HEIHE WATERSHED ALLIED TELEMETRY EXPERIMENTAL RESEARCH (HiWATER)

Scientific Objectives and Experimental Design

BY XIN LI, GUODONG CHENG, SHAOMIN LIU, QING XIAO, MINGGUO MA, RUI JIN, TAO CHE, QINHUO LIU, WEIZHEN WANG, YUAN QI, JIANGUANG WEN, HONGYI LI, GAOFENG ZHU, JIANWEN GUO, YOUHUA RAN, SHUOGUO WANG, ZHONGLI ZHU, JIAN ZHOU, XIAOLI HU, AND ZIWEI XU

An eco-hydrological experiment designed from an interdisciplinary perspective addresses problems including heterogeneity, scaling, uncertainty, and closing water cycle at the watershed scale.

A major research plan entitled "Integrated research on the eco-hydrological process of the Heihe River Basin" (hereafter referred to as the Heihe Plan) was launched by the National Natural Science Foundation of China (NSFC) in 2010. The scientific objectives of the Heihe Plan is to reveal the processes and mechanisms of the eco-hydrological system in an inland river basin at different scales (e.g., leaf, individual plant, community, landscape, and watershed scales); to improve the research capabilities and predictability of the evolution of hydrological, ecological, and economic systems; to determine the responses of eco-hydrological processes to climate change and human activities; and to provide fundamental theory and technical support for water security, ecological security, and sustainable development in inland river basins. Eventually, the implementation of the Heihe Plan will establish a research platform that integrates the observation, data management, and model simulation of both physical and socioeconomic processes to foster twenty-first-century watershed science in China.

The Heihe River basin (HRB) in the arid region of northwest China has been selected as an experimental watershed to carry out this research plan. This area was selected because, first, the HRB is a typical inland river basin (endorheic basin). Inland river basins occupy approximately 11.4% of world's land

AFFILIATIONS: X. LI, CHENG, MA, JIN, CHE, W. WANG, QI, H. LI, G. ZHU, GUO, RAN, S. WANG, ZHOU, AND HU—Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences, Lanzhou, China; S. LIU, Z. ZHU, AND XU—State Key Laboratory of Remote Sensing Science, School of Geography and Remote Sensing Science, Beijing Normal University, Beijing, China; XIAO, Q. LIU, AND WEN—State Key Laboratory of Remote Sensing Science, Institute of Remote Sensing Applications, Chinese Academy of Sciences, Beijing, China
CORRESPONDING AUTHOR: Dr. Xin Li, 320 West Donggang Road, Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences, Lanzhou 730000, Gansu Province, China
E-mail: lixin@lzb.ac.cn

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area. Most of them are distributed over arid regions, where water-stressed ecosystems are massively distributed (Rodriguez-Iturbe and Porporato 2004), eco-hydrological processes are more complicated, and the environment is more fragile to climate change and anthropogenic disturbance and therefore the water conflict between ecosystem's demand and economic development is more severe. All of the above extremes are found in the HRB (Cheng, 1996; Wang and Cheng 1999; Li et al. 2001). Second, the HRB has long served as a test bed for integrated watershed studies as well as land surface or hydrological experiments (Cheng 2009). Comprehensive experiments such as the Heihe Basin Field Experiment (HEIFE; Hu et al. 1994) and Watershed Allied Telemetry Experimental Research (WATER; Li et al. 2009) have taken place in the HRB. A prototype watershed observing system has been developed (Li et al. 2010b). The above-mentioned reasons have made the HRB an ideal field laboratory to further pursue integrated eco-hydrological studies and integrated river basin management that can benefit both the natural ecosystem and society.

Heihe Watershed Allied Telemetry Experimental Research (HiWATER) was initialized based on the reasons provided in the background above. It is designed to be a comprehensive eco-hydrological experiment in the framework of the Heihe Plan, based on the diverse needs of the interdisciplinary studies of the research plan and the existing observing infrastructures in the basin. The overall objective of HiWATER is to improve the observability of hydrological and ecological processes, to build a world-class watershed observing system, and to enhance the applicability of remote sensing in integrated eco-hydrological studies and water recourse management at the basin scale. However, determining how these goals are to be met is a challenging task.

The first challenge is how to take advantage of new trends in hydrological and ecological experiments as well as new Earth observing techniques. In Earth science, there is a tradition of using comprehensive experiments as a tool to improve the understanding of processes, and to test scientific hypotheses and new measurement techniques. However, most land surface or hydrological experiments conducted to date put their emphases on large-scale processes to serve the parameterization of subgrid processes for general circulation or land surface models (André et al. 1986; Sellers et al. 1988). River basin hydroclimatic studies have also focused on the continent scale (Stewart et al. 1998; Raschke et al. 2001; Lawford et al. 2004). Only in recent years has the trend shifted toward using the watershed as a basic observing entity. Some research plans, such as the Consortium of Universities for the Advancement of Hydrologic Science (CUAHSI; CUAHSI 2007), Critical Zone Observatories (Anderson et al. 2008), Water and Environmental Research Systems Network (NRC 2010), and Terrestrial Environmental Observatories (TERENO; Bogena et al. 2006) have selected representative river basins in different climate zones to carry out comprehensive experiments or build multiscale observatories. Indeed, measurement techniques are rapidly advancing. Remote sensing is reshaping hydrological observations. Many traditionally unobservable variables, such as groundwater and river flow, can now be retrieved by remote sensing (NRC 2008a). On the ground, new technologies, such as the eddy covariance system (EC), large aperture scintillometer (LAS), cosmic-ray neutron probe, and wireless sensor network are being applied (NRC 2008b). However, how to effectively use these technical advances in modeling and understanding eco-hydrological processes remains elusive. Understanding how to take advantage of the aforementioned research trends is therefore a serious challenge in HiWATER.

The second challenge is how to capture the strong land surface heterogeneities and associated uncertainties within a watershed. Observing and modeling at the watershed scale is more challenging than at the point scale because of inherent multiscale heterogeneity (Sivapalan et al. 2003). New generation observing techniques (e.g., those introduced in the paragraph above) are reliable in their direct measurements. However, in terms of spatial representativeness, which requires appropriate scaling, both remote sensing and in situ observations feature much greater uncertainties. In terms of the reliability of retrieval and estimation models, which transform direct measurements into the necessary hydrological and ecological variables or parameters, these observations also feature much greater uncertainties. This means, while the original measurements do capture the heterogeneities, translating these measurements into useful information in understanding eco-hydrological processes requires appropriate scaling schemes and carefully developed models that can provide reliable retrievals. In turn, optimal observation network designs and sampling strategies as well as suitable approaches to quantify the uncertainties associated with scaling and estimation/retrieval models are needed.

