ERDC/CHL CHETN-VIII-8
February 2016

US Army Corps
of Engineers®

Development of Predictive Relationships for Flood Hazard Assessments in Ungaged Basins

by Nawa Raj Pradhan, Aaron Byrd, Mark R. Jourdan, and Jeffrey Ellis

---

PURPOSE: The purpose of this Coastal and Hydraulics Engineering Technical Note (CHETN) is to develop predictive relationships for characterizing the flood hazard in ungaged basins.

INTRODUCTION: Historically, the first great civilizations evolved from smaller settlements in river valleys (Diamond 1999); natural hazards, like flooding, have been an ongoing part of human history (Brouwer et al. 2007). Therefore, streamflow and fluvial information is important for designing situation-based approaches to keep the water away from the people or the people away from the water. Most river basins around the globe remain ungaged. However, often the historical records of even gaged basins are insufficient for creating accurate flood hazard assessments and mitigation (Pradhan and Ogden 2010; Sivapalan et al. 2003). Today, combining remotely sensed data and physics-based, distributed hydrological model simulation results enables flood hazard assessments of both gaged and ungaged basins.

There are several theories of hydrodynamics and infiltration equations available (Freeze and Harlan 1969) that can be used in conjunction with recommended hydrodynamic and infiltration parametric values that are found within the literature, all enabling the engineer to provide critical flooding assessments for stakeholders and decision makers (e.g., Rawls et al. 1983; Gioia and Bombardelli 2002). To estimate runoff in ungaged catchments, existing process-based hydrodynamic models can be applied in a distributed form to solve the governing equations for mass, momentum and energy in a spatially explicit way. Nimmo (2007), Brutsaert (2008), Pradhan et al. (2008), and Pradhan and Ogden (2010) show that physics-based parametric values of a model, such as hydraulic conductivity and transmissivity, are transferrable for the deployment of such physics-based hydrologic models. Nimmo (2007) analyzed 64 macropore flow data sets and found that flow velocities in macropores and fractures are well bounded, with a mean value of 13 md^{-1}. An argument posed by Brutsaert (2008) derived from the analysis of river recession data, proposed that there is a fundamental geomorphological control wherein stream drainage density develops to produce a characteristic drainage timescale or *storage half life* of 45±15 days. Pradhan et al. (2008) employed geomorphometric scaling relations to transfer TOPMODEL (Beven and Kirkby 1979) soil transmissivity parameters between watersheds located in vastly different regions of the world: Japan, Nepal, Panama, and the United States. Pradhan and Ogden (2010) transferred soil hydraulic conductivity values while deploying a One Parameter Hydrologic Model (OPM), in vastly different regions of the world: Australia, Nepal, Panama, and the United States. In this study, the physics-based, spatially distributed Gridded Surface Subsurface Hydrological Analysis (GSSHA) model (Downer and Ogden 2004) was deployed in megascale for ungaged basins of the Philippine Islands. The GSSHA hydrological processes have been rigorously tested in well-defined and detailed experimental watersheds on various geophysiological and climatological regions (Downer et al. 2010; Downer et al. 2014;

Ogden et al; 2011; Pradhan et al. 2014; Senarath et al. 2000). Optimized GSSHA performance shows that dominating parameters, such as hydraulic conductivity and manning's roughness, are consistently bounded within a narrow margin, and are significantly close to physically defined critical values depicted within the literature (e.g., Rawls et al. [1983]; Chow et al. [1988]).

STUDY AREA: Two megascale catchments in the Philippine Islands were considered in this study. No stream gage data exists for either basin and the critical input data for the hydrological modelling was entirely derived through satellite-based, globally available, soil and land use imagery.

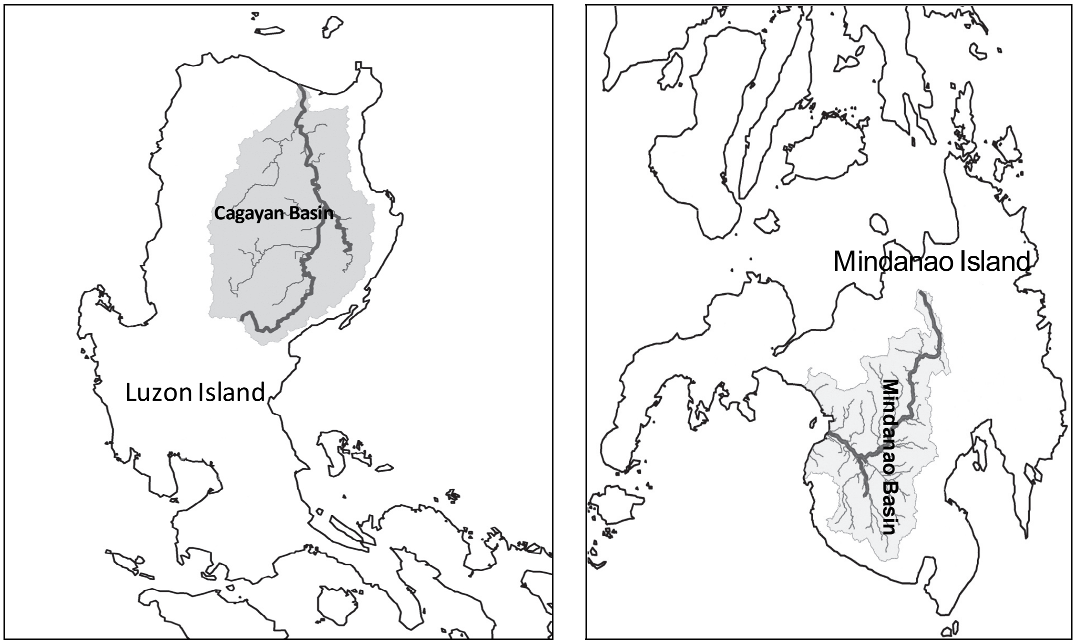
The Cagayan River Basin on Luzon Island (Figure 1[a]) is the largest river in the Philippines with a drainage area of 27,280 km^2 (Alejandrino et al. 1976). The main channel has a length of 505 km. The Cagayan River and its tributaries are subject to extensive flooding during the monsoon season (May to October) in Southeast Asia. The average annual rainfall is 1,000 mm in the northern part and 3,000 mm in the southern mountains where the river's headwaters lie. The headwaters flow relatively slowly through gently sloped meandering gorges attached to extensive floodplains (Milsom et al. 2006). Previous flooding in the Cagayan River basin has caused significant loss of life, property, and substantial economic costs.

