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Space-Based Measurement of River Runoff

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Observations of river inundation areas, water levels, and flow variability from orbital sensors have the potential to directly measure the runoff component of the Earth's hydrologic cycle [*Birkett et al.*, 2002; *Brakenridge et al.*, 1998; *Sippel et al.*, 1994, 1998; *Townsend*, 2001]. A remote-sensing-based measurement strategy for rivers and streams is emerging: Surface water data can be collected, their accuracy evaluated, and the results disseminated without regard to political boundaries. The results can be used to address a wide variety of applications.

In this article, the needs for such measurements, a river reach-based methodology for their collection, and some sample results are presented. Because the international observational capability is increasing, some future opportunities for improving this strategy are also described.

Previous articles document the inadequacy of present observational data concerning surface water [*Shiklomanov et al.*, 2002; *Alsdorf et al.*, 2003]. The problem is twofold: (1) inadequate data collection within many land areas, and (2) poor data access. In regard to the latter, the Global Runoff Data Centre (2004; http://grdc.bafg.de/) states: "Currently, only a few national hydrological services distribute their data in accordance with World Meteorological Organization resolutions which call for free and unrestricted exchange."

Also, depending on a nation's position within a river basin, there are strong disincentives for sharing data. For example, the operation of dams and reservoirs can conflict with water supply needs downstream. Reservoir construction within international river basins such as the Mekong, the Euphrates, and the Brahmaputra unavoidably raises difficult political issues. These issues are common in many regions, and will continue to motivate against free access to river discharge and other surface water data.

The scientific need for such information is, however, critical. Examples of research problems cited by the Data Centre include water balance studies, coupling of hydrological and meteorological models, flux of freshwater and pollutants into the oceans, and comparisons of runoff volume to water quality data. Global climate change, including that associated with greenhouse gases, affects the Earth's water cycle [*Milly et al.*, 2002; *Palmer and Raisanen*, 2002; *Smith*, 1993; *Trenberth et al.*, 2003]. Documentation and eventual prediction of such effects in particular requires consistent, globally distributed data. It will be very difficult to better understand and quantify the global water cycle without improved measurements of the runoff component. Better data sharing can be only part of the solution, because of the large land areas where gaging station networks have been discontinued, or where they have never existed (Figure 1).

Contribution of Orbital Remote Sensing

Orbital remote sensing offers an appropriate technology for obtaining the needed measurements [*Smith et al.*, 1995; *Smith*, 1997]. Smith's