The third challenge is more specific: how to close the water cycle in a river basin. Water should be closed on the various scales of drainage basins,

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from tens of square kilometers to hundreds to tens of thousands of square kilometers for entire river basins. This problem, though not difficult in principle, still involves great uncertainties in the measurement and estimation methods used to study many water cycle components. Evapotranspiration might be the most uncertain component. Its measurement using the EC technique is challenged by the energy balance closure problem (Foken 2008); its remote sensing estimation is far from reaching a mature stage (NRC 2008a). Precipitation, in both cold and arid regions, features great spatiotemporal heterogeneity. Reliable areal estimations of total precipitation and the associated spatiotemporal variation require careful calibrations for different types of precipitation and a specially designed ground observation network (Yang et al. 2009). Soil moisture, when measured by remote sensing, is currently only available at a very coarse resolution that is not particularly useful for watershed-scale applications. Snow water equivalent in mountainous areas still cannot be accurately measured from space (NRC 2008a). Therefore, although HiWATER will measure both hydrological and ecological processes, closing water cycle is a top priority.

Addressing the above-mentioned challenges with innovative ideas will make HiWATER different from previous hydroclimatic experiments and its predecessor WATER. In short, HiWATER is a watershed-scale eco-hydrological experiment designed from an interdisciplinary perspective to address complex problems, such as heterogeneity, scaling, uncertainty, and closing the water cycle at the watershed scale.

SCIENTIFIC OBJECTIVES. The overall objective of HiWATER is to improve the observability of hydrological and ecological processes, to build a world-class watershed observing system, and to enhance the applicability of remote sensing in integrated eco-hydrological studies and water recourse management at the basin scale.

This is being achieved through the following specific objectives:

1) To develop a watershed observing system that serves watershed science and integrated water resource management;
2) To precisely measure each component of water cycle using multiscale observations in order to close water cycle at the river basin scale;
3) To obtain multiscale data critical to understanding ecosystem dynamics and its relationship with water resource availability in the inland river basin;
4) To produce a series of high-quality remote sensing products that can support basin-scale integrated eco-hydrological studies;
5) To validate remote sensing models, algorithms and products through purposeful validation experiments; and
6) To integrate observation data and remote sensing products into a distributed hydrology model, coupled surface water-groundwater-crop growth model and water consumption model upstream, middle stream and downstream of the HRB, respectively. It is expected that through these empirical case studies the applicability of remote sensing in eco-hydrological studies and water recourse management can be enhanced.

There are six scientific questions that will be explored in HiWATER. Most of the questions are proposed from a methodological point of view.

1) How well can remote sensing data be used to improve our understanding of the eco-hydrological processes in a river basin? How can we develop more reliable and robust eco-hydrological remote sensing methods through field experiments?
2) Which types of remote sensing products are urgently needed in eco-hydrological studies? How can remote sensing products be tailored toward water cycle and ecological processes at the watershed scale with better quality and finer resolution?
3) How well can we capture the spatio-temporal variations of each observation item at the basin scale? How well can we design an in situ observation network? What is the optimum density and scale of each individual observation sensor?
4) How can we design in situ sampling strategies aimed at remote sensing validation? How can we acquire ground truths at the pixel scale over heterogeneous land surfaces that can be used as a reference truth for remote sensing validation?
5) How can we effectively use remote sensing observations and products in integrated eco-hydrology studies?
6) How can we integrate remote sensing observations, in situ measurements, and model simulations to accurately estimate the state variables and fluxes in water cycle and ecological processes, and to improve the accuracies of hydrological and ecological simulations and predictions at the basin scale?

EXPERIMENTAL AREA. The experiment will be performed in the Heihe River basin (Fig. 1), which is

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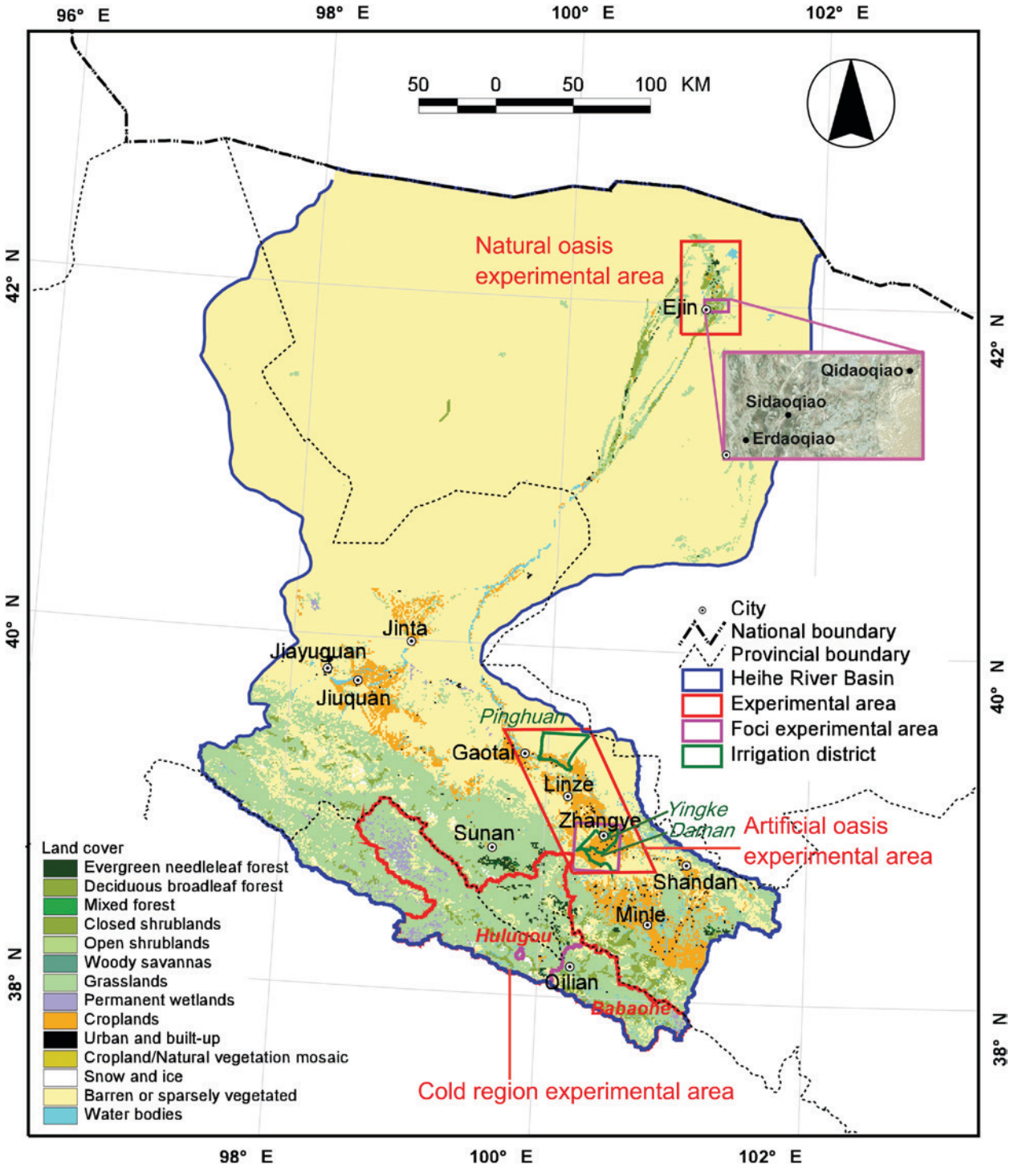


