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USE OF WIRELESS SENSOR NETWORK TECHNOLOGY FOR THE INVESTIGATION OF ROOT ZONE SOIL MOISTURE DYNAMICS IN NEW ZEALAND'S HILL COUNTRY

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Abstract

Hill country farms play a critical role in the New Zealand's economy and precision agriculture solutions have been increasingly utilised to improve their profitability and resilience. The role of soil moisture, a highly variable factor in pasture productivity has received early recognition in hill country pastoral systems. Despite the importance of soil moisture, assessing and acquiring information on soil water content corresponding to the root zone remained a challenging task in these landscapes due to the complexity of the terrain, soil types and land use.

Wireless Sensor Networks (WSN) is a promising, new, in-situ measurement technology for monitoring soil moisture dynamics with high temporal resolution in agricultural soils. A monitoring network utilising WSN technology was designed and deployed over a hill country farm in the Wairarapa region of the North Island by the aid of Geographical Information System assisted spatial methodologies. As soil moisture distribution varies both vertically and laterally, 400 mm long subsurface type, multi-sensor probes were installed at 20 sites to take capacitance based readings at four consecutive depths.

Near real-time monitoring of soil variables will make it possible to better understand the dynamics of drying and wetting events and the soil moisture variability within the rooting zone. The integration of spatially distributed sensors and multi-depth soil moisture measurements from various hillslope positions showed considerable in soil water profile response to significant rainfall events on steep, rolling and flat surfaces allowing us to construct a clearer picture of the topographical controls on soil moisture distribution.

Keywords: soil moisture, wireless sensor networks, geographical information systems

Introduction

Monitoring water content within the rooting zone gives information about plant available water, water uptake, the water stress of plants and also water leaching below the root zone. Despite the importance of soil moisture in pasture productivity, the soil water balance component of the pasture growth models uses a low-resolution estimate of soil water input which also fails to match the variability in hill country soils. It has already been shown that seasonal deficit and the annual pattern of soil moisture change affect plant growth modelling and decision making in feed and stock management (Bircham and Gillingham, 1986; Bretherton et al., 2011). The investigation of temporal dynamics and spatial patterns of soil moisture on a farm scale could be useful for yield prediction as well as for the identification of patterns in hydrological processes.

Daily, monthly and annual soil moisture measurements are extremely valuable for the estimation of stored water variability along the rooting zone (Hillel, 1998; Nolz, 2013). However, monitoring hill country soils in traditional ways is an expensive and labour intensive task. The specific challenges are the slope and aspect landscape features, which dominate pasture productivity levels, with production declining as slope increases (mainly due to moisture limitations) (Roberts and White, 2016).

Due to the advances in computer technologies, wireless sensor networks (WSNs) equipped with soil moisture sensors are commonly used for irrigation scheduling, soil water status modelling and temporal variability assessment (Hedley et al., 2013; Hedley and Yule, 2009).

The objective of this study was to deploy a long-term soil moisture monitoring system using WSN technology to assess the relationship in soil moisture variability, redistribution and topographical factors in hill country landscapes where irrigation is not an option.

Determining soil moisture levels is highly desirable in farm management as soil water is the single most important resource for pasture production on New Zealand hill country farms (Woodward *et al.*, 2001). 10 million hectares of New Zealand is considered as hill country and a significant 4 million hectares designated as pastoral hill country farmland in the North Island (Cameron, 2016), making a major annual contribution to the economy (Statistics New Zealand, 2015).