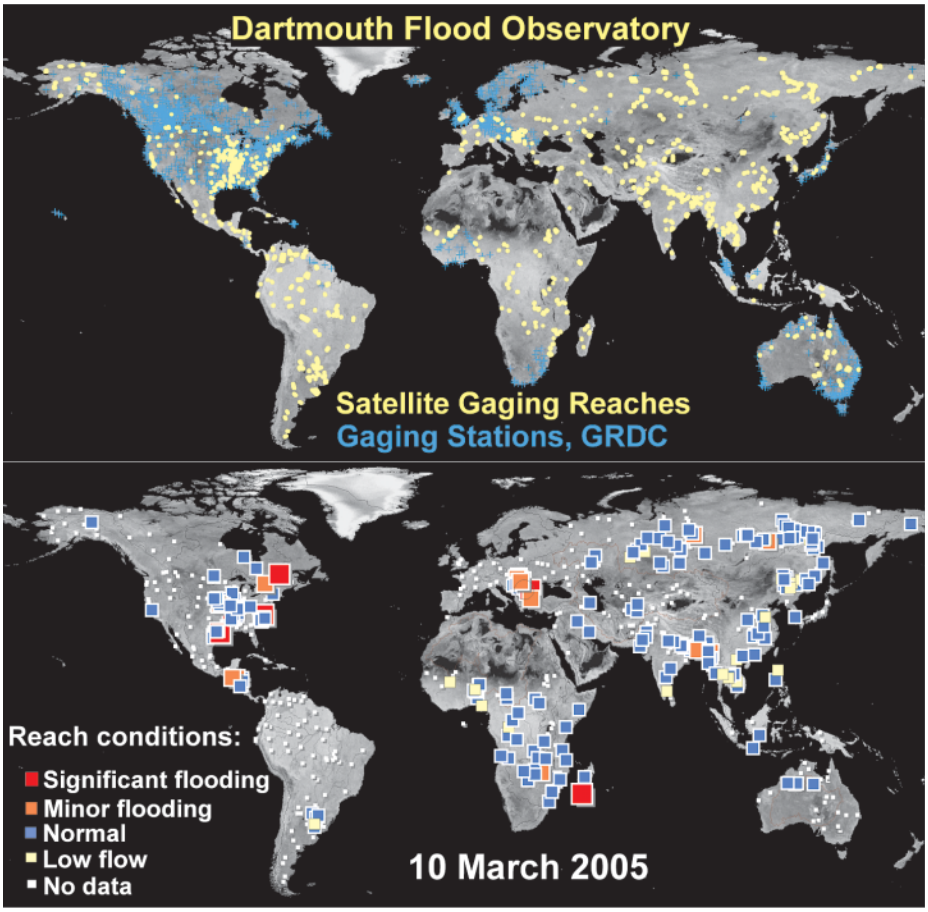

Fig. 1. (top) Presently available daily stream gaging data from the Global Runoff Data Centre in Koblenz, Germany (blue), and Dartmouth College's array of river reaches measured by satellite sensors (yellow). Those gaging stations with records of 10 years or more and which extend to at least 1995, are shown. There are large areas of the world for which contemporary daily discharge data are not available from ground stations. (bottom) QuikSCAT/SeaWinds-based daily hydrologic status display for river reaches within Dartmouth's global array. Flooding status is based on σ_{VV}/σ_{HH} *polarization anomalies.*

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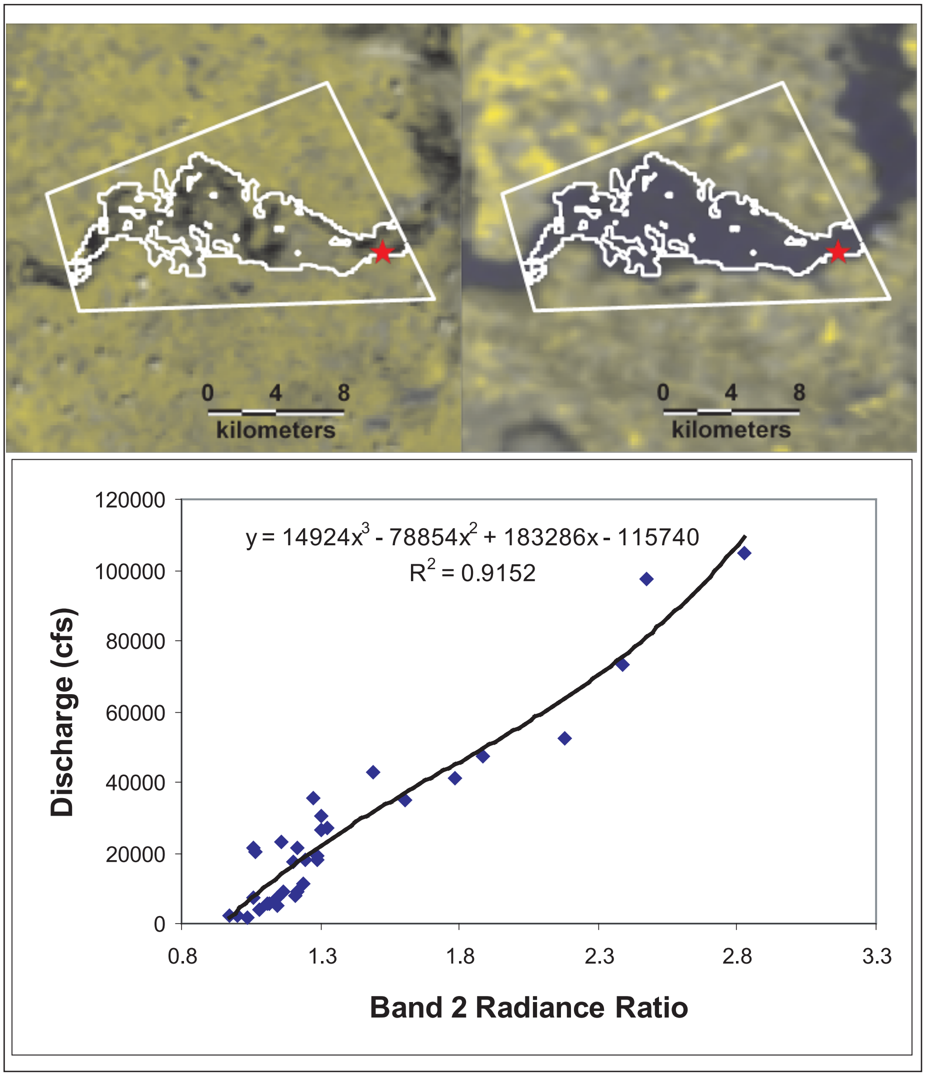

