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Time for in situ renaissance

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gether, these measurements will enable improved characterization of terrestrial, atmospheric, cryospheric, and oceanic water budgets at multiple scales and will allow for evaluation of their responses to climatic variability (*14*). Small-scale airborne measurements of snow-water equivalent are paving the way for a global satellite mission (*15*). Space-geodetic measurements—e.g., from global positioning system (GPS) and interferometric synthetic aperture radar (InSAR)—can measure Earth's crustal response to the addition and removal of water. Such measurements are proving useful in tracking the dynamics of terrestrial water storage (*16*).

TRANSCEND POLITICS, INFORM POLICY. An important feature of satellite observations is that measurements are readily collected and shared across political boundaries. In contrast, many countries refuse to share ground-based hydrologic measurements for socioeconomic and political reasons, whereas others simply lack the capacity to centralize and digitize what data are collected. This impedes investigations on a continental-to-global scale, as well as efforts to avert food and water crises. Because satellites can monitor water resources at scales relevant to effective transboundary water management and because data are often provided through freely accessible digital archives, policies of international data denial may ultimately become obsolete (*17*).

Governments around the world are now instructing their water management agencies to plan for the uncertain hydrologic future that satellite observations have helped reveal. The United States recently ordered its Bureau of Reclamation to rethink water storage strategies to better respond to prolonged drought and climate change impacts in its arid west. India has undertaken a national hydrogeological mapping program to better characterize its available groundwater resources. Australia, Israel, and several other countries have a long history of adaptive water management, guided in part by satellite observations.

Satellite-based studies, such as those of California drought and groundwater depletion (*18*), have affected water policy, e.g., the passage of California's Sustainable Groundwater Management Act of 2014. California will finally manage its once-vast groundwater supply to prolong its availability for future generations. Satellite observations proved highly informative for elected officials, policymakers, and the public.

PRIORITIZING INVESTMENTS. In an era of increased competition for limited federal funding, investments in satellite hydrologic monitoring should be critically evaluated for their anticipated returns, compared with investments in other technologies, including ground-based measurements. Several of us debated the relative merits of the Surface Water and Ocean Topography (SWOT) mission (*10*) to measure the heights, slopes, and inundated areas of water in large rivers and other inland bodies. Would a similar expenditure in traditional stream gauging provide equal science, technology, and management returns on investment? Arguments in favor of the satellite approach prevailed, the SWOT mission earned broad support from the water-science community, and it was ultimately selected for funding by NASA and Centre National d'Etudes Spatiales, with launch scheduled for 2020.

Such support is not always available nor should it be. We fully support comprehensive, ground-based measurements as the backbone of a regional-to-global hydrologic observing network. In situ observations provide important validation data for satellite measurements and are typically collected with greater spatial and temporal frequency. Some measurements, such as the volume of groundwater stored in major aquifers, are poorly suited to remote observation and may only be made with measurements acquired on land (*19*). There is no substitute for a well-maintained in situ network, and we lament the decline of such networks around the world.

Additional investment in data-model integration could help maximize the utility of current and forthcoming satellite hydrology missions. Data-model integration platforms are likely the most reliable means for quantifying freshwater availability at regional scales, as well as for down-scaling coarser-resolution satellite observations to the finer-resolution scales at which regional predictions and water management decisions are made. High-resolution models that represent the main components of natural and managed water cycles and that can ingest ground-, aircraft-, and satellite-based observations should have accelerated development timelines (*20*).

Satellites play a central role in scientific and operational hydrology and water management. Reliable hydrometeorological prediction would not be possible without them nor would rapid response to emergencies like regional flooding. With the scientific community recognizing that the water cycle is changing in profound ways (*1*), satellites provide the best available means to characterize these changes over large regions, to better understand and predict their implications for humanity, and to communicate compelling findings to elected officials and environmental decision-makers. ■

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Time for in situ renaissance

By **Balázs M. Fekete,[1*] Richard D. Robarts,[2] Michio Kumagai,[3] Hans-Peter Nachtnebel,[4] Eric Odada,[5] Alexander V. Zhulidov[6]**

In situ monitoring of water dates to Pharaonic Egypt and remained the primary means of observation into the later part of the 20th century. Monitoring networks have declined (*1–4*) since the 1980s because of budgetary constraints and political instabilities. This decline paradoxically has coincided with growing interest in climate change. The rise of satellite remote sensing promised global observing capabilities and put in situ monitoring on the sidelines. Capabilities offered by in situ monitoring versus satellite remote sensing are very different and mostly complementary (*5*); thus, deployment should depend on monitoring requirements (observed parameter, data quality, spatiotemporal scale, data costs, and access).

