A Nested Ecohydrological Wireless Sensor Network for Capturing the Surface Heterogeneity in the Midstream Areas of the Heihe River Basin, China

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***Abstract*—This letter introduces the ecohydrological wireless sensor network (EHWSN), which we have installed in the middle reach of the Heihe River Basin. The EHWSN has two primary objectives: the first objective is to capture the multiscale spatial variations and temporal dynamics of soil moisture, soil temperature, and land surface temperature in the heterogeneous farmland; and the second objective is to provide a remote-sensing ground-truth estimate with an approximate kilometer pixel scale using spatial upscaling. This ground truth can be used for validation and evaluation of remote-sensing products. The EHWSN integrates distributed observation nodes to achieve an automated, intelligent, and remote-controllable network that provides superior integrated, standardized, and automated observation capabilities for hydrological and ecological processes research at the basin scale.**

***Index Terms*—Eco-hydrological process, remote-sensing validation, spatial variation, wireless sensor network (WSN).**

I. Introduction

AS A revolutionary technique in Earth system science [1], wireless sensor networks (WSNs) are recognized as one of most important near-surface components of Global Earth Observation System of Systems (GEOSSs) [2], with flourished development of low-cost, robust, and integrated data loggers and sensors. It is expected that WSNs will become a standard observation technique that will advance the progress of Earth system science and environmental science [1]. Sensor webs comprised of open, standardized, and interoperable WSNs provide the infrastructure and technical support necessary to achieve GEOSS objectives.

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There have been many successful and diverse applications of WSNs in the research and observation of ecohydrological processes, such as the Critical Zone Observatories [3], the Water and Environmental Research Systems Network project [4], the Terrestrial Environmental Observatories [5], and the Consortium of Universities for the Advancement of Hydrologic Science [6]. A common theme of these observational platforms is a focus on a hierarchy of scales, ranging from local to regional or watershed scales for multidisciplinary process studies.

A prototype of a watershed observation platform was built in the Heihe River Basin (HRB) in the arid region of northwest China. This prototype is supported by the Watershed Allied Telemetry Experimental Research (WATER) project [7]. Based on the infrastructure and experience accumulated by WATER, its successor, i.e., HiWATER (Heihe WATER), is extended to be an ecohydrological process experiment that is designed from an interdisciplinary perspective to address problems, such as heterogeneity, scaling, uncertainty, and closing the water cycle at the watershed scale [8]. The ecohydrological WSN (EHWSN) is highlighted as one of the fundamental experiments to provide a basic data set to answer some of these challenging scientific questions.

This letter gives an overall introduction about the scientific objective, deployment region, construction, and optimal sampling design of this EHWSN.

II. Scientific Objectives

The EHWSN has two primary scientific objectives: the first is to capture the spatial variations and temporal dynamics of soil moisture, soil temperature, and land surface temperature in the heterogeneous farmland. The second objective is to provide a remote-sensing ground-truth estimate at an approximate kilometer pixel scale of using the geostatistics-based aggregation strategy; this ground truth can be used for the validation of remote-sensing products. The EHWSN integrates a variety of distributed nodes to achieve an automatic observation that provides superior integrated and standardized observation capabilities for hydrological and ecological processes research at the basin scale.

Soil moisture is recognized as an essential climate and hydrology variable [9]. Although there is little variation in the quantity of soil moisture in an annual hydrological cycle, it governs how precipitation is divided into evapotranspiration, infiltration, and runoff. In the middle reach of the HRB, soil moisture is a primary driver of ecosystem structure, function, and diversity. Thus, accurate estimates and predictions of the temporal–spatial dynamics of soil moisture are important for ecohydrological modeling, water resource management, crop growth, and drought monitoring.

The soil moisture in the middle region of the HRB is characterized by highly spatial heterogeneity, which is primarily attributed to two causes. First, canal water controlled by artificial irrigation management is assigned to the farming groups in sequence, with each farm receiving water four to five times per year. Second, both the landscape fragmentation and complicated cultivation structure result in spatial variations in evapotranspiration of the crops, which further lead to high spatial heterogeneity of the soil moisture. Therefore, a lack of distributed soil moisture observations limits the accuracy of water balance estimates and prevents efficient water resource utilization in this water-limited region. However, because of their high spatiotemporal resolution, WSNs can potentially capture the spatial variation and temporal dynamics of soil moisture, which is helpful for addressing the scaling, heterogeneity, and uncertainty of soil moisture and other related ecohydrological variables, such as evapotranspiration, land surface temperature, and biomass.

