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Towards Formulation of a Space-borne System for Early Warning of Floods: Can Cost-Effectiveness outweigh Prediction Uncertainty?

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Abstract. The three most important components necessary for functioning of an operational flood warning system are: (1) a rainfall measuring system; (2) a soil moisture updating system; and, (3) a surface discharge measuring system. Although surface based networks for these systems can be largely inadequate in many parts of the world, this inadequacy particularly affects the tropics, which are most vulnerable to flooding hazards. Furthermore, the tropical regions comprise developing countries lacking the financial resources for such surface-based monitoring. The heritage of research conducted on evaluating the potential for measuring discharge from space has now morphed into an agenda for a mission dedicated to space-based surface discharge measurements. This mission juxtaposed with two other upcoming space-based missions: (1) for rainfall measurement (Global Precipitation Measurement, GPM), and (2) soil moisture measurement (Hydrosphere State, HYDROS), bears promise for designing a fully space-borne system for early warning of floods. Such a system, if operational, stands to offer tremendous socio-economic benefit to many flood-prone developing nations of the tropical world. However, there are two competing aspects that need careful assessment to justify the viability of such a system: (1) cost-effectiveness due to surface data scarcity; and (2) flood prediction uncertainty due to uncertainty in the remote sensing measurements. This paper presents the flood hazard mitigation opportunities offered by the assimilation of the three proposed space missions within the context of these two competing aspects. The discussion is cast from the perspective of current understanding of the prediction uncertainties associated with space-based flood prediction. A conceptual framework for a fully space-borne system for early-warning of floods is proposed. The need for retrospective validation of such a system on historical data comprising floods and its associated socio-economic impact is stressed. This proposal for a fully space-borne system, if pursued through wide interdisciplinary effort as recommended herein, promises to enhance the utility of the three space missions more than what their individual agenda can be expected to offer.

Key words: flood hazards, early warning systems, space-based missions, remote sensing, prediction uncertainty

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1. Introduction

Floods are one of the deadliest and economically most destructive natural hazard; more than 2000 lives are lost and at least 10,000,000 people are displaced annually since 1991 (see http://www.dartmouth.edu/~floods). Most importantly, due to the climatological abundance of rainfall over the tropics, floods are more frequent in regions that lack financial resources to employ surface weather stations necessary for flood monitoring (see Figure 1 and Table I). This fact worsens further the destructive nature of floods due to the absence of an early warning system for these ungauged regions (NOAA, 1994).

Rainfall is arguably the primary causative factor for floods. Its intimate interaction with the landform (i.e., topography, vegetation and channel

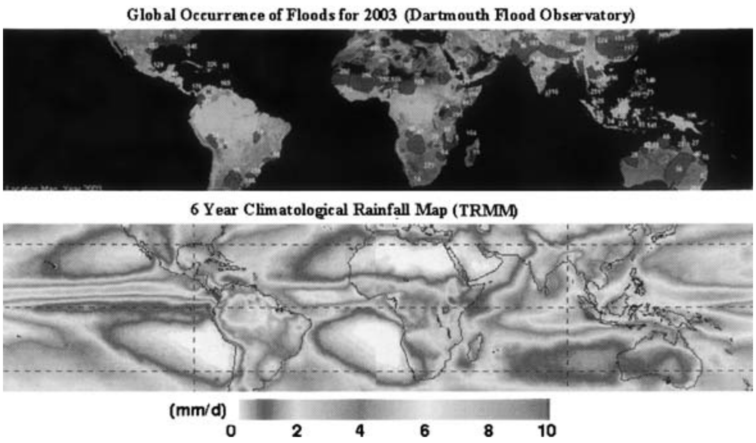

Figure 1. Upper panel – the global occurrence of floods for 2003 (map produced with kind permission of the Dartmouth Flood Observatory, http://www.dartmouth.edu/~floods). Lower panel – a 6-year climatologic rainfall map produced by the Tropical Rainfall Measuring Mission (source: http://www.trmm.gsfc.nasa.gov).

Table I. Summary of major flooding events that took place in tropical countries between August 1, 2004 and December 15, 2004 (complied from Dartmouth Flood Observatory).