Materials and methods

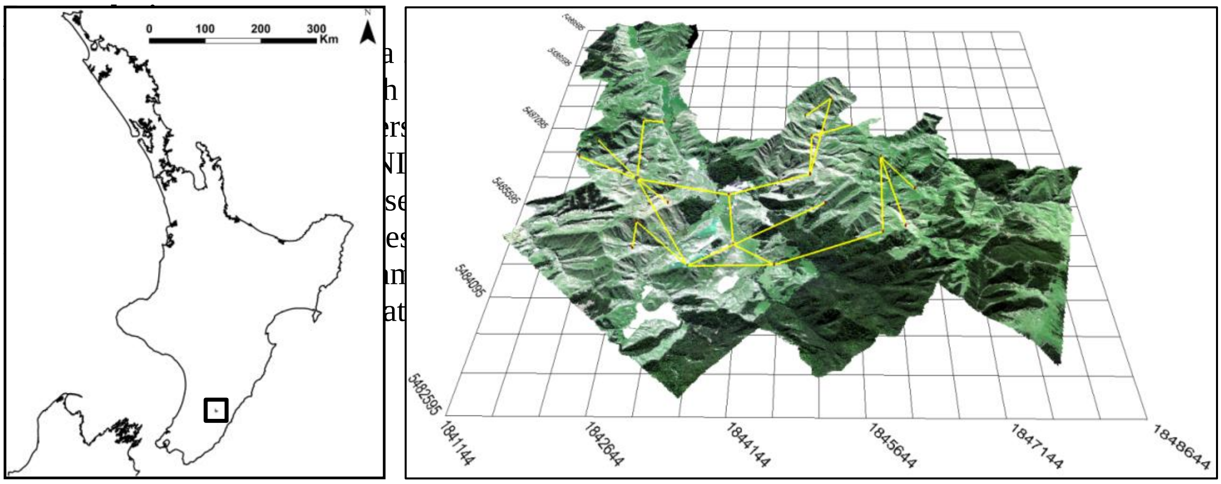

Figure 1 The study site located in the North Island of New Zealand where pasture is the dominant land use type. The architecture of the deployed WSN is also shown along with the main communication paths as yellow lines.

WSN technology

A WSN is composed of a collection of spatially distributed, autonomous devices, called sensor nodes, organised into a cooperative network (Rawat et al., 2014). The advances of WSNs promise cost effective, high temporal resolution observations with slightly disturbed soils providing considerably richer data. These nodes are usually equipped with five main components such as a processing unit, a transmission unit, a power unit, memory and a sensing unit. Consequently, they can sense, measure, gather and communicate information from the targeted field or environment (Fig. 2).

The regular readings are commonly displayed via a secure online dashboard using PCs or mobile computing devices (smartphones, tablets, etc.).The web interface enables near real-time, multilayer data visualisation as well as fault alerts for the quick response. Easy export for further analysis and options for raw data conversion are also available for site-specific calibration purposes.

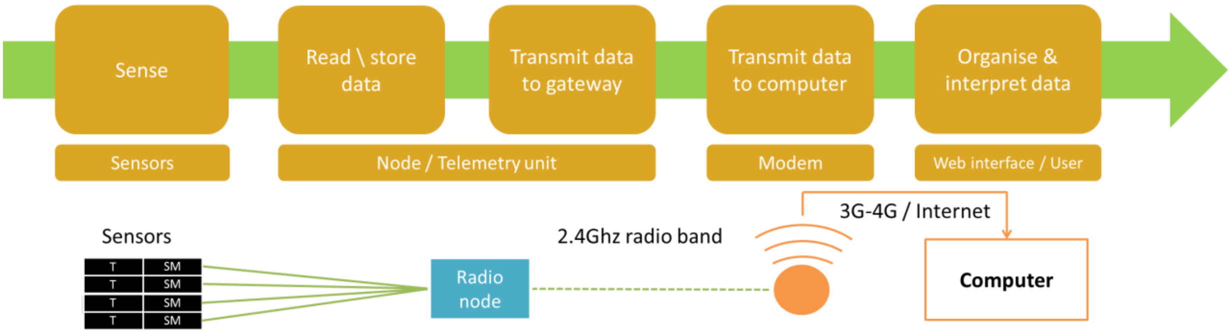

Figure 2 Functions of a wireless sensor network (WSN) with the generally applied sensing, processing and communication units (T: temperature sensor, SM: soil moisture sensor)

