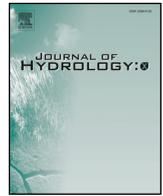




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## Research papers

## Shallow aquifer monitoring using handpump vibration data

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## ABSTRACT

We present a novel technology for monitoring changes in aquifer depth using handpump vibration data. This builds on our previous works using data to track handpump usage and facilitate handpump maintenance systems in rural parts of Kenya. Our motivation is to develop a cost-effective and scalable infrastructure to monitor shallow aquifers in regions where handpumps are already part of water infrastructure, but where traditional sources of groundwater monitoring data may be limited or non-existent. The data is generated using accelerometer sensors attached to the handles of nine handpumps in the study site in Kenya, instrumented for a year. These time-series data from handpumps are individually modelled using machine learning methods to track the changes in the water level with respect to the bottom of the rising main. Results show promise in modelling handpump vibration data with machine learning approaches to provide useful aquifer monitoring information from the “accidental infrastructure” of community handpumps. This technology is intended to complement existing hydrogeological modelling, and one of our key future goals is to integrate these machine learning outputs with hydrogeological information to develop more refined and robust models for shallow aquifer monitoring.

## 1. Introduction

Groundwater is directly linked to United Nations’ Sustainable Development Goal 6 (SDG 6) – clean water and sanitation for all by 2030 (UN, 2018). It is also inexplicably linked to other SDGs related to poverty eradication, food security, gender equality, sustainability of cities and human settlement, combating climate change, and protecting terrestrial ecosystems (Hope and Rouse, 2013; Howard, 2014; UN, 2018; WWAP, 2019). It is estimated that groundwater provides around 50% of all drinking water and 40% of all agricultural irrigation worldwide (FAO, 2011). In Africa, groundwater is the major source of drinking water and its use for irrigation is expected to increase substantially to tackle growing food insecurity (MacDonald et al., 2012).

The magnitude of groundwater’s significance is in sharp contrast to the dearth of reliable quantitative information on groundwater resources, especially in Africa (MacDonald et al., 2012; Fan et al., 2013; UN, 2018). Available data on global groundwater storage estimates, often based on decade-old studies with large uncertainties, limit effective governance of groundwater systems (Richey et al., 2015). Like any other resources, groundwater resource management requires monitoring to make informed plans by water users and water service providers at regional and national levels. However, long-term monitoring

data are often scarce in Africa, and wherever data are available, inconsistencies in methodologies used at different times make comparisons difficult and trend unclear (Comte et al., 2016). Traditional groundwater monitoring technologies (Xu et al., 2012; Van Camp et al., 2013; Kelbe et al., 2016) are often data, resource, and time intensive. Recent efforts have shown remote sensing observations can provide useful cost-effective auxiliary data to improve global groundwater estimates (Richey et al., 2015). We propose a novel complementary shallow aquifer monitoring technology that utilizes the continent’s existing handpump infrastructure. Handpumps remain a reliable and low-cost method to access groundwater in the context of rural water supply for around 200 million people in Sub-Saharan Africa (Thomson et al., 2012). We aim to explore if a network of these handpumps can potentially provide auxiliary information that can be exploited using machine learning approaches to monitor the underlying shallow aquifer systems.

Previous efforts have shown that vibration data collected at the handpump’s handle are indicative of pump malfunction (Thomson et al., 2012; Greeff et al., 2019). Changes in the characteristics of vibration data, potentially due to handpump malfunction, can be tracked using novelty detection approaches. Higher novelty scores signify departure from normal operating conditions. Remote transmission of

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these novelty scores, as part of a handpump maintenance infrastructure, can be used for rapid pump maintenance.

The changes in vibration data were shown to be indicative of changes in the water level at the borehole under controlled circumstances (Colchester et al., 2014; Colchester et al., 2017). These works showed that the vibration generated at the handpump's handle are affected by the weight of the system, i.e. the weight of the rods and the volume of water inside the rising main. In general, the deeper the water level, the higher the volume of water inside the rising main, and the stronger the observed vibration. The variation in vibration characteristics was exploited to estimate the water level at the borehole of the handpump. These experiments were performed using two datasets – (1) data from a handpump on the University site, primarily installed to perform condition monitoring related research, and (2) few weeks of data from handpumps in the study site in Kenya. Both datasets were collected under controlled settings, i.e. handpump users were mostly limited to the research team, and the pump strokes and duration were fairly consistent. Given the short data collection period, the dataset neither captured long-term variation in the aquifer level nor faced challenges commonly encountered during normal operations, e.g. wide variation in the pumping style, variation in the water column at different times of the day, handpump breakdown and subsequent repairs, etc. Besides, for the dataset from the Kenya study site, instead of actually measuring the varying water column, the handpump rod length was used as an approximate measure of the depth of water in the borehole. The preliminary results of these experiments motivated this follow-up field study to determine if (1) the vibration data obtained from community handpumps in an unconstrained real-world setting can be used to track long-term changes in aquifer level (a conditional yes), and (2) the results generalize across different depths of shallow aquifer systems (yes).

Provided a handpump maintenance infrastructure is already in place, there is an opportunity to dual purpose the vibration data to monitor shallow aquifer at minimal extra cost. The distributed maintenance infrastructure (Greeff et al., 2019) allows adaptive transmission of handpump vibration data, controlling when and how much of data is transmitted, thus saving cost in resource-constrained settings. The adaptive framework blends in well with the proposed aquifer monitoring system, whose predictions are only expected to be based on data from normally operational handpumps. This framework is further detailed in Section 2.

### 1.1. Related works and our contribution

Machine learning approaches have been explored to understand hydrological processes and facilitate water resource management (Herrera et al., 2010; Yaseen et al., 2019; Achieng, 2019). These approaches have also been used to model variations in aquifer level based on hydro-climatic data (e.g., rainfall, temperature) (Nayak et al., 2006; Behzad et al., 2010; Yoon et al., 2011; Taormina et al., 2012; Tapoglou et al., 2014; Suryanarayana et al., 2014; Sahoo et al., 2017). These efforts have mostly implemented standard regression approaches, e.g. Support Vector Regression (SVR) (Bishop, 2006), Gaussian Processes (GPs) (Rasmussen, 2004), Multi-layer Perceptron Regression (MLP Regression) (Robert, 2014), or various hybrid combinations of the same. A recent work has shown Long Short Term Memory networks (LSTMs) outperformed standard MLP regression to predict water table depth by using 14 years of monthly water diversion, evaporation, precipitation, temperature, and time as input data (Zhang et al., 2018). These efforts show the potential of using machine learning approaches to predict long-term changes in aquifer level in areas where hydrogeological data are difficult or expensive to obtain.

The proposed work also compares LSTMs with MLP regression for aquifer prediction. However, unlike all prior work, the proposed framework is novel because (1) it uses handpump vibration data to model changes in water level, and (2) setting aside the specific types of models

used, the proposed framework combines regression and novelty detection approaches to develop a novel shallow aquifer monitoring technology that is designed to work alongside a handpump maintenance infrastructure. The proposed framework can also be extended to incorporate hydro-climatic data or outputs from hydrogeological models.