Fig. 1. Experimental areas in HiWATER.

located within 37.7°–42.7°N, 97.1°–102.0°E, covering an area of approximately 1,432,000 km^2.[1] This basin is characterized by its distinct cold and arid landscapes: glaciers, frozen soil, alpine meadow, forest, irrigated crops, riparian ecosystem, and desert, which are distributed upstream to downstream. In the whole river basin, three key experimental areas (KEAs) were selected to conduct intensive and long-

[1] The areal coverage and the area of the HRB are different from those in WATER. This is because we re-delineate the river basin boundary.

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term observations. These KEAs are the cold region experimental area in the mountain cryosphere of the upper reaches, the artificial oasis experimental area in the middle reaches, and the natural oasis experimental area downstream. Within each KEA, the foci experimental area (FEA), the experiment site (ES), and the elementary sampling plot (ESP) were designed as hierarchically nested locations of multiscale ground observations.

1) The cold region experimental area consists of the upstream regions of the main stream of the Heihe River (102,009 km^2). Observation experiments are performed at three scales: the main stream basin, sub-basin (Babao River basin), and watershed (Hulugou catchment).

   The Babao River basin is a sub-basin in the upper reaches of the HRB with an area of approximately 2452 km^2 and an elevation ranging from 2640 to 5000 m. The Hulugou catchment is a typical alpine catchment with an area of 23.1 km^2. These two FEAs have almost all of the typical landscapes of cold regions, including alpine grassland, swamp, alpine meadow, valley bush, *Picea crassifolia*, and *Qilian juniper*, among others. Permafrost, seasonal frozen soil, alpine cold desert, snow, and glaciers exist in the area.
2) The artificial oasis experimental area is located in an artificial oasis–riparian ecosystem–wetland–desert compound in the middle reaches of the HRB. Some typical irrigation districts (e.g., Yingke and Daman as well as Pingchuan) are selected as the FEAs. The precipitation in this area is approximately 100–250 mm per year, but potential evaporation is as high as 1200–1800 mm per year. The major crops are maize, wheat, and vegetables.
3) The natural oasis experimental area is located in the Ejin Banner oasis, which is downstream of the HRB. The landscapes are composed of sandy and gravel deserts, a natural oasis dominated by *Populus euphratica*, *Tamarix*, and other arid region species, as well as terminal lakes. Regions of the river bank from Erdaoqiao to Qidaoqiao are selected as the core FEA. This area is an extremely arid region, with precipitation of less than 50 mm per year and potential evaporation of approximately 3755 mm per year.

OBSERVING VARIABLES AND PARAMETERS. Three categories of variables/parameters are to be observed. These include the state variables and fluxes of key eco-hydrological processes, atmospheric forcing data, and parameters (e.g., vegetation, soil, terrain, hydrology, and aerodynamic parameters). These variables and parameters were selected with reference to some typical distributed hydrological models, groundwater models, crop growth models, dynamic vegetation models, and land surface models; most of these models have been employed in hydrological and ecological studies in the HRB (Li et al. 2010a). The major referenced distributed hydrological models are the Distributed Hydrology Vegetation Model (DHSVM; Wigmosta et al. 1994), the Soil and Water Assessment Tool (SWAT; Arnold and Fohrer 2005), GEOtop (Rigon et al. 2006), and a distributed biosphere hydrological model (WEB-DHM; L. Wang et al. 2009). Various versions of ModFLOW are used as core groundwater models (Harbaugh et al. 2000). The Lund–Potsdam–Jena Dynamic Global Vegetation Model (LPJ-DGVM; Sitch et al. 2003) is the dynamic vegetation models and WOFOST (Vandiepen et al. 1989) is the crop growth model. The Simple Biosphere Model, version 2 (SiB2; Sellers et al. 1996), Common Land Model (CoLM; Dai et al. 2003), and Community Land Model (CLM; Oleson et al. 2010) are referenced as land surface models. The newly developed coupled models for the HRB have also been used as reference models (Tian et al. 2012; Zhang et al. 2013; Zhou et al. 2012).

Tabulation of the variables and parameters can be found online at http://hiwater.westgis.ac.cn/english/index.asp.

EXPERIMENT COMPOSITION. HiWATER is composed of fundamental, thematic, application experiments and integrated studies.

Fundamental experiments. The fundamental experiments focus on the establishment of observing system, provision of basic datasets, enhancement of observation capabilities, and development of reliable and robust methods. The four following experiments are included.

Airborne remote sensing experiment. An imaging spectrometer, light detection and ranging (lidar) system, charge-coupled device (CCD), multi-angle thermal infrared camera, and microwave radiometer are used in the airborne missions. The goal of these missions is to improve the remote sensing methods for observing key eco-hydrological processes and to develop scaling methods by acquiring multispatial-resolution remote sensing data.

The airborne sensors used in HiWATER are listed in Table 1.

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Table 1. Airborne sensors used in HiWATER.