The Mindanao River (Figure 1[b]), also known as The Rio Grande De Mindanao, is the second largest river system in the Philippines. It is the largest river on the southern island of Mindanao, with a drainage area of 23,169 km^2 that covers the majority of the central and eastern portion of the island. It is also the second longest river in the country with a length of approximately 373 km. Its headwaters are in the mountains of Impasug-ong, Bukidnon, south of Gingoog City in Misamis Oriental, where it is referred to as the Pulangi River (Gatmaytan and Dagondon 2004). Pulangi River is now known as the Mindanao River or also known as Rio Grande de Mindanao (Villabeto 2008). Flowing out of the mountains it forms the center of a broad, fertile plain in the south-central portion of the island.

METHODOLOGY: The GSSHA model was employed for hydrologic simulation. The consistency in the identified range of the parametric values and their physical applicability make GSSHA an ideal candidate for ungaged basins where parameters are usually transferred based on soil type and land use (Downer et al. 2010; Downer et al. 2014; Ogden et al. 2011; Pradhan et al. 2008; Pradhan et al. 2014; Senarath et al. 2000).

The essential elements for the development of predictive relationships for characterizing the flood hazard in ungaged basins are as follows:

a. model input requirements, spatial data collection, and processing
b. hydrological processes and physical characterization of the system
c. model simulation
d. development of predictive relationships used for estimating the extent of flood inundation over settlements and agricultural areas.



(a) (b)

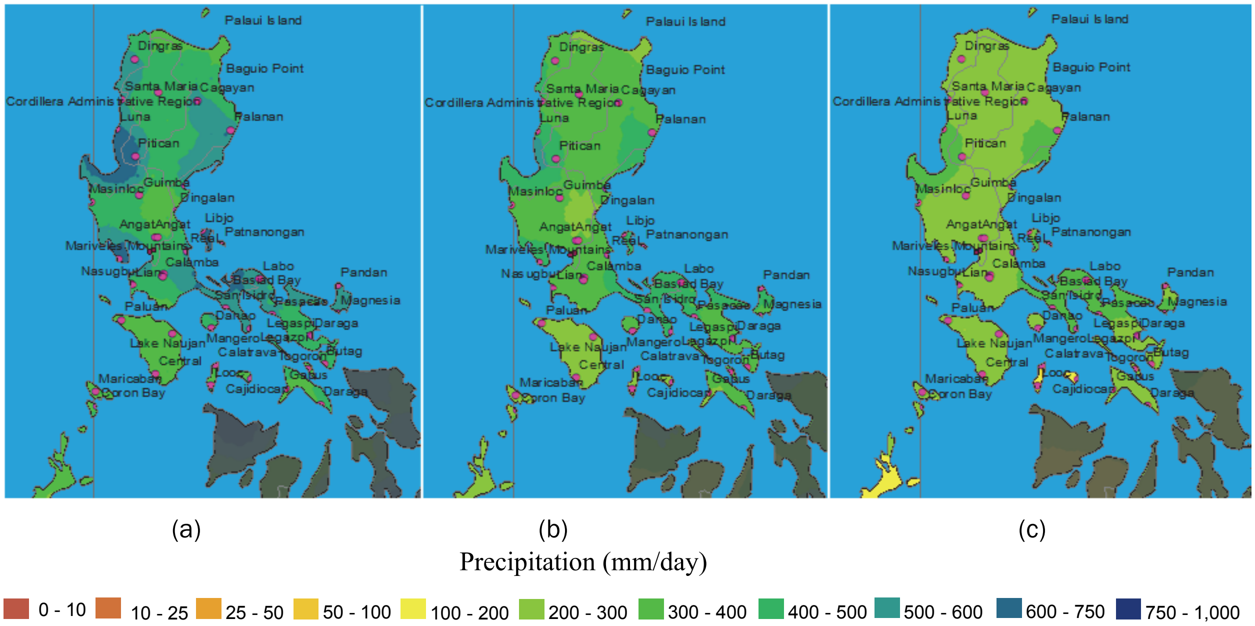
Figure 1. Study area (a) Cagayan River basin, 27,280 km^2 in the Luzon Island, Philippines, (b) Mindanao River basin 23, 169 km^2 in Mindanao Island, Philippines.

MODEL IMPUT REQUIREMENTS, SPATIAL DATA COLLECTION AND PROCESSING: The physics-based GSSHA hydrologic model incorporates spatial data products which characterize precipitation, elevation, soil type, and land use.

PRECIPITATION: The Tropical Rainfall Measuring Mission (TRMM) Version 7 was the source of the return period rainfall intensities. The return period rainfall intensities for Luzon Island and Mindanao Island are illustrated in Figures 2 and 3, respectively. The return period rainfall distributions were obtained by the extrapolation of 15 years of TRMM data using an extreme event regression function.

Physics-based distributed hydrological models, such as GSSHA, run at a fine temporal scale that limits the rainfall forcing intervals to an hour. Temporal downscaling of 24-hour accumulated return period of rainfall intensity to an hourly rate was based on the Soil Conservation Service (SCS) 24-hour rainfall distribution. The SCS 24-hour distributions incorporate the intensity-duration relationship for the design return period. Tropical extreme rainfall events are typically distributed over a longer period. Therefore, SCS Type I distribution was chosen because it is more distributed over the 24-hour period than SCS Type II and Type III distributions.