Fig. 2. (top) Color composite of MODIS band 1 and 2 images during minor flooding (left, 17 July 2003, 42,900 cubic feet per second) and major flooding (right, 13 January 2004, 97,600 cubic feet per second), visually showing surface water changes along a White River, Indiana, gaging reach. (bottom) MODIS band 2 calibrated radiance ratios from this reach versus the discharge measured at a U.S. Geological Survey gaging station at Petersburg, Indiana (red star in images).

work suggests that given the new satellite systems, routine estimation of river discharge changes along hundreds of river reaches should be both possible and economical. A variety of satellites can be used together and toward this end. Some sensors, such as the NASA's SeaWinds scatterometer (an accurate and stable radar on board the QuikSCAT satellite) detect major flow changes along large rivers without interference by cloud cover (Figure 1). Other wide-area optical sensors, such as NASA's Moderate-Resolution Imaging Spectroradiometer (MODIS), map more precisely where such changes are occurring. Still other sensors, at higher spatial resolution, can be coupled with topographic data and hydraulic flow equations [*Bjerklie et al.*, 2003] to infer river stages and discharges.

By cross calibrating the data from different sensors, the objectives of frequent temporal sampling and accurate discharge estimation can be reached. It is also possible to design autonomous "sensorweb" systems of linked sensors, wherein sensors capable of detecting surface water changes are programmed to notify, without human intervention, higher spatial or spectral resolution sensors which then obtain and deliver the new data [*Chien et al.*, 2004]. This could allow focused data collection over areas subjected to flood or drought.

Gaging Reaches as Measurement Sites

The key to satellite-based river measurements is the utilization of gaging reaches rather than gaging stations. River flow cross sections are difficult to measure from space, but measurements of changing water surface areas within carefully defined river reaches can be retrieved with relatively high precision using existing methods. Such gaging reaches range from ~10 km to as much as 30 km in length when using a moderate spatial resolution sensor such as MODIS. Criteria for the selection of gaging reaches differ considerably from criteria used to establish in situ gaging stations. When designing gaging stations, a river cross section is chosen where continuous measurements of river stage (water level) will be collected by the gage. Cross sections where discharge changes are accompanied by large river width changes are avoided, because this weakens the robustness of stage as a predictor of discharge. Calibration of stage to discharge is accomplished by velocity and flow depth retrievals under different flow conditions with a current meter. For gaging reaches, in contrast, the observation used to infer discharge is reach water surface area, or a geophysical measurement strongly correlated to that.

The reaches are, therefore, best situated where discharge changes are accompanied by flow width and water surface area expansions and contractions (Figure 2). The sensitivity of this method depends on reach channel and floodplain morphology, on sensor spatial resolution, and on water area classification precision and accuracy. Moderate spatial resolution, frequent-repeat imaging sensors can be used, provided that changing reach water surface areas produce a well-calibrated signal that can be discriminated from other surface changes.

Illustrated in Figure 2 is a measurement approach with MODIS that records water area changes even within mixed water/land pixels, and also provides the needed inter-scene calibration. First, the gaging reach is subdivided into (1) the measurement sub-reach, which is permanent water and nearby land subject to flood-related inundation, and (2) the calibration sub-reach, which is the remaining land which remains free of surface water even during high water (the inner and outer portions of the Figure 2 reach).