Moreover, enhancing the applicability of remote sensing in hydrological process studies and in water resource management at the basin-scale benefits integrated ecohydrological research. Operational utilization of remote-sensing products will be achieved with careful and extensive validation. The ground-based observations used to accurately evaluate remote-sensing products should meet the requirements of both spatial representativeness and temporal synchronization.

Traditionally, measurements at specific points or at field scales are regarded as the ground truth to directly evaluate remote-sensing products; such ground truths can be uncertain because of heterogeneous land surfaces and coarse pixel resolution. Point observations lack spatial representativeness to provide areal average at remote-sensing pixel scale, which can thus cause researchers to underestimate the accuracy of remote-sensing products. The scale mismatch between ground observations and remote-sensing pixels has been recognized as one of the most important issues in the remote-sensing community.

Distributed WSNs provide potential opportunities to bridge the scale gap and accomplish reasonable remote-sensing validation [10], [11]. Limited by budget and labor, statistical sampling methods accounting for the spatial correlation of a surface variables are instructional for optimization of the arrangement of WSN nodes to capture a spatiotemporally heterogeneous surface [12]. WSN observations can be used to analyze spatial variation and temporal stability and to infer the ground truth and its estimation variance at unsampled positions by the geostatistics.

Because of the instantaneous nature of remote-sensing observations and the quickly changing state of land surfaces, e.g., surface temperatures and freeze/thaw cycles, artificial ground-based measurements cannot satisfy the second validation requirement. An artificial observation requires significant time and labor, and the uncertainty of its measurement is difficult to quantify because of subjectivity even when standardized measurement instruments and specifications are adopted. However, each node in a WSN can be remotely controlled to modify the observation frequency or to set the observation time to accurately synchronize with remote-sensing observations. The observation error can be also estimated through systematically sensor calibration with *in situ* data, which ensure standardization and consistency of the observations.

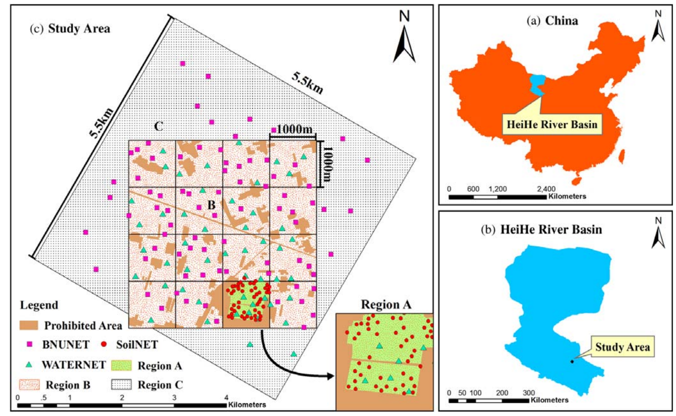

Fig. 1. Observation matrix in the artificial oasis research area of the HRB.

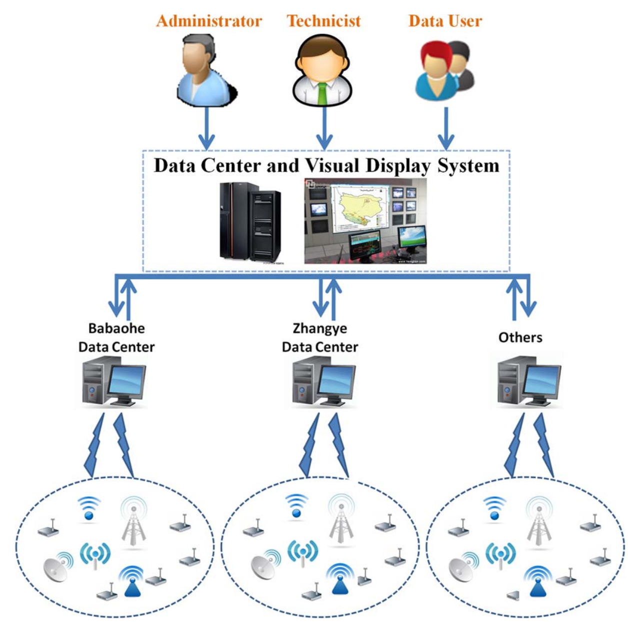

Fig. 2. Three-layer structure of the EHWSN.

III. Research Area

EHWSN, which is one of the fundamental experiments of the HiWATER project, is intensively implemented in a 5.5 km × 5.5 km observation matrix that is located in the Zhangye oasis in the middle region of the HRB (see Fig. 1) [8].

The land cover of the observation matrix is dominated by seed corn (68.6%). Other various land cover types, including wheat, vegetable fields, orchard gardens, shelterbelts, villages, roads, and irrigation canals, are randomly interspersed among the crop fields.