Flood-affected tropical countries	Number of major flooding events	Death toll (Approximate)	Economic damage
Sri Lanka, Malaysia, Indonesia, Philipines, Vietnam, India, Bangladesh, Panama, Nigeria	14	> 520	US$150,000,000

network) magnified by highly wet antecedent conditions is the necessary ingredient for catastrophic flooding. For an operational early-warning system for floods, the three most important components therefore are: (1) a rainfall measuring system (the major input to the hydrological model); (2) a soil moisture updating system (for initializing the hydrological model); and (3) a surface discharge measuring system (for calibration and constraining predictions of the hydrological model). Although surface-based networks for these systems is inadequate in many parts of the world (Alsdorf and Lettenmaier, 2003), this inadequacy particularly affects the tropics that are most vulnerable to flooding hazards (Figure 1). Due to the poor economy of most tropical nations, establishment of an early-warning system based on costly surface-based monitoring is perhaps not always possible.

This situation may soon change. The emergence of cost-effective space-based technologies for large-scale measurement of rainfall, soil moisture and discharge now offer promise as an alternative to the costly ground-based system. The heritage of research conducted on evaluating the potential for measuring discharge from space has now morphed into a coherent call by the scientific community for a mission dedicated to space-based surface discharge measurements (Alsdorf and Lettenmaier, 2003; Alsdorf *et al.*, 2003; Bjerklie *et al.*, 2003), This proposed mission, juxtaposed with two other upcoming space-based missions: (1) for rainfall measurement (Global Precipitation Measurement, GPM), and (2) soil moisture measurement (Hydrosphere State, HYDROS), bears promise for assimilation of a fully space-borne system for early warning of floods. Such a system, if operational, stands to offer tremendous socio-economic benefit to many flood-prone tropical nations of the world.

However, there are two competing aspects that need careful assessment to justify the viability of a fully space-borne system: (1) cost-effectiveness due to (expensive) surface data scarcity universally experienced by poor countries; and (2) flood prediction uncertainty due to uncertainty in the remote sensing measurements and hydrologic modeling. This paper presents the flood hazard mitigation opportunities offered by the assimilation of the three space missions (two nearing launch and one being proposed) within the context of these two competing aspects. The objectives of the paper are as follows. (1) To provide a summary of research heritage on space-borne remote sensing of rainfall, soil moisture and surface discharge; (2) To formulate a conceptual framework for an operational early-warning system for floods that assimilates the three future space missions; and (3) To briefly discuss possible ways for evaluating the viability of the framework. The discussion is cast from the perspective of current understanding of the prediction uncertainties associated with space-based flood prediction. The need for retrospective validation of such a system on historical data comprising floods and its associated socio-economic impact is also stressed. This proposal for a fully space-borne system, if pursued through wide inter-disciplinary effort as recommended herein, promises to enhance the utility of the three space missions more than what their individual agenda can be expected to offer.

2. The Research Heritage of Space-borne Measurements

2.1. REMOTE SENSING OF RAINFALL

Of the three hydrologic variables (soil moisture, discharge and rainfall), space-borne rainfall remote sensing is perhaps the most well-researched, well-understood and promising technology today (Foufoula-Gerogiou and Krajewski, 1995). The history of rainfall estimation from space dates back to the 1970s, when infra-red (IR) sensors on geo-stationary platforms were used to track cloud movement, advance climate and weather prediction and even qualitatively monitor flash floods (Griffith *et al.*, 1978; Scofield and Oliver, 1987; Huffman *et al.*, 2001; Janowiak *et al.*, 2001). While IR radiometers on geo-synchronous satellites provide excellent time and space sampling, the quantity being sensed (mostly cloud-top temperature) is indirectly connected to rainfall (Huffman *et al.*, 2001). As a response to this limitation, space-borne Passive microwave (PM) radiometers evolved as a more credible alternative in the late 1980s. PM sensors are more accurate because of the direct interaction between hydrometeors and the radiation field. In 1987, the first Special Sensor Microwave/Imager (SSM/I) was launched on the Defense Meteorological Satellite Program (DMSP) F-8 satellite. Currently, there are three SSM/I spacecrafts (F13, F14 and F15) providing PM rainfall measurements in sun-synchronous orbits. In 1997, the Tropical Rainfall Measuring Mission was launched (TRMM). TRMM carries a Microwave Imager (TMI) similar to SSM/I (Simpson *et al.*, 1996). Very recently, another PM sensor rainfall measurement, the Advanced Microwave Scanning Radiometer for EOS (AMSR-E) was launched in 2002 as part of the AQUA mission.