Calibrated near-infrared radiances are obtained for pixels within the two reach subsets. When total water surface area increases along the river, the mean radiance declines for the measurement sub-reach, but not outside it: The radiance ratio records the water area increase. Because of the large difference in water and land radiances at this spectral band (841–876 nm), the ratio calibration reach/measurement reach is a sensitive and consistent measure of surface water. If, instead, illumination, atmospheric scattering, or vegetation properties vary, and measured radiances change in tandem, the ratio remains relatively constant. The paired-measurement approach is an economical and effective way of using MODIS optical data to measure surface water changes.

Discharge Estimation

If adequate floodplain topographic data are available, bank-full and various overbank river stages can be measured on higher resolution data by determining the elevation of the water/land boundaries. This provides a path forward to inferring discharge in the absence of in situ gaging stations.

First, the imaged inundation pattern at the upstream and downstream ends of the reach are compared with topography. This results in two stage estimates for each reach image, as well as the longitudinal water surface slope. Then, hydraulic geometry equations such as those of *Bjerklie et al.* [2003] are applied to the imaged flow parameters and the

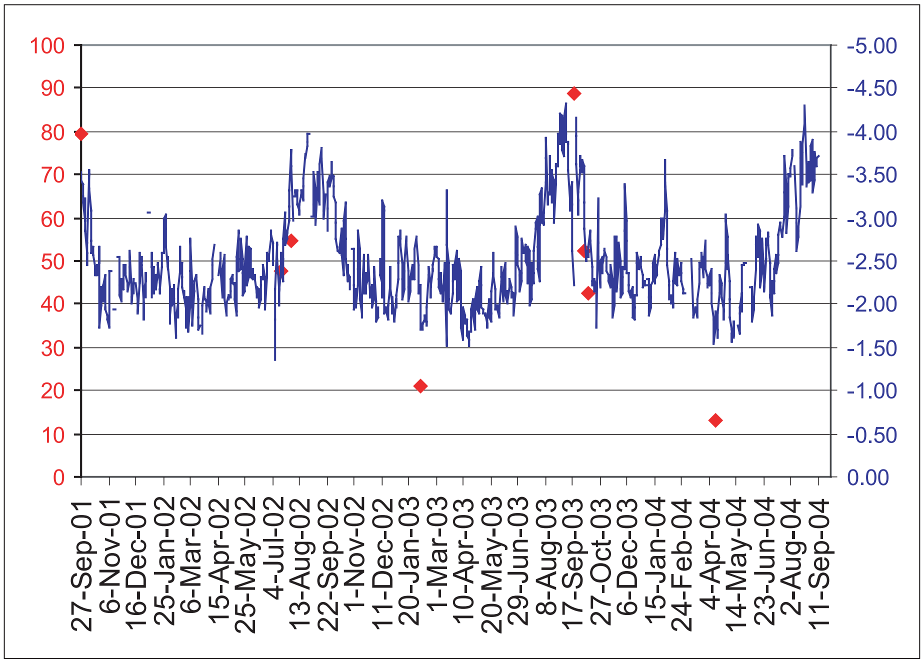

Fig. 3. Time series of QuikSCAT/SeaWinds polarization ratio measurements in dB over Gaging Reach 22, Gandak River, India (blue line, 3-day forward running means), compared with MODIS reach water surface area measurements in square kilometers (red dots). Timing and extent of the monsoon-related seasonal discharge changes can be precisely determined with this sensor.

channel and floodplain characteristics (including slope and resistance-to-flow), in order to derive reasonable discharge estimates. The process is repeated for a variety of flow conditions, resulting in empirical area/stage and stage/discharge relations similar to those constructed for in situ gaging stations.

Alternatively, two-dimensional hydraulic modeling methods can be employed [*Bates et al.*, 1992]. Without direct velocity measurements, the calibration of surface area to discharge will be less accurate than that obtained for stage at gaging stations. However, the surface water time series itself can be used in many types of analyses, and it becomes increasingly valuable as the period of record lengthens. Also, if flow velocities can be obtained, even intermittently, and if channel bathymetry can be observationally constrained (via lidar or other techniques), then the accuracy of the area/discharge calibration can be much improved. The overall strategy is to use one kind of sensor for frequent repeat imaging of a defined river reach, and other, higher spatial resolution sensors and ancillary data to assist in accurate discharge inference at such measurement sites.