WSN deployment and geomorphometric analysis

This study used GIS-assisted methodologies to explore potential sensor locations and to design a WSN to monitor soil moisture over a broad range of topographic attributes (Fig. 3). The geomorphometric analysis used an 8 m pixel size DEM obtained from Land Information New Zealand. The quantitative comparison of the DEM to higher accuracy ground control points was needed to ensure the accuracy of the elevation data set (Fisher and Tate, 2006). Root Mean Square Error (RMSE) was chosen as vertical error descriptor using 368 ground control points, surveyed by Real Time Kinematic Global Positioning System (RTK-GPS), resulting in an RMSE value of 5.05 m. Four aspect and six slope categories were selected based on the LUC (Lynn et al., 2009) classes. The topographic wetness index was calculated (Moore et al., 1991) to avoid potentially extremely wet or dry areas such as swamps, gullies or hill crests. Those landscape features could affect the representativeness of the data collection which targets the effective pastoral areas. Moreover, soils tend to be deeper and often mixed at lower slopes and shallower on crests having an impact on the sensor deployment. Additionally, a landform classification was performed to identify suitable topographic units by the construction of topographic position index. Since line-of-sight communication was required between nodes, intervisibility analysis was applied to ensure connectivity within the telemetry range.

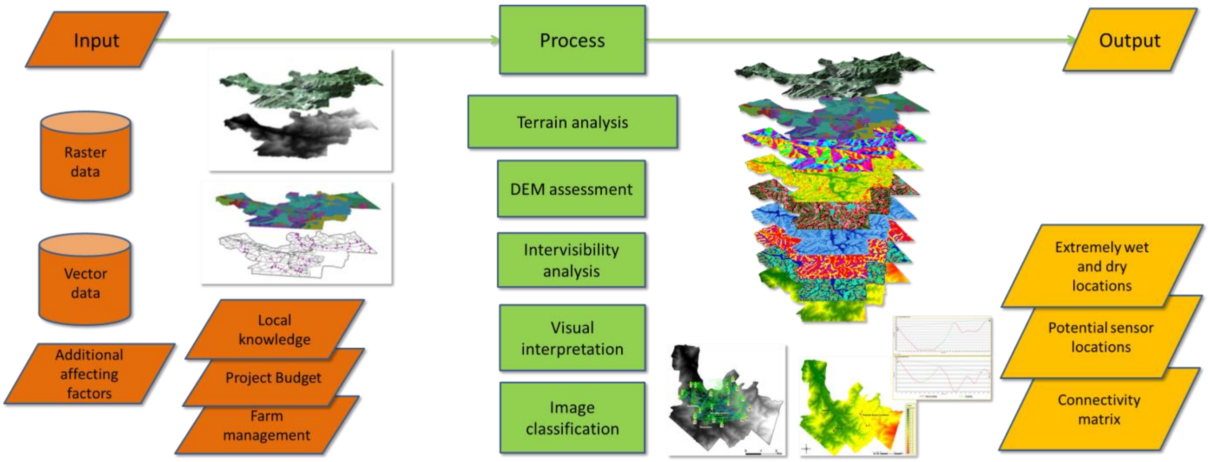

Figure 3 Investigation of potential sensing sites for soil moisture monitoring using geographical information systems (GIS) assisted methods

Instrumentation

As water extraction occurs to a depth of at least 350mm in the hill country (Bretherton *et al.*, 2011), a capacitance-based, 400 mm AquaCheck Sub-surface Probe (AquaCheck Soil Moisture Management, Durbanville, South Africa) was chosen. It is a robust multi-sensor probe designed to be completely buried (Fig. 1C). AquaCheck sensors are used to derive soil moisture from frequency-based dielectric measurements (Aquacheck, 2008). The probes are connected to firmly protected, long-range telemetry units (Tag I.T Technologies Ltd, Hamilton, New Zealand) for logging and transmitting data. They have embedded processors, limited memory and the whole unit is operated by batteries recharged by a solar panel. The sensor and radio connection interface board, batteries and wiring are placed in a weatherproof WSN enclosure mounted on a galvanised pole along with a high range antenna (Fig. 1C).

