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Measurements and Observations in the XXI century (MOXXI): innovation and multidisciplinarity to disclose the hydrological cycle

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ABSTRACT

To promote the advancement of novel observational techniques that may lead to new sources of information to help better understand the hydrological cycle, the International Association of Hydrological Sciences (IAHS) established the Measurements and Observations in the XXI century (MOXXI) working group in July 2013. The group comprises a growing community of tech-enthusiast hydrologists that design and develop their own sensing systems, adopt a multidisciplinary perspective in

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tackling complex observations, and often use low-cost equipment intended for other applications to build innovative sensors. This paper states the objectives of the group and reviews major advancements carried out by MOXXI members. Finally, future MOXXI challenges and opportunities are outlined.

**KEYWORDS**
Measurements and Observations in the XXI century (MOXXI); IAHS; experimental hydrology: hydrological measurements; sensors

1. Introduction

Since the beginning of the 21st century, considerable efforts have been devoted to a better comprehension of natural processes for improved hydrological predictions in case of data scarcity. Enhanced process understanding has been the main objective of the predictions in ungauged basins (PUB) decade (Blöschl et al. 2013, Hrachowitz et al. 2013), which has contributed to enrich the modelling and conceptual toolbox available to hydrologists for comprehensive description of water processes. Within the PUB decade, it has become clear that improving our understanding of the hydrological functioning of river catchments can help in properly answering questions on how much water is found and transfers among diverse catchment compartments (Selker and Ferre 2009). Therefore, the ability of hydrologists to accurately measure processes and state variables is a priority for improving the understanding of processes. In a recent community survey among 336 hydrologists (Blume et al. 2017), the participants thought that measurement techniques had advanced slightly more than modelling approaches in the last two decades. At the same time they also thought that new measurement techniques and equipment as well as generally more field measurements and monitoring were more strongly needed to advance the hydrological sciences than new modeling approaches, and they furthermore saw the greatest challenges and difficulties in the maintenance of monitoring networks. These community opinions highlighting the importance of experimental work and monitoring are offset by the observation (by 66% of the participants) that there is a general tendency of more data mining and modeling projects and less experimental research (Blume et al. 2017, see also: Sidle (2006), Burt and McDonell (2015), Vidon (2015)).

Proficiency in modelling techniques has not been paralleled by similar advancements in our ability to quantitatively observe the hydrological cycle (Mishra and Coulibaly 2009). Traditional monitoring systems suffer from major limitations, and observations through standard equipment are still inadequate to fully grasp natural processes. In addition, they often tend to be expensive, and offer limited spatial coverage (Gleick 1998, Hannah et al. 2011, WMO 2015). Dealing with sophisticated technology also involves high maintenance costs and adequate access to trained staff and resources (Turnipseed and Sauer 2010). Such difficulties hinder the implementation of dense monitoring networks in difficult-to-access environments or developing countries (van de Giesen et al. 2014, Feki et al. 2016). Furthermore, the majority of research groups cannot afford costly monitoring equipment, thereby considerably constraining the opportunity for novel research avenues. Such monitoring limitations hamper the assessment of change in hydrological and related behaviours (Koutsoyiannis 2013, Montanari et al. 2013) and of water security (Vörösmarty et al. 2010, UN WATER 2013, Young et al. 2015).

Since the value of hydrological measurements is rooted in sensors, hydrologists have addressed the challenge of accurately measuring water by resorting to multidisciplinarity and innovation. In recent years, numerous research groups have put forward the
idea that scientists should leave their ivory computers and neat laboratories, and get their hands dirty to design and develop their own sensors. This awareness coincided with the rise of open source controllers, such as Arduino, which fostered scientists to either build their own instruments or modifying off-the-shelf (and often unintended) equipment. Compared to standard measurement technology, this approach promoted the development of low-cost, easily accessible, and tailorble sensors that enabled observations with unprecedented capabilities.

While the community of tech-savvy and sensor-enthusiastic hydrologists kept blossoming during the decade 2003-2013, towards the end of PUB initiative, the community came together into the Measurements and Observations in the XXI century (MOXXI) working group of the International Association of Hydrological Sciences (IAHS). The working group was founded in 2013 during the IAHS, International Association for the Physical Sciences of the Oceans (IAPSO), International Association of Seismology and Physics of the Earth’s Interior (IASPEI) Joint Assembly held in Gothenburg and it was the result of a debate initiated in 2011 at the XXV IUGG General Assembly in Melbourne. The foundation of MOXXI was concurrent with the establishment of the new scientific decade Panta Rhei, with whom the working group shared many objectives and research activities (Montanari et al. 2013, McMillan et al. 2016). As stated by the IAHS bureau, the main objective of MOXXI consists of promoting the advancement of novel observational techniques, leading to new sources of information to help better understand the hydrological cycle. MOXXI addresses science questions 1 and 5 of Panta Rhei, which target the identification of key gaps in the common understanding of hydrological change and focus on advancing our monitoring and data analysis capabilities to predict and manage hydrological change.

In more practical terms, the MOXXI working group aims at providing a network for scientists with a shared interest in sensors and innovative observational approaches. MOXXI’s milestones and interests can be stated as follows:

(a) The understanding of hydrological processes can benefit from a novel approach of experimental observations, where scientists proactively design and develop their measurement tools by adjusting them to answer their specific questions.

Despite the demonstrated capabilities of standard measurement approaches, traditional approaches may be inadequate to deal with hydrological heterogeneity and complexity. For instance, standard streamflow measurement systems require the deployment of bulky and expensive equipment in the water current along with the assistance by trained staff. Unfortunately, such requirements have prevented the availability of streamflow data at high spatial and temporal resolution or the acquisition of data in case of flood events. Conversely, limitations in traditional monitoring techniques have fostered the use of remote and proximal sensing, such as optical cameras, radar technology, and aircrafts and unmanned aerial system platforms for streamflow observations.

With regards to water quality, high frequency and multi-species monitoring is now being explored, both to characterize some water pollution crises and to better understand the biogeochemical and erosion-sedimentation natural vs. anthropogenic drivers and improvement paths (Aubert et al. 2013); yet these remain limited to experimental basins so far. More generally, a multiple approach of various water-related processes and compartments of the critical zone is under progress (White et al. 2015, Cudennec et al. 2016), in the wider emerging complexity of the Anthropocene and global change (Bai et al. 2016, Brondizio et al. 2016), but comprehensiveness remains a huge metrological and epistemological challenge.

(b) Successful observational approaches often rely on knowledge from other fields
of science. Hydrologists may advance their experimental toolbox by adopting a multidisciplinary perspective in designing their own sensors.

Building one’s own sensors directly involves orienting oneself in electronics, 3D printing, soldering, coding, etc. Relying on notions that are typically far from the expertise of hydrologists has contributed to shaping a novel class of researchers, who have diverse backgrounds and actively interact with experts from fields other than hydrology. An example of the promise of a multidisciplinary approach in hydrology is the use of thermal imagery or robotics in hydrological observations.

Ad hoc designed measurement systems may entail scientists directly building/assembling sensors using low-cost and unintended instrumentation.