The particular success of TRMM in improving our understanding on Tropical and Sub-tropical rainfall distribution and precipitation structures has now spurred a larger scale mission aimed at the study of global water cycle. This mission, named the GPM, envisions a constellation of PM sensors that will provide global rainfall products at scales ranging from 3 to 6 h over regions as small as 100 km^2 (Smith, 2001; Bidwell *et al.*, 2002; Flaming, 2002; Yuter *et al.*, 2003). GPM also envisions the extension of ❷ ‘scientific and societal applications’ of this high-resolution global rainfall data as one of its major objectives.

2.2. REMOTE SENSING OF SOIL MOISTURE

Due to the strong sensitivity of dielectric constant to water content, microwave (MW) wavelengths are considered most suitable for remote sensing of soil moisture. However, there is currently no operational space-borne mission dedicated fully to its measurement despite the fact that remote sensing of soil moisture has a history comparable to that of rainfall remote sensing. This absence is primarily due to the fact that microwave sensors require operation at low frequencies (<1.5 GHz) to provide reliable estimates at wide range of land cover conditions (Entekhabi *et al.*, 1994; Njoku and Entekhabi, 1994; Jackson, 1997). Hence, the same passive radiometers used for rainfall measurement have also been evaluated of their accuracy in soil moisture estimation by Jackson (1997) (SSM/I), Njoku and Li (1999) (AMSR-E). While active microwave remote sensing can also be used for soil moisture estimation (Hoeben and Troch, 2000), its application from space-borne platforms has been almost non-existent due to the absence of active MW space-based sensors (until TRMM, in 1997). Recently, Du *et al.* (2000) studied the relative merits of passive and active MW remote sensing for soil moisture measurement.

Realizing the importance of soil moisture in understanding the hydrological state of the global environment, the scientific community has recently translated this realization successfully into a future space mission – HYDROS – dedicated solely to soil moisture measurements. In 2009, HYDROS, armed with low frequency (<1.5 GHz) active and passive MW sensors, is expected to make unprecedented measurements of Earth's changing soil moisture and the freeze/thaw status of land surface that, together, define the state of Earth's hydrosphere (for more information, visit http://www.hydros.gsfc.nasa.gov). Although, soil moisture estimates from HYDROS will be limited to the upper 5 cm layer, there is a wide body of literature that has demonstrated an ability to retrieve the soil moisture content at much greater depths when this near-surface information is assimilated into a land surface model (see for example: Entekhabi *et al*, 1994), HYDROS, for the first time, can therefore be actively considered in a flood warning system due to its high level of accuracy (discussed in next section).

2.3. REMOTE SENSING OF DISCHARGE

In a comprehensive review of satellite remote sensing techniques of river discharge, Smith (1997) presents a promising picture of the technology being applicable for ungauged river reaches. Smith *et al.* (1996) has also demonstrated that the use of Synthetic aperture radar (SAR) imagery is potentially useful even for large braided rivers in Alaska and British

Columbia. Using similar SAR imagery combined with topographic information, Brakenridge *et al.* (1998) successfully recreated to a reasonable degree of accuracy the water surface profiles during the Great Flood of summer 1993 in the Upper Mississippi Valley. Vorosmarty *et al.* (1996a) on the other hand, have demonstrated the potential for applying 37 GHz passive MW satellite sensor data to infer discharge dynamics of large river systems using the main stem Amazon river as their test case. Their application was, however, confined to a very coarse temporal resolution (monthly) and suitable only for water balance and climatologic inquiries. Its application to the much finer flood-scale spatio–temporal resolution needs to be explored. Recent uncertainty analysis indicates that existing satellite-based sensors can measure water surface width, elevation and velocity with accuracies sufficient to provide discharge estimates with less than 20% uncertainty for large rivers of North America (e.g. Connecticut river), Africa (Okvango river) and South America (Amazon river) (Bjerkle *et al.*, 2003).

