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Observing Global Surface Water Flood Dynamics

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Abstract Flood waves moving along river systems are both a key determinant of globally important biogeochemical and ecological processes and, at particular times and particular places, a major environmental hazard. In developed countries, sophisticated observing networks and ancillary data, such as channel bathymetry and floodplain terrain, exist with which to understand and model floods. However, at global scales, satellite data currently provide the only means of undertaking such studies. At present, there is no satellite mission dedicated to observing surface water dynamics and, therefore, surface water scientists make use of a range of sensors developed for other purposes that are distinctly sub-optimal for the task in hand. Nevertheless, by careful combination of the data available from topographic mapping, oceanographic, cryospheric and geodetic satellites, progress in understanding some of the world's major river, floodplain and wetland systems can be made. This paper reviews the surface water data sets available to hydrologists on a global scale and the recent progress made in the field. Further, the paper looks forward to the proposed NASA/CNES Surface Water Ocean Topography satellite mission that may for the first time provide an instrument that meets the needs of the hydrology community.

Keywords Floods · Surface water · Floodplains · Rivers · Wetlands · Remote sensing · Surface water ocean topography (SWOT) mission

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1 Introduction: Surface Water Floods in the Earth System

Flood waves moving along river systems are both a key determinant of globally important biogeochemical and ecological processes and, at particular times and particular places, a major environmental hazard. The time and length scales of such waves vary depending on river basin area, basin shape, basin slope, geology, vegetation and land use. In the very smallest urban catchments, rivers respond near instantaneously to rainfall, whilst in the world's largest river systems, there may a single annual flood pulse and river flood waves may span whole continents. Such waves therefore vary in length from perhaps 1 to 1,000 s of km and in duration from a few minutes to a whole year. Compared to their length, river flood waves are extremely low amplitude: for example, the Amazon flood wave in the middle reach of the river has a maximum amplitude of ~ 12 m for a wave thousands of kilometres in length. In most other basins, even catastrophic flash floods have amplitudes much less than this, and typically, flood waves are just a few metres in height. Flood waves are therefore shallow water phenomenon where typical horizontal length scales far exceed those in the vertical. Hydraulically, most flood waves are gradually varying sub-critical flows (Froude number <1) where the influence of downstream water level controls can propagate upstream (the so-called backwater effect). Sub-critical hydrodynamics occur because most river longitudinal slopes are low (typical river slopes are in the range 1–100 cm km^{-1}) and change only gradually. Flood waves are translated with speed or celerity, c, and attenuated by frictional losses such that in downstream sections, the hydrograph is flattened out. Wave speeds vary with discharge (see NERC 1975) such that maximum wave speed occurs at approximately two-thirds bankfull capacity (Knight and Shiono 1996). Typical observed values for c reported by NERC (1975) and Bates et al. (1998) for UK rivers are in the ranges 0.5–1.8 and 0.3–0.67 ms^{-1}, respectively.

Shallow water waves are described, in one dimension, by the Saint–Venant equation:

$$\underbrace{\frac{\partial u}{\partial t}}_{(i)} + \underbrace{u\frac{\partial u}{\partial x}}_{(ii)} u + g\left(\underbrace{\frac{\partial h}{\partial x}}_{(iii)} + \underbrace{S_{\mathrm{f}}}_{(iv)} - \underbrace{S_{\mathrm{o}}}_{(v)}\right) = 0 \tag{1}$$

where wave propagation is controlled by the balance of the various forces in Eq. 1. Here, (i) represents the local inertia (or acceleration), (ii) represents the advective inertia, (iii) represents the pressure differential, and (iv) and (v) account for the friction and bed slope, respectively. The relative magnitude of these terms for different types of shallow water flow is discussed in detail by Hunter et al. (2007), but in general, for sub-critical flow, the advective inertia term (ii) can be disregarded, and the pressure differential, friction slope and bed slope terms (iii, iv and v, respectively) are significantly more important than local inertia. For super-critical flow however, where shocks, hydraulic jumps and bores may exist, term (i) assumes much greater importance, and term (ii) cannot be disregarded.