	Instrument	Major instrument characteristics
	Lidar+CCD	Leica ALS70, maximum flight altitude: 5000 m AGL, field of vision (FOV) 75°, first, second, and third return intensities, vertical placement accuracy: 5–30 cm, integral digital camera: 1280 × 1024 pixels
	CASI-1500 VNIR & SASI-600 SWIR imaging spectrometer	CASI: spectral range: 380–1050 nm, 1500 across-track pixels, 48 bands, bandwidth: 7 nm, FOV: 40°; SASI: spectral range: 950–2450 nm, 600 across-track pixels, 101 bands, bandwidth:15 nm, FOV: 40°
	TASI-600 pushbroom hyperspectral thermal sensor system	Spectral range: 8000–11500 nm, 600 spatial pixels, 32 bands, bandwidth:110 nm, FOV: 40°
	Wide-angle infrared dual-mode line/area array scanner	Thermal imaging camera: 8–12 μm, FOV: 80°, observation angles: ±46° (+forward, -backward); CCD camera: five bands at 550, 650, 700, 750, and 750 nm, 1360 × 1024 pixels, observation angles: ±52°
	PLMR	Frequency: 1.413 GHz, bandwidth: 24 MHz, resolution: 1 km (flight altitude: 3 km AGL), adjustable incident angle: ±7°, ±21.5°, ±38.5°, sensitivity <1 K, polarization: V/H
	L-band passive microwave radiometer	Frequency: 1.413 GHz, bandwidth: 20 MHz, sensitivity: 0.08 K, beam angle: 15°, incident angle: 45°, polarization: V/H
 	K- and Ka-band passive microwave radiometers	Frequency: 18.7 GHz (K-band) & 37 GHz (Ka-band), bandwidth: 400 MHz, sensitivity: 0.15 K, beam angle: 2.5°, incident angle: 45°, polarization: V/H, imaging scan range: ±12°

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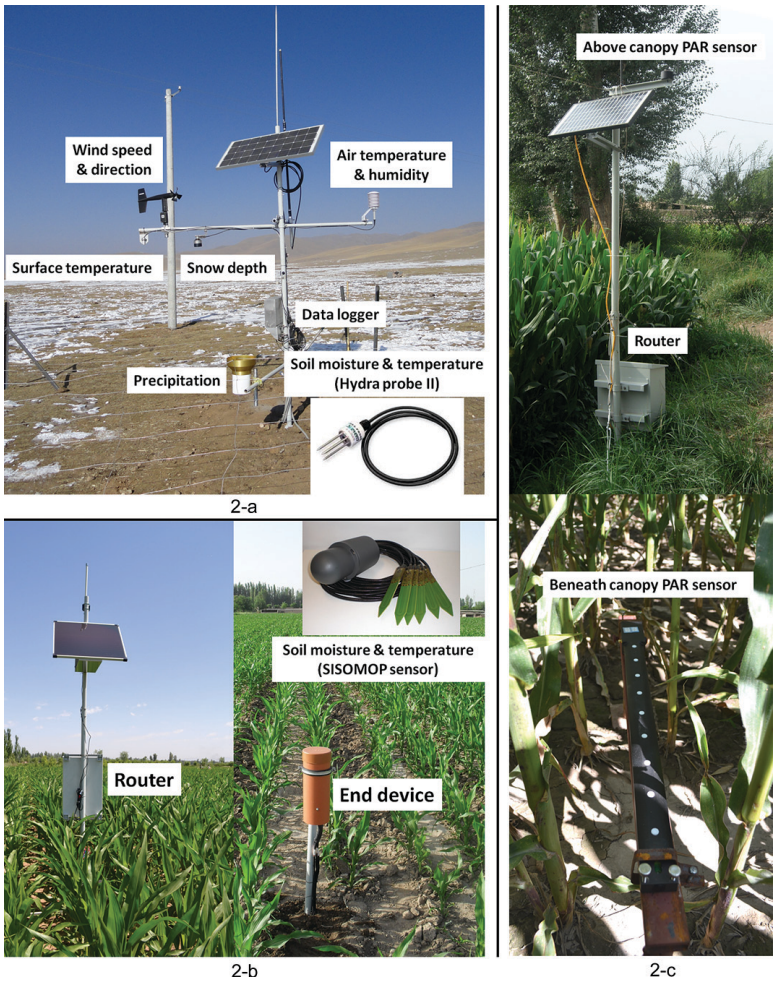


Fig. 2. Wireless sensor network: three types of new sensor nodes used in HiWATER: (a) WATERNET, (b) SoilNet, and (c) LAI measurement system.

Hydrometeorological network. This aims to establish a comprehensive hydrometeorological observation network composed of super, research, ordinary, and conventional stations that cover the whole HRB to provide representative atmospheric forcing data and validation data for the watershed models.

The ordinary automatic meteorological station (AMS) measures the radiation, precipitation, air pressure, wind speed and direction, air temperature, humidity, soil moisture and temperature profiles, and soil heat flux. The superstation is outfitted with an EC system, a Bowen ration energy balance system, an LAS, and a lysimeter (optional) to measure fluxes at multiple scales. Additionally, besides the standard observations performed in an ordinary station, photosynthetically active radiation (PAR) and land surface temperature (LST) are measured at a superstation.

Precipitation is highly uncertain in cold and arid regions for wind-induced error and wetting loss (Yang et al. 2009). Therefore, a precipitation correction experiment is carried out to develop calibration formulas for different rain gauges employed in the HRB. Additionally, intensive river runoff observations supplement existing hydrological stations along the mainstream of the Heihe River.

Eco-hydrological wireless sensor network. The eco-hydrological wireless sensor network (WSN) in HiWATER aims to integrate a variety of hydrological, ecological, and meteorological observation facilities distributed in the HRB. Three types of new sensor nodes are designed or used, including the WATERNET (Fig. 2a), SoilNet (Fig. 2b), and leaf area index (LAI) measurement systems (Fig. 2c). The AMSs and flux towers are reconfigured with wireless transmission capacities. Relevant studies about the optimal spatial sampling strategy of the sensor nodes have been performed to capture the spatiotemporal variations of key eco-hydrological parameters over heterogeneous land surface, for example, at the watershed or pixel scale (Ge et al. 2012).

The sensor nodes communicate with the data center through wireless transmission techniques such as Zigbee, General Packet Radio Service (GPRS), and microwave antenna. A software platform for the WSN has been developed. This system has the functions of transmitting and archiving automatically observed data and controlling sensor nodes and instruments remotely. As a result, the platform is anticipated to establish an automatic, intelligent, and remote-controllable eco-hydrological WSN in the HRB (Jin et al. 2012).

Calibration and validation experiment. The main tasks of the calibration and validation experiment are as follows.

- Calibration. Measurements on the radiometric calibration, atmospheric correction, and geometric rectification of airborne and satellite remote

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sensing data are carried out. In particular, air temperature and humidity profiles and aerosol properties are measured by a digital sounder and sun spectrophotometers. GPS-tracking sounding balloons are released before and after each airborne mission. The wind speed at various heights above the ground and the thermodynamic structure of the lower layer of the atmosphere are measured by an acoustic wind profiler, with a vertical range of up to 1000 m above the ground.

