IAHS General Assembly at Sapporo, Japan, July 3-11, 2003
HS03: International Symposium on
Information from Weather Radar and Distributed Hydrological Modeling
July 7-8, 2003

Operational Deployment of a Physics-based Distributed Rainfall-runoff Model for Flood Forecasting in Taiwan

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Abstract The Central Weather Bureau in cooperation with the Water Resources Agency of Taiwan, among others, seeks to improve technology and techniques employed to monitor and predict rainfall-runoff throughout Taiwan. The rainfall and runoff techniques and technologies are critical to the potential mitigation of specific hazards such as flash floods, river floods, debris flow, and landslides. A program initiative for the research and development of a flood alert and water resources management system is to unify monitoring and prediction of floods within a single system. Enhancing the accuracy and efficiency of information disseminated from the central government to the public, and to regional and local water management and emergency response agencies is the major goal of this project.

Key words: Hydrology, floods, hydrological modeling, radar rainfall, distributed modeling, real-time flood monitoring operations

INTRODUCTION

Operational deployment of a physics-based fully distributed rainfall-runoff model, called Vflo™, coupled in real-time with quantitative precipitation estimates (QPE) from radar, satellite and rain gauges, allows monitoring and prediction of river stage at any geographic location. QPE using multiple sensors provides hydrologic model input for improving prediction of rainfall-runoff and resulting flood hazards. Vflo™ relies on digital elevations and other geographic information to predict discharge and stage at any selected location within a drainage network described by Vieux and Vieux (2002). This implementation of the model relies on the QPE derived from multiple sensors (rain gauges, satellite, and radar); an approach developed by the US National Oceanic and Atmospheric Agency (NOAA)—National Severe Storms Laboratory (NSSL) called QPESUMS (Gourley, 1998; Howard *et al.*, 1997).

Vflo™ and QPESUMS were installed in June 2002, and were operational within a few days before rain bands from Typhoon Rammasan struck the island the first week of July. This event caused localized flooding and some landslides in mountainous areas, while ending water usage restrictions by partially filling reservoirs that supply Taipei, the capitol city of Taiwan. One of the most damaging of recent tropical cyclones was Typhoon Nari, which occurred in September 2001. Typhoon Nari resulted in 93 dead, 10 people missing and extensive damage to the northern part of the island and to the City of Taipei. This event is the subject of retrospective analysis and event re-construction for calibration of the flood alert system, which is the subject of this paper. Analysis of land-sea interactions that may have augmented precipitation processes in Typhoon Nari causing severe flooding in Taipei is reported by Sui *et al.* (2002). The paper herein presents an overview of the flood warning system design and operational requirements, a sensitivity study, and simulation of river stage compared with observed stream flow using an operational distributed hydrologic model with multiple radar input.

Monitoring and prediction technologies and techniques are critical, not only for hazards associated with floods, but also for, debris flow, landslides and water resources management. The 35 980 km^2 Island of Taiwan is located north of the Philippines, off the southeastern coast of China; and surrounded by the East China Sea, Philippine Sea, South China Sea, and Taiwan Strait. The climate is typical of tropical maritime conditions with a rainy season during the southwest monsoon period from June to August. Typhoons average 3.6 per year often bringing damages from wind and flooding, but also filling reservoirs that supply water after the monsoon season ends. Average annual rainfall is in excess of 2 500 mm. The terrain is mountainous in the interior with flat to gently rolling plains in the west along the coast. The highest elevation is 3 997 m above mean sea level. The terrain is complex with extremely steep gradients in the mountainous areas. As the drainage network encounters coastal areas, progressively flatter gradients affect velocities. Channelization in urban areas restricts inundation until dikes or walls are overtopped. With no river exceeding 30 km, runoff generated in the mountains arrives at sea level in less than a few hours.

The Central Weather Bureau (CWB) is responsible for issuing forecasts of typhoon tracks and heavy rains which may result in floods throughout the island. Flooding is prevalent during the typhoon season because of intense and prolonged rainfall coupled with orographic influences creating torrential runoff. Once runoff reaches the flatter coastal plains, where most of the population and economic development is concentrated, flood disasters result. Recent advancement in radar-based QPE offered the opportunity to improve the monitoring of conditions that may result in flooding on very small time and space scales. The central government desired monitoring and prediction capability encompassing all ten river basins. Central planning and emergency relief efforts benefit from having timely information on flooding locations; and not just locations of heavy rainfall. A comprehensive system was required that integrated multiple sensor-based QPE with a distributed model for flood prediction. Because flooding is both a hydrometeorological and hydrologic phenomenon, cross governmental cooperation between CWB and WRA became an important first step to developing an integrated flood warning system. The flood prediction system now deployed in Taiwan is being upgraded and improved over a multi-year period. The architecture of the system provides monitoring and hydrologic prediction in addition to analysis functions. There are several key components in the overall system, which is described below.