This one-dimensional description is reasonable when flood waves are contained within defined river channels; however, when bankfull height is exceeded and water is transferred to floodplains and wetlands adjacent to the main channel, this description is insufficient. Here, water flow paths cannot be predicted a priori and such flows are clearly two-dimensional phenomena where flow spreads according to the hydraulic gradient and floodplain topography, which may be exceedingly complex (see, for example, Nicholas and Mitchell 2003). Floodplains and wetlands act as additional routes for flow conveyance or areas of water storage. Even when floodplains convey flow, the typically higher friction and shallower depth means that flow velocities are usually significantly smaller than those in the main channel. Typical river flows have velocities in the range 1–3 ms^{-1}, whilst floodplain flows in all but the most extreme events have velocity of <1 ms^{-1}. Floodplain storage therefore alters wave propagation and has important consequences for many physical processes. Hence, whilst floodplains and wetlands cover only approximately 4 % of the Earth's land surface, they exert a critical influence on global biogeochemical cycles (Richey et al. 2002; Frey and Smith 2005; Zhuang et al. 2009), terrestrial run-off to the world's oceans (Richey et al. 1989), sediment and nutrient transport (Beighley et al. 2008), basinwide flood response (Turner-Gillespie et al. 2003) and global biodiversity (Tockner and Stanford 2002) as a result of the multitude of landscapes generated by floodplain geomorphologic complexity (Mertes et al. 1996). Moreover, over longer timescales, floodplains and wetlands form sedimentary basins where significant oil and natural gas reserves are found. It follows from this that surface water processes occur within, and are mediated by, the wider catchment hydrological system (Destouni et al. 2010; Cvetkovic et al. 2012) which also includes significant human activity (Destouni et al. 2013), and these interactions become especially important when considering the role of water fluxes as drivers of biogeochemical and ecological processes (e.g., Lyon et al. 2010).

Extreme floods can also be a significant natural hazard. According to the World Health Organization EM-DAT natural hazards database (www.em-dat.be), in 2011 floods and related hydrological hazards (e.g., wet mass landslides) accounted for over half of all reported disasters and affected ~140 million people (Guha-Sapir et al. 2012). In the UK alone, 5 million people (i.e. 1 in 12 of the population) in 2 million properties live on coastal and fluvial floodplains, and over 200,000 of these properties have less than the standard of protection mandated by the UK government (1 in 75-year recurrence interval). The proportion of at-risk population is likely to be similar in many other developed countries and perhaps worse in developing nations, where risk is often poorly understood due to a lack of numerical modelling supported by suitable hydrometric and topographic data sets. Moreover, when they do inevitably occur, floods cause major social disruption, civil unrest, economic loss and insurance sector bankruptcies (e.g., the floods in Mozambique, 2000; New Orleans, 2005; Thailand, 2007; UK, 2007).

Surface water floods therefore play an important role in the Earth system, yet despite a number of groundbreaking studies (e.g., Alsdorf et al. 2000; Hamilton et al. 2002; Mertes et al. 1995), their dynamics at global scales remain poorly quantified through either ground observations, satellite observations or modelling. For example, current estimates of global inundated area from ground and satellite instruments vary from 1 to 12 million square kilometres (Zhuang et al. 2009) and do not capture seasonal variation adequately. As a consequence, estimates of the magnitude of other processes driven by such dynamics, such as methane emissions from flooded wetlands, which are a significant contributor to global atmospheric methane, also cannot be well estimated.

Given the importance of surface water floods in the Earth system over the last decade, an increasing volume of research has been undertaken to better observe and understand the above phenomena. The aim of this paper is to review this progress and look forward to future satellite missions, which may further add to our knowledge.