Despite the promising progress made on space-based discharge measurements in the last decade, it is only recently that the pertinent scientific community has started to voice the desire for a space mission dedicated solely to measurement of surface waters (Alsdorf and Lettenmaier, 2003; Alsdorf *et al.*, 2003). Bjerkle *et al.* (2003) critically evaluated the pros and cons of the range of technology options for space-borne discharge measurement. Alsdorf and Lettenmaier (2003) on the other hand, commented that despite the range of options available (including new missions), none of these technologies supply the water volume measurements needed to accurately model the water cycle. Nevertheless, the existing and future missions provide a conceptual framework for a surface discharge satellite mission that could provide the required information. Alsdorf and Lettenmaier (2003) summarized the desired features of such a dedicated space-borne mission for discharge measurement as follows: (1) it should have a spatial resolution of 100 m; (2) it should have an overpass frequency less than a few days to capture the short flood events; and (3) it should have a vertical resolution of a few centimeters. It should be noted that for many countries, the overpass frequency would need to be less than a day (3–6 hourly), such as for the case of Bangladesh during the Monsoon season (Paudyal, 2002). Alsdorf and Lettenmaier (2003) concludes that such a satellite mission would enable hydrologists to move beyond the point-based gauging methods of the last century to measurements that capture the spatial variability inherent in surface water hydrology. Furthermore, global coverage of such a mission would ensure that, despite local economic and logistic problems, all countries could access measurements critical for forecasting of floods.

3. A Conceptual Framework for a Space-borne Early Warning System

This section provides a conceptual framework for a fully space-borne early warning system for floods. It assumes that GPM, HYDROS, and the proposed mission for discharge (hereafter called GDM Global Discharge Measurement) are all in orbit after 2010. The framework is specifically confined to the tropics bounded by the ± 40° latitudes where it is expected to be most cost-effective due to the prevalence ungauged watersheds within (Figure 1), For this region, GPM will provide rainfall estimates ranging from 3 to 6 h at the 10×10 km^2 resolution. HYDROS will provide soil moisture estimates of the upper 5 cm layer at 10×10 km^2 resolution every 2–3 days. Similarly GDM will provide surface discharge measurements along the channel networks within 10×10 km^2 grids with a 2–3 day repeat cycle. Except for rainfall, measurements of soil moisture and discharge are assumed deterministic processes due to their very low uncertainty ($<4\%$ and $<20\%$, respectively). Hence, the primary function of HYDROS and GDM is in updating and constraining the warnings (prediction) produced by the framework. Since the framework is only conceptual in nature, its quantitative specifications that follow hereafter should be regarded as 'flexible' and the subjective details of operation are considered open to debate.