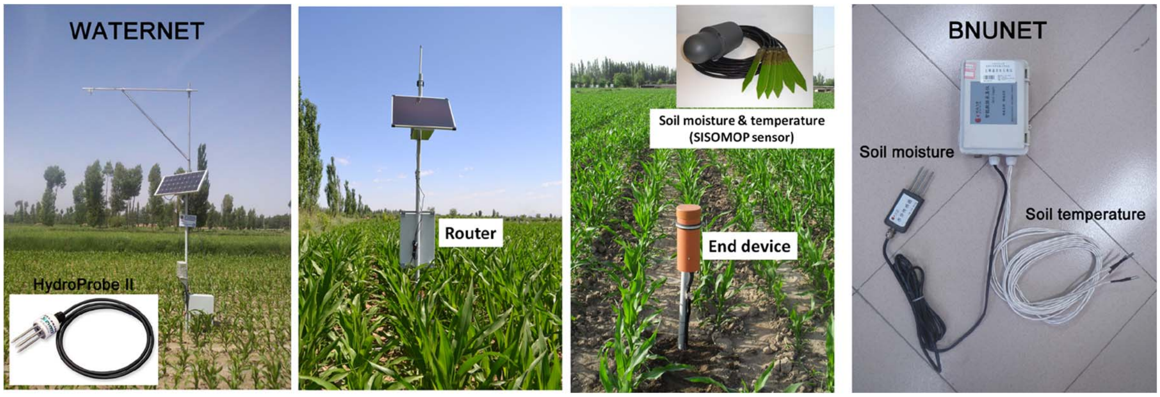

Fig. 3. Observation nodes of the EHWSN.

According to the Chinese data set of soil hydraulic parameters for land surface modeling [13], the soil texture is dominated by silt loam. Laboratory measurement of 50 soil samples have revealed that the clay and sand content average 8.0% and 34.5%, respectively, according to the United States Department of Agriculture soil texture classification system. Because of a long-term tillage, the soil texture profile between 0 and 40 cm is relatively uniform.

Annual precipitation in this region is approximately 100–250 mm, but the potential evaporation is as great as 1200–1800 mm per year. The soil moisture pattern is primarily controlled by crop type and artificial irrigation management. Rotation irrigation is performed four to five times each year, and each rotation continues for approximately 20 days. During the growing season, the soil moisture changes from 8.7 vol.%, which is the minimum observed by EHWSN during the period of May to September 2012, to saturation. The maximum frozen depth can reach 80–100 cm, with soil moisture starting to freeze by the end of October and thawing again in April.

The distance between field ridges and their azimuth, crop height, coverage, biomass, water content, and leaf area index are periodically measured at intervals of 5–10 days during the growing season.

IV. Construction of the EHWSN

With an aim to combine remote-sensing information used to support ecohydrological process modeling and the hydrological data assimilation system, a three-layer structure was designed to configure the network and to effectively manage the bidirectional data streams (see Fig. 2). The observation platform is expected to establish an automated, intelligent and remote-controllable ecohydrological WSN in the HRB.

The first layer of the EHWSN consists of a remote data server and a real-time 3-D visualization system located at Cold and Arid Regions Environmental and Engineering Research Institute (CAREERI). This data server is responsible for data collection, quality control, archiving, and node management; and it offers data services that include visualization, mistake diagnostics, data query, data sharing, and scientific applications. The visualization system supplies a real-time 3-D spatial display of field measurements within the Web-Geographic Information System (GIS) environment and automatically produces and sends a periodic data quality report to the responsible person.

The second layer comprises several regional data centers located in the Babaohe River Basin (upstream), Zhangye City (midstream), and other prospective sites in the HRB. These regional data centers independently operate from each other and directly communicate with the remote data center. The main functions of the regional data centers are to collect data and deliver commands, particularly focusing on the transfer of large-volume data sets using microwave and optical cables, e.g., the measurements from eddy covariance systems and high-definition web cameras.

The third layer incorporates various types of wireless sensor nodes distributed in the field to monitor the ecohydrological elements. A node is the terminal unit of a WSN and is defined as an assemblage of one or more sensors at a hardware software interface that connects the sensors to the observational network [4]. There are three types of newly developed WSN nodes adopted in the EHWSN, including WATERNET, SoilNet, and Beijing Normal University Sensor Network (BNUNET) [see Fig. 3(c)].