The paper is organized as follows. In Sect. 2, we review the data sets currently available to describe flood dynamics globally and the recent progress in combining these data to further our understanding. At present, there is no satellite mission dedicated to making these observations, and therefore, surface water scientists make use of a range of sensors developed for other purposes that are distinctly sub-optimal for the task in hand. Nevertheless, by careful combination of the data available from topographic mapping, oceanographic, cryospheric and geodetic satellites, progress in understanding some of the world's major river, floodplain and wetland systems can be made. In Sect. 3, we describe the proposed NASA/CNES Surface Water Ocean Topography (SWOT) satellite mission, which would provide the first dedicated observing system for surface water by measuring water height (h), water slope ($\partial h/\partial x$) and water height change over time ($\partial h/\partial t$) at $\sim$100-m spatial resolution between 78°N and 78°S every 11 days. SWOT would not measure river discharge directly, and instead, this would need to be estimated using a hydraulic model driven by the SWOT water elevation observations. Constructing such a model requires knowledge of the channel bathymetry, which may be poorly known for many rivers, and estimation of the unknown channel friction. Section 4 therefore describes recent studies that have explored data assimilation techniques that could use the anticipated SWOT and existing observations to infer the unknown bathymetry and friction and hence estimate discharge. Section 5 summarizes progress to date and future prospects for research in this area.

2 Observing Global Flood Dynamics

An ideal set of measurements for observing global flood dynamics would comprise data describing channel bathymetry, floodplain topography, river discharge, inundation extent, water level and water storage at appropriate spatial and temporal resolutions as determined by our understanding of flood wave physics outlined in Sect. 1. Determining these resolutions in some situations, however, may not be straightforward. For example, we know that floodplains consist of features such as former channels, levees, pans and crevasse splays which give a complex microtopography that can affect both local-scale patterns and larger-scale flow routing (see, for example, Neal et al. 2012). Similarly, on the basis of a small number of unique and opportunistically acquired data sets, we know that water levels in inundated floodplains and wetlands show significant variability in time over periods of 24 h and in space over length scales down to 10–100 m (see, for example, Nicholas and Mitchell 2003; Bates et al. 2006; Alsdorf et al. 2007b), yet currently available observations are incapable of capturing this. Appropriate sampling density will therefore vary with event dynamics, which will be controlled to first order by basin size and climatology (Biancamaria et al. 2010) and complicated by such factors as basin shape, geology and land use. Measurements can be taken either through ground observations or using remote sensing platforms, and these are discussed in more detail below.

Ground observations of surface waters are made through discharge gauging stations; however, these are located on main rivers only where flow is confined to a single channel and can be fully sampled by a single measurement. Developed countries may have extensive ground gauging networks with long records but, worldwide, the number of gauges is declining (Vörösmarty 2002) and there can be significant barriers to data access. Moreover, floodplains and wetlands, which may convey a significant quantity of the total flow (e.g., Richey et al. 1989), are almost entirely ungauged. We therefore do not currently possess a comprehensive and globally consistent observing system for surface water. Nevertheless, at ground gauging sites, frequent water depth measurements can be taken to centimetric precision and made available in near real time with appropriate telemetry systems. If the gauge site is geodetically levelled, then absolute water elevation measurements referenced to a local ellipsoid or global geoid are possible. Flow rating curves constructed by fitting a relationship between repeated simultaneous measurements of flow cross-sectional area, velocity and depth can then be used to determine discharge through time. Where rating curves have been carefully constructed and flows remain in channel, then discharge can be estimated to an accuracy of perhaps 5–10 % (Fekete et al. 2012). However, where flow is out of bank, such that small increases in water height lead to large increases in discharge, where fewer observations are available to constrain the shape of the rating curve, or where flow is so high that the rating curve needs to be extrapolated, then errors may increase significantly. For example, Di Baldassarre and Montanari (2009) conducted a quantitative assessment of the effect of rating curve uncertainty on river discharge estimation for a reach of the River Po in Italy and found errors in the range 6.2–42.8 % at the 95 % significance level, with an average of 25.6 %. In an extensive previous study, Pelletier (1987) reviewed 140 publications that quantified uncertainty in river discharge and found errors in the range 8–20 %. Ground gauging stations typically record data at intervals between 15 min and 1 day and are located between tens and hundreds of kilometres apart, depending on the flashiness of the flow regime and the purpose for which the network is being used. Ground observations of inundation extent can be made, although the possible coverage is very limited and typically remote sensing platforms offer a much better solution for this variable. No global ground-based topography and channel bathymetry data sets currently exist, and this situation appears unlikely to change in the future.