The proposed framework discretizes the entire domain under the ± 40° latitudes into $1° \times 1°$ grids. Past applications of macro-scale hydrological models for discharge prediction of global rivers (Nijssen *et al.*, 1997; Coe, 2000; Nijssen *et al.*, 2001) and the socioeconomic value of warning over the tropics (Paudyal, 2002), indicate that this spatial resolution is perhaps adequate, although it may be altered in accordance with computational resources and specific objectives. This discretization yields about 9000 pixels overland, each approximately representing an administrative unit within the tropical countries. Within each pixel, two kinds of model will operate: (1) an offline Land Surface Model (LSM) in continuous mode (half-hourly); and (2) a Hydrologic/Flood Model in event mode (total time period of simulation is about 48 h). The purpose of the LSM is to provide reliable estimates of the antecedent soil moisture conditions for each pixel with equally reliable estimates of the ranges of uncertainty. These estimates are then used to initialize the Hydrologic model according to the ranges of possible initial moisture conditions within the uncertainty limits (predicted by the LSM). Furthermore, the soil moisture estimates from the LSM will be regularly updated and constrained by HYDROS measurements using numerical filtering schemes similar to those currently used in the Land Data Assimilation System (LDAS, Margulis *et al.*, 2003; Robock *et al.*, 2003; Walker and Houser, 2004). The Hydrologic model will be used for forecasting of floods by passing through it, the next possible 48-h realization of rainfall forecast. The term 'forecasting' is used loosely in reference to ‘prediction’ and does not necessarily imply the use of stochastic-dynamic models. The rainfall forecast may be derived from either a cloud model that is initialized with the most current rain estimates from GPM, or a statistical time-series model, depending on the required level of complexity (which is currently unknown). An ensemble approach is proposed for modeling the possible scenarios of initial soil moisture conditions, rainfall realizations and model parameter states (LSM and Hydrologic event-based). This ensemble approach has the potential to promote the following: (1) probabilistic forecast (i.e., prediction with error bounds) of the stream discharge; (2) risk assessment and decision-making; (3) conceptual appeal the ensemble data assimilation schemes for updating model state with space observations (Margulis *et al.*, 2002). For ensemble approaches to modeling satellite rainfall and hydrologic model states, the reader is referred to Hossain and Anagnostou (2004a, b), Hossain *et al.* (2004a, b). For ensemble modeling of soil moisture states and its updating, Margulis *et al.* (2002) provides the necessary background to understand in detail its importance. With the modeling of different scenarios of soil moisture initial conditions and the probable rainfall realizations, a probabilistic prediction of the flood event for the next 48 h can now produced in a fashion similar to the Ensemble Prediction System (ESP) used by the National Weather Service (Day, 1985) or that developed by Hossain and Anagnostou (2005). Similar to the LSM, the hydrograph of discharge predicted by the Hydrological model can be compared, updated and constrained by the GDM measurements available every 2–3 days.

Literature review suggests the following as potentially suitable set of candidates for the models: (1) LSM–Common Land Model (CLM) (Dai *et al.*, 2003) and NOAH–LSM (Chen *et al.*, 1996); and (2) Hydrological Model – MIKE 11 (DHI, 1999), VIC-2L (Liang *et al.* 1994; Nijssen *et al.*, 2001), HyDRA (Coe, 2000) and TOPMODEL (Beven and Kirkby, 1979). A large proportion of the supporting data for operating the LSM and Hydrological model in the above mode is available from space-borne platforms, For example, requisite topographic information (DEM, channel network) are available from Topex/Poseidon, while vegetation information can be availed from MODIS or AVHRR on a regular basis.

The ultimate objective of the framework is to be able to provide useful probabilistic estimates of flood warning for the next 48 h on a relative scale of intensity (say from 1 to 10, like the Fujita scale for tornadoes). This scale may be calibrated for each pixel depending on the socio-economic factors, level of flood protection and public warning infra-structure at the local level. Measurements from HYDROS and GDM will be used for the updating of the framework every 2–3 days, while GPM measurements will be the primary driver (e.g. a forecast sequence of 48 h via Cloud Model or a stochastic time-series model) for forecasting the next

48 h sequence of the flood. Figure 2 provides a schematic to summarize the conceptual nature of the framework. Again, a detailed elaboration of the framework is deliberately avoided herein, as the main purpose of this study is to present (qualitatively) the possibility of assimilating future space missions for an early warning system over ungauged regions. Although it is recognized that there may be other important criteria that are not examined here, it is hoped that this paper will lead to further studies involving a wide range of ideas, model structures, resolutions and objectives towards optimal integration of remotely sensed data in a space-borne flood warning framework.