- Ground-based remote sensing. The emissivity spectra of different land surfaces during different seasons are systematically measured by an infrared spectrum analyzer. The microwave radiation characteristics of typical land surfaces are measured using a ground-based microwave radiometer.
- Validation. The remote sensing products to be validated are products of land cover type, plant structure, vegetation type, LST, albedo, soil moisture, snow depth, LAI, fraction of PAR (FPAR), fraction of vegetation cover (FVC), net primary production (NPP), and net ecosystem production (NEP). Pixel-scale ground truths are obtained simultaneously with airborne and satellite overpasses with the aid of the WSN.

Thematic experiments. The thematic experiments are concentrated on specific hydrological or ecological processes. The first thematic experiment in HiWATER is the multiscale observation experiment on evapotranspiration (ET) over inhomogeneous land surfaces (Liu et al. 2013, unpublished manuscript). During the lifetime of HiWATER, more thematic experiments are planned, such as one for soil moisture and one for ecosystem biomass.

ET is the most important component of the water cycle in arid regions. It is also a key process that links hydrology with ecosystem dynamics, from stoma to landscape scales. Therefore, a multiscale observation experiment on ET using a flux observing matrix is carried out to reveal the spatial heterogeneities of ET, to explore the energy balance closure problem, to identify scaling effects, and to provide ground truths that correspond to the development of the remote sensing models and scale transformation approaches for ET over heterogeneous land surfaces (Jia et al. 2012).

Application experiments. The application experiments aim to prove the applicability of remote sensing in integrated eco-hydrological modeling and water resource management by carrying out comprehensive experiments in the upper, middle, and lower reaches of the HRB, in association with fundamental experiments. The following experiments are included.

Remote sensing hydrology experiment for cold regions. Carefully designed observations will be performed to calibrate and validate distributed cold region hydrological models that feature detailed descriptions of snow and soil freeze/thaw processes. Algorithms for the estimation of snow cover area (SCA) under complex terrains and a dynamic function between SCA and snow water equivalent (SWE) at the grid scale will be developed and validated through airborne missions and in situ measurements. These algorithms are expected to improve the forecasting of runoff, especially spring runoff, in mountainous areas by assimilating remote-sensed SCA and soil moisture products into a distributed cold region hydrological model.

Remote sensing experiment for optimal allocation of irrigation water in the middle stream of the HRB. Measurements of water balance components in some irrigation districts are being carried out to calibrate and improve coupled surface water–groundwater–crop growth models. With the aid of remote sensing products, such as vegetation type, vegetation coverage, phenophase, NPP, and soil moisture, the coupled model is to be expanded to the irrigation district scale based on a state-of-the-art data assimilation method. With these data, the coupled model is expected to realize real-time monitoring and the short-term forecast of water demand/supply and crop growth situation at the irrigation district scale to further optimize irrigation management and enhance water use efficiency.

Remote sensing experiment to support scale transformation of ecosystem water consumption in the downstream oases of the HRB. This experiment will carry out multiscale comprehensive observations to measure the water consumption of the oasis ecosystem downstream to validate and calibrate scale transformation approaches of water consumption from the single plant-canopy-community to regional scale. Airborne lidar missions will be performed to acquire key vegetation structure parameters that are needed in scale transformation. In this context, the water consumption of the riparian forest ecosystem will be quantified with the support of remote sensing.

Integrated studies. Except for field campaigns, integrated research also plays an important role in HiWATER. These studies aim at producing remote

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sensing products to study water cycle and key ecological processes.

For water cycle, a daily SCA product with a resolution of 500 m will be created by using Moderate Resolution Imaging Spectroradiometer (MODIS) data and based on a nonlinear spectral mixture analysis model. A soil moisture product with a resolution of 1 km will be generated by merging microwave remote sensed data and MODIS VI products. Hourly precipitation products with resolutions of 1–5 km will be created by assimilating passive microwave observations, Doppler radar, and ground measured rainfall data into the Weather Research And Forecasting (WRF) model.

For ecological variables/parameters, monthly vegetation maps across the whole HRB will be generated based on differences in topography, vegetation type, and vegetation structure to reveal the characteristics of vegetation phenology. The data products of FVC, LAI, FPAR, NPP, and other key parameters that can represent plant growth processes will be produced with a spatial resolution finer than 1 km.

INSTRUMENT SETTINGS AND AIRBORNE MISSIONS.

Upstream area. Three-level nested experimental areas are chosen. The first level is the upstream area of the Heihe River main stream, the second level is composed of the two FEAs, and the third level consists of a snow observatory and a frozen soil observatory (Fig. 3).

Airborne missions. A high-resolution CCD camera and an imaging spectrometer are flown over the Heihe River Valley. In the Hulugou and other selected catchments, a 1-m resolution digital elevation model (DEM) is to be generated using airborne lidar. The L-, K-, and Ka-band radiometers are flown with manned and unmanned missions to develop more reliable remote sensing methods for deriving soil moisture (including surface soil freeze/thaw status), snow depth, and SWE.

The upstream area of the Heihe River main stream. The whole region is equipped with 10 AMSs and 3 flux towers (Fig. 3a). The flux towers are installed in a permafrost area, a seasonally frozen ground area and a snow-covered area.

The Babao River basin. It will be instrumented with a densely distributed network of AMSs and WSN. Six ordinary AMSs and a superstation at A'rou will be installed in different landscapes and elevation zones to capture the heterogeneity of near-surface atmospheric states (Fig. 3b). A WSN with more than 40 WATERNET nodes will be deployed according to an optimal design based on the spatial variation of terrain, soil moisture, and soil temperature, so that the major hydrological heterogeneity can be captured (Ge et al. 2012) (Fig. 3b). The observation items of a WATERNET node include soil moisture, soil temperature, LST, precipitation, snow depth, air temperature, humidity, and wind speed and direction.

Snow observatory and frozen soil observatory. In the Hulugou catchment, a snow observatory was constructed (Fig. 3c). A γ-ray (GMON) observation system is employed to measure the SWE with a footprint of 100 m^2. A snow water sensor (SWS) is used to measure the snowpack liquid water content, snow density, and SWE. FlowCapt records the blowing snow flux and the EC system observes the evaporation and sublimation on the snow surface. A snow pillow records the SWE and the melts. A digital camera monitors snow coverage. Snow stakes are laid out at an interval of 10 m to periodically measure snow depth.