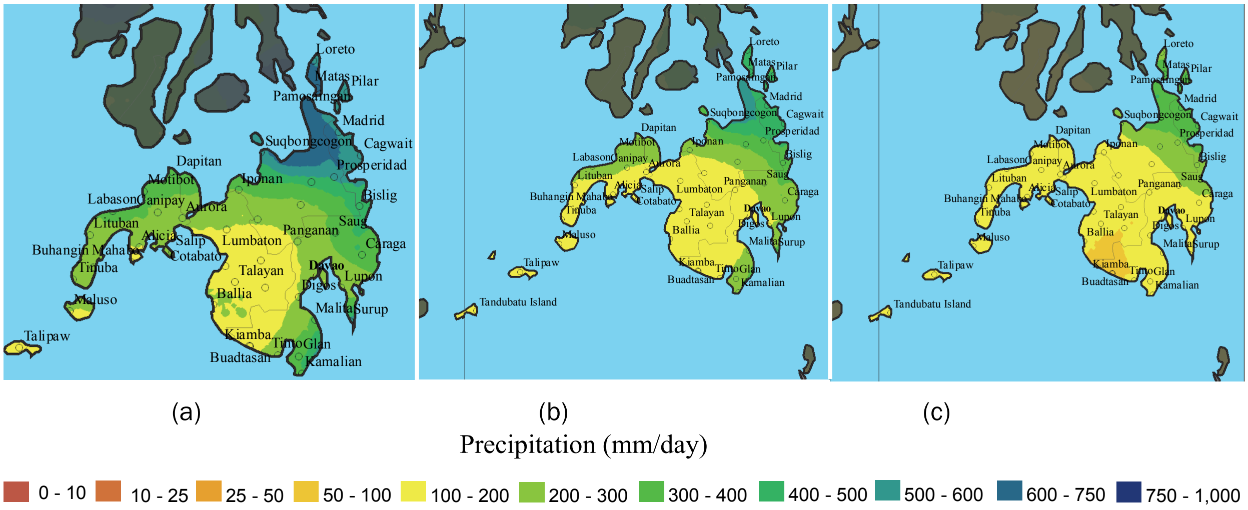
ELEVATION DATA: A 30 m digital elevation model (DEM) from the Shuttle Radar Topography Mission (SRTM), is available for the majority of Luzon Island. Voids in the 30 m DEM were filled using resampled 30 m DEM data from the SRTM 90 m DEM. The DEM was resampled to 500 m in order to reduce the computational burden.



(a) (b) (c)

Precipitation (mm/day)

Figure 2. Maps of return period rainfall intensities (mm/day) for Luzon Island, Philippines: (a) 100-year return period (b) 20-year return period, and (c) 5-year return period. (Source: METCON, Meteorological Connections LLC.)



(a) (b) (c)

Precipitation (mm/day)

Figure 3. Maps of return period rainfall intensities (mm/day) for Mindanao Island, Philippines: (a) 100-year return period (b) 20-year return period, and (c) 5-year return period. (Source: METCON, Meteorological Connections LLC.)

SOIL DATA: The Food and Agriculture Organization (FAO) United Nations world soil database was used to determine the percentage of sand, silt, and clay in Cagayan and Mindanao River basins. The FAO soil information identified the dominant soil type by applying the United States Department of Agriculture (USDA) textural classification standards. Figure 4 shows the dominant soil type identified from the textural classification triangle as applied to the FAO soil information. The soil index maps for the hydrologic models of Cagayan and Mindanao River basins were based on the maps in Figure 4.