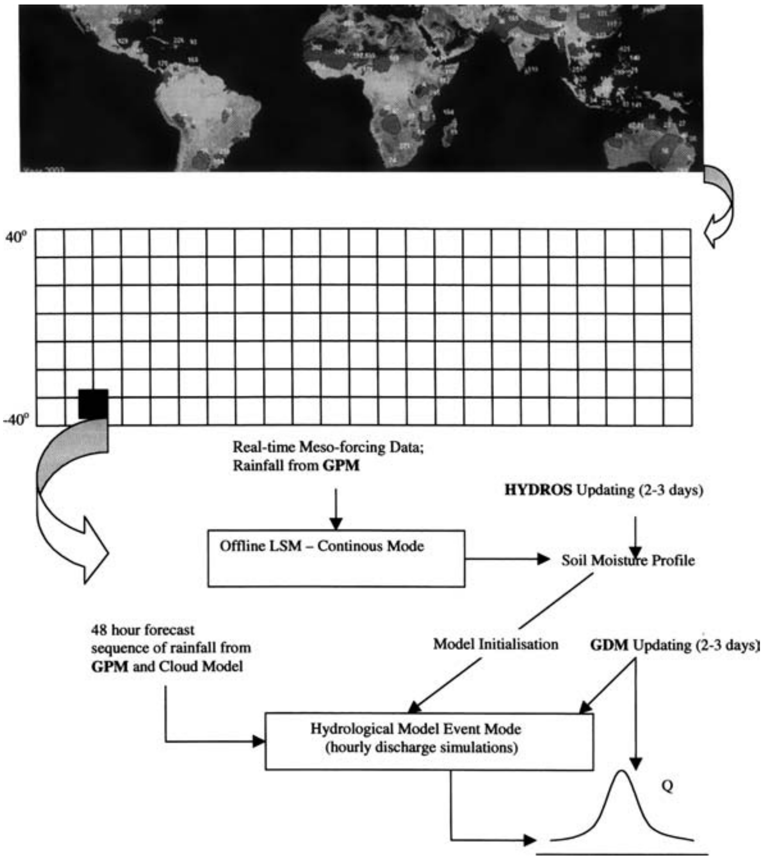

Figure 2. A conceptual framework for a space-borne early warning system for floods over ungauged tropical regions. Uppermost panel – the global occurrence of floods for 2003 (as in Figure 1); Middle panel – a conceptual discretization of the region bounded by ±40° latitudes into 1° × 1° grids (al grids are not shown). Lowermost panel – the conceptual assimilation of models and space missions for flood forecasting.

4. Cost Effectiveness Versus Prediction Uncertainty: The Need for Retrospective Validation

While any proposed framework for an early warning system for floods over poor ungauged areas will be highly cost-effective once operational, one particular aspect that, however, undermines this cost-effectiveness is the flood prediction (forecast) uncertainty of the framework, This uncertainty arises mainly from the inherent uncertainty in the remote sensing measurements of rainfall that propagates in the rainfall–runoff transformation or the rainfall–soil moisture transformation, Hence, the GPM measurements need to be modeled as a random process for an assessment of the predictive uncertainty (Hossain *et al.*, 2003; Hossain and Anagnostou, 2004). HYDROS soil moisture and GDM discharge measurements on the other hand, are treated as deterministic processes due to their comparatively lower levels of uncertainty.

Fortunately, assessment of uncertainty in flood and soil moisture prediction in anticipation of GPM and HYDROS has begun recently (Hossain and Anagnostou, 2004a; Nijssen and Lettenmaier, 2004; Walker and Houser, 2004). Hossain and Anagnostou (2004a) have shown that GPM can be expected to reduce by about 50% of the flood prediction uncertainty although significant uncertainty would still remain for prediction of flood events longer than 2 days. Walker and Houser (2004) have shown that HYDROS should have a measurement error less than 4% with a repeat time of 1 day to be most useful for updating moisture states. However, due to absence of studies that assess HYDROS and GPM in a combined framework, it is not clear right now as to what the level of uncertainty can be expected at the forecasting level of the conceptual framework proposed herein. Hence exploratory studies attempting to assess the flood forecasting uncertainty needs to be initiated soon.

Addressing the issue of global-scale predictive variability of floods in anticipation of future remote sensing missions is one of the most complex and challenging societal applications. The problem is multifaceted, multidisciplinary and interface oriented. Knowledge of both the rainfall measurement process and the modeling of its surface transformation to floods are required. The requirement for this inter-disciplinary knowledge needs to be further brought under an objective framework that aims to provide feedback between the efforts at addressing hydrologic application and the efforts to improve measurement of rainfall. In the past, this feedback has been virtually absent in literature, hence both these knowledge bases evolved independently of the other. However, feedback is vital, because it is the feedback that has the potential to enhance the application of rainfall, soil moisture and discharge measurement from future missions for prediction of floods.