Results and discussion

WSN architecture and communication

The deployed WSN architecture consists of a gateway, a repeater station and twenty sensor nodes arrayed in a hybrid topology collecting soil moisture values at four depths (Fig. 1A). The gateway unit provides a connection between a PC-based user platform and the physical world.

The HALO Farm System, an online service developed by Tag I.T is used for monitoring and visualising the data received from the network via an Internet connection. The data packages are passed through underground wires from the sensors to the telemetry units among which the data is transmitted via radio connection until they reach the gateway. The radio protocol used implements a self-healing tree structure for routing utilising 15 channels in the 2.4 GHz band. The information is uploaded to a server via 3G ensuring near real-time access to the data. The repeater station has a role in extending the coverage area and increasing the number of backup routes. The hybrid structure provides extended range and self-healing, dynamic tree-structured communication with enhanced fault tolerance where the nodes can communicate with every node within radio distance creating numerous alternative paths for stable data transfer. A 1.5 km communication range was taken into account during the design phase.

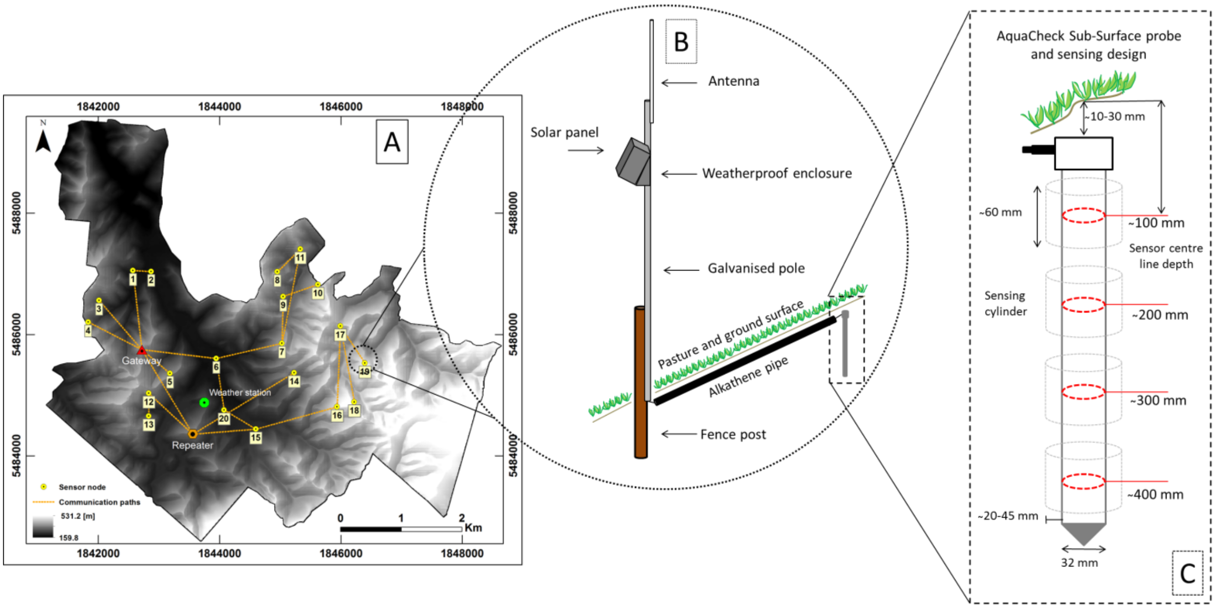

Figure 4 The farm extent is displayed with the deployed WSN architecture and probe ID numbers on a DEM (A). The sensor node design is presented in the middle (B) and the configuration of the probe can be seen on the right (C).