Global coverage is clearly much easier to attain using remote sensing platforms; however, this may come at the expense of accuracy, and the orbit and instrument characteristics of existing systems may provide only a partial view of river, floodplain and wetland surface water dynamics. Indeed, satellite systems may often miss flood events entirely due to their particular orbital period/revisit times. This is largely because the satellite data used by surface water scientists come from either generic systems (e.g., the optical Landsat sensors) or more bespoke systems designed for applications in different geophysical fields such as oceanography, glaciology or geodesy. These systems are less than ideal for observing surface water floods, but can, if carefully employed, yield important insights at certain scales. Below, we discuss the available systems for measuring floodplain topography, water elevation, inundation extent and water storage. No current or planned future satellite system is capable of measuring either river bathymetry or discharge directly.

2.1 Remote Measurements of Floodplain Topography

For local-, regional- and national-scale studies, a number of high accuracy and fine spatial resolution systems are available for collecting remotely sensed terrain data. These include aerial stereo-photogrammetry (Baltsavias 1999; Lane 2000; Westaway et al. 2003), airborne laser altimetry or LiDAR (Krabill et al. 1984; Gomes-Pereira and Wicherson 1999) and airborne synthetic aperture radar (SAR) interferometry (Hodgson et al. 2003). LiDAR instruments in particular are now capable of generating data at sub-metre spatial resolution with vertical accuracy of $\sim$5 cm root mean square error (RMSE) over wide areas and are ideal for flood modelling. For example, over 70 % of England and Wales is now mapped using LiDAR. Such data are capable of capturing the complexity of floodplain microtopography and have vertical errors much lower than typical flood wave amplitudes. Globally, however, comparable data do not exist, and the terrain data available to surface water scientists are of much lower resolution and accuracy. A number of near-global terrain models are available, but amongst the most useful for surface water scientists are the measurements from the NASA Shuttle Radar Topography Mission (SRTM, Farr et al. 2007). SRTM was captured using an interferometric synthetic aperture radar flown on board the space shuttle in February 2000. SRTM was used to produce a digital elevation model (DEM) from 56°S to 60°N at 3-arc-second (~90 m) spatial resolution. Average global height accuracies vary between 5 and 9 m (Farr et al. 2007) with pixel-to-pixel noise of ~6 m (Rodriguez et al. 2006), and this is problematic given typical flood amplitudes. The vertical error has been shown to be correlated with topographic relief with large errors and data voids over high-relief terrain, whilst in the low-relief sites, such as river valleys, floodplains and wetlands, errors are smaller (Falorni et al. 2005). However, despite better accuracy over low-relief terrain, pixel-to-pixel noise is not reduced and the X- and C-band radars used for the SRTM mission only partially penetrate vegetation canopies such that for forested floodplains, the DEM is corrupted by vegetation artefacts. Accordingly, the SRTM spatial resolution cannot capture the floodplain and wetland microtopography that can be critical to an understanding of flow dynamics (see Trigg et al. 2012) and at their native resolution have noise that can be larger than the flood "signal". Attempts at solving these problems by post-processing to remove the vegetation signal and spatial averaging to reduce uncorrelated noise (Paz et al. 2010; Paiva et al. 2011, 2013) have been attempted with limited success, and with careful handling, SRTM data have been shown to be useful for some flood modelling problems (Sanders 2007; Wilson et al. 2007; Di Baldassarre et al. 2009; Neal et al. 2012).