In an effort to facilitate reproducibility and data reuse, the dataset (Greeff et al., 2020)<sup>1</sup> and the software (Manandhar, 2019) are both made publicly available.

## 2. Methods

In this work, we use a machine learning approach to model water column variation in a borehole based on vibration data observed at the handle of the handpump. We note that there are two types of changes in the water level – (i) the daily change in water level due to daily drawdown and recovery and (ii) the long-term seasonal change in water level due to aquifer discharge and recharge. In this work, we are interested in the latter. Although modelling the daily cycle is in itself an interesting problem, the challenge here is the unavailability of sufficient relevant vibration data because the drawdown occurs rapidly (and is often associated with pump priming whose vibration characteristics were observed to be different), and the recovery, by definition, is associated with pump disuse, which does not generate any vibration data. The majority of the vibration data collected during pumping corresponds to the available daily water level at the borehole, which in the long-term changes similarly to the daily maximum water level. We exploit this long-term change in the vibration data to model the long-term change in water level at the borehole, which we expect to approximately correspond to the variation in the corresponding shallow aquifer from which the water is being drawn out. We expect the water column variation in the borehole to approximately correspond to the variation in the corresponding shallow aquifer system from which the water is being drawn out.

We use a regression model to learn a mapping function from vibration data to water column. Since we expect vibration data at each handpump to be unique, an independent model is learned for each handpump. To learn such a model, a collection of vibration data and corresponding water column observations are required. These data are collected at three different sites (three handpumps per site) in the study area to test if the model generalizes to different depths of shallow aquifer systems.

A schematic of the shallow aquifer monitoring framework is shown in Fig. 1. The proposed framework is designed to work alongside a handpump maintenance system, represented by dashed lines and not part of the framework itself. The handpump maintenance system monitors the condition of handpumps by tracking the changes in characteristics of vibration data using a novelty detection approach. The outputs of this novelty detection approach, known as novelty scores, may be used to flag a potential pump malfunction if the future vibration data looks substantially different from the previously observed data, thus facilitating rapid maintenance (Greeff et al., 2019).

The proposed technology is based on vibration data obtained from community handpumps, which are regularly used, and tend to break down quite frequently, once every few months on average. Depending on the severity of malfunction and the type of subsequent repair, the characteristics of vibration data may change substantially, affecting the outputs of the regression model. The vibration data will also change when the water in the borehole reaches previously unobserved levels. When the characteristics of the vibration data changes substantially, the regression model learned using previously observed vibration data may not provide correct estimation. During such circumstances, the novelty scores may also serve as a guideline to indicate the confidence in the

<sup>1</sup> The dataset will be available at the cited address once the embargo is lifted.

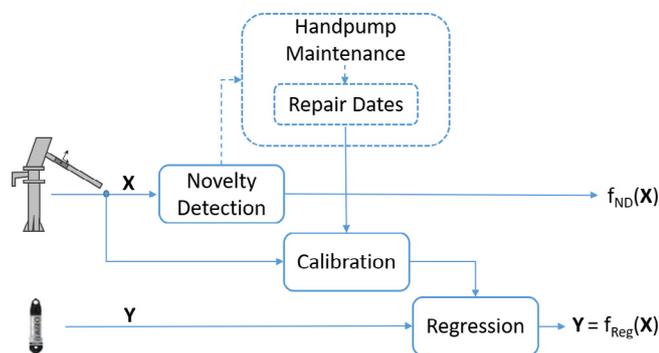


Fig. 1. The shallow aquifer monitoring framework designed to work alongside an existing handpump maintenance framework. Vibration data from handpump is used to learn a novelty detection model. Separately, the vibration data along with the water column data measured in the borehole of the handpump are used to learn a regression model. If the handpump is repaired, the vibration data is calibrated before feeding to the regression model.

regression model's outputs, where higher novelty scores would correspond to lower confidence in the regression model's outputs.

When the vibration data has changed due to a pump malfunction and subsequent repair, a simple solution to continue using the same regression model may be to calibrate the post-repair vibration data back to the pre-repair data. We propose using a regression model to learn a map from post-repair to pre-repair vibration data by assuming the vibration data averaged over few days pre vs. post repair are the same. With respect to the water column estimation model, this simple calibration technique inherently assumes the daily maximum height of water column in the borehole does not change substantially in a few days, which is generally not a bad assumption based on Fig. 7. To avoid confusing water column-related regression with calibration-related regression, the latter is referred to as calibration in rest of the document.

Data from nine handpumps are collected for over a year, out of which two-thirds are used for learning the model (i.e. training for novelty detection, and training and validation for regression), and the remaining one-thirds are used for evaluating the model (i.e. testing).

### 2.1. Study area and sample selection

The study area is located in Kwale County, Kenya, south of Mombasa and adjacent to northern Tanzania, as shown in Fig. 2. From western Shimba Hills to eastern Coastal Plain, the area slopes towards the Indian ocean. The County population of 880,000 people mostly live in rural areas (82%) with the majority (70%) living below the poverty line of less than USD 1.25 a day (KNBS, 2005). The study area includes the long-established coastal tourism industry in Diani and the more recent mining and commercial sugar production industries. To sustainably manage the resulting competition for water resources, reliable data on groundwater is vital.

A hydrogeological study of the area (Ferrer et al., 2019) reports on the groundwater level change in the coastal coral and sand formations (Pleistocene, Magarini, Kalindini) but not the deeper Mazeras sandstone during a La Nina year. They find groundwater levels vary from 4 m below groundwater level (bgl) to 27 m bgl in response to the wetter and drier periods. They also note communities depend on groundwater from boreholes with handpumps as well as open wells in the shallow aquifer. In contrast, the commercial use for irrigation and mining is largely in the deeper aquifer system with limited interaction with the shallow aquifer. The monitoring sites selected for this study are all non-commercial community handpumps. Readers interested in further hydrogeological or socio-economic details of the study area may refer to (Ferrer et al., 2019; Katuva et al., 2019).

To test if the model generalizes to handpumps drawing water from different depths of shallow aquifer systems, three different monitoring

sites are selected corresponding to three different depth ranges – shallow, medium, and deep, where these categories are arbitrarily defined based on available samples. Table 1 summarizes table of columns (TOCs) and water columns (WCs) at the boreholes at the time of sensor installation. We also note that all boreholes were mechanically drilled.

The rate of daily drawdown/recovery as well as long-term discharge/recharge are expected to differ at these three sites due to different hydrogeological, socio-economic, and other factors. Besides, the water columns in the boreholes in the coast are directly affected by both daily and bi-weekly tidal cycles. Pre-processing steps related to removing tidal effects are further described in Section 3.1.