An imaging strategy for runoff measurement can be applied in a wide variety of favorable settings. These include tributary and trunk stream junctions, slip-off slopes across the inside bends and point bars of meandering rivers, most anastomosing (branching) or braided reaches, and the upstream margins of many artificial impoundments.

Some rivers have been trained into relatively narrow channels, with protective levees further confining their flow. In-channel discharge variation along such reaches may be accompanied mainly by changes in depth and velocity. However, even along such rivers, increases in river discharge cause some changes in reach water area, such as at small tributary mouths due to backwater effects, or by inundation of in-channel bars and islands. Orbital imaging sensors can record and quantify such variation if sensor spatial resolution, water/land discrimination, and inter-scene calibration are adequate.

Figure 1 shows the use of MODIS to obtain time series of water surface areas at several hundred gaging reaches worldwide. This optical sensor provides a daily opportunity for new data, but it is constrained by cloud cover. Experimental work indicates that microwave sensors, working at relatively coarse spatial resolutions, can also record reach water surface area variations: for example, by changes in reach-averaged polarization ratios (Figures 1 and 3), where σ_{VV} and σ_{HH} are the vertically and horizontally polarized backscatter. Microwave sensors can thereby detect the onset of flooding in response to intense or prolonged rainfall without interference by cloud cover. Many rivers exhibit seasonal variation in flow in response to monsoons or snowmelt: Such seasonal cycles can be observed and their timing and intensity can be measured. The ability of microwave sensors to obtain new data over a reach in a predictable manner and at daily or higher revisit frequencies makes these sensors potentially useful also as operational flood warning tools.

Summary and Future Opportunities

Remote sensing observation of flow areas along gaging reaches can observe changes in river discharge, without regard to national borders and at incremental costs very much lower than in situ stations. Existing moderate-resolution sensors, such as MODIS, can provide repeat measurements on a near-daily basis (less often in heavily cloud obscured areas).

The value of such data is enhanced by intermittent observation by higher-resolution sensors, coevally to MODIS data acquisition, and by constraining floodplain topography, channel bathymetry, and resistance to flow characteristics. In this regard, the NASA Shuttle Radar Topography Mission (SRTM) topographic data, with 90-m postings outside the United States, has also been processed to a spatial resolution of 30 m, and the availability of such data for river gaging reaches would significantly improve discharge accuracy.

NASA is planning a wide-swath, L-band beam-sharpened scatterometer (Hydros: Hydrosphere State Mission; to be launched in 2009). Depending on the data distribution capabilities, and building on experience with data such as QuikSCAT, this sensor could provide frequent re-measurement of surface water changes over gaging reaches where cloud cover is a constraint. Also, the addition of satellite altimetry could provide independent river stage information, and thus greatly assist in the translation of observed flow areas to discharge.

Space-based surface water observations are not as precise as gaging station data, and the relationship of reach surface water area to discharge may be affected by errors such as hysteresis (for example, during waxing and waning flood, identical areas may correspond to somewhat different discharges). These measurement difficulties are, however, familiar to hydrologists using gaging station data and can be addressed. Just as a constellation of orbiting sensors currently provides meteorological information in real time, there is presently the potential to use existing and planned orbital sensors to measure changes in the Earth's surface water as they occur and without regard to political boundaries.

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A Strategy to Rapidly Determine the Magnitude of Great Earthquakes

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In the initial hours following the origin of the Sumatra-Andaman Islands earthquake at 0058:53 GMT on 26 December 2004, the event was widely reported as having a magnitude of about 8. Thus, its potential for generating a damaging teletsunami (ocean-crossing tsunami) was considered minimal.

The event's size later was shown to be approximately 10 times larger, but only after more than four and a half hours had passed, when a moment estimate based on 2.5 hours of data became available from Harvard University's Centroid-Moment Tensor (CMT) Project (M. Nettles and G. Ekstrom, Quick CMT of the 2004 Sumatra-Andaman Islands earthquake, Seismoware FID: BR345, e-mailed announcement, 26 December 2004). This estimate placed its magnitude at $M_w \approx 9.0$, in the range capable of generating a damaging teletsunami. Actually, the earthquake had caused a teletsunami, one that by that time had already killed more than a hundred thousand people. The magnitude estimate has been subsequently revised to at least 9.3 (Stein and Okal, http://www.earth.northwestern.edu/people/~seth/research/sumatra.html), with the exact magnitude of the event likely to be a subject of further research in the coming years.