Raw data conversion

Conversion from Scaled Frequency (SF) to volumetric water content (θ by means of the respective calibration function is provided by the manufacturer (Aquacheck, 2008):

$$\theta = \alpha + \beta * \text{SF-reading}$$

where the calibration parameters (α and β) are determined in the laboratory for common soil textures. For generic soil texture $\alpha = -7.4347$ and $\beta = 0.5564$ implying a linear relationship.

Preliminary data analysis

Soil moisture data was collected from all sensing probes between the 14th and 25th of December 2016, when a significant precipitation event (total daily rainfall of 13mm) occurred. Figure 5 illustrates the average maximum, mean, and minimum soil moisture values at the 20 sensing sites over the farm. The maximum, mean and minimum measurements increase at nearly a steady rate from 100- to 200- to 300- to 400-mm profile depths.

Precipitation events affect soil moisture values at the near surface level differently to the water content in the lower sections of the profile. Generally deeper sensors take longer to receive soil water via infiltration and there is a delay in their response. These lower sections dry out more slowly than the near-surface layers, where the highest variation can also be seen.

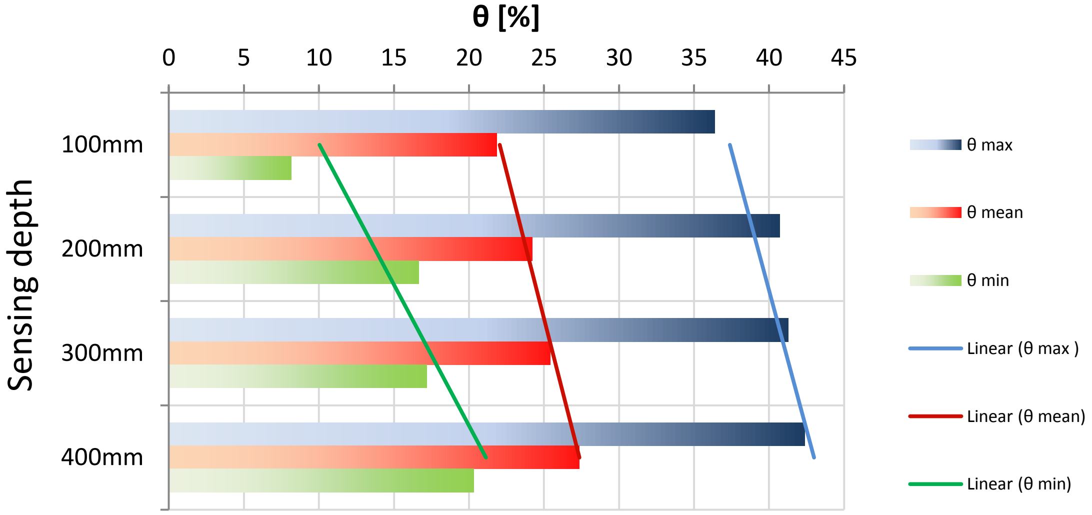

Figure 5 Soil moisture (Θ) ranges [%] as a function of depth with best fitted linear trendlines.

Soil water response at one selected sensing probe was examined for 10 days following the rainfall event. The sensing probe is installed on a 20° slope with silty clay loam type of soil. The sensing site is located on a west-facing slope to avoid the more significant effects of north or south aspects on soil moisture. Sensor readings from 100, 200, 300 and 400 mm depths were collected with a time interval of 15 minutes and converted to volumetric soil water content (VWC) by means of the respective calibration function. In order to apply the most suitable conversion, soil texture information was derived from a spatial soil database created by the Horizons Regional Council (Landvision Ltd., 2009).

The high-resolution time series of multi-level soil moisture measurements allowed us to understand the water movement within the root-zone and recognise drying, wetting and redistribution patterns.