### 2.2. Regression approaches for water column estimation

Regression approaches are supervised learning techniques that map examples (inputs) to continuous labels (outputs). We use these approaches to map handpump vibration data (inputs) to their corresponding water column data (outputs). A wide variety of regression approaches exist, e.g. Relevance Vector Machines (RVMs), Gaussian Processes (GPs), decision forest tree regression, multi-layer perceptron regression (MLP regression), etc. Although experiments were performed using different types of regression approaches (yielding comparable results), we focus on MLP (also known as feedforward neural network) regression because they form a natural baseline to compare with Long Short Term Memory (LSTM) networks, the primary approach implemented in this work. Since we wish to provide temporal context to model water column data in terms of past examples of daily handpump vibration data, LSTMs constitute a suitable model for our application.

#### 2.2.1. Recurrent Neural Networks (RNNs)

Feedforward networks do not have feedback, i.e. outputs of the model are not fed back into itself. When feedforward networks are extended to include feedback connections, they are called Recurrent Neural Networks (RNNs). Since feedforward networks assume samples are independent, they are unable to utilize information from past samples. Recurrent Neural Networks (RNNs) overcome this limitation by allowing information from past samples to persist by using feedback connections. They do so by repeating the feedback loop structure recursively to model a sequence of samples as shown in Fig. 3. The recursive framework allows parameters to be shared across the repetitive structures, which in turn makes parameter estimation feasible. However, although theoretically possible, in practice, RNNs are unable to model long-term dependence because gradients propagated over many stages tend to either vanish (more common) or explode (rarely, but causing much damage to optimization) (Goodfellow et al., 2016).

#### 2.2.2. Long Short Term Memory (LSTM) networks

To solve RNN's long-term dependence problem gated RNNs are the most effective solutions designed to date. They do so by allowing gradients to flow for a long duration using gated self-loops. Examples of gated RNNs include Long Short Term Memory (LSTM) networks and gated recurrent units (GRUs) (Goodfellow et al., 2016), the former being the most widely used. LSTMs have the same basic repetitive structure like RNNs, except the repeating structure (called LSTM cell) has three gated self-loops (Fig. 4). A forget gate decides what information will be discarded from the previous cell state. An input gate controls what new information will be stored in the current cell state. Then the outputs from the forget gate and the input gate are used to update the old cell state into a new cell state. Finally, an output gate decides what information will be output from the new cell state. The corresponding equations are

$$f_t = \sigma(\mathbf{W}_f[\mathbf{h}_{t-1}, \mathbf{x}_t] + b_f) \quad (1)$$

$$i_t = \sigma(\mathbf{W}_i[\mathbf{h}_{t-1}, \mathbf{x}_t] + b_i) \quad (2)$$

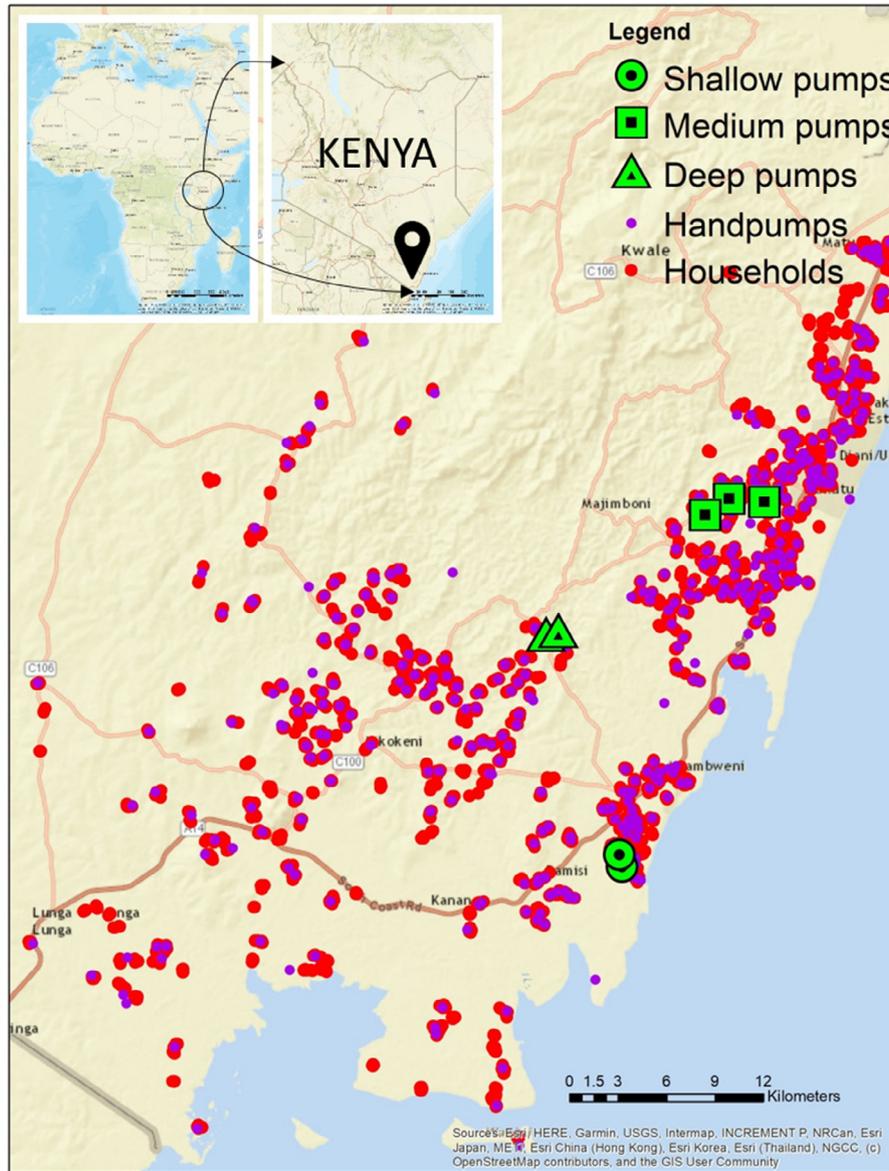


Fig. 2. Study area showing households, handpumps, and the sampled handpumps.

**Table 1**  
A summary of handpumps selected at three different sites in the study area. Fig. 6a explains the notations.

| Depth   | Pump Code | Table of Column TOC (m) | Water Column WC (m) |
|---------|-----------|-------------------------|---------------------|
| Shallow | SP1       | 6.4                     | 1.1                 |
|         | SP2       | 5.4                     | 1.7                 |
|         | SP3       | 8.9                     | 2.0                 |
| Medium  | MP1       | 22.2                    | 5.8                 |
|         | MP2       | 24.2                    | 2.3                 |
|         | MP3       | 17.4                    | 19.4                |
| Deep    | DP1       | 30.4                    | 11.9                |
|         | DP2       | 42.5                    | 6.7                 |
|         | DP3       | 35.5                    | 14.9                |

$$\tilde{C}_t = \tanh(\mathbf{W}_c[\mathbf{h}_{t-1}, \mathbf{x}_t] + b_c) \tag{3}$$

$$C_t = f_t * C_{t-1} + i_t * \tilde{C}_t \tag{4}$$

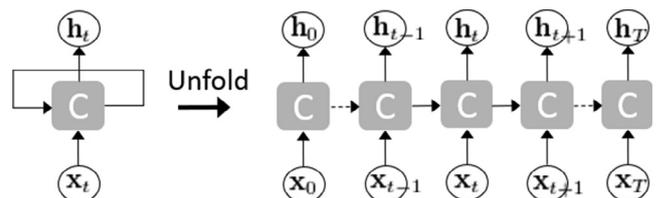


Fig. 3. A folded computational graph of RNN (left), and the corresponding unfolded graph (right).

$$o_t = \sigma(\mathbf{W}_o[\mathbf{h}_{t-1}, \mathbf{x}_t] + b_o) \tag{5}$$

$$\mathbf{h}_t = o_t * \tanh(C_t), \tag{6}$$

where 1, 2–4, and 5–6 correspond to respectively forget, input, and output gates. Here,  $C_t$  is the current cell state,  $x_t$  is the current input vector,  $\mathbf{h}_t$  is the current hidden layer vector containing the outputs of all LSTM cells, and  $b$ 's and  $\mathbf{W}$ 's are respectively biases and weights.

