by the Sustainable Groundwater Management Act [44], landmark legislation that requires sustainable groundwater levels, among other objectives. The technological foundations of the GWO are scalable to a regional or national level, pending stakeholder support [10]. When properly instrumented, LSCNs may form the basis of a continuous real-time data stream that informs decision-making by stakeholders, scientific researchers, and policy makers.

Continued additions to the GWO will be particularly important for further developing the three-dimensionality of the groundwater level monitoring networks in stratified alluvial aquifer systems such as the South American River Basin. In such systems, abundant confining interbeds (e.g., clay and silt stratigraphic units) produce strong vertical head gradients such that the deeper wells exhibit potentiometric surfaces significantly different from the shallow, unconfined water table elevation. In such systems, a full image of the state of the groundwater system must come from 3D head monitoring in which wells of different depths are instrumented.

4.6. Sustainability Implications

A semi-public (i.e., where exact locations of wells are obscured) high density groundwater monitoring network would allow neighboring landowners to compare their volume of pumping and subsequent loss of groundwater storage. This form of anonymous peer pressure was effective in improving urban household water conservation during a drought with a basic rating scale and comparison [47,48]. Additionally, monitoring groundwater in a locally available, near real-time network may help groundwater pumpers view groundwater as an active and fluctuating reservoir similar to surface reservoirs, effectively revealing cause (e.g., pumping) and effect (e.g., groundwater level decline) relationships that are difficult to understand with hidden-from-view subsurface groundwater systems. Locally available, near real-time groundwater monitoring must be cost effective and easy to implement, such as the GWO framework provided here. Unlike existing proprietary monitoring systems, the deployment of the GWO will foster a broader impact on groundwater monitoring thus deepening the impact on groundwater management worldwide.

Countries around the world experiencing rapid economic growth and development such as China are beginning to feel the effects of groundwater dependence and can benefit from low cost groundwater monitoring methods [49]. Groundwater telemetry technology has long existed, but pairing it with free and open source software to create scalable networks is a novel contribution with potential to lower the financial and technical barrier of entry into real-time groundwater monitoring. Additionally, the prevalence of cellular network coverage in developing countries presents an opportunity for LCSN applications where remote locations may be more accessible via wireless technology [50]. The LCSN model thus represents a method to sustainably monitor and manage natural resources with minimal infrastructure and funding.

5. Conclusions

Declining aquifer levels worldwide are partially the result of a lack of understanding of cause (e.g., pumping) and effect (e.g., groundwater level decline) by water managers and users. Similar to the disconnect that was addressed when continuous, quantitative, surface water data became available worldwide, this disconnect can be addressed by the implementation of real-time groundwater monitoring, but previously existing approaches have not become widespread due to cost-related barriers and/or a lack of customizability. In this study, we developed an LSCN framework called the GWO built on open source software in the South American Subbasin of California, USA for the research aim of studying the impact of managed aquifer recharge. The GWO consists of sensors that monitor groundwater level, telemetry units that transmit these data through an open source data processing pipeline, and a web dashboard for interactive data visualization and data access. Compared to manual measurements, we find that the data from the GWO is comparable in cost at a weekly measurement frequency, and more cost effective for sub-weekly measurements. However, the GWO offers additional benefits over manual measurements such as data access when environmental conditions prohibit sampling (e.g., rain and flooding). Compared to commercially available telemetry and dashboard systems, the GWO is between three and four times less expensive in terms of annualized cost and initial investment, largely owing to the data processing scripts and web dashboard built with free and open source software provided via this paper. The GWO framework provides a tool for water managers worldwide that can be modified with a moderate proficiency in R and applied to any groundwater system to develop high-resolution and high-frequency data. The data demonstrated with a GWO [51] can aid in the implementation of sustainable natural resources management, informed decision making by stakeholders, and scientific research.

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Appendix A

Additional Information on Hardware

Leveloggers connect to the telemetry unit with a reader cable that determines the depth of the pressure transducer (Figure 3a). The length of the cable is adjusted in such a way that during the wet season the Levelogger does not receive more than 10 meters of head and during the dry season it maintains 1–2 meters of head based on historical groundwater data. The Leveloggers have a 10-meter upper limit, after which they have lower accuracy [16].

Cellular reception was improved by drilling holes in the steel well housing and mounting the antennas on top, as demonstrated in Appendix Figure A1.

Figure A1. Installation of a telemetry unit with antenna extension in a monitoring well.

The main cause for the loss of a data report is if the batteries in a LevelSender become fully depleted. If a LevelSender does not report for a day due to poor cellular service, it will append the previous day's data to the next day's report. The web dashboard has a built-in report that sends out the battery levels of the LevelSenders and will show them as red when they drop below 70%, indicating that it is an appropriate time to replace the batteries.

An update was added to the dashboard to allow the addition of missing data due to a stop in LevelSender reporting. The update consists of two tables containing: (a) the time and date of LevelSender and Levelogger outages, and (b) the recovered data during the time period where an outage occurred, which is manually adjusted to water elevation following Equations (1)–(3). These tables are read by the data cleaning scripts (Figure 3e), and inserted into the correct space in the data.

When a new well is added (Figure A2) to the dashboard, the elevation table must be manually updated to add the new LevelSender and Levelogger IDs, the reference point elevation, the depth to water and corresponding compensated water level above the logger and to calculate the effective cable length. This configuration file is hosted on GitHub, and read by the cleaning scripts (Figure 3e).

Figure A2. Installation of a telemetry unit for a pumping well.

Network Maintenance

A wireless sensor maintenance schedule was created to ensure that each unit continually reported data to the receiving computer. Each LevelSender requires three AAA batteries that must be replaced when the unit reaches a battery level of 60%, as signal transmission is likely to fail thereafter. Thus, we continuously monitor battery life and replace batteries when they reach a level of 70% to ensure uninterrupted data access. In the event that a LevelSender battery dies, the Leveloggers deployed in the well still collect data, so there is no loss in data, only a loss in real-time data access. Generally, Leveloggers are much more energy efficient than the telemetry LevelSender units, and thus require less attention towards replacing batteries. In addition to battery maintenance, the sensors may require occasional firmware updates, recommended by the sensor retailer, that require a field visit to upload the new firmware and restart the unit.

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