NSSL has developed QPESUMS, which is a suite of algorithms that utilizes radar and satellite data to provide precipitation estimates. Depending on the region and application, these sensors may include rain gauge, lightning, surface observation data, and satellite imagery. The QPE is produced within a GIS framework consisting of three components: 1) data integration, radar quality control; 2) 3-D reflectivity mosaics of storm structure; and 3) quantitative precipitation estimation. Vflo™ accepts input from a variety of common radar and gauge formats and can operate independently using radar reflectivity processing algorithms and rain gauge calibration for real-time operation or post-analysis. The deployment in Taiwan required integration of four radars of different manufacturer specifications and scanning strategies. Besides radar, an extensive rain gauge network of over 200 sites provides information for real-time bias adjustment. The resulting QPE comprised of radar and rain gauges are processed providing input to the hydrologic model.

Vflo™ Model Description and Attributes

Vflo™ is a fully distributed, physics-based hydrologic model capable of utilizing geographic information and multi-sensor input to simulate rainfall runoff from major river basins to small catchments. Vflo™ is a *hydraulic* approach to hydrologic analysis and prediction. Overland flow and channels are simulated using the kinematic wave analogy. With the addition of Muskingum-Cunge, and Modified Puls, the model is extended to larger rivers and more complex hydraulics defined by rating curves or measured cross-sections. The theoretical basis for the distributed modeling that underlies Vflo™ is given by Vieux (2001); Vieux and Moreda (2002); and Vieux (2002).

Real-time flood forecasting requires ingest of radar rainfall data directly into Vflo™. The model is implemented in Java to take advantage of secure Servlet/Applet technology for multi-user access via the Internet or intranets. Vflo™ utilizes GIS grids to represent the spatial variability of factors controlling runoff. Runoff production is from infiltration excess and is routed downstream using the kinematic wave analogy. Computational efficiency of the fully distributed physics-based model is achieved using finite elements in space and finite difference in time. Evolution of rain fields during a tropical storm is measured by radar and updated every 10 minutes.

The finite element approach is based on a drainage network, which allows flexibility in selecting the location for reporting stream flow information (see inset in Fig. 1). Configuring hydrologic prediction on a drainage network basis makes the model scalable from small catchments to major river basins eliminating the need for separate models for different scales of catchment. Terrestrial parameters are derived from commonly available sources of digital geospatial data. Parameters include topography and drainage networks derived from a digital elevation model (DEM), infiltration parameters derived from soils, and hydraulic roughness derived from land use/cover (e.g., Landsat). Parameterization proceeds by importing GIS grids to the model, then adjusting parameters with a multiplicative factor. Once the model is calibrated, the settings and parameters are saved in a basin-overland-properties (bop) file. Model application to a particular basin is achieved by comparing observed discharge and stage with simulated at select locations. A limited sensitivity and calibration study was undertaken and is described in the following sections.

Study Area

The initial study area selected is the Keelung River because of its tendency to flood in critically sensitive social and economic areas. The headwaters originating in the mountains to the southeast of Taipei, the runoff typically moves rapidly downstream to where it joins the Tanshui River in Taipei. No suitable sites for flood control reservoirs exist in the Keelung due to the topographical characteristics of the basin. Accurate monitoring is one of the key alternatives for mitigating flooding experienced by the city Taipei from this river. The Keelung River is shown in Fig. 1. Beginning in the highlands (see black line), the river takes a northeasterly route with very steep gradients on the order of 10 %, then takes a sharp turn to the west and then proceeds in a southwesterly route through flatter terrain as it approaches Taipei. The arrows shown in the inset indicate the finite elements that connect each digital elevation grid cell. The drainage network composed of overland and channel cells are parameterized according to expected hydraulic characteristics. These parameters are then adjusted on a global, basin, or incremental basis to affect peak and timing. The ordered adjustment of the parameters controlling the runoff process follows the OPPA methodology described by Vieux and Moreda (2002).