Other global terrain data sets include the ASTER GDEM (global digital elevation model), the SPOT 5 DEM and the forthcoming TanDEM-X products. ASTER GDEM is a 30-m spatial resolution DEM developed using stereo-photogrammetry and available from 83°S to 83°N. However, its accuracy of 17 m at the 95 % confidence level (Tachikawa et al. 2011) means that SRTM has significant advantages for most flood modelling studies. More promising perhaps is the TanDEM-X global DEM available from 2014 which will use X-band synthetic aperture radar interferometry to create a global DEM with ~12-m spatial resolution and target accuracy of better than 2 m. Whilst potentially of greater accuracy and resolution than SRTM, the use of X-band radars will mean that TanDEM-X may still be corrupted by vegetation artefacts that may be difficult to fully remove even with sophisticated processing techniques.

2.2 Remote Measurements of Inundation Extent

Globally available remote measurements of inundation extent are reviewed in detail by Marcus and Fonstad (2008) and Schumann et al. (2012), and these are made principally using (a) optical sensors; (b) passive microwave instruments; or (c) synthetic aperture radars. Visible-band satellite imagery (e.g., 30-m resolution Landsat or coarser 250-m resolution MODIS data) can detect floods (e.g., Bates et al. 1997); however, cloud cover and restriction to daytime only operation may limit the utility of these data. Passive microwave instruments, such as the scanning multichannel microwave radiometer (SMMR), have good temporal but limited spatial resolution (6-day revisit time and 0.25° pixels in the case of SMMR) that limits their use to particular types of study (see, for example, Hamilton et al. 2002). For these reasons, SAR data are often preferred for flood remote sensing.

SARs are active systems that emit microwave pulses at an oblique angle towards the target. Open water acts as a specular reflector, and the microwave energy is reflected away from the sensor so such areas appear as smooth areas of low backscatter in the resulting imagery. Terrestrial land surfaces, by contrast, reflect the energy in many directions, including back towards the sensor, and therefore appear as noisy high-backscatter zones. These differences allow flood extent to be mapped using a variety of techniques to an accuracy of ~1 pixel. Pixel sizes range from ~3 to ~100 m in space-borne imagery (e.g., Horritt 2000; Di Baldassarre et al. 2009), depending on the orbit revisit time, and can potentially be excellent for flood extent determination. Misclassification errors do occur however, with flattened and wet vegetation behaving, in certain situations, in the same way as open water, and emergent vegetation disrupting the specular reflections in shallow open water to appear more like dry land. Moreover, orbit repeat times may be low (3 days for ASAR wide swath mode, 7–10 days for RADARSAT and 35 days for ERS-1 and ERS-2) compared to the flood dynamics in many basins. From records of flood events all around the world since 1985 collected by the Dartmouth Flood Observatory (http://www.dartmouth.edu/~floods/archiveatlas/index.htm), it appears that the mean duration of floods is around 9.5 days and the median duration is 5 days. Accordingly, there may only be a low probability of a SAR overpass occurring simultaneously with a flood in all but the largest river systems. Moreover, SAR sensors are designed to be all-purpose instruments and may not be optimal for flood mapping (see, for example, Bates et al. 2004). Constellations of satellites are likely to be the only way to achieve a suitable combination of resolution and revisit frequency (García-Pintado 2013). For example, the COSMO–Sky-Med constellation can offer a revisit time as short as 12 h. The few studies to have obtained simultaneous aerial photograph and satellite SAR data have shown that the accuracy of satellite radars in classifying flood extent to be only of the order 80–85 % (Biggin and Blyth 1996). As a consequence, significant research effort has been expended in developing sophisticated techniques to classify SAR imagery into wet and dry areas (see, for example, Matgen et al. 2007; Mason et al. 2007; Giustarini et al. 2013).