Kerr's [2005] account of difficulties that seismologists encountered in those first hours is gripping—and damning! Seismologists couldn't get right the magnitude of the most important earthquake to occur in over 40 years. This is serious criticism, and seismologists everywhere should be outraged. But more important, seismologists should start thinking about how to get it right the next time.

As shown here, a reliable magnitude estimate—one that identifies the Sumatra–Andaman Islands earthquake as capable of causing a damaging teletsunami—can be achieved using only data collected within one half hour of its origin, and using only a magnitude-based (as contrasted to a moment-based) approach. Had such a determination been made in the first hour after the event's origin, it could have been used to issue a timely preliminary alert.

The size of an earthquake can be objectively quantified by its seismic moment, m_0, (the product of fault area, average slip, and the rigidity of the surrounding rock), or, equivalently, the moment magnitude, M_w, a quantity directly computed from moment using the standard formula $M_w = 2 \log 10(m_0)/3–10.73$.

Moment estimation is based on laborious, wiggle-for-wiggle matching of observed and predicted seismograms. Routine magnitude determination techniques use only the peak amplitude of the observed seismograms, and produce quicker results. They are widely used, even though they have a tendency to underestimate the size of the very largest earthquakes (a fact well known amongst seismologists since the 1970s) [*Aki,* 1972; *Geller,* 1976]. This magnitude underestimation problem arises from the fact that the slip that occurs on a long fault is not instantaneous. Slip on a thousand-kilometer-long fault, such as that of the Sumatra-Andaman Islands earthquake, occurs over about 500 s, because the rupture front propagates at a speed of about 2 km/s from one end of the fault to the other. Consequently, the seismic waves that radiate from the fault are systematically deficient in energy at periods shorter than this characteristic timescale.

Routine techniques typically are optimized for estimating magnitudes of small earthquakes. That is because earthquakes with magnitude 6 or 7 occur many times each year, and everyone wants to know their magnitude. These routine methods use seismic waves with periods in the 1–20 s range—much less than 500 s—because the signal-to-noise ratio is highest in that band.

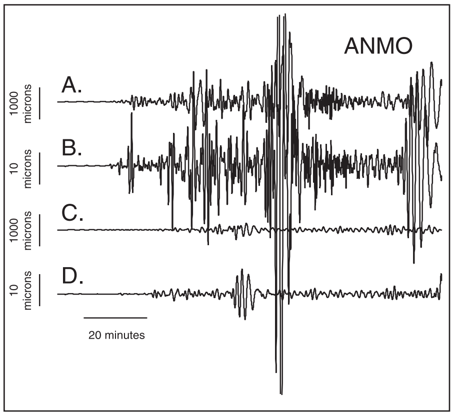

Fig. 1. Vertical displacement seismograms, band-pass filtered between periods of 50 and 200 s, for (a) the moment magnitude M_w = 9.0 great Sumatra–Andaman Islands earthquake, (b) a nearby M_w = 7.2 event occurring on 11 November 2002, (c) the M_w = 8.1 2004 Macquarie Island earthquake, and (d) a nearby M_w = 6.7 event occurring on 20 March 1998. All moment magnitudes are from the Harvard University Centroid Moment Tensor catalogue.

Consequently, routine magnitude estimation procedures have a systematic downward bias when applied to the rare magnitude 9 or larger event. The upper magnitude limit of these techniques can be extended by attempting to correct for the bias [*Sipkin,* 2003]. For very large earthquakes, longer periods must be used in the magnitude estimation procedure. However, the longer the period, the more data that must be collected before a magnitude estimate can be made, leading to a delay in issuing a public announcement of a very large earthquake's magnitude.

That the Sumatra–Andaman Islands earthquake had a magnitude much greater than 8.0 is apparent even at the 50–200 s period band. As an example, the vertical ground displacement of this earthquake is compared with the smaller, magnitude M_w = 8.1 Macquarie Island earthquake of 23 December 2004. Both earthquakes were observed at station ANMO (Albuquerque, New Mexico) (Figure 1).

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