TIME FOR IN SITU RENAISSANCE

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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*ï *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).

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.

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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*ï *9*), the algorithm is almost indistinguishable from land surface hydrology models, such that it is questionable that this qualifies as ñobservation.ò

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 ñexperimentalò 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.

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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12. ↵The Global Runoff Data Center (GRDC), Global Precipitation Climatology Centre (GPCC), and United Nations Global Environment Monitoring System (GEMS/Water) provide longterm hydrological data