Combining the observations of inundation extent available from optical, passive microwave and active microwave systems, a number of researchers have developed global floodplain and wetland inundation extent data sets. For example, Prigent et al. (2007) used passive microwave land surface emissivities calculated from SSM/I and ISCCP observations, ERS scatterometer responses, and AVHRR visible and near-infrared reflectances from 1993 to 2000 to calculate average monthly inundated fractions of equal-area grid cells (0.25° × 0.25° at the equator). Similarly, the Dartmouth Flood Observatory (http://floodobservatory.colorado.edu/, see Adhikari et al. 2010) uses 250 m resolution MODIS and other data, such as the SRTM Water Body Data set (SWBD), to map flooding in near real time and from this compile an archive of large floods. Such data sets provide a first comprehensive global view of surface water dynamics and flooding.

2.3 Remote Measurements of Water Elevation

Remote measurements of water surface elevation can be obtained from (a) profiling altimeters such as the JASON and Topex–Poseidon radar altimeters or the Geoscience Laser Altimeter System (GLAS) on board the ICESat satellite; (b) interferometric measurements of water surface elevation change using pairs of synthetic aperture radar images; and (c) the intersection of shorelines derived from inundation extent data (e.g., a satellite SAR scene) with a suitable digital elevation model.

Satellite radar altimeters were primarily designed from oceanic studies and have a footprint of ~2 km and vertical accuracy of decimetres to metres (Birkett et al. 2011). Such instruments also have wide (hundreds of kilometres) spacing between tracks which miss many of the world's rivers and most of the world's lakes. Over the continental land surface, such instruments therefore only record elevations over the very largest rivers; however, sophisticated retracking algorithms have recently been developed (e.g., Berry et al. 2005), which allow separation of water and other signals in mixed pixels. In this way, the elevation of smaller water bodies (~hundreds of metres across) can be obtained and used for flood model validation (e.g., Wilson et al. 2007). The GLAS laser aboard the ICESat satellite, although primarily designed to measure ice sheet topography, produced data with a footprint of ~70 m, which makes it more suitable for observing river water levels than radar altimeters. However, GLAS only operated between 2003 and 2009 and the laser instruments on board suffered from a number of technical issues such that only limited data with track spacing similar to radar altimeters are available. Nevertheless, the data have proved useful in particular areas of surface water science, such as geodetically levelling river gauges in remote basins (Hall et al. 2012) and determining water surface slopes in large unmonitored rivers (e.g., O'Loughlin et al. 2013).

As an alternative to profiling instruments, images of relative water height change over time ($\partial h/\partial t$) can be obtained from interferometric analysis of pairs of coherent SAR scenes taken from slightly different viewing geometries. Coregistration of the images to sub-pixel accuracy and subtraction of the complex phase and amplitude for each image allows surface displacement to be measured to centimetric accuracy. Such techniques were originally developed for ground deformation and glaciological studies (see, for example, Massonnet et al. 1993; Goldstein et al. 1993), but have subsequently been employed to map surface waters in particular circumstances (see Alsdorf et al. 2000, 2001a, b). For open water, specular reflection of the radar signal usually results in complete loss of temporal coherence, but for inundated floodplains, where there is emergent vegetation, Alsdorf et al. (2000) show that it is possible to obtain reliable repeat-pass interferometric measurements because of the so-called double bounce effect whereby the radar path includes both water and tree trunk surfaces. This allows relative water elevation change between images to be mapped to ~100-m resolution with centimetric accuracy and has been used to map complex water height change patterns in the Amazon floodplain (Alsdorf et al. 2007b) and to undertake rigorous testing of the ability of two-dimensional floodplain models to simulate the spatial and temporal dynamics of inundation (Jung et al. 2012).

Finally, from maps of inundation extent determined using the techniques outlined in Sect. 2.2, estimates of water elevation can be obtained by intersecting the shoreline vector with a suitable DEM. Such techniques are reviewed in detail by Schumann et al. (2009) who note their utility for constraining hydraulic models. The accuracy of water elevation data derived in this way clearly depends on both the quality of the image processing and the resolution and accuracy of the DEM, but Schumann et al. (2010) show that useful information for flood wave analysis can be obtained even when using low-resolution (75 m pixel) ASAR wide swath mode images and the SRTM DEM. Moreover, Mason et al. (2009) show that water elevations obtained by intersecting SAR imagery with DEM data are better at discriminating between competing model formulations than inundation extent data.