Often, low-cost equipment has been instrumental to overcome financial and logistical time constraints, and has also offered powerful diagnostics tools. It also provides the chance to involve the public via crowdsourcing and thus to get people interested in environmental sensing and science in general. Inexpensive and open source resources have afforded high versatility by allowing scientists to adjust and modify sensors per their specific needs. By building their own sensors, hydrology has embraced a do-it-yourself (DIY) approach, whereby low cost instrumentation is preferred to sophisticated equipment. For example, commercial sport cameras (such as GoPro) have advanced features, such as extremely high frame acquisition rates and high resolution, which were unimaginable just a decade ago. Similar instrumentation is affordable by most research groups and opens novel perspectives on the establishment of spatially dense monitoring networks. Also, rapid technological progress is expected to lead to more and more advanced sensors available on the market at competitive costs in few years. Resorting to inexpensive commercial products has stimulated scientists’ invention capabilities, thus leading to unintended electronics to be used as hydrological sensors. For instance, precipitation has been measured with moving cars (Rabiei et al. 2016) and accelerometers (Stewart et al. 2012), and water levels have been monitored with game-console remotes (Hut et al. 2010). These research activities have facilitated the acquisition of hydrological data and have also paved the way for the implementation of public and collaborative sensing platforms (see, for instance, Crowd Hydrology, OPENs Lab and others).

Paradoxically, while conventional hydrology is increasingly relying on information from satellites as input (Kummerow et al. 1998, Hou et al. 2014) or validation (Smith 2002, Malenovský et al. 2012) for models, the increased use of satellite data has raised rather than lowered the demand for ground based observations Hut (2013). This is due to the low spatial coverage of current operational on the ground sensors (Moradkhani 2008) and the need for satellite data to be constantly calibrated using ground observation points. Many such ground based observations often mandate ad hoc designed and developed sensors.

The MOXXI initiative gathers scientists with an interest in novel observations and provides a friendly place to share, promote, and discuss research activities. In the first topical conference held on November 21st, 2016, at the European Space Agency (ESA) - European Space Research Institute (ESRIN) campus in Frascati, Italy, researchers from more than 15 universities, and several research centers and private companies shared their research and ideas for future collaborations. The group also aims at providing an updated database of innovative observational approaches and a shared platform with experts from other fields. In our vision, hydrologists could find solutions to their experimental questions just by taking a look at the MOXXI website and contacting members of the working group with similar interests.

This paper was originally conceived at the First Topical MOXXI Conference in
November 2016, and it aims to report on the many research activities that revolve around the establishment of the MOXXI working group, to state the major challenges faced by the MOXXI community, and to provide guidance on future research directions.

2. How did it all begin?

Since its inception in 1922, IAHS has always offered fora to progress on instrumentation and metrological issues about subdisciplines of hydrology and related fields of science (see the history of publications from 1924, available at www.iahs.info), and it has been at the forefront of scientific debates about emerging techniques (such as, for instance, the debates that preceded the establishment of the committees on remote sensing and data transmission in 1981 and the committee on tracers). Before the establishment of MOXXI, several groups and initiatives had stressed the importance of innovation and multidisciplinarity for experimental hydrology. At the beginning of the 21st century, sensing the need to communicate advancements in self-made-sensors, authors Hut, Selker, Blume and colleague Willem Luxemburg organized a poster only session at the 2009 AGU Fall meeting. Since presenters brought their self made sensors to the session and due to the copious amount of duct-tape present, the hydrologists attending the session quickly gave it the nickname “the MacGyver session”. The session was a succes, got repeated yearly, is still going strong and has a sister session at the EGU General Assembly. The presenters and conveners at this session got to be known as The MacGyver community. The MacGyver community noticed that experimental hydrology practice and methodologies were outpaced, as compared to theoretical hydrology and hydrological modelling. To advance observations, experimental hydrologists could instead rely on inexpensive sensors, open source hardware, and multidisciplinarity. The MacGyvers pillars are still at the core of MOXXI interests, and the MacGyver community was asked to establish MOXXI as a focal point for the hydrological community.

Within the PUB decade, a growing community of hydrologists and environmental scientists tackled the observation of complex natural phenomena by adopting innovative experimental approaches. In fact, the PUB initiative focused on ungauged basins, where incomplete understanding of hydrological processes is caused by little or no available information. PUB addressed this challenge by either extracting more information from available data or using newly acquired data. Lack of data motivated considerable advancements in radar, satellite, and ground-based observation technology.

Results sharing formed the core of such efforts in innovative experimental hydrology. Novel experimental approaches that were achieved by this growing group within the hydrological community were collected in a special issue (Selker and Ferre 2009) and made available through the Experimental Hydrology Wiki page (Blume 2010). This latter initiative seeks to keep scientists abreast of the latest experimental advances and informing the choice of the best possible sensor for the intended purpose.

3. MOXXI Topics

In this Section, we report on the major innovations carried out by the MOXXI community in the field of hydrology. While this review is far from being exhaustive, it provides numerous references for further in-depth reading. Novel approaches and methodologies are summarized with regards to the hydrological observation they enable.
3.1. Streamflow measurements

Historically, the scarcity of streamflow observations is a major problem and a source of considerable uncertainty in hydrology. Unfortunately, river streamflow cannot be directly measured neither with ground-based instruments nor with remote sensors, and its estimate is normally executed by referring to other hydrological variables, which are easier to collect (that is, water depth, water surface elevation, flow velocity, water extent, etc.) and used in previously calibrated theoretical or empirical approaches (Smith 1997). In addition, continuous funding cut-backs challenge frequent monitoring campaigns or the implementation of a dense network of measurement stations. However, river floods are responsible for thousands of lives every year and stream flow monitoring is crucial for flood preparedness and mitigation strategies.

Since MOXXI’s establishment, progress has been achieved in the observation of flow in difficult-to-access environments and during extreme events through diverse multidisciplinary techniques. For instance, to partially address the issue of observing stream processes in case of scarce measurement stations, satellite nightlight data have been used to prove that nocturnal lights in the proximity of rivers are consistently linked to flood damages and that increasing nightlights are associated to flood damage intensification (Ceola et al. 2014). Alternatively, participatory data collection methods and data mining have proved promising to expand the dataset currently available to the research community. For instance, water level time series have been derived from the analysis of several YouTube videos for a Saudi Arabian cave (Michelsen et al. 2016). To calibrate satellite-based and participatory approaches, actual streamflow observations are needed. In the following, we report novel approaches to sample water and estimate water level and velocity.

3.1.1. Water sampling

Understanding stream processes often requires sampling the time-changing properties of water. This could include the interest in major ion chemistry, suspended load, dissolved gas concentrations or isotopic composition. Commercial samplers leave the water samples open to the air, making precise sampling for gas and isotopic composition inaccurate (for instance, Isco 6712). These samplers typically cost on the order of US$5,000. With these issues in mind, a gas-tight sampler was designed that would be substantially less expensive than current options.