Different variations of LSTMs have been successfully implemented in many applications, e.g. unconstrained handwriting recognition (Graves et al., 2009), speech recognition (Graves, 2013), handwriting

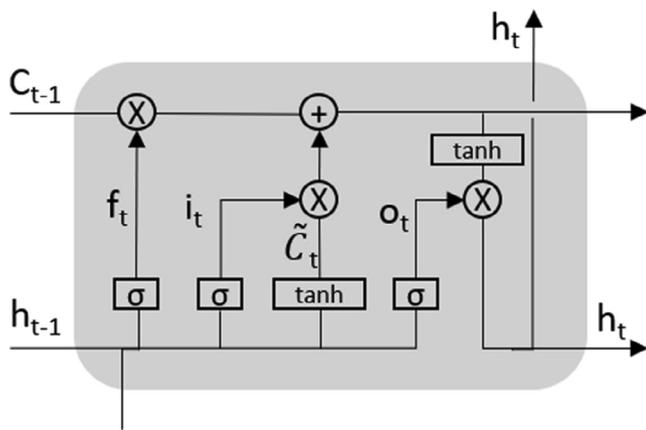


Fig. 4. An LSTM cell.

generation (Graves, 2013), machine translation (Sutskever et al., 2014), image captioning (Kiros et al., 2014; Vinyals et al., 2014). RNNs and LSTMs have also been implemented to estimate aquifer using hydro-climatic data (Zhang et al., 2018).

Given the relatively small size of the training data, we opt for a simple neural network architecture, consisting of a LSTM unit, a dropout unit (to prevent over-fitting), and a dense layer in sequence (Fig. 5). As more data becomes available in future, there are opportunities to implement deeper (e.g. stacked layers) and other variations (e.g. shared layers) of networks, which are further discussed in Section 5. The model was implemented in © keras using © tensorflow backend. The model parameters (learning rate [ $10^{-2} - 10^{-5}$ ], number of hidden nodes [50 – 200], epochs [10 – 200], batch size [10 – 50], and input time steps [1 – 14 days]) were coarsely optimized using separate training and validation sets with (80–20% splits). A separate test set (one-third of data) was held out for evaluating the trained model. The training, validation, and test sets were split sequentially in time (from past to future) to reflect a real implementation scenario.

### 2.3. Novelty detection approaches for condition monitoring

In a standard binary supervised classification approach (Bishop, 2006), models of “normality” and “abnormality” are learned, either separately or simultaneously, using examples of “normal” and “abnormal” observations respectively. When there are not enough examples of abnormal observations, one way to classify these examples is to only learn a model of normality from normal examples, and use this model to classify new examples. Novelty detection is a type of such one-class classification approach, which has been applied in many fields, including electronic IT security, healthcare informatics, industrial monitoring, etc. (Pimentel et al., 2014). This approach is very applicable to condition monitoring in handpumps because usually compared to “normal” handpump operations, there are very limited examples of “abnormal” handpump operations (e.g. broken seal, valve or handle malfunction, etc.). Different types of novelty detection approaches exist, e.g.  $k$  nearest neighbour ( $k$ -NN), kernel density estimation (KDE), mixture models, one-class Support Vector Machines (one-class SVMs) (Pimentel et al., 2014; Bishop, 2006).

In this work, we use a Gaussian Mixture Model (GMM) (Bishop, 2006) to learn a normal model by representing normal examples with a mixture of multivariate normal densities. Here, an appropriate number of the mixture components is determined based on the data by using Dirichlet process mixtures (Blei and Jordan, 2006) based on a publicly



Fig. 5. A sequential Neural Network architecture using LSTM.

available toolbox (Morton and Torrione, 2013). For each handpump, a Gaussian Mixture Model is used to learn a normal model based on daily average frequency features generated from handpump vibration data. To help parameter estimation in the mixture model, instead of using all 20 frequency bins, only the first three principal components are considered, which represent more than 95% of total variance in data. The mixture model can be used to compute log-likelihood of examples, the inverse of which can be considered as novelty scores, i.e. lower the log-likelihood, more novel the examples. Since GMM provides probabilistic novelty scores, it is suitable for our application where we intend to use the novelty scores as a measure of confidence of the regression model’s outputs.

## 3. Data

### 3.1. Water column data

To both learn and evaluate the regression model, water column in the borehole represents the ground truth. The water column is measured using a diver sensor (manufactured by ©Van Essen Instruments) that is fixed close to the bottom of the rising main. Fig. 6a details the nomenclatures used in this document, where water column represents the ground truth for learning the regression model. Data is collected at a sampling interval of five minutes. An example data collected over few days is shown in Fig. 6b, where the blue line shows a typical daily cycle of draw-down during the day, followed by recovery during the night. Since our primary goal is to track the variation in the aquifer level, we use the daily recovered level, approximated by the daily maximum level, as the ground truth for modelling.

Water column in the boreholes in the coast is affected by both daily and bi-weekly tidal cycles. Considering the daily maximum level removes the daily cycle (blue line in Fig. 6c), and low-pass filtering the resulting data removes the bi-weekly cycle (orange line in Fig. 6c). Fig. 7a and c show the change in water column data in the boreholes at three monitoring sites – shallow, medium, and deep with reference to the start date. These data have been compensated with respect to the atmospheric pressure and pre-processed to represent daily recovered level.

Theoretically, a network of these diver sensors would allow us to directly monitor the shallow aquifer without having to do any modelling. However, given the intended scale of the proposed technology (country to sub-continent), such monitoring program would be cost-prohibitively impractical. Here, the costs not only refer to the cost of the sensor, but also the ones involved in installing the sensor and downloading the data periodically, both extremely laborious process.

### 3.2. Handpump vibration data

The vibration data is collected using a consumer grade accelerometer sensor attached to the handle of the handpump as shown in Fig. 8a. The sensor measures accelerometer data in three orthogonal axes at a sampling frequency of 95 Hz. A typical pumping cycle, i.e. a cycle of the handle being raised and pushed down, corresponds to one second interval. An example data collected over few pumping cycles is shown in Fig. 8b.