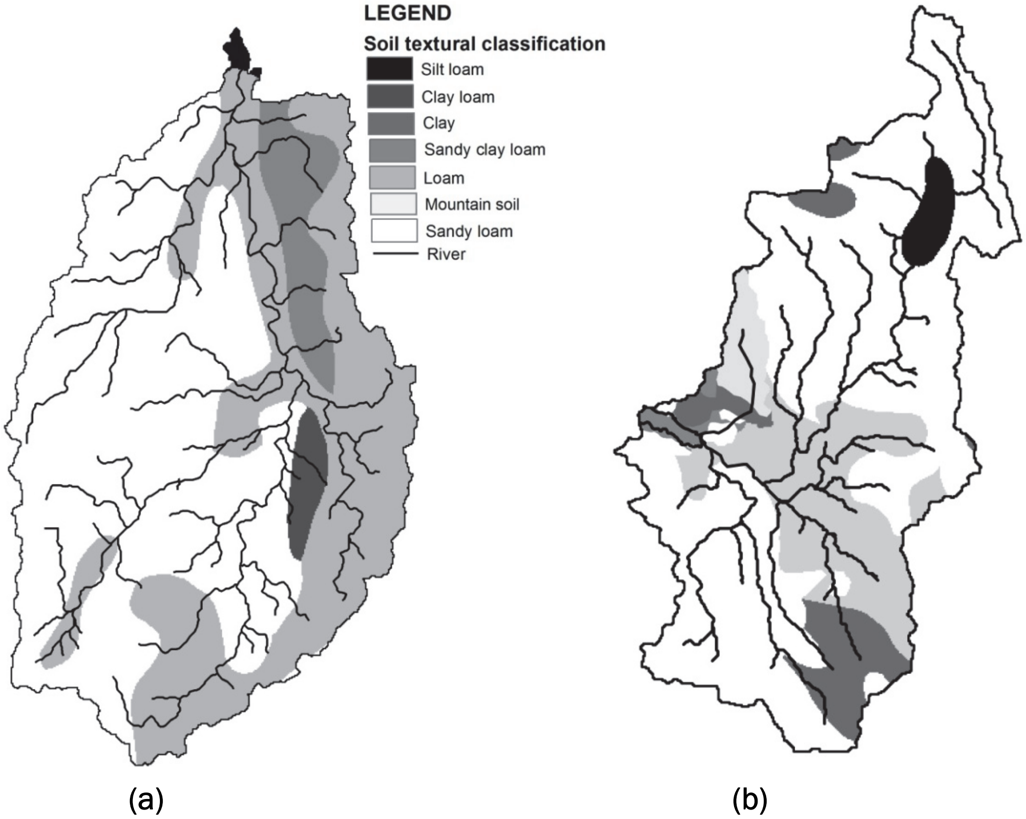
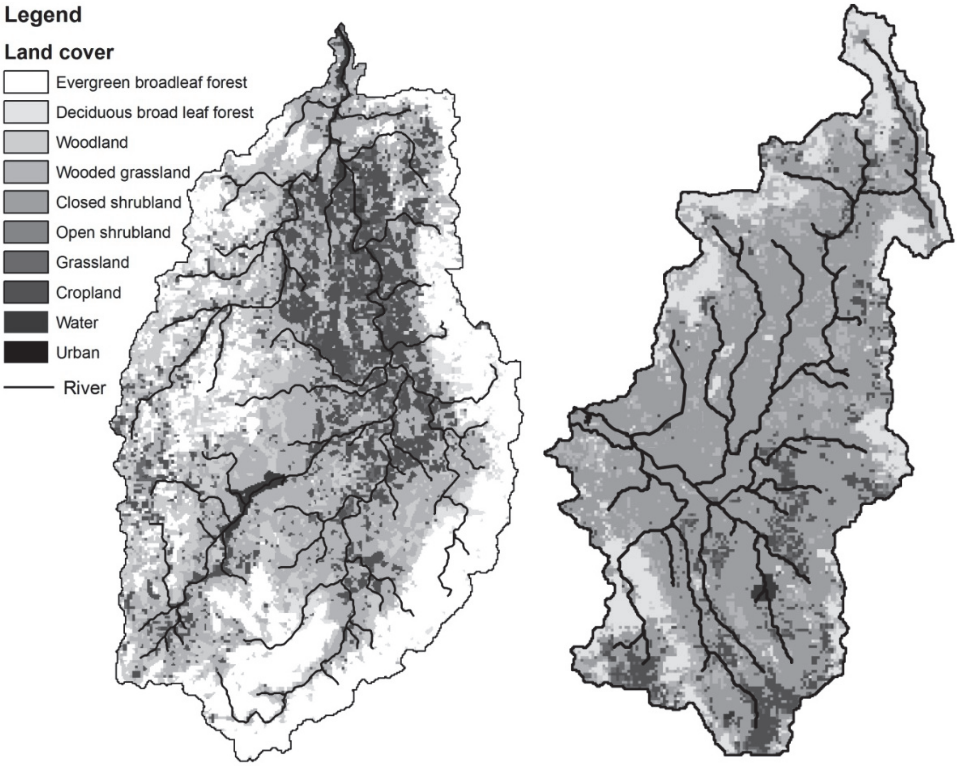


Figure 4. Soil textural classification for (a) Cagayan River basin and (b) Mindanao River basin.

LAND USE DATA: Land cover digital data was downloaded from the Global Land Cover Facility (GLCF). Managed by the University of Maryland, Department of Geographical Sciences, GLCF contains the data processed from the Advanced Very High Resolution Radiometer (AVHRR) satellite. The AVHRR raster data product was converted into an ASCII format and then used to generate the index map for the hydrological models of Cagayan and Mindanao River basins. The maps in Figure 5 (a)(b) were applied to assign land use properties, such as: overland roughness, in the hydrological models of Cagayan and Mindanao River basins.

INITIAL SOIL MOISTURE: A physics-based, spatially distributed hydrologic model like GSSHA is highly sensitive to the initial state of soil moisture for short-period simulations. Soil moisture data is difficult to attain, even in a well-gauged basin. Satellite imagery is a good source for acquiring derived soil moisture data in a data sparse area (Pradhan et al. 2012). The Normal Difference Vegetation Index (NDVI) can be employed to estimate root zone soil moisture at distant sites (Schnur et al. 2010). The NDVI was derived from near-infrared (NIR) (841–876 nm) and red (620–670 nm) bands of the Moderate Resolution Imaging Spectroradiometer (MODIS) surface reflectance data (Schnur et al. 2010). Soil moisture states for the entire Cagayan Island were estimated using this NDVI.



(a) (b)

Figure 5. Land use classification for (a) Cagayan River basin and (b) Mindanao River basin.

HYDROLOGICAL PROCESSES AND PHYSICAL CHARACTERIZATION OF THE SYSTEM: One-dimensional (1D) infiltration, two-dimensional (2D) overland flow, and 1D stream flow simulate the runoff generation, overland transport, and channel transport processes, respectively.

The infiltration model partitions the rainfall between infiltrated water and surface runoff. For this application, the Green and Ampt infiltration scheme (Green and Ampt 1911) was selected. The rate of infiltration in the Green and Ampt model is governed by the soil physical properties, which vary by soil type. Therefore, the soil properties were linked to a soil index map that was derived from the Food and Agriculture Organization (FAO) world soil database. Properties assigned included porosity, field capacity, hydraulic conductivity, residual saturation, pore size distribution, and suction head (Rawls et al. 1983).

The runoff generated within each pixel was then transferred over the grid through a 2D finite volume numerical scheme. The surface runoff is coupled to channel routing, where lateral inflow from surface runoff cells is then numerically routed through a 1D stream network with a finite volume scheme. The width of the stream was estimated from measurements within Google Earth imagery (NASA, CNES/Astrium, DigitalGlobe™). Hydrological models implemented the Manning equation to relate surface roughness to flow rate, from which hydraulic roughness was represented by Manning's roughness coefficient, *n* (Gioia and Bombardelli 2002). Spatial data products depicting land use and land cover (LULC) support GSSHA model parameterization.

AVHRR satellite LULC data was employed to assign Manning's *n* values for overland flow, referenced from published values (http://www.gsshawiki.com).

MODEL SIMULATION: For both of the hydrological models, Cagayan and Mindanao, the simulation runs were made for 100-year, 20-year, and 5-year return period rainfall. Overland flow depths were mapped at 30-minute intervals throughout the simulation period, and the maximum inundation depths were obtained for each return-period rainfall.