Firstly, aluminum-lined bags were utilized to store the samples. These have been shown to retain isotopic and dissolved gas properties of water samples (based on our tests and the work of Weiler et al. poster need to get the citation). Next, 12 volt mini-peristaltic pumps which cost about US$10 each were positioned two side-by-side to give redundancy and increased flow. Gas-tight solenoid valves built for soda dispensers were adopted which also operate on 12 V, cost under US$3 each, and are rated for over 100,000 cycles of operation. All of the physical elements were mounted to an aluminum back-bone, and encased in layers of foam that is cut laser-cutter. All other parts were standard hardware, or made using a 3-D printer. The system was controlled with an Arduino programmed to first purge all the lines, then take a sample, and then prepare for the next sample. The device can be programmed to also deliver the samples to an analysis instrument via two-way communication to the Arduino, and in fact can clean itself in preparation for the next deployment through another 10-cycle filling and emptying program with the device provided with pure water from the laboratory. The entire device has parts that cost under US$300, and is transformative in its capabilities.
in comparison to the currently standard devices.

- soft sensors, Cudennec

### 3.1.2. Water level measurements from satellite data

The use of satellite instruments for the estimation of water level is a current practice that has seen its first applications in the 80s, when the combination of high-resolution satellite imagery (that is, Landsat) with topographic maps or digital elevation models (DEM), enabled the estimation of the water surface elevation over large reservoirs (Gupta and Banerji 1985). Originally designed for other scopes (such as, Earth observations, ice-covered areas and ocean monitoring), since first studies in the 80s, remotely sensors have been widely used also for hydrological purposes (Schumann and Domeneghetti 2016).

Among available alternatives for water level sensing (such as, satellite imagery, laser altimetry (Hall et al. 2012)), radar altimetry represents the most suitable and reliable technique (Birkinshaw et al. 2010), with the water elevation measured as a function of the two-way return time of a radar pulse emitted from the satellite and backscattered by the liquid surface. Despite none of common re-trackers is expressly thought for inland waters, latest progresses in technical instrumentations enforced a remarkable improvement of radar altimeters’ accuracy, ensuring errors on the order of 20 – 30 cm for the water height of large rivers or lakes (Berry et al. 2010, Bercher and Kosuth 2013, Tarpanelli et al. 2013).

Recently, those advances have allowed to extend the use of altimetry data to smaller rivers (water extent smaller than 100 m) with performances comparable to those previously experienced over large water bodies (errors up to 50 – 70 cm, see, for instance, (Sulistioadi et al. 2015)). The scientific community may count on a number of altimetry missions (such as, ENVISAT, ERS 1-2; TOPEX/Poseidon, Cryosat, SARAL, Jason 1-2-3) that adopt different instrumentations and provide data with various accuracy and spatial resolutions (Schumann and Domeneghetti 2016). Despite the wealth of measurements, in some cases made up of long time series (Tourian et al. 2016), satellites’ low revisit time (typically ranging from 10 to 35 days), ground-track spacing (from few hundreds of meters up to some kilometres) and the measurements’ lead time constrain the use of such sources for operational procedures and for application over small-medium rivers. Nevertheless, the potential of altimetry data is considerable, with applications that regard the enhancement of hydrological and hydraulic models (Biancamaria et al. 2009, Getirana 2010, Domeneghetti et al. 2015) and the estimation of river discharges (Tourian et al. 2013, Durand et al. 2014).

### 3.1.3. Radar surveys

Surface flow velocity can be easily surveyed by using handheld Surface Velocity Radar (SVR) technology (Costa et al. 2000, Welber et al. 2016), which well lends itself for high flows monitoring and represents a cheaper and easy-to-use solution to gauge multiple field sites. In this context, surface velocity sampled by SVR across a river site, can be turned into a two-dimensional velocity field as proposed in Chiu (1987), where the probability distribution function of surface velocity is derived through the entropy theory (Shannon 1948). Moreover, based on observed surface velocities, secondary currents in the cross-sectional flow area can also be simulated (Moramarco et al. 2017), and the bathymetry of river cross-sections can be inferred circumventing the estimation of hydraulic quantities, such as the energy slope and Manning’s roughness (Moramarco 2009).
et al. 2013).

3.1.4. Image analysis

Images enable non-intrusive and distributed observations of water bodies at high temporal resolution. The use of optics-based approaches for streamflow measurements is documented since the end of the 1990s, when techniques historically adopted in fluid dynamics laboratories were successfully applied to natural rivers (Fujita et al. 1997). In light of the advances in resolution, acquisition rates and quality of images captured in both the visible, near-infrared, and infrared spectra using commercially available digital cameras, our capability of detecting distinct water-surface features has improved. Subsequently, optical flow tracking techniques based on cross-correlation, and feature-based tracking enable the displacement rates of detected features to be computed. This may be achieved through application of one of several methodological approaches including large scale particle image velocimetry (LSPIV) (Muste et al. 2008, LeCoz et al. 2010), particle tracking velocimetry (PTV) (Tauro and Grimaldi 2017), or Kanade-Lucas-Tomasi (KLT) flow tracking (Perks et al. 2016). These approaches have allowed for reconstructing the surface flow velocity field and for estimating surface transit times in mountainous streams, hillslope rills, and medium-scale rivers. Combined with high-visibility buoyant tracers, such as fluorescent particles, image-based analysis has demonstrated considerable potential for surface hydrology (Tauro et al. 2014).

Application of flow visualization algorithms may allow displacement rates to be obtained in near real-time, across image domains spanning several hundreds of m², and in environments where the deployment of conventional flow monitoring approaches would be logistically, or financially unfeasible, or unduly hazardous. The integration of resilient and high-performance cameras with laser modules has afforded fully remote image acquisition and calibration. This remote streamflow sensing platform has been permanently installed underneath urban bridges (Tauro et al. 2016a), compacted in a portable apparatus (Tauro et al. 2014), and mounted onboard unmanned aerial systems (UASs) for large scale monitoring (Tauro et al. 2016b).

3.2. River bathymetry

River bathymetry represents a key element in many hydrological and hydraulic applications. Apart from its use in the implementation of flow routing models, knowledge of the water depth along rivers is fundamental for monitoring geomorphological processes, sediment dynamics, natural habitats, and for the prediction of pollutant diffusion. However, the high cost/area ratio of point-wise and ground-based measurement campaigns constrains the spatial coverage of such surveys, thus fostering alternative and cost-saving techniques. The employment of remote sensing data to this scope represents a complementary solution that ensures spatio-temporal coverage unaffordable with traditional tools (Feurer et al. 2008, Gao 2009).

First attempts for the estimation of the river bathymetry involved photogrammetric techniques: optical refraction-correction theories applied to images taken with different viewing angles enable the estimation of the elevation of submerged areas (Westaway et al. 2003). Passive optical instruments estimate the water depth by interpreting sunlight attenuation through water columns by means of analytical, semi-analytical or empirical approaches. Based on physical laws regarding light propagation into the water, analytical criteria require a huge amount of physical parameters of the water and the atmosphere, thus limiting the fields of applicability of the approach. Differently,
empirical methods take advantage of simple relationships, calibrated over sample areas, that relate the radiance estimated from images and water depths.