2.4 Remote Measurements of Water Storage

Change in water storage on the land surface can be measured either indirectly by calculating the implied volume difference between two flood extent measurements when intersected with a suitable DEM or directly using observations of the Earth's changing gravity field. Data on the latter are available from the GRACE and GOCE satellite missions, although with limited spatial (~hundreds of kilometres) and temporal (~monthly) resolution. In their raw state, such data may therefore not be terribly useful for surface flood studies; however, Alsdorf et al. (2010) show that by carefully combining GRACE data with information on precipitation, evaporation and inundation extent, it was possible to estimate floodplain inundation rate, water storage and drainage rate for six sections of the Amazon main stem in Brazil. Whilst satellite gravimetry is of lower resolution than many of the measurements discussed so far, water storage change is relevant to a range of hydraulic, biogeochemical and ecological processes, and therefore, such data add usefully to our knowledge of surface water processes.

3 The Proposed SWOT Satellite Mission

Section 2 demonstrates convincingly that no current satellite system can capture the detail of surface flows in rivers, floodplains and wetlands (e.g., Alsdorf et al. 2000, 2007a; Bates et al. 2006) and that we lack a comprehensive and consistent view of global surface water dynamics at a scale commensurate with known process variability. In the absence of reliable observations, it is also impossible to build, calibrate and validate models that can be applied with confidence to river, floodplain and wetland systems. Whilst progress can be made by carefully employing the data derived from topographic mapping, oceanographic, cryospheric and geodetic satellites, the lack of a dedicated surface water observing mission fundamentally limits our ability to map, model and understand surface water dynamics. Against this background, NASA and CNES are currently developing a new satellite mission to address this gap in the global observing system: the proposed Surface Water Ocean Topography mission or SWOT (see http://swot.jpl.nasa.gov/).

SWOT is being designed as a small version of SRTM. Both are "interferometers" that construct radar interferometric phase using one pass of two SAR antennae that are permanently connected by a fixed baseline. The interferometric phase is a measurement of surface elevations, i.e. topography of land and elevations of water. Because SWOT would use a Ka-band wavelength, which is shorter than the C-band and X-band wavelengths used by SRTM, the SWOT boom separating the two SAR antennae would be 10 m compared to the 60-m boom used by SRTM. SWOT would use a near-nadir viewing geometry with look angles of well less than 10°. In contrast, SRTM used $\sim$30°–58° look angles. This near-vertical geometry results in height accuracies that would be at least an order of magnitude better than those of SRTM. The proposed SWOT mission is expected to produce ±50 cm height accuracies per sampling element (e.g., pixel). However, this viewing geometry would also result in a greater amount of layover for SWOT compared to SRTM (layover results when higher elevations are mapped by the SAR geometry into spatial locations closer to the radar). Also because of this viewing geometry, the spatial samples would vary in size from potentially as small as 2.5 m × 10 m to as large as 10 m × 70 m. The height error is normally distributed, so averaging samples improves the height accuracy by $1/\sqrt{(m)}$, where m is the number of samples. For example, a 250 m × 250 m lake sampled entirely by the finest spatial resolution would have a ±1 cm height accuracy after averaging, whereas when sampled entirely by the coarsest spatial resolution, the height accuracy is reduced to about ±5 cm.