Model Sensitivity

The sensitivity of simulated stage and discharge to inputs and parameters helps guide the development of the model. Knowing which parameter causes the most response in stage or discharge identifies where effort should be expended to improve parameter specification. A limited sensitivity study was conducted for the Keelung with input from Typhoon Nari. Multiple locations were used to test the sensitivity with results shown for four bridge locations along the Keelung. Two sensitivity tests are shown: sensitivity to infiltration, and to rainfall. Infiltration is treated as a constant loss rate equivalent to saturated hydraulic conductivity in the Green and Ampt equation. Given the short residence time of runoff on the land surface before it arrives in a channel, infiltration may not be as important as other factors. Clay soils and intense rainfall also limit the importance of infiltration rates on controlling runoff in many areas including Taiwan. The infiltration rate, I (mm/hr) is adjusted by scalar multipliers in steps of 0.2 from 0.4 to 2.0. The multiplication of the scalar times the parameter map is indicated in the legend of the respective figures, e.g., infiltration, I multiplied by 2.0 is indicated as: *I_2.0*. Selected infiltration trials are shown for scalars of 0.4, 1.0, 1.4, and 2.0 in Fig. 2. The narrow range of variation in simulated stage is indicative that runoff production is not dominated or significantly affected by infiltration rates at this location in the basin.

The radar rainfall is reproduced from reflectivity data and was not calibrated to rain gauges. Reflectivity conversion to rain rates is sensitive to the relationship used. A tropical relationship was tested using the approach described by Vieux and Bedient (1998). Applying a scalar multiplier is analogous to systematic bias removal when radar is gauge-adjusted using mean-field techniques. The scalars applied to the spatially variable radar rainfall maps range from 0.5, 1.0, 1.5 and 2.0. The scalar multiplier for radar rainfall rate, R multiplied by 2.0 is shown as: *R_2.0*. The range in response is sensitive to the rainfall scalar as shown in Fig. 3. The slope of the best fit line for R_1.0 is 0.9184 indicating an 8% bias towards under-prediction in this case. The broad range of response in stage, from 10 to over 30 m, to rainfall rates is in marked contrast to infiltration, which affects stage on the order of only several meters. As is generally accepted, rainfall rates and spatial distribution have dramatic impacts on runoff. The sensitivity shown to radar rainfall confirms that radar-based QPE is a critically important factor for accurate stream flow prediction. As more typhoon and tropical storm events become available, further calibration and validation will be possible.

Simulated and observed stage hydrographs at the Wu Du Bridge located along the Keelung River is shown in Fig. 4. The model closely matches the observed stage in the rising limb and for the second peak. The third observed peak occurred after the end of the radar rainfall processed for this post-analysis study. The shape of the recession limb is important from the standpoint of judging the adequacy of the model representation. Except for the third peak, which was not simulated, the recession limb of the model tends to follow the observed recession. Table 1 shows the comparison between simulated and observed stage at locations along the Keelung. The statistics for several points along the river where observed hydrographs may be compared with simulated results indicate that the mean absolute percentage error (MAPE) is 8.6%.

Table 1. Simulated and observed maximum stages for Typhoon Nari at select locations.

Keelung River Location	Simulated Stage (m)	Observed Stage (m)	Absolute Percentage Error
Zhang An Bridge	17.01	18.94	10.2
Wu Du	12.93	14.54	11.1
Da Hua Bridge	10.97	10.61	3.4
Jie Shou Bridge	7.94	7.22	9.9
			MAPE=8.6

These are calibration results and remain to be validated as more events occur and data recorded.

SUMMARY

Close collaboration between Taiwan government agencies, the United States government, and private industry has resulted in the creation of new monitoring and prediction techniques and technologies to assist Taiwan in monitoring and predicting the occurrence of flooding. The coupling of advanced multiple sensor techniques for QPE and a physics-based fully distributed hydrologic model provides improved accuracy for streamflow prediction in a critical social and economic region of Taiwan. The coupling of advanced techniques in rainfall monitoring with distributed hydrological modeling allows prediction to occur on smaller time and space scales. The terrain and hydroclimatic conditions in Taiwan cause a complex rainfall structure to evolve during typhoon landfall. Sensitivity demonstrated for this region shows that accurate rainfall rates are critically important to operational flood forecasts.