In machine learning approaches, raw data are often first summarized by useful information (known as features) before using them to learn a model. The low frequency component of the data, which corresponds to the pumping motion, is found to be uninformative of water column variation. The pumping motion is removed using a high-pass filter, and the resulting high-pass filtered time-series signal (top plot in Fig. 8c) is transformed to frequency domain using a morelet transform. The magnitude of the morelet transform (bottom plot in Fig. 8c), averaged across the time window, represents the frequency features corresponding to that window. A daily average of these temporal windows along with the corresponding daily maximum water column

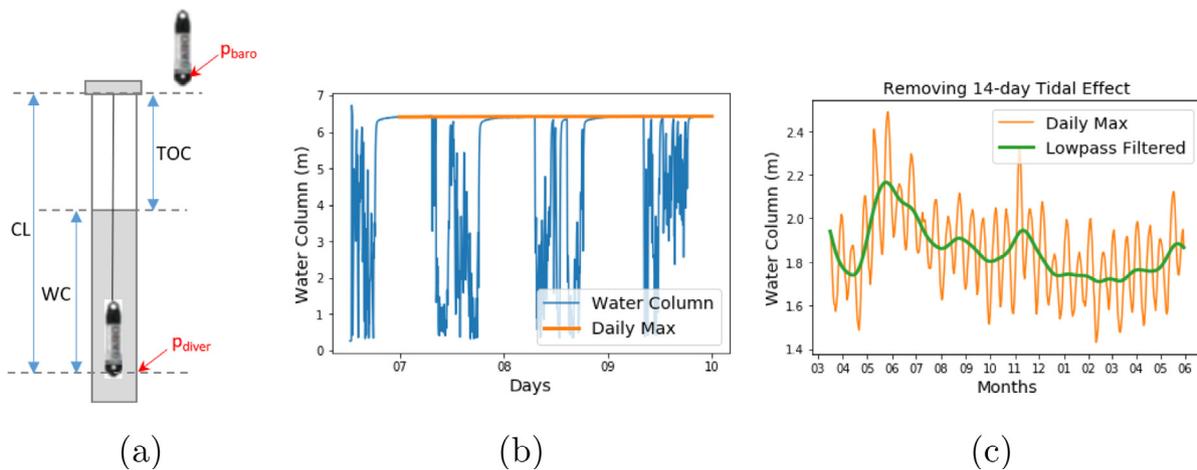


Fig. 6. (a) Diver sensor installation close to the bottom of the rising main in the borehole, where the notations mean cable length, table of column, water column, pressure under water and on the surface (Figure adapted from (VanEssen, 2018)), (b and c) Typical variation in water column data in one of the boreholes at (b) the medium depth site and the calculated daily maximum, and (c) the shallow depth site showing daily maximum (that removes daily tidal cycle), and its corresponding low pass filtered signal (that removes bi-weekly tidal cycle).

represent a feature-label pair. A collection of these feature-label pairs per handpump constitutes a training and testing dataset for that handpump.

Vibration data maybe unavailable for a period of time due to several reasons, most commonly due to battery or sensor malfunction, or handpump disuse. A handpump may be temporarily out of operation usually because of malfunction or alternate water sources (e.g. surface water) being available during rainy season, or school closures in case of handpumps installed at the schools. We propose using Gaussian Processes (Rasmussen, 2004) to impute frequency features corresponding to missing days. Unfortunately, for two handpumps, one shallow and one deep, too much data were missing to allow reasonable data imputation. Hence, we only report results on the seven remaining handpumps. Since the highest proportion of data is available for the medium depth handpumps, we provide detailed results for that site while only providing key results for the other two sites.

### 4. Results

The machine learning approaches described in Section 2 are used to perform several experiments related to water column estimation using the dataset described in Section 3. At this stage, our primary goal is to assess the feasibility of the proposed technology in a real world setting, i.e. whether vibration data from a collection of community handpumps at a location can be used to infer the trend in water column variation of the corresponding aquifer.

#### 4.1. Novelty detection analysis

Figs. 9–11 show the novelty scores of training (blue dots) and test (red dots) examples in terms of log-likelihood of examples given the normal model. In general, the examples in future incrementally appear to be more different from the normal examples. This trend is expected because the vibration data is expected to change over time either due to gradual pump wear and/or change in water level in the borehole to previously unobserved levels (a relatively smooth change), or due to severe pump malfunction and subsequent repair (a relatively abrupt change). A continuous drop in the log-likelihood, suggesting a gradual change in vibration data, may correspond to change in water column over time (e.g. Fig. 10c). On the other hand, an abrupt change in vibration data due to severe pump malfunction/repair often corresponds to a sharp drop in the log-likelihood. Most of these cases (e.g. Fig. 10a and b, etc.) stand out visually, and are aligned to their corresponding pump repair dates (black dashed lines), whenever the repair dates are available. These insights from novelty detection analysis help understand the results of experiments related to calibration and water column estimation.

#### 4.2. Vibration data calibration

Usually the novelty scores appear to be higher (i.e. the log-likelihood values are lower) immediately following a repair (e.g. Fig. 9b), indicating a substantial change in the vibration data after the repair. To enable using a single regression model to estimate water column, the post-repair vibration data is calibrated to match the pre-repair data. An

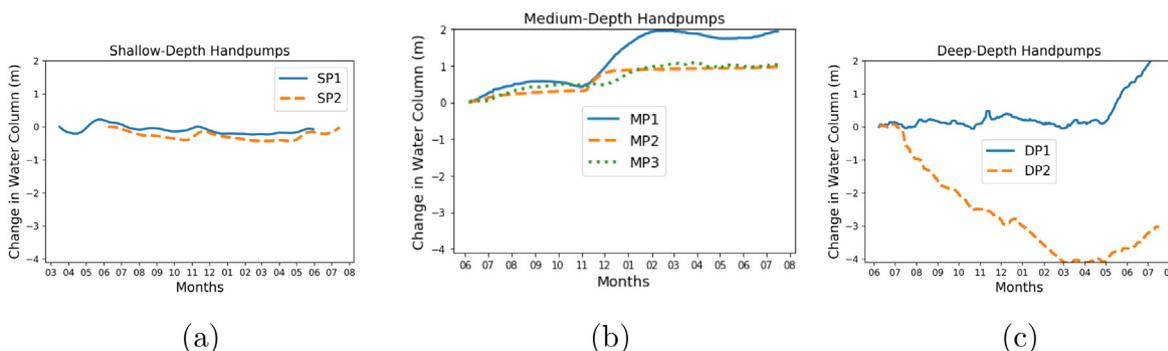


Fig. 7. With reference to the start of monitoring date, change in water column data in the boreholes of three sites – (a) Shallow, (b) Medium, and (c) Deep.