The frozen soil observatory is located at the A'rou Superstation. In addition to the basic observations configured in the superstation, the top 30-cm depth soil is stratified into 5-cm intervals and the soils at a depth of 30–100 cm are stratified into 10-cm intervals. In each layer, soil temperature and moisture are measured. Soil heat flux and water potential are measured in selected layers. Additionally, a footprint-scale (approximately 600-m diameter) soil moisture is measured by a cosmic-ray soil moisture observing system, in association with WSN (Fig. 3d).

Middle stream area. Airborne missions. VNIR imaging spectrometers (i.e., the CASI and SASI systems) are flown over the experimental area (Fig. 4) to support the inversion of surface reflectance, albedo, FPAR, LAI, chlorophyll content, and FVC. The TASI imaging spectrometer is utilized to measure the emission characteristics of soils, vegetation, and desert and for the retrieval of LST and emissivity. The WiDAS is flown to measure the directional characteristics of surface reflectance and thermal radiation. The lidar and CCD camera are to measure the structure parameter of crops and other vegetation and to derive the aerodynamic roughness. The L-band microwave radiometer is flown during different growing seasons to derive soil moisture products and to validate the soil moisture algorithms. These observations will be further used to estimate some components of water and carbon cycles, such as ET and NPP.

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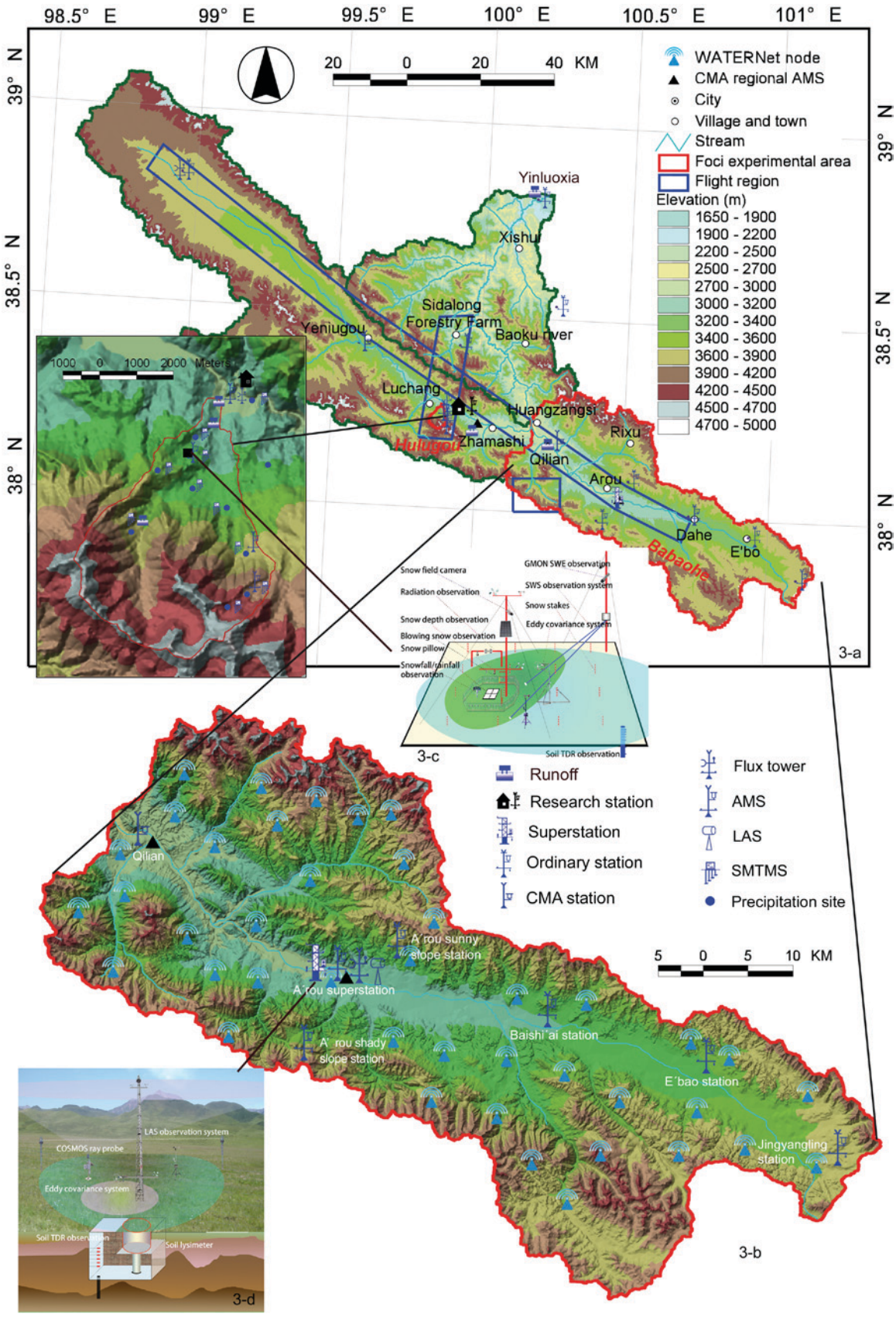


Fig. 3. Instrumentation setting and the airborne mission flight regions in the upstream area of the Heihe River basin and the snow and frozen soil observatories.

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Very high-resolution airborne CCD images (~20 cm) are used to map land cover and vegetation types and to obtain the characteristics of the channels in the irrigation district, including their spatial distribution, types, roughness, and other static parameters.

Multi-scale observation on ET. The instrumentation plan is illustrated in Figs. 4a and 4b. In larger areas, the observation system is used to monitor the spatial–temporal variation of ET and its impact factors within the oasis–desert ecosystem. Four AMSs are installed around the oasis (i.e., sandy desert, desert steppe, Gobi, and wetland stations) and each one is supplemented with an EC system (Fig. 4a). The Daman Superstation is installed in the central oasis, which is a 40-m boundary layer tower.

Within the oasis, an observing matrix composed of 17 EC towers and ordinary AMSs and 4 pairs of LAS systems that span 2–3 km each are located in the Yingke and Daman irrigation district, where the land surface is heterogeneous, dominated by seed corn, corn interplanted with spring wheat, vegetables, orchards, and residential areas (Fig. 4b). Continuous single-point and simultaneous multipoint soil evaporation and vegetation transpiration partitioning measurements are implemented using stable isotope technology to obtain the temporal and spatial patterns of soil evaporation and vegetation transpiration. A WSN composed of 50 WATERNET, 50 SoilNet, and 45 LAI measurement system nodes and another soil moisture measurement system are deployed to capture the heterogeneity of soil moisture, soil temperature, LST, and LAI (Fig. 4b). The configuration of the WSN has been optimized by the means of surfaces with the stratified nonhomogeneity method (J.-F. Wang et al. 2009; J. Kang et al. 2012, unpublished manuscript).