DEVELOPMENT OF PREDICTIVE RELATIONSHIPS: The maximum inundation maps were overlaid on the LandScan 2012 population maps shown in Figure 6, and urban and agricultural land cover maps shown in Figure 7, to develop the relationship between return period rainfall intensities and flood affected agricultural area, urban area, and population.

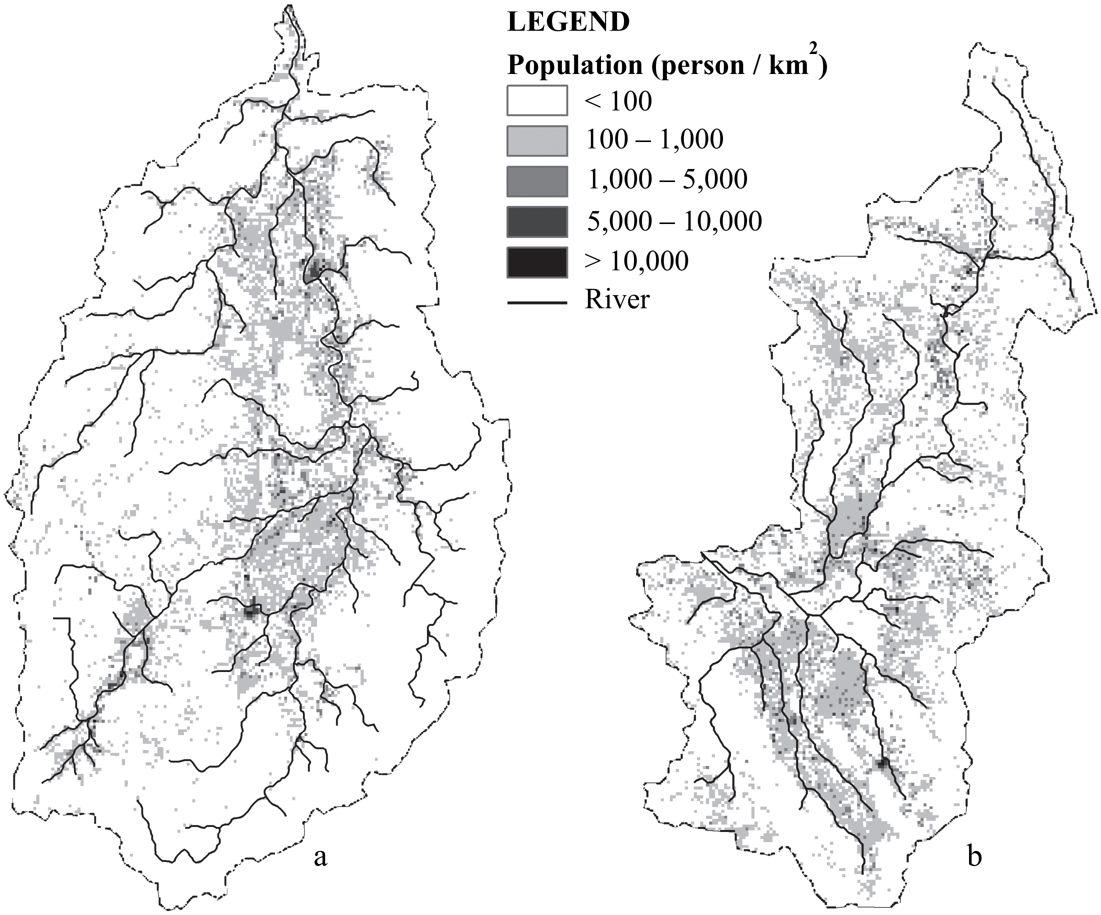


Figure 6. Population density map for (a) Cagayan River basin and (b) Mindanao River basin. Population density data was obtained from LandScan 2012 Global Population Project, Geographic Information Science and Technology, Oak Ridge National Laboratory (http://www.ornl.gov/gist).