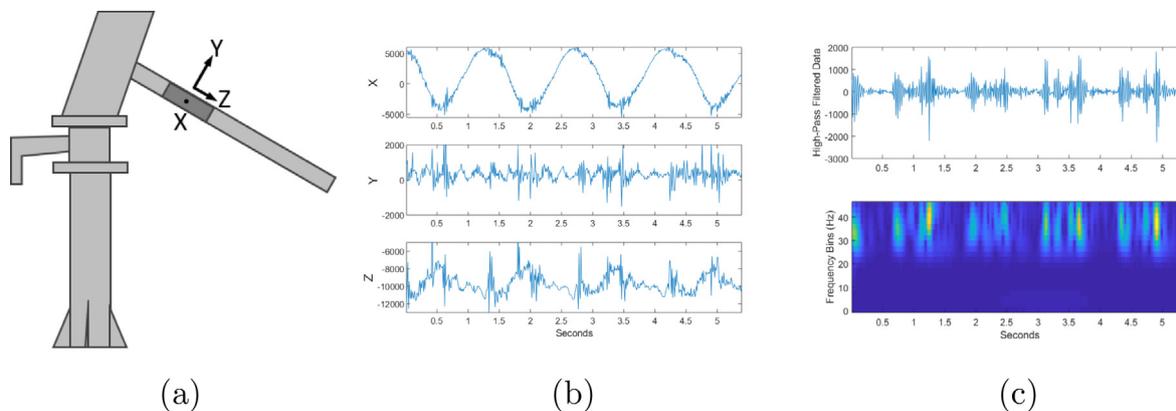


Fig. 8. (a) Accelerometer sensor installation close to the fulcrum of the handpump's handle, showing three different acceleration axes, (b) typical vibration data measured at three different axes, and (c) high pass filtered signal of the z-axis vibration data (top) and the corresponding magnitude of its morelet transform (bottom).

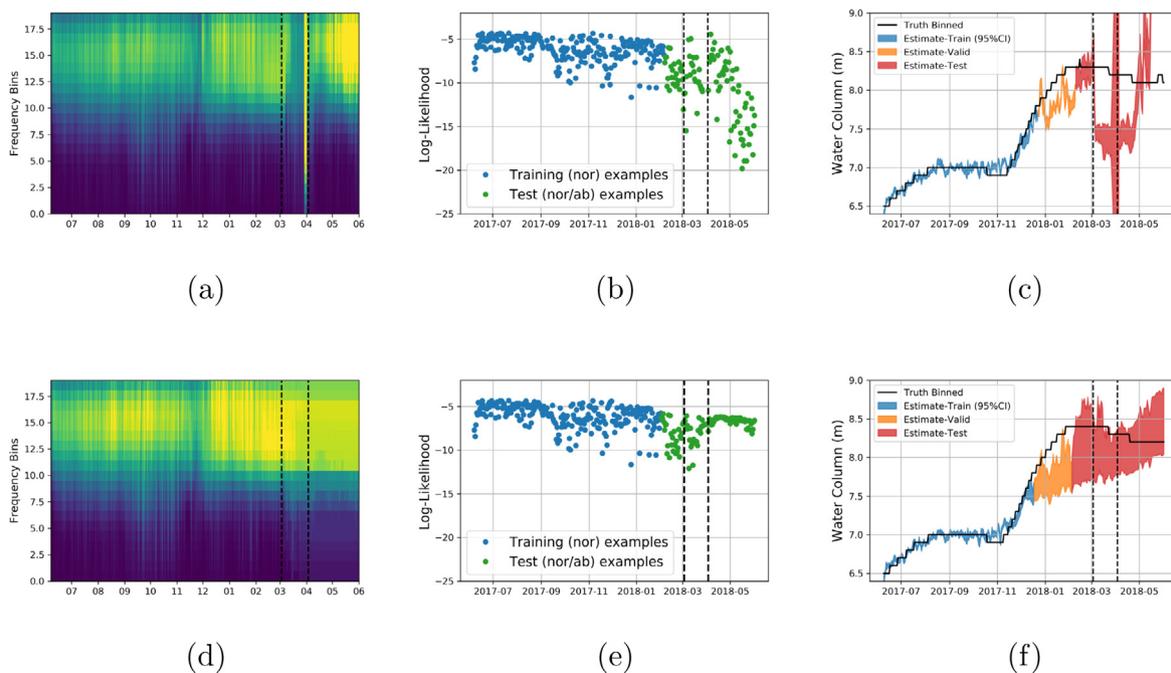


Fig. 9. For a particular handpump (MP1), (a) features generated from vibration data, (b) log-likelihood of examples given normal model, and (c) water column estimates using LSTM. These plots are redrawn in (d)–(f) once the features are calibrated at handpump repair dates, represented by the dashed lines.

example of this calibration process is detailed in Fig. 9, where the top row shows the features generated from the vibration data (Fig. 9a), the log-likelihoods (Fig. 9b), and the water column estimates (Fig. 9c), and the bottom row shows the corresponding plots after calibration. Since a very simple regression model was used to calibrate the vibration data, its quality is expected to degrade as further calibrations are performed in future. In the example, the second calibration does not work as well as the first calibration. As part of our future work, we intend to explore more principled ways to model this problem, e.g. transfer learning, which is discussed in Section 5.

### 4.3. Water column estimation analysis

For medium-depth handpumps, results are shown for LSTM, and for reference, compared to MLP regression in Fig. 10. For shallow and deep handpumps, results are only shown for LSTM in Fig. 11. In both figures, each column corresponds to results for a particular handpump, where the rows correspond to the novelty scores, novelty scores post-calibration, LSTM estimates, and MLP estimates (only in Fig. 10) from top to

bottom. The estimates for training, validation, and test sets are shown in blue, orange, and red colours respectively. The estimates are shown in terms of their 95% confidence interval based on 10 iterations of training LSTM model with random initialization. While parameters for each approach were coarsely optimized using cross-validation, we have not performed exhaustive parameter optimization because our primary goal at this stage is to assess whether the estimates roughly tracks the true changes in water column rather than obtain the best possible outputs. A summary of results for all handpumps for both MLP and LSTM techniques are provided in Table 2.

Results show that, in general, vibration data are indicative of changes in the water column. LSTM generally outperforms standard MLP regression technique, where LSTM is expected to perform even better as more training data become available. In most cases, pump repairs change the vibration data features substantially, which when “corrected” via calibration, does somewhat help to improve water column estimation. But the frequency and/or the nature of repairs may determine the efficacy of the simple calibration technique implemented in this work. Nevertheless, the novelty detection outputs provide a