WATER DEBATE SERIES

Monitoring systems in situ support water management and policy development, as well as serving a range of users and uses (e.g., agricultural operations, environmental management, and regional planning). Remote sensing depends on in situ monitoring for essential calibration and validation. Water managers tend to use in situ observations because they need continuous, long-term, high-frequency, and accurate data for designing infrastructures and effective management plans, as well as sustained real-time data for operation.

FIDELITY, RESOLUTION, CONSISTENCY. Only in situ sensors, typically in close contact with the monitored medium, can measure a host of water-related quantity and quality parameters and processes (*6*) with reliable accuracy and sufficient frequency. Remote sensing provides indirect measurements normally limited to the near surface of the monitored object and affected by the media between the sensors and the monitored object. Remote-sensing observations are often the result of complex retrieval algorithms. In extreme cases, like satellite-derived evapotranspiration (*7*–*9*), the algorithm is almost indistinguishable from land surface hydrology models, such that it is questionable that this qualifies as "observation."

In situ observations are better suited for gradually changing observational targets, when strategically placed point measurement sensors are representative for larger areas. River discharge in particular is an ideal target for point monitoring because discharge only changes gradually along a river channel (except for confluences) and represents an integrated signal of the hydrological processes from a larger area upstream (*1*). Unless measurement requires laboratory processing of samples, in situ monitoring can provide observations at high temporal frequency. Many in situ observational records cover multiple decades of continuous data at high temporal resolution. Observation consistency depends on continuous instrument maintenance and recalibration that is often the most expensive part of the monitoring program. Remote sensing that only replaces relatively inexpensive measurements without comparably rigorous calibration will compromise monitoring (*5*).

Satellites are placed either in geostationary orbit, where they can provide continuous observations at low spatial resolution, or in low Earth orbits, which results in low repeat frequencies flying over the same area unless a constellation of satellites is deployed at added expense. It can be difficult to derive continuous (multidecadal) time series from satellite records, because technology changes and space agencies do not pay adequate attention to the homogeneity of observational records. Many satellite platforms (with the exception of meteorological satellites in geostationary orbits) are still in an "experimental" phase without long-term commitment for continued operations. Satellite sensors without adequate backup present a single point of failure leading to abrupt termination of observations.

COST, INNOVATION, ACCESS. Cost comparison of satellite remote sensing versus in situ monitoring is difficult because the final products are rarely comparable. Satellite remote sensing only competes in large-scale or global applications, because it cannot replace in situ monitoring in most cases. Cost comparison should be posed as the additional expense of extending existing in situ monitoring, including incentives for data sharing and aggregating observations, versus operating an independent satellite monitoring infrastructure. A recent World Bank report (*10*) estimated that \$1.5 to \$2 billion would be necessary to modernize developing countries' hydrometeorological monitoring infrastructure and an additional \$0.4 to \$0.5 billion annually for maintenance. These are comparable to the typical \$0.3 to \$0.6 billion price tag of medium-sized satellite missions.

Telecommunication breakthroughs and their widespread use lower barriers to data transmission. New sensor and deployment technologies are improving performance and cost. Autonomous drone vehicles (aircraft, boats, or submarines) could operate as monitoring platforms, which would blur the distinction between remote sensing and in situ observations. Solar unmanned aerial vehicles may offer cost-effective alternatives to satellites.

> ***"[D]ata sharing is voluntary, and agencies collecting in situ observations rarely have the obligation or incentives to share."***

Differences in in situ monitoring are inevitable to meet specific needs, but much monitoring could be standardized to ease data processing over larger geographic domains. Spatiotemporal synthesis of in situ observations often leads to more refined and accurate assessment. Yet lack of international collaboration in data sharing is often a motivation to develop remote-sensing alternatives. Global data centers are criticized for inefficiencies in collecting and disseminating in situ data. But data sharing is voluntary, and agencies collecting in situ observations rarely have the obligation or incentives to share. International agreements [e.g., the Danube, Mekong, Zadec, Rhine basins; World Meteorological Organization (WMO) Resolution 25 (*11*)] and data centers [GRDC, GPCC, and GEMS/Water (*12*)] are paving the way to improved standardization and access for in situ monitoring data. Investments in in situ monitoring and data centers at funding levels comparable to satellite remote sensing, contingent upon unrestricted access to data, likely can break many data-sharing barriers.

Sustained coordination and maintenance of in situ observing networks is far more challenging than flying a few satellites but could improve the quality of observations and serve as a positive precedent for international collaborations that fosters trust among nations. Succeeding in coordinated efforts for improved Earth observations could encourage commitments to larger goals like combating climate change. ■

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