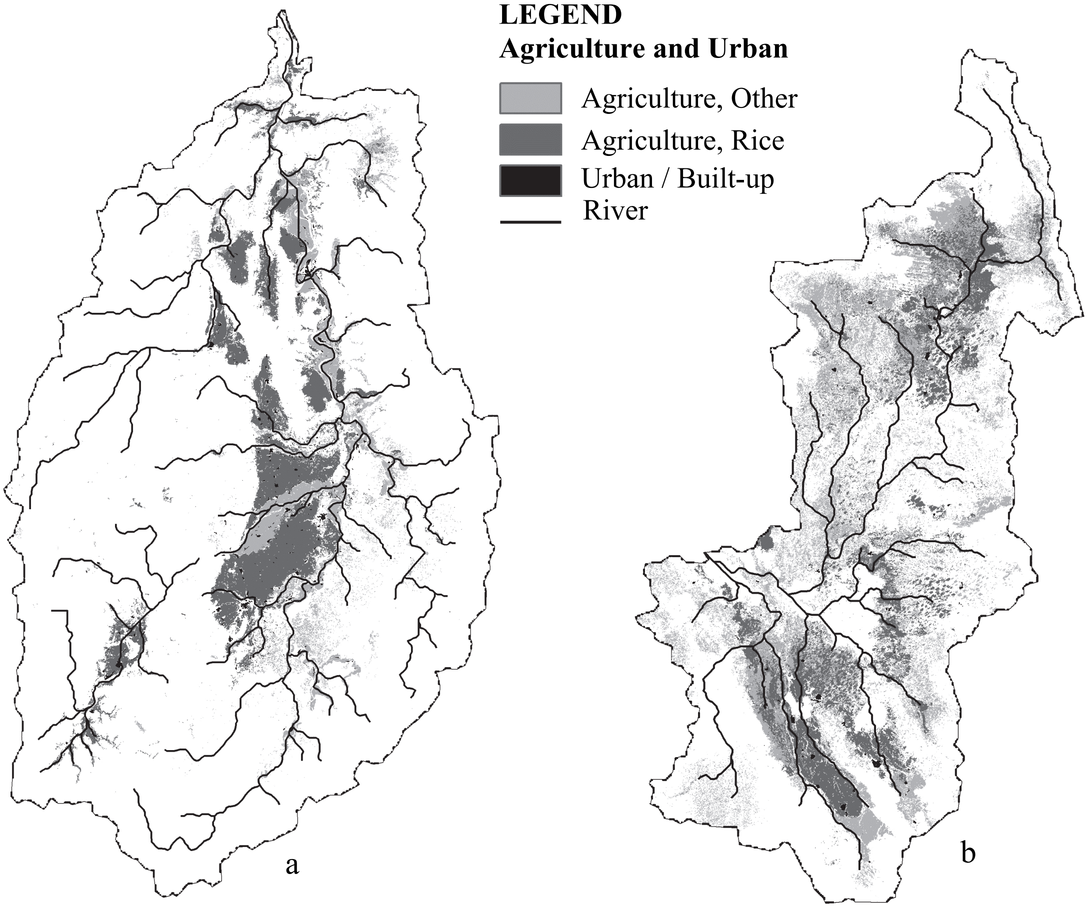


Figure 7. Agricultural and Urban area map for (a) Cagayan River basin and (b) Mindanao River basin.

Figures 8 and 9 show the relationship between return period rainfall intensities and flood affected agricultural areas, urban areas, and population in Cagayan and Mindanao River basins, respectively. In Figures 8 and 9, a 0.5 m flood depth was considered as a critical inundation depth (Tingsanchali and Karim 2005), above which the inundation extent over settlement and agricultural area were taken into account. Figures 8 and 9 show the relationships obtained that represent the best-fit flood inundated extents over settlements and agricultural areas. The best-fit relationship for Cagayan as shown in Figure 8, is a logarithmic function. Whereas the best-fit for Mindanao in as shown in Figure 9 is a power function.

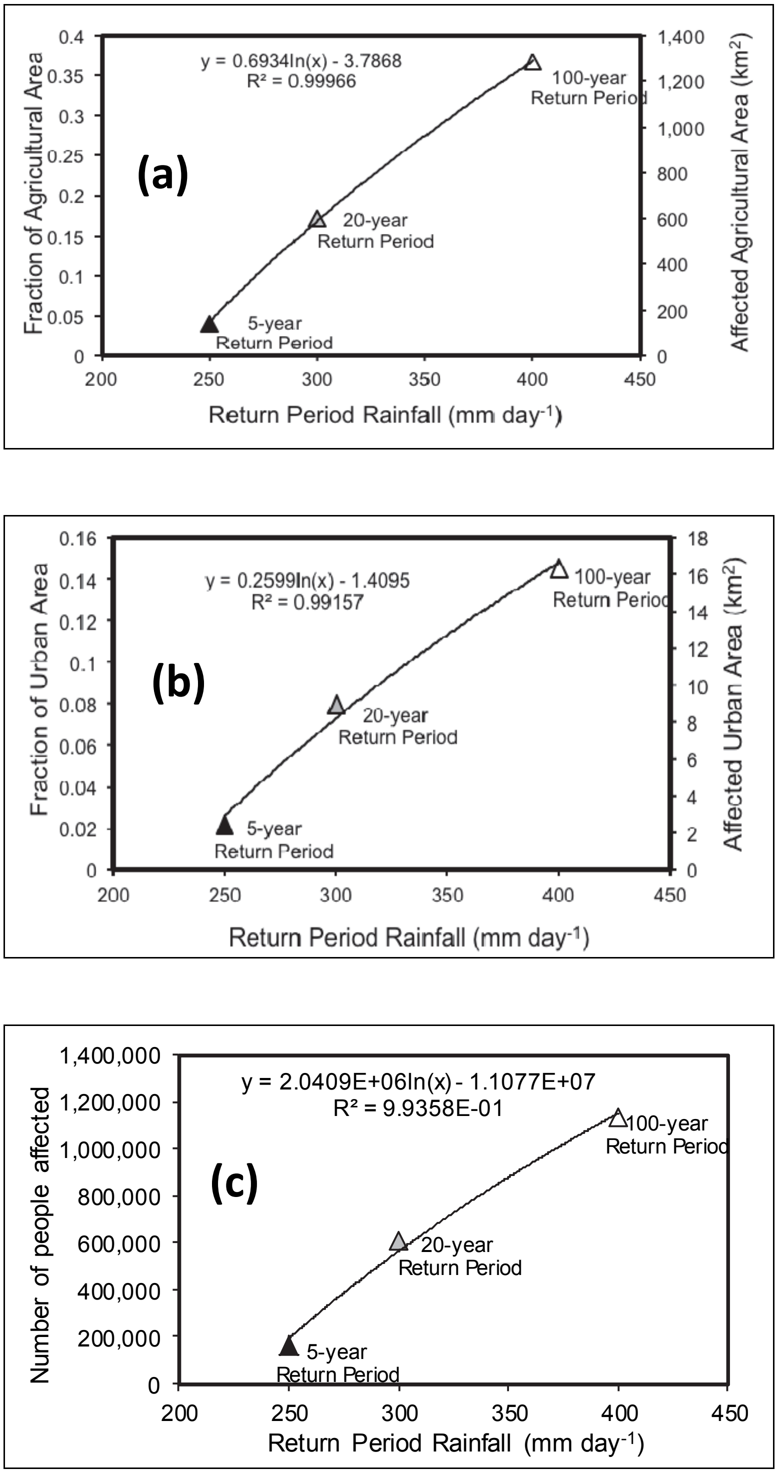


Figure 8. Development of relationships between return period rainfall intensities and flood-affected (a) agricultural land (b) urban land and (c) population in the Cagayan River basin.