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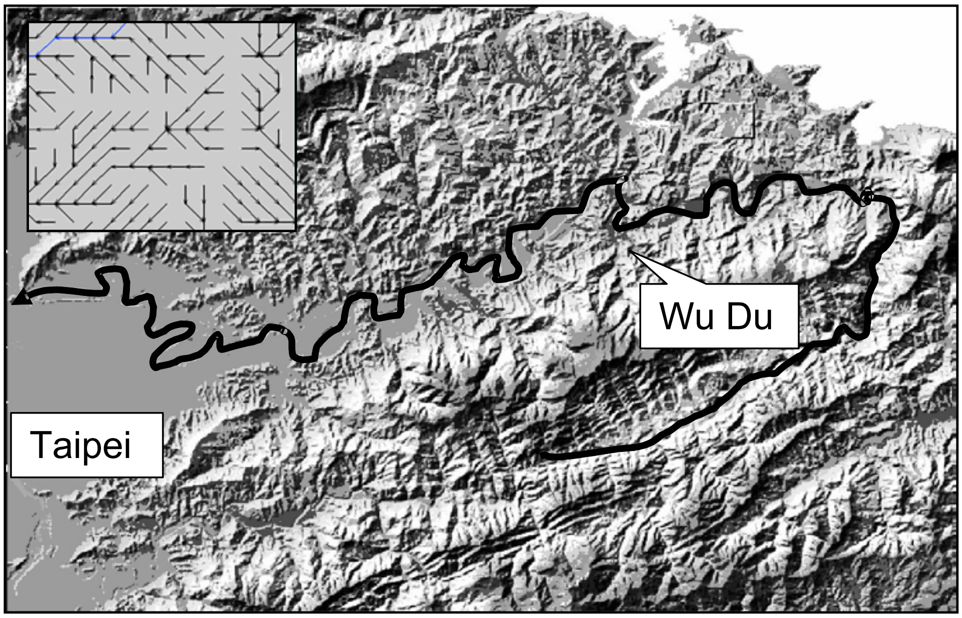

Figure 1 Shaded relief map shown here at 40 m resolution, Keelung River (black line) and Wu Du bridge location. The inset shows a typical finite element representation of the drainage network defined by the DEM (upper left)

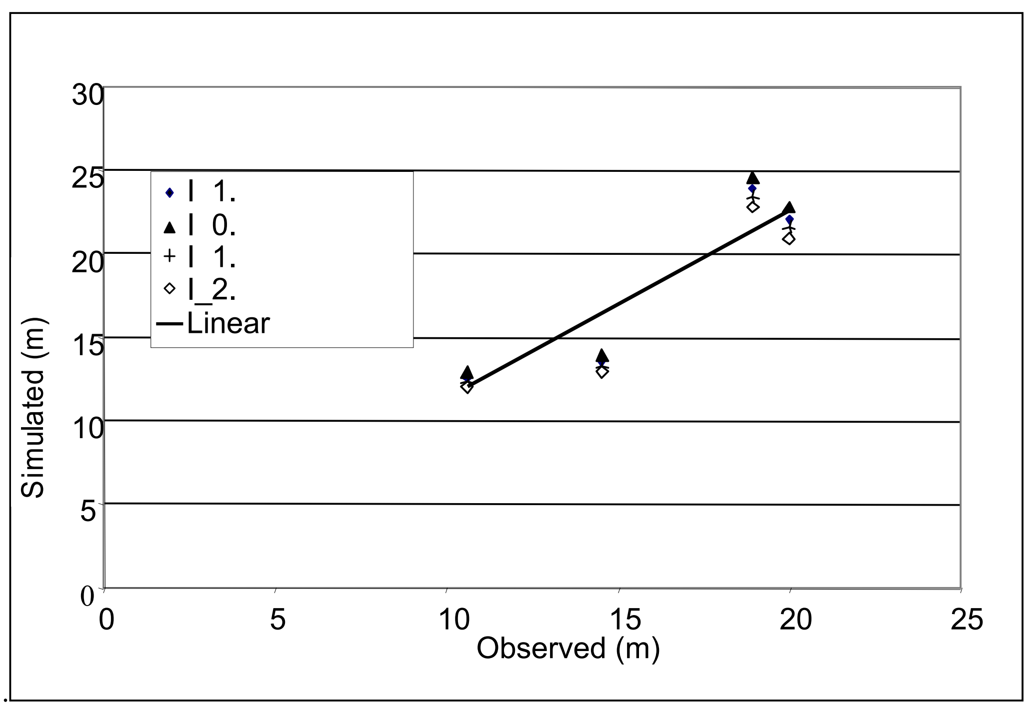

Figure 2 Stage sensitivity to infiltration scalars with linear best fit line applied to the I_1.0 data only.