The proposed SWOT mission is presently in "Phase A" of the NASA and CNES mission development life cycle. An international science definition team is working with SWOT project engineers and planners to define the required spatial, temporal and height accuracies. These requirements are expected to allow sampling of rivers at least as small as 100 m in channel width and perhaps smaller. Lakes and other water bodies 250 m × 250 m in size and perhaps even smaller are also under consideration for the mission design. To further help in defining the mission, an airborne version of SWOT has been created. AirSWOT has initiated test flights and is expected to sample rivers, lake and wetlands during 2013 and thereafter. Amongst the AirSWOT goals is to demonstrate the capability of the radar system to penetrate vegetation to the underlying water surface. Given the radar design, both SWOT and AirSWOT are expected to penetrate vegetation through canopy openings.

4 Inferring Remaining Unknown Variables Using DA

As noted above, no current or planned future satellite system is capable of measuring either river bathymetry or discharge directly, and to determine discharge from space requires that the river bathymetry and friction are known (see, for example, Smith 1997; Bjerklie et al. 2003). Discharge is a key variable for surface water science, for which we currently have no globally consistent and comprehensive data. However, by combining dynamical information on changing water level and flood extent derived from remote sensing with a suitable hydraulic model, it may be possible to infer the unknown bathymetry and friction and hence estimate discharge from space. Data assimilation provides the mathematical framework for this analysis as it allows for optimal estimation of the unknown variables given the observed data and the constraints provided by the physical laws encoded by the model. To first order the problem of estimating, discharge from space can be illustrated by the well-known Manning equation:

$$Q = \frac{AR^{2/3}S_f^{1/2}}{n} \tag{2}$$

where Q is the discharge; A is the channel cross-sectional area; R is the hydraulic radius; S_f is the water surface slope; and n is the Manning resistance coefficient which describes all the frictional losses. Clearly, only S_f is observable from space, yet to estimate discharge, we also need to know A, R and n. Early research in this area showed that if either friction or bathymetry was assumed to be known, it was relatively easy to estimate the remaining unknown variable (see, for example, Andreadis et al. 2007; Durand et al. 2008; Neal et al. 2009; Biancamaria et al. 2011; Yoon et al. 2012). However, Eq. 2 clearly shows that A, R and n trade-off against each other, which complicates the joint estimation problem. Joint estimation therefore requires considerably more dynamical information to isolate the differing effects of bathymetry and friction on water level dynamics. However, recent research (e.g., Lai and Monnier 2009; Hostache et al. 2010; Durand et al. 2010, submitted) is beginning to show that such joint estimation may indeed be possible because friction and bathymetry vary in distinctive and different ways in space and affect the various terms in the Saint–Venant equation (Eq. 1) in different ways. Changing friction or bathymetry has different "signature" effects on water surface height and slope change in time and space, and only a few combinations of both can fully explain observations of floods with different wave speeds or water surface slopes. Physically, water surface slopes respond only gradually to changing friction, whereas a sudden change in channel capacity or bed slope can have a much more immediate effect on the flow and wave propagation. Data assimilation methods can be developed to exploit these differences and hence estimate unknown bathymetry and friction simultaneously based only on repeated observations of water level and slope and an appropriate dynamical model to obtain discharge. Key research questions are therefore exactly how much water elevation and slope data are required and how much dynamical variation in the observations is necessary to obtain a (near) unique solution.

5 Conclusions

This paper has reviewed our understanding of global surface water flood dynamics and the role such waves play in the Earth system. Flood waves are both a key determinant of globally important biogeochemical and ecological processes and, at particular times and particular places, a major environmental hazard. Despite this, the current global observing system cannot capture the detail of surface flows in rivers, floodplains and wetlands, and we lack a comprehensive and consistent view of global surface water dynamics at a scale commensurate with known process variability. The paper demonstrates that by careful use of the data obtained from remote sensing instruments designed for different geophysical applications, progress can be made in our understanding of the surface water dynamics of a number of major floodplain and wetland systems. Ultimately, however, a detailed understanding would only be possible with the launch of a dedicated satellite mission for surface water carrying an instrument capable of capturing data of the right resolution and accuracy. The proposed SWOT satellite mission would have the potential to address this need and help answer new and exciting science questions that would be likely to revolutionize our view of hydrology.

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