Another valuable technique for the monitoring river bathymetry is based on the use of ground penetrating radars (GPRs). Classified as an active sensor, the GPR is typically positioned close to the water surface and measures the water depth by means of electromagnetic waves partially backscattered from the river bed. LiDAR (Light detection and ranging) instrumentation, typically mounted on airplanes, uses the same concepts but emits a near-infrared laser beam (blue-green wavelength) that ensures the penetration of a rather deep water column (Feurer et al. 2008). Starting from a detailed LiDAR-based topographic survey of river embankments, Mersel et al. (2013) estimated the submerged river portion by adopting simplified linear relationships among the water elevation and the concurrent river width. Despite being considered as remote techniques, the application of these two approaches usually requires expensive ad-hoc and low-flying surveys and, hence, are not considered for satellite monitoring. On the other hand, optical techniques are more promising and much more commonly used since they can take advantage of both satellite and aircraft surveys that are available and accessible to a larger community.

The efficiency of optical methods is controlled by several factors, such as water turbidity, specular reflection, vegetation, and uniformity of the river (Gao 2009). The accuracy of water depth estimates depends on the characteristics of the study area, and it remains acceptable (errors ranging from −12.1% to 22.7%) up to 15.5 m (McIntyre et al. 2006). Resorting to very fine-resolution imagery (such as IKONOS, which exceeds 1 m in resolution), Lyzenga et al. (2006) applied a simple physically based algorithm that led to an aggregate root mean square error of 2.3 m with water depths over 20 m. Recently, to overcome the need of in-situ data for optical image calibration, Legleiter (2015) proposed an algorithm that estimates river bathymetry by combining the spectral analysis of satellite images with simplified hydraulic equations.

Finally, alternative methodologies start from globally available satellite sensed DEMs (such as, SRTM; 30 or 90 m in resolution), and try to reproduce river bathymetry by: i) data assimilation techniques (Durand et al. 2008), ii) referring to hydraulic geometry equations (Neal et al. 2012), iii) adopting simplifying hydraulic assumptions (Alfieri et al. 2014), and iv) investigating simplified geometric assumptions on river geometry (Domeneghetti 2016).

An interesting stream bathymetry mapping application involved the use of the Microsoft Kinect camera, a commercial device that includes a light emitter, an infrared camera, an RGB camera, a three-axis accelerometer, and four microphones (Mankoff and Russo 2013). In a calibration experiment in laboratory conditions, the Kinect was adopted to estimate water depths up to 0.20 m based on the apparent distance of captured objects from the camera itself.

3.3. Rainfall

Analyzing the hydrological cycle accurately is only possible with reliable data sources. Furthermore, our current understanding of hydrological processes is restricted to data availability. Among the required variety of data, rainfall data is an important input for the analyses. Depending on the scale of the analyses, certain temporal and spatial resolutions of rainfall data are needed. For instance, Schilling (1991) has discussed the need for 1 min temporal resolution and 1 km² spatial resolution for urban hydrology. Interpolation techniques are usually implemented for spatial and temporal estimation
of rainfall by observation data. The accuracy of rainfall estimation becomes crucial when considering highly dynamic temporal and spatial distribution of rainfall. Several studies seek to achieve rainfall estimations in alternative ways that are not initially aimed for this specific purpose and have low operational costs. Therefore, such approaches are mostly not as accurate as conventional rain gauges, but could provide valuable additional information in combination with conventional techniques. Implementing a large number of inaccurate observations may result in a better areal rainfall estimation than only using a couple of accurate rain gauges (Haberlandt and Sester 2010, Rabiei et al. 2016). The need for reliable rainfall data might not be fulfilled using only conventional data sources, whereas merging all possible data sources such as rain gauges, radar data, crowdsourced observations, etc., may provide a better rainfall estimation. This would result in a better understanding of the hydrological cycle which helps to increase our knowledge and, consequently, to improve the quality of hydrological analyses.

Conventional rain gauges have been used for point measurement purposes. Although conventional measurements provide accurate point-information, they are costly and irregularly located over the study area. In addition to the conventional rainfall measurement techniques, using innovative methods for compensating the need for denser observation networks has been on focus recently. For example, microwave links from cellular communication networks have been proposed as a promising new rainfall measurement technique (Upton et al. 2005, Messer et al. 2006, Rahimi et al. 2006, Leijnse et al. 2007, Zinevich et al. 2009). They are particularly relevant for those places where few surface rainfall observations are available, such as developing countries (Gosset et al. 2016) or urban areas (Overeem et al. 2011). The basic principle of rainfall estimation using microwave links is the nearly linear relationship between the rain-induced attenuation of electromagnetic signals transmitted from one telephone tower to another and the path-average rain rate. Overeem et al. (2013a) were the first to present country-wide rainfall maps based on attenuation data from a network of commercial microwave links (CMLs) operated by a major cellular communication company in The Netherlands. Their CML rainfall retrieval and mapping algorithm is freely available (Overeem et al. 2016a). More recently, Overeem et al. (2016b) demonstrated the potential of CMLs for long-term large-scale operational rainfall monitoring, based on a 2.5-year data set from a cellular communication network consisting of about 2,000 links covering the land surface of The Netherlands (35,000 km²). Good results were obtained particularly for the summer season, which shows the potential of this opportunistic technique for large-scale application in developing countries in (sub)tropical climates, with few rain gauges and little or no weather radars.

Rabiei et al. (2013) used moving cars for short time-step rainfall estimation. The ubiquitous diffusion of cars motivated the idea of exploiting them as moving rain gauges with windshield wipers or optical sensors as rainfall measurement devices. Laboratory experiments have been established relationships between sensor readings, such as wiper speed and automatic wiper adjustment through optical sensors, and rainfall intensity. Experimental findings show that manual wiper speed adjustment is strongly related to rainfall intensity.

Similar to streamflow measurements, image analysis has also afforded the quantitative detection of rain rate with errors on the order of ±25% (Allamano et al. 2015). By providing rainfall measurements at high temporal resolution and extremely low costs, the camera rain gauge opens novel avenues toward increasing the density of rainfall observations. In addition, the eventual combination of the methodology with citizen science platforms is foreseen to revolutionize rainfall measurements.
3.4. Soil moisture

Knowledge of soil water content (SWC) is essential, as it represents a key variable in many hydrological (Tramblay et al. 2010, Brocca et al. 2017), climatological (Seneviratne et al. 2010), environmental and ecohydrological processes (Grayson et al. 1997, Manfreda et al. 2017). Determining the temporal and spatial variability of SWC is essential for a wide range of studies, and a large number of measurement techniques have been developed in the past decade (Robinson et al. 2008, Bogena et al. 2015). Besides destructive gravimetric sampling, electromagnetic (EM) methods based on the dependency of the soil dielectric permittivity on SWC (Romano 2014), such as time domain reflectometry (TDR), time domain transmission (TDT), and capacitance and impedance sensors, are most commonly used for soil water content measurements at the point scale. In the last decade, new technologies have been developed to measure integral soil moisture at the field or small catchment scale (Bogena et al. 2015). Cosmic ray neutron sensors (Zreda et al. 2012), Global Positioning System (GPS, Larson et al. (2008)), and geophysical measurements as electrical resistivity and electromagnetic induction (Calamita et al. 2015) are among the most promising techniques. For instance, cosmic ray exploits the correlation between near-surface fast neutron counts and SWC, and enables the use of the cosmic-ray probe to sense soil moisture in a footprint much larger than the point-scale methods (that is, approximately 200 m in radius).