A defining advantage of the EHWSN is its bidirectional communication, i.e., observations and device status information are sent from the nodes to the data server and control orders are sent from a remote server to the nodes to modify the sensor operations. For example, in addition to a node sending data at specific intervals, the data server can also fetch data at any time from a node by issuing a remote command. Sensor nodes communicate with the data server through wireless transmission techniques, such as Zigbee, General Packet Radio Service (GPRS), and microwave. Each node has internal storage to ensure that all of the observations are completely and accurately sent to the remote servers; successful transmission is assured through a confirmation mechanism.

There are a total of 50 WATERNET, 50 SoilNET, and 80 BNUNET nodes distributed in the 5.5 km $\times$ 5.5 km observation matrix. Detailed information about each sensor type, e.g., the data transfer technique of the power supply, which is presented in the following.

A. *WATERNET*

WATERNET was specially customized by the close collaboration of CAREERI, the Computer Network Information Center of the Chinese Academy of Sciences, and Beijing Normal University.

Advanced system functions were developed based on the embedded operation system Zhongke Operating System (ZKOS) [14]. The wireless transfer techniques used include GPRS, digital radio station, and Wi-Fi; these techniques aim to accommodate the complex land surface and topography conditions in the field. As a challenging attempt, data transmissions based on the IPv6 address is also used. The power is supplied by a solar panel and a gel battery and is controlled via a protective solution to avoid overcharge and overdischarge. A sleep mechanism, which is activated when there is no observation task, is used to conserve power consumption. Because of the unattended operation of each WSN node, remote control and software update functions are necessary. Moreover, precise clock calibration is provided by a Global Positioning System module.

Each WATERNET node includes two Steven Hydra Probe II soil moisture and salinity sensors installed horizontally at depths of 4 and 10 cm below the surface, and an SI-111 infrared radiometer is located at a height of 4 m and observes the surface below it.

Observations are performed at 10-min intervals in its normal mode, and the interval is automatically switched to 1 min during an intensive mode from 8:00–16:30 and 21:00–4:30 to ensure that observations are precisely synchronized with related satellite and airborne remote sensor overpasses, particularly for land surface temperature data, which are dramatically changed because of the dynamics of boundary layer conditions and cloud cover.

B. SoilNET

SoilNET is an ad hoc network that was designed by the Jülich Research Center [15]. It comprises three communication layers, including a coordinator that serves as a sink node, a router that serves as a relay node, and an end device that serves as an observation node. Each end device can dynamically establish data links through low-cost IEEE 802.15.4 standard and transmit the observed data to one of the neighboring routers with the best communication signal. Then, the router forwards the data to the coordinator, which remotely sends a data package to the remote data server via a GPRS module.

The power demand of an end device is very small, and it enters a sleep mode when there is no observation task. A 3.6-V lithium battery can support an end device for six months. SoilNET is robust and supports automatic routing formation and restoration, adding and moving nodes and handshaking mechanisms to ensure unbroken data package transfers.

There are also some restrictive conditions for the deployment of SoilNET. Free sight and a distance of less than 1000 m is necessary between an end device and at least one router. The maximum distance between two routers and between at least one of the used routers in the network and the central coordinator is 2000 m.

Four SPADE sensors connected to end devices are installed at depths of 4, 10, 20, and 40 cm and observed at intervals of 10 min. The SPADE is a cost-effective and integrated soil moisture and temperature sensor. The soil moisture sensor is a frequency-domain probe with 0.4 vol.% theoretical accuracy depending on the sensor-specific calibration [16]. The temperature sensor is a semiconductor band-gap sensor with an accuracy of $\pm 0.5\ ^\circ$C and a measurement range from $-10\ ^\circ$C to 85 °C. An integrated temperature measurement circuit can compensate for thermal effects and detect frozen material.

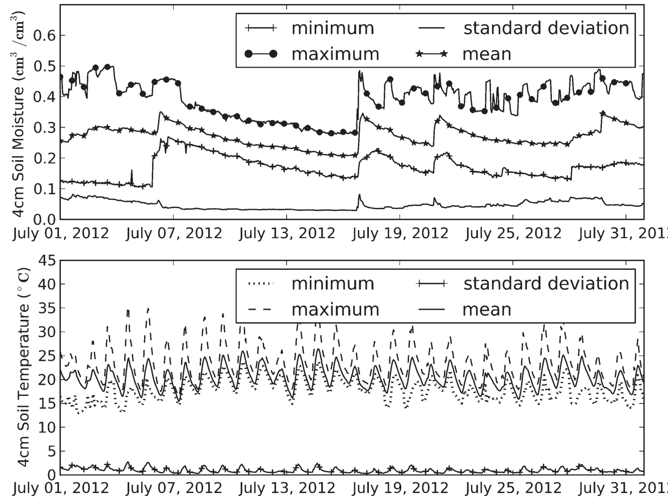

Fig. 4. Soil moisture and temperature observations at 4 cm by the EHWSN.