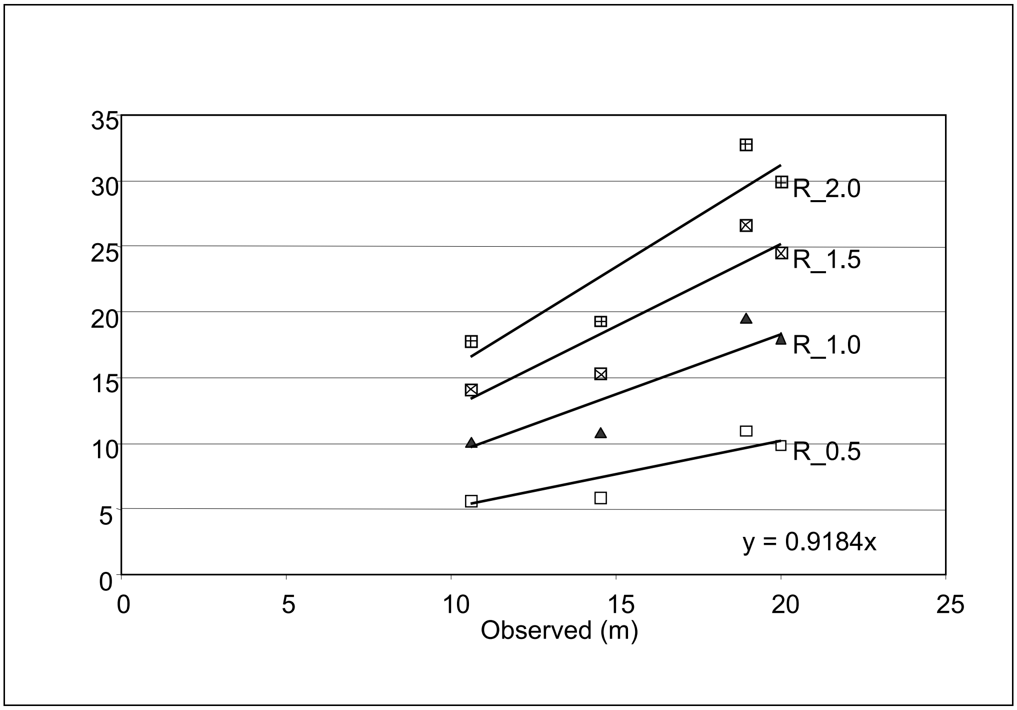

Figure 3 Stage sensitivity to radar rainfall scalars

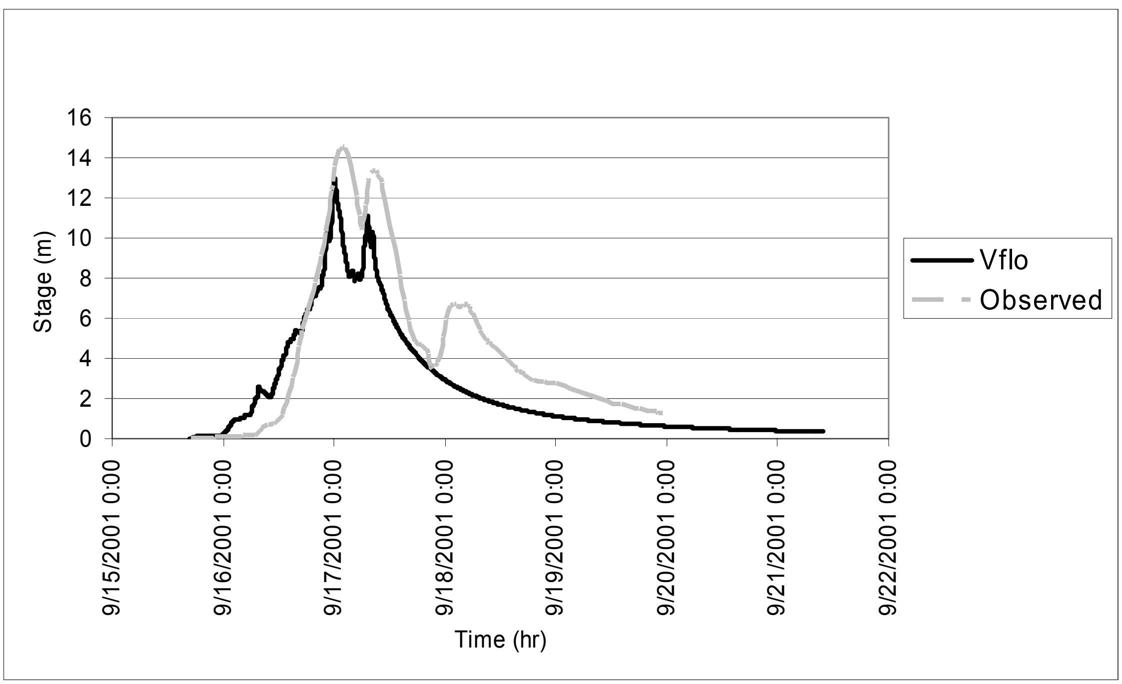

Figure 4 Simulated and observed stage hydrographs at the Wu Du Bridge.