Besides in situ measurements, remote sensing of soil moisture has significantly advanced in the last decade as demonstrated by two dedicated missions (Soil Moisture Ocean Salinity, SMOS, and Soil Moisture Active and Passive, SMAP). The most widely used approaches employ active (scatterometer) and passive (radiometer) microwave sensors (Brocca et al. In press) that provide (freely available) soil moisture product at nearly daily temporal resolution and coarse spatial resolution of ~ 20 km. To estimate soil moisture at higher resolution, active microwave Synthetic Aperture Radars (SARs) have been employed with the latest sensors (such as, Sentinel-1), potentially providing 1 – km/6 – day soil moisture products (Paloscia et al. 2013). To enable the retrieval of SWC from SARs, empirical, semi-empirical, and theoretical models have been implemented. Empirical models (Zribi and Dechambre 2002) allow for obtaining accurate results under the setup conditions; theoretical models (Chen et al. 2003) are implemented under a theoretical basis to predict backscattering in response to sensor and soil parameters but are more difficult to apply. Among available semi-empirical models, Capodici et al. (2013) recently proposed a coupled algorithm for soil moisture estimation using co- and cross-polarized imagery, obtaining satisfactory assessments.

Soil moisture monitoring over large scales is limited by the fact that remote sensing sensors only provide surface measurements (< 5 cm) that are not representative of the effective amount of water stored in the subsurface. Therefore, a methodology able to infer root-zone soil moisture starting from surface measurements is highly desirable (Wagner et al. 1999). Recently a new simplified formulation has been introduced to provide a formal description of the mathematical relationship, named SMAR, between surface measurements and root-zone soil moisture (Manfreda et al. 2014). The SMAR model has been coupled with Ensemble Kalman Filter (EnKF) in order to reduce regional-scale bias of satellite near-surface moisture data (Baldwin et al. 2017). The SMAR-EnKF system can predict root zone soil moisture over broad extents and has applications in drought predictions and other operational hydrological modeling purposes.

New data-model integration methods are combining remotely-sensed and field based
measurements with models to better predict soil moisture and interactions in ecohydrology (Ng et al. 2014). Within passive remote sensing, some methods employ thermal and visible/near infrared bands to determine soil surface water content. The thermal inertia method (Xue and Cracknell 1995, Sobrino and El Kharraz 1999, Maltese et al. 2013) determines soil moisture over bare or barely vegetated soils using diachronic thermal acquisitions. The method is founded around the evidence that the ability of a material to accumulate heat and release it within a defined time interval depends on the water content of the material itself. The triangle method (Carlson et al. 1995) is based on the fact that optical and thermal features of vegetated soils are primarily controlled by the root zone water content. In practical implementations of the triangle method, daytime air temperature can be replaced with nighttime land surface temperature to take into account the thermal inertia of the soil (Maltese et al. 2015).

Monitoring soil moisture is also crucial to increase irrigation water use efficiency and agricultural production in the context of climate change. Several studies focused on “smart farming” by coupling meteorological and hydrological models to predict soil moisture (SM) and crop water requirement for precise irrigation scheduling (Gowing and Ejieji 2001, Cai et al. 2007, Melton et al. 2012, Ravazzani et al. 2016). To uptake this technology to the watershed level, spatially distributed hydrological models based on energy-water balance schemes could be integrated with satellite data allowing to compute continuously in time and distributed in space SWC and evapotranspiration fluxes. Satellite data provide both input parameters (such as leaf area index) and variables for model state updates (land surface temperature, LST). A very recent effort has focused on using remotely sensed LST to calibrate hydrological models’ soil parameters improving the understanding of model internal variables (Corbari and Mancini 2014, Immerzeel and Droogers 2008, Crow et al. 2003, Gutmann and Small 2010).

Finally, among most recent soil moisture applications, a new method for estimating rainfall from soil moisture observations has been developed by (Brocca et al. 2014). The method is named SM2RAIN and relies on the inversion of the soil water balance equation considering the soil as a natural raingauge. The method was successfully applied on in situ (Brocca et al. 2015) and satellite data for obtaining rainfall products on a regional (Brocca et al. 2016, Ciabatta et al. 2017) and a global (Brocca et al. 2014, Koster et al. 2016) scale. The methodology can also be exploited for irrigation estimation (Brocca et al. 2017) and for the assessing the performance of satellite rainfall products (Massari et al. 2017), thus opening a number of novel and promising applications.

- Modular soil gas sampling system - J. Selker

### 3.5. Temperature

A reliable quantification of evapotranspiration, along with the related energy balance fluxes, is crucial in several hydrological and agro-meteorological applications, including drought monitoring and agricultural water management (Allen et al. 2005, Anderson et al. 1997, Cammalleri et al. 2012) under a wide range of water availability. Single source (SEBAL, Bastiaanssen et al. (1998), SEBS (Su 2002)) and two source (TSEB, Norman et al. (1995)) energy balance models are widely used to estimate the spatial distribution of evapotranspiration through remote sensing data on homogeneous and sparsely vegetated soil vegetation systems, respectively. However, inconsistencies could arise from using different data sources. The absolute accuracy
of land surface temperature (LST) becomes a relevant source of uncertainty in SEB approaches (Liu et al. 2007).

A surface renewal method to estimate sensible heat flux requiring only LST and few meteorological forcings as input (Castellvi et al. 2016) was derived under unstable conditions over a heterogeneous canopy. By using multi-temporal thermal acquisitions, the method overcomes inconsistency between LST and mean aerodynamic temperature. The ALEXI/DisALEXI package provides self-consistent evapotranspiration retrievals as well (Anderson et al. 2011). The Atmosphere-Land Exchange Inverse (ALEXI) model is a multi-sensor TIR approach to evapotranspiration mapping, coupling a two-source land-surface model with an atmospheric boundary layer model in time-differencing mode. The related disaggregation algorithm (DisALEXI) spatially downscales ALEXI fluxes to finer spatial scales through higher spatial resolution TIR imagery.

Overeem et al. (2013b) demonstrate that smartphones can be employed to retrieve relatively accurate air temperature information for urban areas. Using an Android application they collected more than two million readings of smartphone battery temperatures for eight major cities around the world, covering a wide range of climate zones: Buenos Aires (Argentina), London (UK), Los Angeles (USA), Paris (France), Mexico City (Mexico), Moscow (Russia), Rome (Italy), and So Paulo (Brazil). They employ a simple steady-state heat transfer model to estimate daily mean air temperatures from the crowdsourced smartphone battery temperatures. Their results show the potential of this opportunistic technique for real-time air temperature monitoring in densely populated areas.

At the bottom of the surface water system, temperature sensors can be used to measure fluxes between surface water and groundwater (Keery et al. 2007). Surface water, with diurnally-varying temperature, mixes with groundwater, with constant temperature. Advection and diffusion of heat can be solved for vertical water fluxes. Emerging software (Voytek et al. 2014, Koch et al. 2016) and inexpensive temperature profilers (Yourd 2017) make this approach likely to grow, especially considering contaminant transport and biogeochemical reactions across the hyporheic zone.