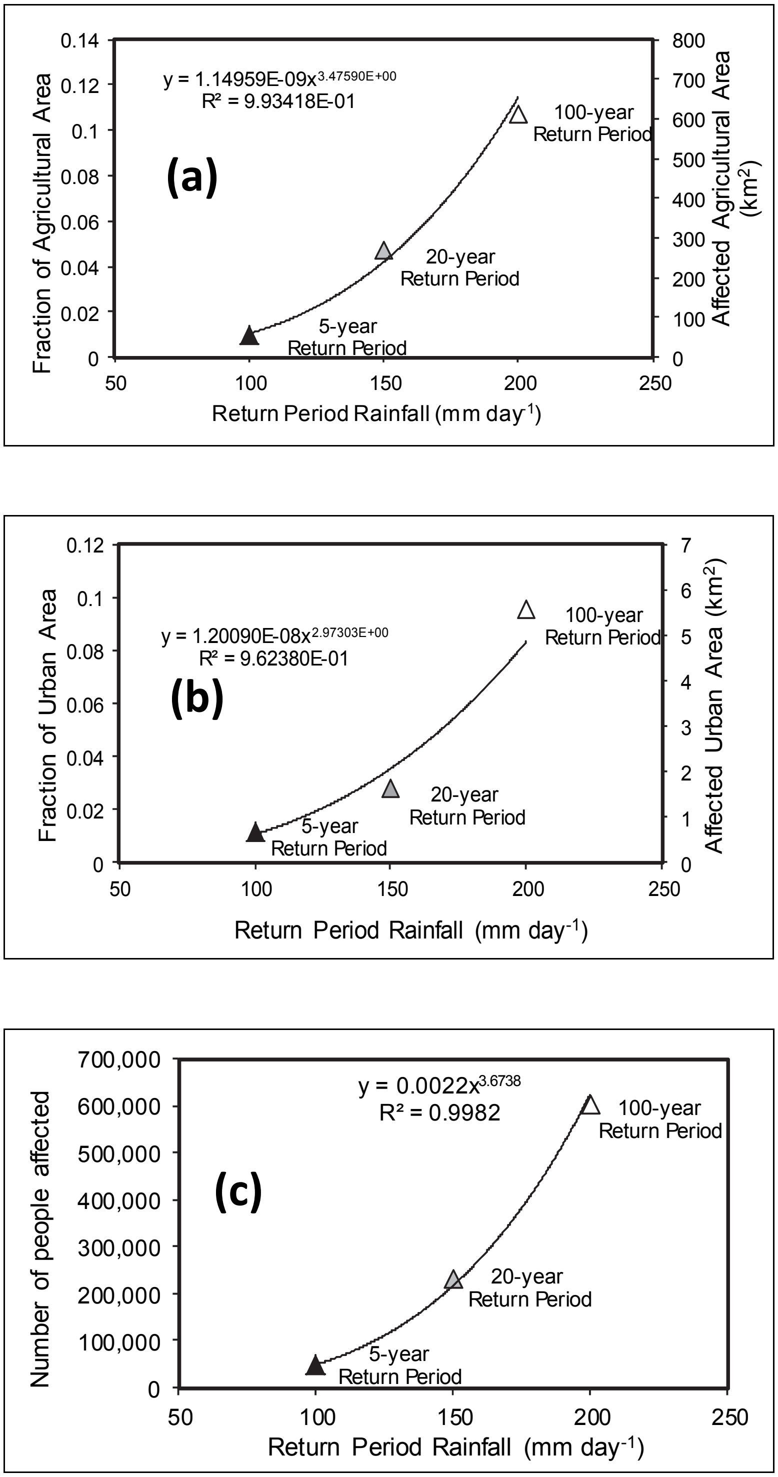


Figure 9. Development of relationships between return period rainfall intensities with flood-affected (a) agricultural land (b) urban land and (c) population in the Mindanao River basin.

CONCLUSIONS: The majority of river basins around the globe are ungaged; therefore, flood hazard assessments based on direct measurements are not possible. However, remotely sensed data results, and physics-based distributed hydrological model simulation data results, enable the possibility of flood hazard assessments in ungaged basins.

Functions were derived to correlate return period rainfall intensities with flood inundation extents from simulation results. The flood extents can then be mapped to agricultural areas and population centers as a means of assessing the amount socioeconomic impact. It is interesting to note that although the type of functions used to derive individual catchments differed (logarithmic function for Cagayan and power function for Mindanao), the nature of the relationship remained the same for all socioeconomic factors considered within the catchment. Factors that take into account varying distribution function laws in catchments as well as those that examine the effect of mass migration or significant land-use change on the distribution function should be considered for future research topics.

This TN demonstrates how functions can be derived to correlate return period rainfall intensities with flood inundation extent on socio-economic factors by performing data calculations derived from various sources on ungaged river basins. The approach described in this technical note predicts flood inundation in ungaged basins. The results provide stakeholders and decision makers with a characterization of the flood hazard which can then be used to enhance their ability to cope with the uncertainty of flood hazards and proactively mobilize sources of resilience (Adger et al. 2005).

ADDITIONAL INFORMATION: For additional information, contact Nawa Raj Pradhan, Coastal and Hydraulics Laboratory, U.S. Army Research and Development Center, 3909 Halls Ferry Road, Vicksburg, MS 39180, at 601-634-2473, or e-mail: Nawa.Pradhan@usace.army.mil. This CHETN should be cited as follows:

> Pradhan, N. R., A. R. Byrd, M. Jourdan, and J. Ellis. 2016. *Development of predictive relationships for the estimates of a return period flood effects in ungaged basins.* ERDC/CHL CHETN-VIII-8. Vicksburg, MS: U.S. Army Engineer Research and Development Center.

An electronic copy of this CHETN is available from http://chl.erdc.usace.army.mil/chetn.

REFERENCES

Adger, W. N., T. P. C. Folke, S. R. Carpenter, and J. Rockström. 2005. Social-ecological resilience to coastal disasters. *Science* 309(5737):1036–1039.

Alejandrino, A. A., M. L. Diaz, R. C. Bruce, A. P. Basilio, C. E. Yñiguez, R. G. Salas, and H. B. Bayhon. 1976. Principal river basins of the Philippines. *National Water Resources Council, Philippines* (4)82.