C. BNUNET

BNUNET was developed in China. It has three soil temperature probes installed at 4, 10, and 20 cm below the land surface and one soil moisture sensor at 4 cm. There is no wireless transfer function; rather, the observations are stored in memory and periodically downloaded. Power is supplied by eight AA batteries. BNUNET has the same 10-min observation frequency as WATERNET and SoilNET.

D. Senor Calibration

Before installation, each sensor is verified by a two-point calibration method. For soil moisture, one point is measured in the desert sand after air seasoning, and another is observed in saturated soil sampled from a local crop field. Meanwhile, the true soil moisture content is obtained through an oven-drying method to evaluate the sensor measurement accuracy. For soil temperature verification, the cooling process of warm water is continuously measured from 40 °C to 10 °C. SI-111 sensors are verified using the BDB blackbody calibrator at a constant temperature of 23 °C and a water-ice mixture at 0 °C.

The calibration experiments indicate that the consistency between sensors is greater than 95%, the accuracies of the soil moisture measurements for SPADE and Hydra Probe II are 3.2 and 1.1 vol.%, respectively, and the accuracy of the surface radiative temperature for SI-111 is 0.15 °C.

Fig. 4 illustrates the mean, minimum, maximum, and standard deviations of soil moisture and temperature observations of the EHWSN during July, which indicate considerable spatial heterogeneity in soil moisture dynamics.

V. Optimal Sampling Design of the EHWSN

The EHWSN was designed as a nested monitoring network to distribute and observe the soil temperature, soil moisture, and land surface temperature by using a specified number of nodes. Optimal spatial sampling strategies have been performed to select suitable locations for the 180 WSN nodes in the 5.5 km × 5.5 km observation matrix.

The observing matrix is divided into three subregions, including the intensive region (A) with an area that is the same size as a Moderate Resolution Imaging Spectroradiometer (MODIS) pixel, a 4×4 MODIS pixels region (B), and the surrounding region (C), to achieve multiscale observations (see Fig. 1).

The geostatistical analysis method, which is affected by the spatial configuration of nodes, is used to optimize the spatial distribution of WSN nodes. To satisfy both objectives of capturing the spatial variability and inferring the ground truth on remote-sensing pixel scales, we propose a hybrid criterion method based on a free model without any assumption about the variogram. The method is defined as follows:

$$\varnothing_{\mathrm{hybrid}}(S) = w_1 \varnothing_{\mathrm{EP}}^{\mathrm{norm}}(S) + w_2 \varnothing_{\mathrm{SP}}^{\mathrm{norm}}(S) \quad (1)$$

where $\varnothing_{\mathrm{hybrid}}$ is a weighted sum of the two subcriteria, and S is the optimized point set. $\varnothing_{\mathrm{EP}}^{\mathrm{norm}}$ makes the number of point pairs evenly distributed in each lag to ensure accurate estimation of the variogram, whereas the $\varnothing_{\mathrm{SP}}^{\mathrm{norm}}$ is used to separate the sampling points to avoid cluster. w_1 and w_2 are the weighting coefficients of both subcriteria. The optimal distribution are obtained by the simulated annealing algorithm when the $\varnothing_{\mathrm{hybrid}}$ is converged. For more details about the algorithm development and implementation, please refer to [18].

VI. Summary and Outlook

We have established a multiscale EHWSN monitoring network in the midstream areas of the HRB, China to support ecohydrological process, remote sensing, and scaling studies.

The EHWSN obtained measurements during the crop-growing period from May to September 2012. The observed variables include soil moisture, soil temperature, and land surface temperature. This data set is published at http://westdc.westgis.ac.cn/hiwater.

The sharing of data encourages continued scientific research and new applications, such as the following.

1) The EHWSN can be used to develop a multiscale validation for remote-sensing products at the basin scale, particularly for the kilometer-scale downscaled soil moisture product, which is urgently needed for ecohydrological research.
2) The EHWSN can support spatial-scale-related research, such as studies of spatial variation, optimal sampling design, and the development and comparison of various upscaling and downscaling strategies.
3) The EHWSN can be used to study spatial variations and the temporal dynamics of surface soil water and temperature and to determine the spatial structure of the observation error for the hydrological assimilation system.
4) The EHWSN can offer useful information to support drought and irrigation management for the reasonable and timely optimal allocation of water resources in the middle region of the HRB.

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