Small, self-recording temperature sensors have been utilized to estimate variability in snow-covered areas and, therefore, infer the amount of snow accumulated until the melt season (Lundquist and Lott 2008). In this application, self-recording temperature sensors with an accuracy better than ±0.5°C and $30 in price have been deployed to record hourly data for about a year in California and Colorado. Similarly, air temperature has been monitored by hanging such inexpensive sensors in dense stands of trees (Lundquist and Huggett 2008). Trees have proved to provide inexpensive radiation shields for temperature sensors from incident and reflected solar radiation, thus considerably improving their accuracy.

### 3.5.1. Distributed Temperature Sensing

The development of innovative measurement systems represents a critical step in the understanding of earth surface processes. An equally important step is the effective delivery of these emerging technologies to researchers who can use enhanced measurements. Critical barriers include experimental design, access to appropriate equipment and access to expert technical support. Here we make the case that community-serving technology centers are an essential ingredient to the efficient adoption of new technologies. We will use the The Center for Transformative Environmental Monitoring Programs (CTEMP) as an example of this concept, and later note parallel develop-
opments at the Openly Published Environmental Sensing Laboratory (OPENs lab, Open-Sensing.org).

CTEMPs have developed and disseminated the emerging technology of distributed fiber-optic temperature sensing (DTS) to over 60 projects worldwide over the past six years of operation. CTEMPs has been the main catalyst for introducing DTS technology to the earth science community through more than 20 hands-on technology transfer workshops presented on five continents, on-site training and extensive scientific publications and presentations. Research activities ranging from hydrological monitoring of fisheries restoration to volcanic gas emissions have all benefitted from the advanced spatial and temporal resolution of DTS promoted by CTEMPs, and from its mission to make technology available at low cost and to provide training and expertise to make each deployment successful. While CTEMPs represents the first community user facility specifically focused on the hydrological sciences, it has successfully “jumped disciplines” to support many of the earth, oceanographic, polar, and environmental sciences, demonstrating the demand for this transformative technology. The measurement of high resolution temperature has now made significant contributions to the understanding of environmental fluid dynamics with many of these advances made with assistance and motivation from CTEMPs.

Within the hydrological sciences, DTS first gained prominence in the measurement of groundwater/ surface water exchanges (Selker et al. 2006b,a). Subsequently, DTS use has expanded to monitoring vertical exchange (Vogt et al. 2010, Briggs et al. 2012) and large scale river exchange (Slater et al. 2010, Mwakanyamale et al. 2012). The majority of CTEMPs-supported stream aquifer exchange research has been conducted and reported by young investigators and students who have taken these early advances and applied DTS to fisheries and stream restoration research (Buck and Null 2013, Bond et al. 2015, Boughton et al. 2012), to the analysis of contaminant inputs into eastern streams (Tripathi 2013). Petrides et al. (2011) was the first to apply DTS to the measurement of radiation balances in streams, using a suspended optical fiber to monitor the daily progression of direct and diffuse light over a 300 meter reach of salmon spawning stream, while (Neilson et al. 2010) developed correction factors for radiation gain on DTS cables to allow for realistic temperature monitoring in aquatic environments.

DTS has now been extensively utilized to study groundwater flow and karst aquifer dynamics. Under an early CTEMPs Pilot Project, Leaf et al. (2012) developed a new thermal borehole logging approach to identify zones of aquifer exchange within boreholes. Short-circuiting of aquifer exchange through open boreholes represents a significant potential for contamination, and by injecting a point source of heat at various depths in a borehole, Leaf et al. (2012) were able to continuously measure the advection of the thermal pulse and calculate both groundwater exchange, as well as directly observe inflow back into the formation. Hausner et al. (2012, 2013) used DTS fibers in Devils Hole, a karst aquatic environment home to the last remaining Devils Hole pupfish, to document the rate of habitat warming due to climate change. Developments by the CTEMPs team (Sayde et al. 2010, Steele-Dunne et al. 2010, Sayde et al. 2015, Dong et al. 2016) in the measurement of soil temperatures over large spatial scales have led to a number of advances in quantifying soil heat flux (Lutz et al. 2012) and soil moisture (Striegl and Loheide II 2012, Benitez-Buelga et al. 2016). Lutz et al. (2012) investigated the changes brought about by forest management (thinning and logging) on forest floor temperatures by stringing optical fibers on and through an actively managed forest floor. While the installation was challenging, the authors were able to observe much higher and more spatially variable soil temperatures following
thinning, and documented links between increased temperature and reduced species diversity, likely due to both radiation and reduced moisture content. DTS systems have also opened up new opportunities for high spatial/temporal monitoring of ocean mixing (Stern et al. 2013), internal waves, surface temperature dynamics (Arnon et al. 2016) and solar pond dynamics (Suárez et al. 2011). The ability to remotely measure, at high spatial scales, the evolution of temperature within the water column now provides much higher resolution of mixing processes and provides observations to drive ocean and sub-ice shelf mixing models.

CTEMPs has also supported atmospheric observatories, specifically focusing on boundary layer dynamics (Thomas et al. 2012, Sayde et al. 2015) and heat transfer within tree canopies (Hausner et al. 2013). Thomas et al. (2012) installed a fine mesh of low thermal mass optical fiber to measure two-dimensional atmospheric flow and heat transport under stable boundary layer conditions; which pose challenges for traditional single-point measurement systems. For the first time, high-resolution fast-response DTS was demonstrated to be capable of visualizing the thermal structure of the near-surface flow leading to direct estimation of length scales and flow dynamics unknown before.

CTEMPs instrumentation has also been deployed in polar conditions with a focus on heat transfer in glaciers and ice shelves, ice caves and subglacial lakes. Tyler et al. (2013) installed two permanent fiber-optic moorings through the McMurdo Ice Shelf in Antarctica to measure both ocean circulation and melting of the ice shelf from below, a critical measurement to quantify the stability of Antarctic ice sheets and their impact on sea level rise. Kobs et al. (2014) has recently developed an approach to extend the thermal gradient to its intercept with the pressure freezing temperature of seawater beneath the ice shelf to monitor daily changes in the position of the ice/ocean interface.

We see that advancement in earth observation has been facilitated by CTEMPs by acting on three facts. First, new observation methods can provide transformative science. Here the DTS provides about four orders of magnitude improvement in observation when compared to traditional temperature monitoring approaches. A “Follow the zeros” approach to novel observations is at play here: if new approaches allow orders of magnitude greater resolution of observation due to lower cost, improved technology, or a combination of both, then transformation of observation is to be expected. Secondly, adoption of new technology must be guided. The greatest risk to a young investigator is to be seduced by a new approach that turns out to have hidden pitfalls that preclude success. CTEMPs provides deep training so that potential users can correctly identify if the technology they read about is truly appropriate for their goals. Finally, we must collaborate as a community to remove the financial and logistical barriers to adoption of new tools. In the case of CTEMPs, they provide users with hundreds of thousands of dollars worth of equipment at low (for professors) or no (for students) cost. But cost is just one of the barriers. People think of 3-D printing and micro-processor-based data systems as “cheap,” but they forget the knowledge base required to be successful in using these technologies. After all, how else can we explain the rather low rate of penetration of these technologies into hydrological science given they have been readily available for a decade? Here we see again that forming a community approach will be transformative, and we point to the OPEnS lab (Open-Sensing.org) as an example of how to remove these critical barriers to adoption.
3.6. Vegetation

Improving the representation of vegetation dynamics is essential to increasing the accuracy and reliability of hydrological assessments, such as land surface hydrological models (Liang et al. 1994). At a field scale, monitoring vegetation growth over seasonal time scales typically relies on point-based estimates of attributes such as leaf area index (LAI) and biomass, and for many agricultural species, destructive sampling to obtain yield estimates. In addition to being time and labor intensive, these field methods can also produce unreliable estimates (Burke and Lobell 2017). Imagery has demonstrated remarkable potential toward monitoring vegetation and biomass structure. For instance, the Microsoft Kinect infrared sensor has been utilized to determine the plant structure and size of several species (Azzari et al. 2013).