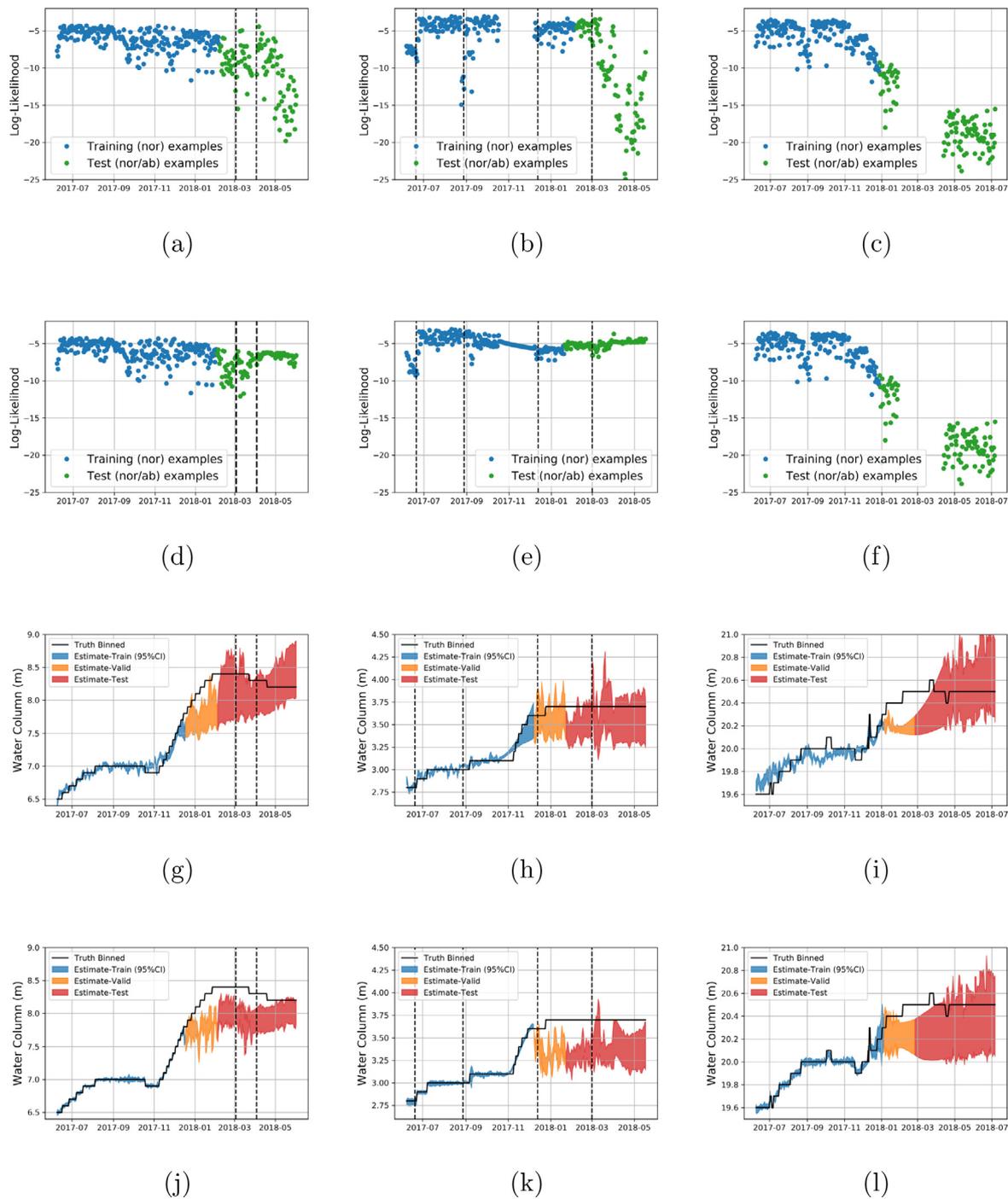


Fig. 10. For each column, from top to bottom rows, log-likelihood of examples given normal model, log-likelihood after calibration, water column estimates using LSTM and MLP regressor. Columns correspond to medium-depth handpumps MP1, MP2, and MP3 in the Ukunda area.

reasonably accurate guideline to determine when to trust the regression model outputs. Typically a drop in the log-likelihood corresponds to either an inaccurate water column estimate or one with high uncertainty.

The proposed technology is intended to be implemented at scale by concurrently modeling a network of community handpumps. Rather than estimating continuous changes in water column at individual boreholes, our ultimate goal is to use a network of handpumps to infer the overall trend in the water levels in the corresponding shallow aquifer. With this goal in mind, we plot the fractional change in water columns at the boreholes at two locations with respect to a common reference date. Fig. 12a and b show these plots for medium and shallow

handpumps respectively. These results show the estimated changes in water column approximately track the true trend. However, the estimates deteriorate as we start predicting further ahead in time due to the limitations in the model, which are discussed in Section 4.4. Similar plots are not shown for deep handpumps because the difference in their water column data variation suggests that there may be differences in the hydrogeological dynamics of the aquifers from which the two deep handpumps are drawing water.

#### 4.4. Limitations

Despite the resources invested in collecting a unique handpump

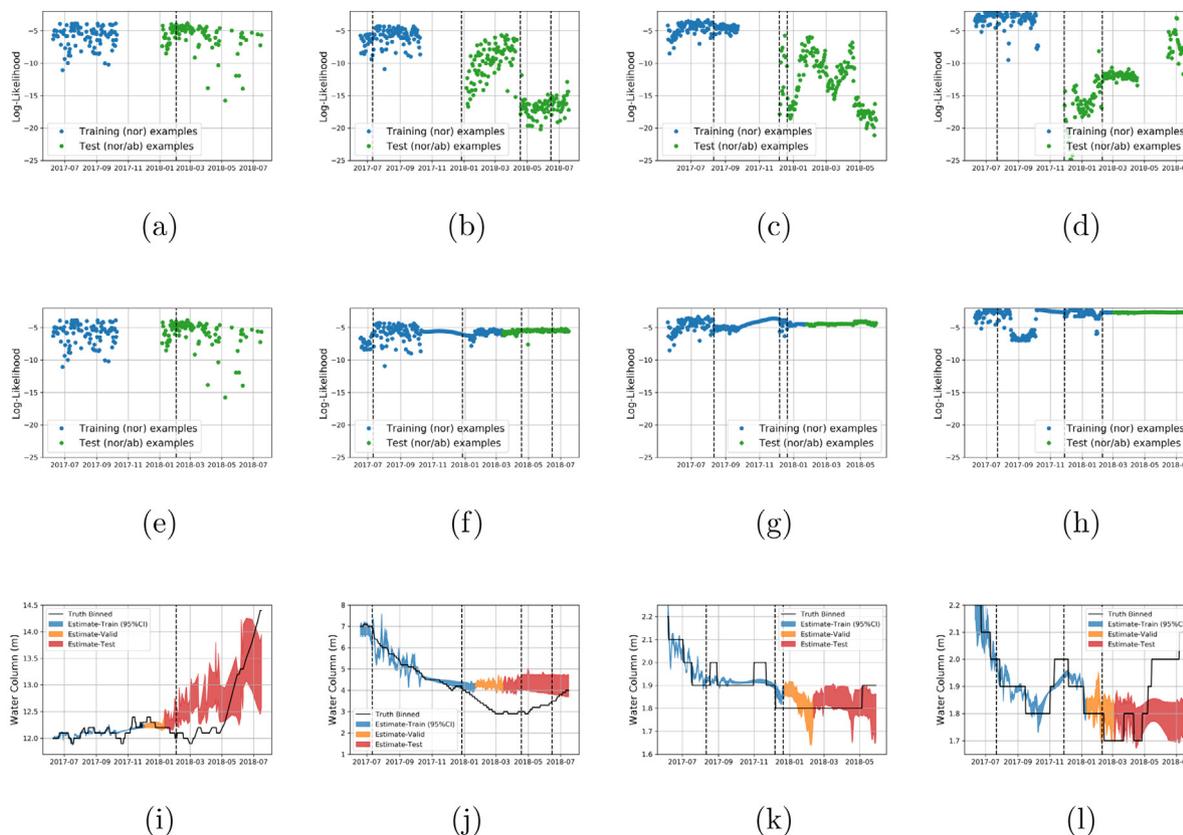


Fig. 11. For each column, from top to bottom rows, log-likelihood of examples given normal model, log-likelihood after calibration, and water column estimates using LSTM. Columns correspond to deep handpumps DP1, DP2 and shallow handpumps SP1, SP2 at the Shimba Hills and the Coast sites respectively.

