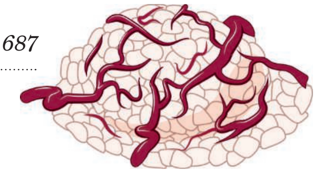
INSIGHTS

Mountain range formation *p. 687*

Rethinking vascular therapy for cancer *p. 694* ▸



PERSPECTIVES

WATER

Watching water: From sky or stream?

Monitoring and management of freshwater resources has long depended upon on-the-ground measurements. Satellite remote sensing has brought new complementing capabilities. In this final of three debates, *Science* invited arguments about the appropriate roles for, and balance between, each approach.

Satellites provide the big picture

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POLICY

Satellite observations have revolutionized our understanding of hydrology, water availability, and global change, while catalyzing modern advances in weather, flood, drought, and fire prediction in ways that would not have occurred with relatively sparse ground-based measurements alone. Earth-observing satellites provide the necessary "big-picture" spatial coverage, as well as the regional-to-global understanding essential for improving predictive models and informing policy-makers, resource managers, and the general public.

Sustained investments in a robust satellite hydrology program have enabled a plethora of discoveries, along with modernization of water management, that have increased the human, economic, and water security of many nations. We now recognize distinct human- and climate-driven fingerprints on the water landscape that are dramatically changing the distribution of freshwater on Earth (*1*). Improved understanding and heightened societal awareness of the global extent of sea-level rise (*2*), ice sheet and glacial melt (*3*), changing rainfall patterns (*4*), declining snow cover (*5*), groundwater depletion (*6*), and the changing extremes of flooding (*7*) and drought (*8*) simply would not have occurred without satellite observations.

As we look ahead, ongoing and near-future missions will soon provide routine global monitoring of the stocks of soil moisture (*9*), surface water (*10*), and total water storage (*11*)—which will improve estimates of groundwater storage changes (*12*)—and of the fluxes of precipitation (*4*) and evapotranspiration (*13*). Taken to-

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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

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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*–*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 manage-