Irrigation and the water balance. Other components of water balance in an irrigation district (conceptualized in Fig. 4c) are measured, including the surface water irrigation that flows into and the surface return flow that drains out of the irrigation district, the lateral groundwater flow that seeps into and drains out of the irrigation district, and channel evaporation. In particular, because of the effects of seepage and channel evaporation, the amount of water loss accounts for 49% of the total amount of water in the channels, so this phenomenon cannot be ignored. Therefore, flow meters are installed at the entrance and terminal in some typical main canals, subcanals, and field ditches to observe flows in different levels of the channels, in association with section measurements to calculate the amount of water losses based on water balance method. The leakage pools are set up to obtain the amount of water seepage. Eventually, the water use efficiency of different channels can be calculated.

Meanwhile, groundwater exploitation and spring flow are also key components in irrigation water balance. Water meters are performed to quantify the amount of groundwater exploited. Spring flows are estimated from measurements at wells. All these data support determining the total and segmental amount of irrigation water in the channels and different farmland parcels.

Downstream area. In Ejin Basin, *Populus euphratica* and *Tamarix* are primarily distributed in the area between Erdaoqiao and Qidaoqiao, which is selected as the aviation area (Fig. 5). Airborne lidar is flown to acquire structure parameters (e.g., tree height and diameter at breast height of the typical vegetation). The airborne multi-angle VNIR and thermal imager are used to estimate land surface albedo, LST, canopy temperature, FPAR, LAI, and chlorophyll content.

Two ESs equipped with EC towers and AMSs as well as LAS are to be established to measure the sensible and latent heat fluxes over the heterogeneous landscapes (Fig. 5b). In between, a WSN will be set up to capture the spatial variation of soil moisture and soil temperature. Intensive ground measurements are performed in several relatively homogeneous plots toward *Populus euphratica* and *Tamarix*. In these plots, which are focused on a "standard tree" (Fig. 5c), a series of instruments, including sap flow instruments, Li-6400, TDRs, and tensiometers, are set up to measure the parameters related to multiscale eco-hydrological processes to eventually improve our understanding of these processes in arid regions.

DATA MANAGEMENT AND SATELLITE DATA COLLECTION.

Data management in HiWATER involves data collection, standardization, quality control, processing, warehousing, and release. It must achieve the following tasks to provide data services for HiWATER: 1) formulate observing specifications and standards for various observations and data and metadata formats; 2) design, plan, and implement data gathering and management; and 3) perform quality control and store data (including metadata).

Various satellite remote sensing data from VNIR, thermal infrared, and active and passive microwave and lidar sensors are being collected by data sharing

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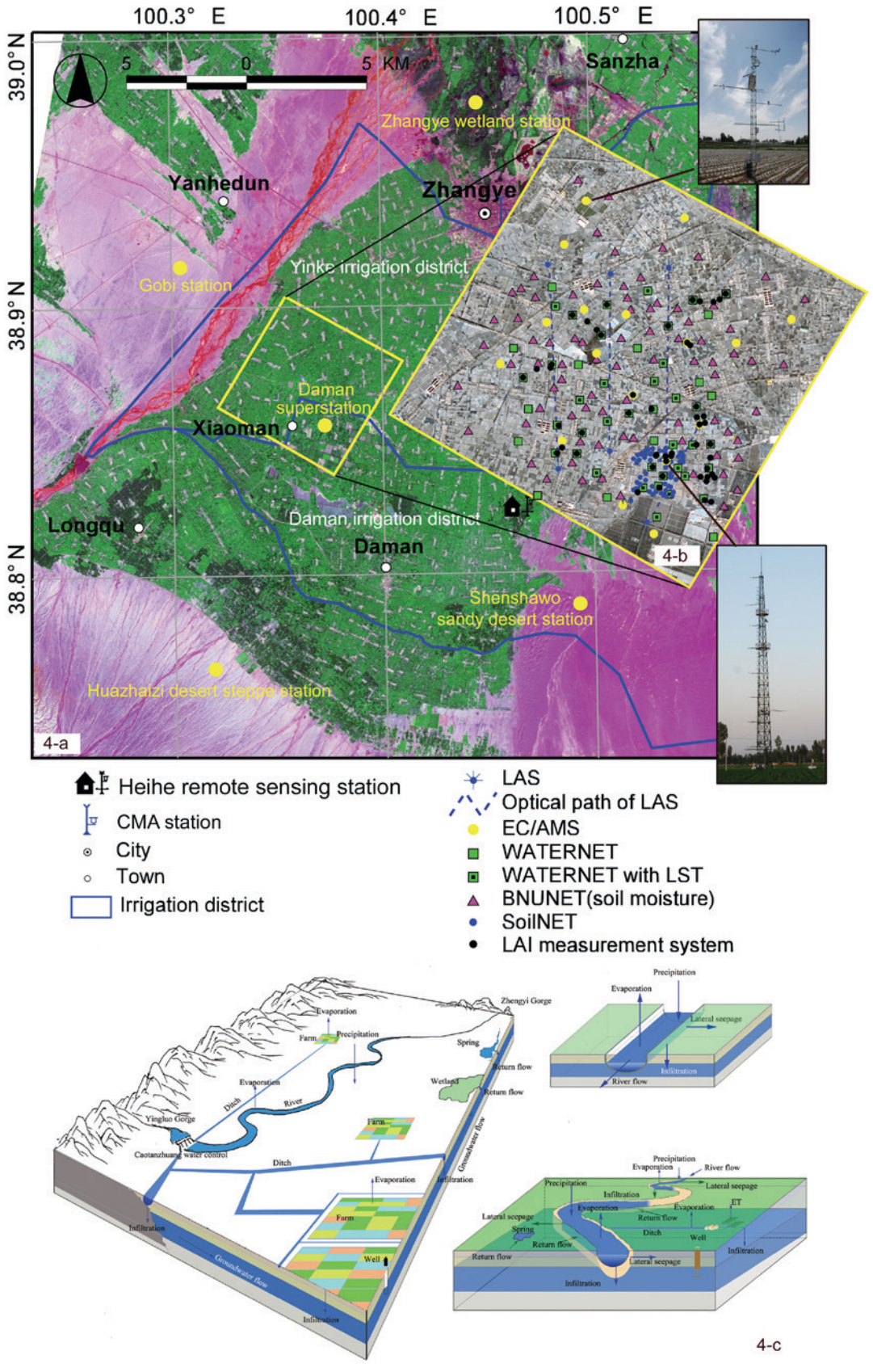


Fig. 4. Instrumentation setting in the middle stream area of the Heihe River basin and the conceptualization of the water balance at the irrigation district scale.