Validation (or assessment of the proposed framework) on retrospective (historical) flood data is therefore the only way of assessing the true worth of the cost-effectiveness of a proposed space-borne early warning system. The Dartmouth Flood Observatory (http://www.dartmouth.edu/~floods) is perhaps the most resourceful institution in this regard for gaining an insight on historical cases ideal for retrospective validation. Data used by other studies such as Nijssen *et al.* (2001) and Coe (2000) in global discharge measurements using hydrological models, combined with the global river database by Vorosmarty *et al.* (1996b) should be considered for the selection of test cases. However, much work needs to be done to finalize the datasets that will numerically allow testing of the proposed scheme. Retrospective validation of the framework should also be based on how effectively the framework issues flood warnings compatible with the actual occurrence of the flood. This should also take into consideration the probability of false hopes and false alarms – both of which can actually be economically debilitating for poor tropical economies. Additionally, false hopes and false alarms undermine the faith of the public in the flood warnings of the system.

It should be noted therefore that operational sustainability of the proposed space-borne framework can be pursued only after satisfactory results in retrospective validation. Hence, the critical question on cost-effectiveness versus prediction uncertainty will need to be closed before an assessment of an actual flood forecasting scenario in real-time can be investigated. For investigating such operational sustainability, we shall need to factor in the currently adopted procedures institutionalized by the flood forecasting agency. The goal will need to be to remain within these procedures so that the existing forecast warning dissemination framework for disaster management is not hampered during the critical flooding season after the necessary customizations of the warning system for satellite data.

5. Conclusion

This paper discussed the state-of-the-art, challenges and opportunities posed by the three most important components necessary for functioning of an operational flood warning system. These components are: (l) a rainfall measuring system; (2) a soil moisture updating system; and, (3) a surface discharge measuring system. Although surface based networks for these systems are largely inadequate in many parts of the world, this inadequacy particularly affects the tropics which are most vulnerable to flooding hazards. Furthermore, the tropical regions comprise developing countries lacking the financial resources for adequate maintenance of such surface-based systems. The heritage of research conducted on evaluating the potential for measuring discharge from space have now morphed into an agenda for a mission dedicated to space-based surface discharge measurements. This mission juxtaposed with two other upcoming space-based missions: (l) for rainfall measurement (GPM), and (2) soil moisture measurement (Hydrosphere State, HYDROS), bears promise for designing a fully space-borne system for early warning of floods. A conceptual framework for a fully space-borne system for early-warning of floods has been proposed, Such a framework, if operational, stands to offer tremendous socio-economic benefit to many flood prone developing nations of the tropical world, However, there are two competing aspects that need careful assessment to justify the viability of such a system; (1) cost-effectiveness due to surface data scarcity; and (2) flood prediction uncertainty due to uncertainty in the remote sensing measurements, This paper has discussed the potential flood hazard mitigation opportunities offered by the assimilation of the three space missions within the context of these two competing aspects. The discussion is cast from the perspective of current understanding of the prediction uncertainties associated with space-based flood prediction. The need for retrospective validation of such a system on historical data comprising floods and its associated socio-economic impact was also stressed. This proposal for a fully space-borne system, if pursued through wide inter-disciplinary effort as recommended herein, promises to enhance the utility of the three space missions more than what their individual agenda can be expected to offer.

Although the paper aimed at presenting only a conceptual type framework for assimilation of a space-borne early warning system, there are no doubt certain elements of the framework that may be found to be operationally intractable once actively pursued. For example, there may be certain scale mis-match issues in the use of remote sensing data and model prediction that may require some upscaling approach for reconciliation. Also, none of these three missions is highly unlikely to have identical sampling overpass pattern for a region. It is therefore vital that the multi-disciplinary research community come forward under one umbrella to communicate their understanding of the potential pros and cons to the other. There is a need for increased inter-disciplinary collaboration between the two major disciplines of research most pertinent to floods – (a) space-borne remote sensing of rainfall, soil moisture and discharge; and (b) hydrologic modeling of floods using data in (a) as major inputs.

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