To estimate the seasonal evolution of these variables over broad areas, time series of satellite imagery collected in the visible and near-infrared wavelengths are used, relying on established correlations between derived vegetation indices (for instance, NDVI, EVI, MSAVI) and leaf area index (LAI), as well as yield (such as seasonally integrated NDVI; Estes et al. (2013)). Remote assessments of vegetation properties face several important challenges. One is that the data collected by sensors often do not directly measure variables of interest (for instance, crop yield), but instead are more closely correlated with a proxy variable (such as net primary production Tucker et al. (1981)). Another problem is the necessary trade-off between spatial and temporal resolution that faces satellite imaging, which results in the reliance on coarser sensors (such as MODIS) to obtain high frequency (daily to weekly or twice-weekly, depending on cloud cover) observations, whereas higher resolution imaging via Landsat, Sentinel and the increasing constellation of commercial satellites is necessarily less frequent (weekly to monthly or multi-monthly).

Lately, however, a number of developments are helping to overcome the second limitation. The recent launch of the higher-frequency Sentinel 2 constellation (Drusch et al. 2012) and the large constellations of low-cost satellites that are now being deployed (Hand 2015) create the possibility for near-daily high to moderate resolution images to be collected. These advances in satellite imaging are occurring at the same time as new automated, low-cost, in situ sensing technologies are being developed (Wolf et al. 2012), which allow the creation of extensive sensor networks that can provide high quality time series of data that can be used to validate space-borne vegetation measurements. Using intermediate scale imaging collected from unmanned aerial systems may help to further improve the accuracy of up-scaling from field to space (Gaveau et al. 2014).

Advances in analytical approaches are combining with these sensing advances in ways that can help to reduce the first problem. For example, more direct estimates of yield can be made using new methods that combine process-based models with satellite observation. In this approach, ensemble runs of a mechanistic crop model are used to develop simpler empirical relationships between final yield and leaf area index (LAI) throughout the growing season, whereupon these relationships are applied with satellite-based measurements of LAI to retrieve predicted yield values over large areas (Burke and Lobell 2017, Lobell et al. 2015). Such approaches circumvent the need for dense LAI time series, and therefore allow higher resolution, lower-frequency observations to be used. The accuracy of such approaches will be further improved as more accurate agricultural land cover maps are developed, using new approaches that combine crowdsourcing (Estes et al. 2016) and newer computer vision and machine learning methods (Debats et al. 2016). Improved land cover maps help to minimize
the error in agricultural monitoring approaches by filtering out non-crop vegetation signals (Estes et al. 2013).

UAS-based imagery has terrific implications for vegetation monitoring by enabling high-throughput phenotyping of vegetation under stressed conditions (Berni et al. 2009, Zarco-Tejada et al. 2012). In changing climatic and hydrological conditions, high-yield plant-based feedstocks offer a valid alternative to alleviate global dependence on fossil fuels (Harfouche et al. 2012). However, feedstocks should offer yield stability in increasingly extreme and frequent drought conditions. To this end, proximal sensing, based on the integration of UAS technology and imagery, affords monitoring extended areas (on the order of several ha) at high spatial and temporal resolution. Advanced image processing, such as segmentation and semi-automatic machine learning algorithms (Lim 1990, Forsyth and Ponce 2011), have the potential to rapidly dissect the response of the ecosystem to challenging climatic conditions, thus opening novel avenues in forest management and environmental monitoring.

3.7. Measurements at the catchment scale

Measurements at the catchment scale are key for understanding the formation and timing of flood event and, therefore, mitigate risk in exposed areas. An interesting method to measure the response times of small burned catchments to rainfall relies on the use of low-cost pressure transducers to identify the passage of floods and debris flow (Kean et al. 2012). These inexpensive instruments have been installed in bedrock sections of channels to measure flow timing in numerous catchments across the US. Analysis of flow paths is also crucial to understand hydrological processes at the catchment level. To this end, isotopic data are routinely used in experimental hydrology and sampling isotopic rain water collection is crucial for accurate measurements. For instance, La Frenierre and Mark (In press) developed and deployed a totalizing rain gauge that was sampled periodically to develop a water budget on Volcán Chimborazo, in Ecuador. Alternative approaches entail the use of wireless sensor networks and advanced data loggers.

Wireless sensor network (WSN) technology enables the distributed sensing of hydrological states and fluxes at the catchment scale (Inagaki et al. 2011, Jin et al. 2014). WSNs consist of a multitude of small sensor nodes embedded in the environment that can quantify spatially heterogeneous phenomena, such as temperature or soil moisture fields and vegetation conditions, at high spatiotemporal resolution (Qu et al. 2014, Wiekenkamp et al. 2016).

One of the first low-cost mesh networking proprietary standards used for WSNs is ZigBee (Valente et al. 2006). However, the 2.4 GHz low-power radio module of ZigBee limits the communication range between sensor nodes (less than 1 km). The recently introduced LoRa system for long-range, low-power, low-bitrate, and wireless communication offers network coverage of several kilometers (Augustin et al. 2016). In order to maximize the number of WSN nodes, the sensors are inexpensive and easy to calibrate (Bogena et al. 2017). WSNs are extremely flexible and can also be used temporarily to assess spatial heterogeneity of ecosystem states in areas that are not part of a “fixed” sensor network. Moreover, WSNs can operate periodically on a regular or event-driven basis, thus allowing to better capture non-linear processes in catchments, such as soil saturation excess, preferential flow patterns and heat islands.

Hydrological monitoring often requires a central system to store data, communicate with sensors, and record the timing of measurements. Such systems are also often
responsible for powering instruments and using telemetry to send information back to a place where scientists can retrieve it.

Data loggers have often been among the most expensive parts of a field sensor platform, so several groups set out to develop their own data logging hardware and software based on Arduino hardware and software. Two of these are focused on hydrological applications. The Mayfly data logger, developed by Hicks et al. (2015), features telemetry for use in hydrological monitoring networks, and is an integral part of the EnviroDIY community. Wickert (2014) developed the ALog data logger for extreme low-power remote field deployments. Programming the ALog is made simpler through the “Logger” software library that manages its internal utilities and includes an expandable set of pre-written functions to connect with sensors. These functions currently support common sensors for weather stations, soil moisture, and stream and snow gauging.