The intense rainfall and the initial soil conditions resulted in very rapid water infiltration through the profile despite the fact that fine textured (silty clay loam) soil was determined at the site location according to the available soil resource information. The two bottommost sensors reported saturated conditions in 2 hours while the entire root zone reached saturation within 4 hours since the infiltration began. The 200-400 mm depths reached saturation earlier and at significantly higher water contents than the 100 mm depth proposing the presence of bypass flows. The appearance of transition points suggests that the soil moisture content decreased rapidly after the rainfall ceased. The change in slope indicates that the removal of water due to gravity slowed down and approached the upper limit of field capacity in 14-48 hours, depending on the depth. 4-5 hours after the precipitation event the percolation started from the top two sensing levels while the 300 and 400mm sensors showed that the soil moisture was retained at saturation level for 8 and 14 hours, respectively.

Soil moisture redistribution is a crucial function of the soils hydrologic response to input water and plays a significant role in plant water abstraction processes as well. Therefore, the soil moisture profiles were plotted for 30 hours following the rain at 6 hours intervals (Fig. 6, right). The water was transferred to the bottom sensors during the redistribution stage with the sharp wetting front dissipating gradually, leaving the sublayers wet and the top layers drying.

After 15 hours, the water movement slowed down and reached a more stable phase with steadily decreasing water content rate at each sensing level.

Once the excess water was removed and the soil transitioned to field capacity (about 2 days for the entire profile) the soil reached the most important and optimal conditions for crop production. Readily available water (water uptake without stress) within the active rooting zone is ideal pasture growth. Daytime water consumption and night time resting patterns can be recognised from the plot (Fig. 6, left). It took approximately 8 days for the soil water to level off which might be an indication of the onset of stress.

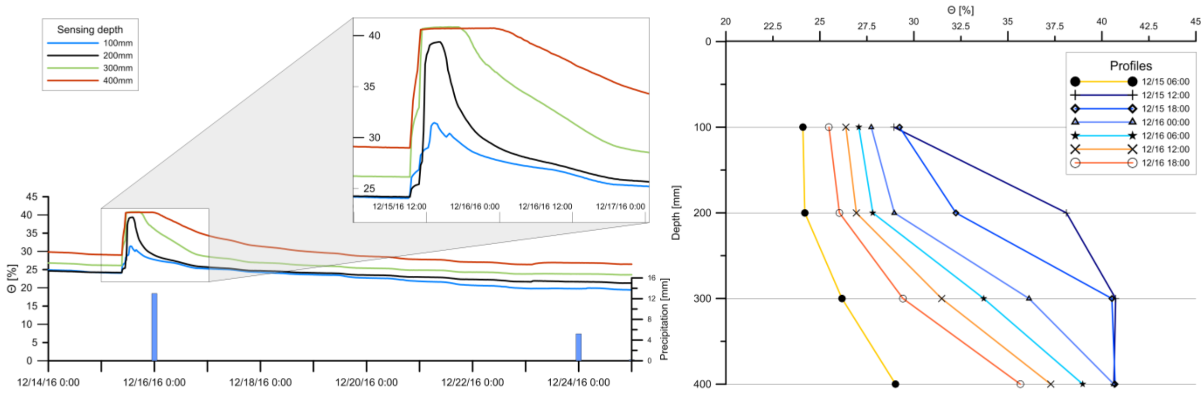

Figure 6 Time series (14-25 December 2016) of rainfall and soil moisture (left) along with moisture profiles (right) at 100, 200, 300, and 400 mm depths on a 20° slope

Summary and conclusions

During this initial phase of the study, a WSN system was deployed for near real-time, in-field multi-level soil moisture data collection displayed via a web interface. The study found that geomorphometry, integrating primary and secondary landscape parameters, are powerful tools for designing WSNs on large hill country farms. Initial indications are that high-resolution time series of soil moisture measurements collected by a WSN are valuable for investigating root zone water movements at various parts of a hill country farm. Familiarity with soil water dynamics and the processes that control soil water management are critical for proper management. The data can be used for studying wetting and drying cycles and sensor response to rainfall. Site-specific calibration along with soil sampling will be carried out in the next stage of the study to acquire soil physical information affecting water movements in the rooting zone.

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