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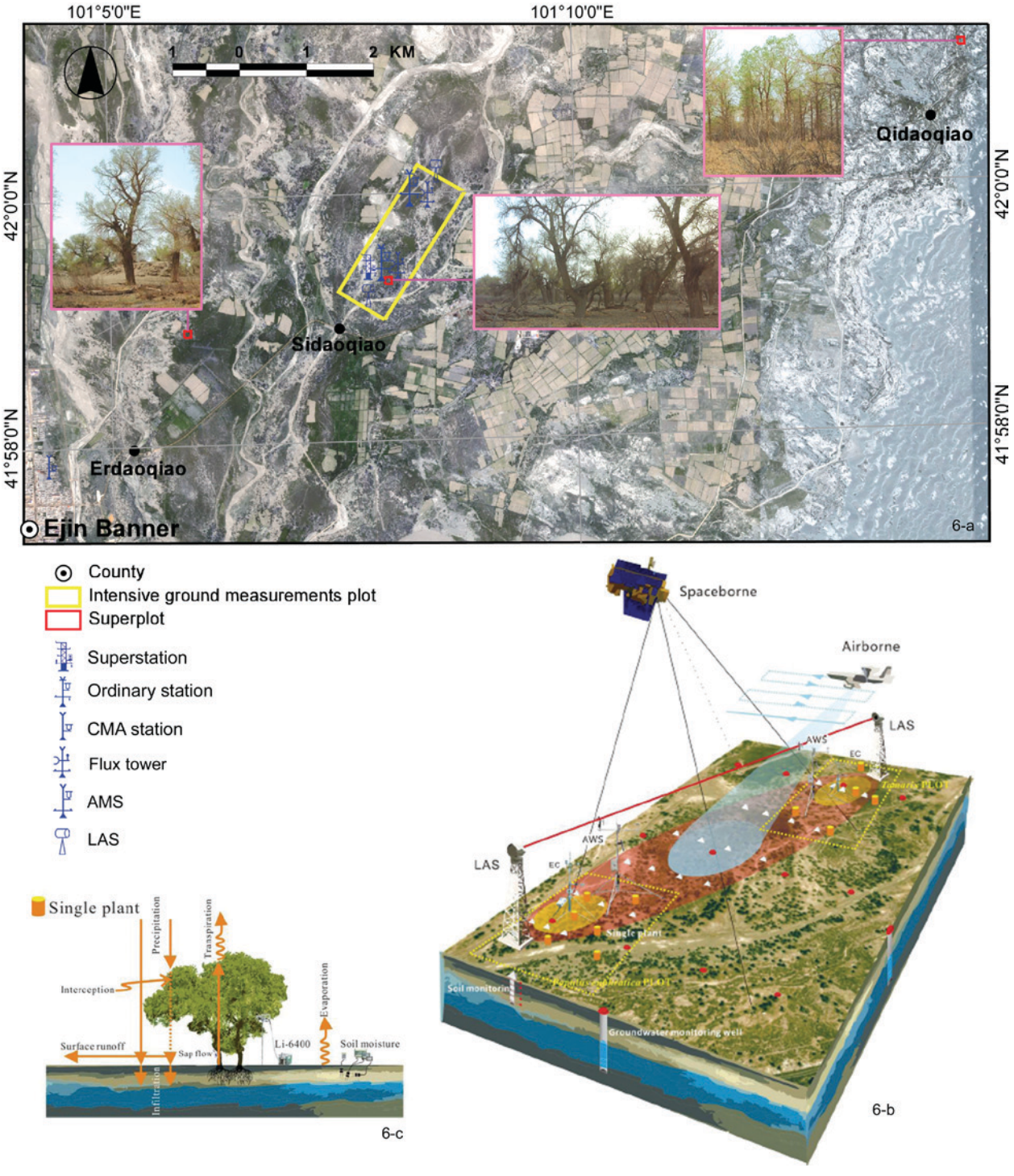


Fig. 4. Instrumentation setting in the middle stream area of the Heihe River basin and the conceptualization of the water balance at the irrigation district scale.

programs, international cooperation, and limited commercial purchase. Data are ordered before airborne missions and in situ measurements are deployed to guarantee the completion of simultaneous satellite–airborne–ground-based observations and corresponding calibration/validation activities. In addition, to run data assimilation systems, medium and low spatial resolution remote sensing data will be acquired on a daily basis from 2012 to 2015.

The open data policy of HiWATER will ensure that the experimental data are timely and adequately utilized. However, there will be a protection period so

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that observers can have priority in using original data. After the data protection period, HiWATER data will be submitted to the data management and sharing platform of the Environmental and Ecological Science Data Center for West China (http://westdc.westgis.ac.cn/).

EXPERIMENTAL DURATION. HiWATER is planned to last four years, from 2012 to 2015. Within this period, a 1-yr intensive observation will be conducted in each of the three KEAs. The HiWATER intensive observation period field work started in May 2012 from the middle stream. The persistent observations period over the whole river basin will continue from 2013 to 2015. Airborne missions with a manned airplane are mainly executed in summer 2012. Unmanned airborne missions are to be performed periodically in three KEAs according to the requirements.

SUMMARY. This paper introduces the background, scientific objectives, and overall experimental design of HiWATER. The instrumental setting and airborne mission plans of HiWATER are also outlined. More detailed information regarding the implementation plan can be found online at http://hiwater.westgis.ac.cn.

HiWATER has formally kicked off in May 2012, the field campaigns are currently going on, and some important data have been obtained. Data will be available half a year later for each experiment. Scientists internationally are welcomed to participate in the field campaigns and use the data in their analyses.

As a comprehensive eco-hydrological experiment, HiWATER should make a difference in continental-scale hydroclimatic or hydrometeorological experiments. It should address the large issues that have puzzled watershed-scale hydrological and ecological studies for a long time, such as heterogeneity, scaling, uncertainty, and closing water cycle at the watershed scale. Practical utilization for water resource management should also be considered.

Compared with WATER, HiWATER will be more oriented toward answering scientific questions and more organized, with more information integration. It will provide a test bed to testify or falsify new ideas on eco-hydrology and new hypotheses on scaling because it is designed to capture multiscale heterogeneities within a river basin with very diverse landscapes.

Finally, HiWATER must be well coordinated, within the experiment itself and within the NSFC Heihe Plan, to ensure that the scientific objectives envisioned are accomplished and to best meet the diverse needs of interdisciplinary studies in the Heihe Plan and ultimately the needs of integrated eco-hydrological studies.

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