Toward upscaling hydrological measurements, UASs are an emerging technology that is rapidly transforming the way we sense the environment. The flexibility of such platforms affords fully remote observations of stream flow, temperature, and water level, among others. Latest technological advancements have contributed to a large diffusion of low-cost yet high-performance platforms in the market. In the realm of hydrology, UASs are an important component of the available experimental toolbox, with unprecedented potential in ecohydrology, landscape evolution, and agricultural management. Most frequently, UAS technology is combined with image sensing equipment, such as RGB, thermal, and hyperspectral cameras for quick and high-resolution monitoring of extended or difficult-to-access environments. Once images are collected, they are usually orthorectified, georeferenced, mosaicked, and then processed to extract quantitative data. Several studies have utilized UAS-based images to estimate the NDVI and LAI over cultivated areas. The characterization of the kinematics of surface waters is another promising application that is rapidly growing in the hydrological community (Detert and Weitbrecht 2015, Tauro et al. 2016b, Bandini et al. 2017, Bolognesi et al. In press).

3.8. Collaborative efforts

Citizen science and participatory platform constitute promising approaches for massive collection and analysis of hydrological data. In the following, we report MOXXI-related initiatives involving the collection of hydrological data by non-technical individuals.

Brooklyn Atlantis offers a first example of the integration of water measurements in an online citizen science environment (Laut et al. 2014). From their homes, Citizen scientists log in to the Brooklyn Atlantis project to help analyze images that are routinely collected by aquatic robots in the Gowanus Canal in Brooklyn. By tagging objects on the images and relating them to key water parameters acquired by the robot, such as pH and temperature, Brooklyn Atlantis could help advance our understanding of the Gowanus Canal, one of the most polluted bodies of water in the United States. Citizen science could contribute to scientific research for a number of reasons, from a desire to help the environment to individual reputation. Brooklyn Atlantis researchers have sought to clarify the psychological underpinnings of citizen science participations through a number of hypothesis-driven studies in human behavior (Cappa et al. 2016, Nov et al. 2016, Laut et al. 2017, Diner et al. In press).

The Trans-African Hydro-Meteorological Observatory (TAHMO, www.tahmo.org) is an initiative that seeks to develop, install, and maintain a dense network of weather
stations across sub-Saharan Africa (van de Giesen et al. 2014). Eventually, the goal is to have one station per 1000 km$^2$, corresponding to a total of 20,000 stations. Presently, one-day rainfall predictions over Africa are of comparable accuracy as ten-day forecasts over Europe (Haiden et al. 2012). By improving ground observations, the all-important rainfall and weather forecasts are expected to improve considerably and thereby support planning of agricultural, logistical, and construction activities. TAHMO fits well with the MOXXI initiative as an important characteristic of the weather stations is that they are based on innovative sensing techniques. Specifically, there are no moving parts as these tend to require a lot of maintenance in the African climate. The presentely used stations were developed by the Meter Group and measures rainfall, wind-speed and -direction, incoming shortwave radiation, air temperature and relative humidity, as well as barometric pressure. Interestingly, robust validation for the TAHMO rain gauge, which would provide indication if other sensors on the TAHMO station were malfunctioning, was guaranteed by developing a “Super Validator” which consists of a Pythagorean cup packed with fiberglass wick. The device is supported on a temperature-compensated strain gauge (under US$3) and read with a 24-bit A-to-D recorded by an Arduino (electronics under US$10). The rain is recorded like a classical self-emptying rain gauge, while the system retains about 6 cm of water in the wick which is monitored between rainfall/irrigation events as a measure of evaporation. By comparing the observed evaporation to the measured wind, humidity, solar radiation, and temperature, discrepancies in predicted and observed values can be used as indicators of faulty sensors. Further, the observed evaporation is highly informative with respect to hydrological processes. Within TAHMO weather stations, a GPS, compass, and accelerometer are also included to allow control of the continued proper installation of the station. The sensor suite and communication module are powered by a single embedded solar cell the size of a business card. Data are communicated between 4 and 24 times per day through GPRS (mobile phone). The stations have some redundancy to further allow quality control. Automated QA/QC is performed on the TAHMO servers. In addition to the novel technology, TAHMO distinguishes itself from earlier initiatives by actively building public-private partnerships (PPPs) with national meteorological agencies. MoUs are now in place in 13 African countries. Although non-commercial data use for science and government is free, commercial usage is subject to a fee to make the system financially sustainable. The PPPs serve to both strengthen the national meteorological agencies and develop new business models and activities. Finally, it is important to note that TAHMO stations are mainly being installed at secondary schools, where they are linked to the Science, Technology, Engineering and Mathematics curriculum.

An increasing number of personal weather stations (PWSs) automatically upload rainfall measurements to online platforms, particularly in urban areas. de Vos et al. (2017) examined the potential of such crowdsourced data for obtaining high-resolution rainfall measurements for the Amsterdam metropolitan area, The Netherlands. A detailed analysis of rainfall data from more than 60 stations over an area of nearly 600 km$^2$ during several months confirmed that the growing number of internet-connected PWSs can be used successfully for urban rainfall monitoring. Remaining challenges include accounting for uncertainties in the PWS data resulting from both the imperfect measurement setup and rounding and threshold processes that occur during the data transfer to the online PWS platform. These sources of error may cause considerable deviations from rainfall measurements obtained using dedicated rain gauges and gauge-adjusted weather radars.
4. Future opportunities and challenges

Although the MOXXI community is relatively young, the group is working toward the establishment of a common language between scientists and is promoting collaboration among diverse research groups in hydrology and other fields of science. The group is expected to help redefine the role and expertise of hydrologists. In our vision, complex hydrological problems should be addressed by teams of scientists, whereby hydrologists will be able to share their research questions and interact with experts in robotics and electronics.

In this respect, MOXXI strives to be an inclusive community by inviting experts from fields other than hydrology to participate in conferences and research projects. Hopefully, its diversity will facilitate research progress by keeping MOXXI members updated with respect to the latest innovations and achievements and by providing access to a multidisciplinary pool of experts. The Sustainable Development Goals (SDGs), especially SDG 6 Clean Water and Sanitation adopted by the UN General Assembly in 2015 (UN 2015), as well as the need for assessing the impacts of climate change on the water cycle, are creating an increased demand for more extensive observations, denser monitoring networks, their long term sustainability, especially in developing countries, and a quality of observed data compatible with the international requirements, also from non-conventional sources, such as citizen observations. WMO’s Global Innovation Hub would provide a framework to develop and implement innovative tools for water monitoring and information systems through calls for novel hydrometric designs, coordination with ongoing projects and donors including testing and implementation of new monitoring technology and methodology in field projects.

Despite these promising opportunities, several challenges remain to be addressed when establishing novel observational approaches:

(a) Many recently introduced observational approaches need thorough assessment to be routinely adopted in monitoring practice. Building novel sensing instrumentation requires extensive calibration and validation, and sometimes collaboration from local authorities should be sought to allow the installation of novel equipment in natural systems or at existing gauging stations. Also, in some cases, national regulations do not allow the use of robotic platforms (UASs) for monitoring purposes.

(b) Recent (see, for instance, Sentinel-1/3, Jason-3) and upcoming (such as SWOT) satellite missions will provide more accurate and spatially distributed hydrological variables. However, the exploitation of this wealth of data requires a capacity-building community that ensures the identification and validation of proper methodologies, as well as the promotion of a closer relationship among authorities, stakeholders, and the research community (Schumann and Domeneghetti 2016).

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