Beven, K. J., and M. J. Kirkby. 1979. A physically based, variable contributing area model of basin hydrology. *Hydrological Science Bulletin* 24(1)43–69.

Brouwer, R., S. Akter, L. Brander, and E. Haque. 2007. Socioeconomic vulnerability and adaptation to environmental risk: A case study of climate change and flooding in Bangladesh. *Risk Analysis* 27(2):313–326.

Brutsaert, W. 2008. Long-term groundwater storage trends estimated from streamflow records: Climatic perspective, Water Resources W02409. doi:10.1029/2007WR006518.

Chow, V. T., D. R. Maidment, and L. W. Mays. 1988. *Applied hydrology*. New York: McGraw-Hill.

Diamond, J. 1999. *Guns, germs, and steel*. New York: Norton.

Downer, C. W., and F. L. Ogden. 2004. GSSHA: A model for simulating diverse streamflow generating processes. *Journal of Hydrological Engineering* 10.1061/(ASCE)1084-0699(2004)9:3(161)161–174.

Downer, C. W, N. R. Pradhan, F. L. Ogden, and A. Byrd. 2014. Testing the effects of detachment limits and transport capacity formulation on sediment runoff predictions using the US Army Corps of Engineers GSSHA model, ASCE. *Journal of Hydrologic Engineering* 10.1061/(ASCE)HE.1943-5584.0001104.

Downer, C. W., F. L. Ogden, N. R. Pradhan, S. Liu, and A. R. Byrd. 2010. *Improved soil erosion and sediment transport in GSSHA*. ERDC TN-SWWRP-10-3, Vicksburg, MS: U.S. Army Engineer Research and Development Center. *https://swwrp.usace.army.mil/*

Freeze, R. A., and R. L. Harlan. 1969. Blueprint for a physically-based, digitally-simulated hydrologic response model. *Journal of Hydrology* 9:237–258.

Gatmaytan A. B., and G. O. Dagondon. 2004 Dagondon. Sustainability and survival four case studies from indigenous communities in Northern Mindanaw. *ICRAF Southeast Asia Working Paper* (5) Bogor, Indonesia.

Gioia, G., and F. A. Bombardelli. 2002. Scaling and similarity in rough channel flow. *Physical Review Letters* 88(1):1–4.

Green, W. H., and G. A. Ampt. 1911. Studies of soil physics: 1. Flow of air and water through soils. *Journal of Agricultural Sciences* 4:1–24.

Milsom, J., J. R. Ali, and K. L. Queano. 2006. Peculiar geometry of northern Luzon, Philippines: Implications for regional tectonics of new gravity and paleomagnetic data. *Tectonics* 25:TC4017. doi:10.1029/2005TC001930.

Nimmo, J. R. 2007. Simple predictions of maximum transport rate in unsaturated soil and rock. *Water Resource Research* 43*:W05426. doi:10.1029/2006WR005372.*

Ogden, F.L., N. R. Pradhan, C. W. Downer, and J. A Zahner. 2011. Relative importance of impervious area, drainage density, width function and subsurface storm drainage on flood runoff from an urbanized catchment. *Water Resources Research* 47(12). doi:10.1029/2011WR010550.

Pradhan, N. R., and F. L. Ogden. 2010. Development of a one-parameter variable source area runoff model for ungauged basins. *Advances in Water Resources* 33:572–584. doi:10.1016/j.advwatres.2010.03.002.

Pradhan, N. R., F. L. Ogden, Y. Tachikawa, and K. Takara. 2008. Scaling of slope, upslope area and soil water deficit: Implications for transferability and regionalization in topographic index modeling. *Water Resources Research* 44:W12421. doi:10.1029/2007WR006667.

Pradhan, N. R., A. R. Byrd, F. L. Ogden, and J. M. H. Hendrickx. 2012. SEBAL evapotranspiration estimates for the improvement of distributed hydrological model runoff and soil moisture predictions. *International Association of Hydrological Sciences* 352:435–439.

Pradhan, N. R., C. W. Downer, and B. E. Johnson. 2014. A physics based hydrologic modeling approach to simulate non-point source pollution for the purposes of calculating TMDLs and designing abatement measures. In *Practical Aspects of Computational Chemistry III*, ed. J. Leszczynski and M. K. Shukla, 249–282. New York: Springer. doi:10.1007/978-1-4899-7445-7_9.

Rawls, W. J., D. L. Brakensiek, and N. Miller. 1983. Green–Ampt infiltration parameters from soils data. *Journal of Hydraulic Engineering* 109:62–70.

Schnur, M. T., H. Xie, and X. Wang. 2010. Estimating root zone soil moisture at distant sites using MODIS NDVI and EVI in a semi-arid region of southwestern USA. *Ecological Informatics* 5:400–409.

Senarath, S. U. S., F. L. Ogden, C. W. Downer, and H. O. Sharif. 2000. On the calibration and verification of two dimensional distributed, Hortonian, continuous watershed models. *Water Resources Research* 36(6):1495–1510.

Sivapalan, M., K. Takeuchi, S. W. Franks, V. K. Gupta, H. Karambiri, V. Lakshmi, X. Liang, J. J. McDonnell, E. M. Mendiondo, P. E. O'Connell, T. Oki, J. W. Pomeroy, D. Schertzer, S. Uhlenbrook, and E. Zehe. 2003. IAHS decade on predictions in ungauged basins (PUB), 2003–2012: Shaping an exciting future for the hydrological sciences. *Hydrological Sciences Journal* 48(6):857–880. doi:10.1623/hysj.48.6.857.51421.

Tingsanchali, T., and M. F. Karim. 2005. Flood hazard and risk analysis in the southwest region of Bangladesh. *Hydrological Processes* 19:2055–2069.

Villabeto, S. C. 2008. Monitoring of water samples from Kulaman and Tinanan rivers and baseline profile of their confluence. *The CFCST Research Journal* 8(2):1–11.