Table 2

For each regressor, mean error (metres) on test dataset (top row), and one standard deviation (bottom row).

|      | SP1  | SP2  | MP1  | MP2  | MP3  | DP1  | DP2  |
|------|------|------|------|------|------|------|------|
| MLP  | 0.14 | 0.26 | 0.31 | 0.29 | 0.18 | 0.60 | 0.85 |
|      | 0.12 | 0.19 | 0.15 | 0.11 | 0.10 | 0.34 | 0.71 |
| LSTM | 0.09 | 0.12 | 0.23 | 0.14 | 0.15 | 0.43 | 1.07 |
|      | 0.04 | 0.06 | 0.17 | 0.11 | 0.12 | 0.47 | 0.41 |

vibration dataset using novel sensing technology, in terms of hydrogeology, one year of data is insufficient to track long-term changes in aquifer level. Few years of data may be required to capture a typical range of aquifer level changes. In the current dataset, validation and

test data are often very different from training data, complicating both training and testing the model.

Approximately 15% of data were missing, usually over continuous streams of time (from days to months), primarily due to discharged batteries or other hardware-related problems, handpump malfunction, or temporary handpump disuse because of availability of alternate water sources during rainy season (e.g. rain harvesting, surface water). Despite using Gaussian Processes to impute the missing data, the accuracy of the imputed data degrades as the duration of missing data increases.

The effectiveness of the vibration data calibration technique depends on the frequency and type of handpump repair, with the calibration being less effective as the number and/or severity of breakdowns/repairs increase. Although the novelty scores provide a guideline to assess the confidence of the water column estimates, better

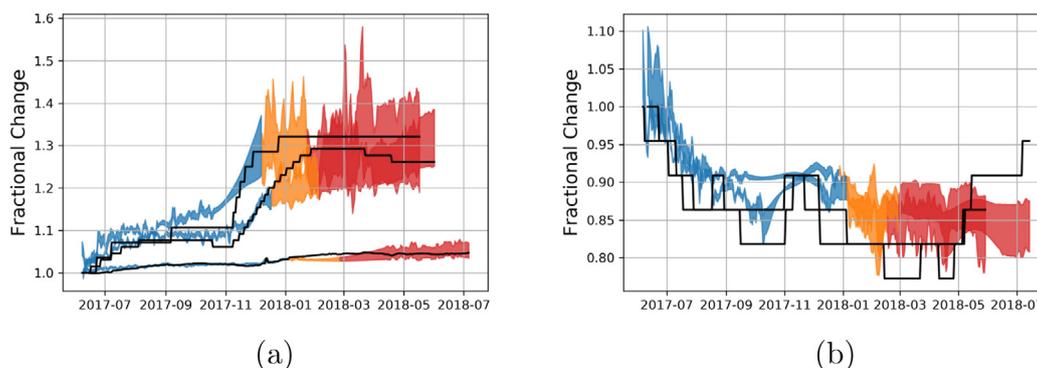


Fig. 12. Fractional change in water column with respect to the reference water column observed on 2017/6/1 for the handpumps in (a) medium-depth and (b) shallow-depth clusters.

techniques are required to model this problem in a principled manner, e.g. transfer learning.

## 5. Conclusions

The proposed technology based on handpump vibration data and machine learning approaches show promise in providing useful aquifer monitoring information in resource-constrained regions where alternate sources of data are either scarce or cost-prohibitive and where handpumps already constitute part of the rural water infrastructure. In regions where handpump maintenance infrastructure is already in place, there is an opportunity to use the vibration data for the additional purpose of providing rudimentary shallow aquifer monitoring at minimal extra cost. As expected, going from constrained to unconstrained real-world environment brings challenges. The most pressing one concerns frequent handpump breakdown and subsequent repair that complicates learning a consistent model to estimate changes in water level. Beside the solutions implemented in this work in the form of novelty scores and vibration data calibration, we intend to explore more principled methods in future to model this problem. Given a pre-trained model, transfer learning (Zoph et al., 2016; Yang et al., 2017) allows learning a variation of the learned model for a dataset with different characteristics by only requiring a relatively smaller dataset. Further field-experiments will be required to determine if transfer learning is feasible, and how much new data (hours-days) will be required to re-train the model. We note that in practice, the proposed technology is designed to be implemented at scale using a network of handpumps. As long as a sufficiently large number of these handpumps at a location are operational, the framework may allow useful approximate inference about the underlying aquifer behaviour within a degree of uncertainty. Further large-scale field experiments are required to ascertain the viability of this technology for real-world application as well as to determine under which conditions this technology is likely to fail and succeed. We note that the proposed technology is aimed to complement cost-effectively any traditional hydrogeological models rather than replace them.

As part of our future work, there are opportunities to model multiple handpumps simultaneously and fuse hydro-climatic data, and wherever available, outputs from hydrogeological models. Multi-task learning extensions of LSTM (Liu et al., 2016; Chen et al., 2018) are well-suited to model such scenarios.

Given the increasing global importance of groundwater monitoring technology, there needs to be more research to fill the gap between available state-of-the-art but cost-prohibitive technologies and the capacity of developing nations to adopt them. Novel cost-effective technologies that utilize the available infrastructure of these regions may be a plausible path moving forward. Given the success and ongoing trials of machine learning approaches to solve global socio-developmental challenges (Beckel et al., 2013; Blumenstock et al., 2015; Jean et al., 2016; Rolnick et al., 2019), experimentation of these approaches may provide cost-effective complementary options to boost on-going progress in hydrogeological modeling to monitor groundwater.

## CRediT authorship contribution statement

**Achut Manandhar:** Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing - original draft, Writing - review & editing, Visualization. **Heloise Greeff:** Conceptualization, Data curation, Writing - original draft, Writing - review & editing. **Patrick Thomson:** Conceptualization, Methodology, Validation, Writing - original draft, Writing - review & editing, Supervision, Funding acquisition. **Rob Hope Hope:** Conceptualization, Resources, Writing - review & editing, Supervision. **David A. Clifton:** Conceptualization, Methodology, Validation, Resources, Funding acquisition.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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