U.S. Army Corps of Engineers
Institute for Water Resources
Hydrologic Engineering Center

DELAWARE RIVER BASIN

FLOOD ANALYSIS MODEL

A Project Proposal

Prepared for

Delaware River Basin Commission

Submitted by:
U.S. Geological Survey
U.S. Army Corps of Engineers – Hydrologic Engineering Center
NOAA - National Weather Service

May 4, 2007

DELAWARE RIVER BASIN
FLOOD ANALYSIS MODEL

Problem:

Three major main stem floods between September of 2004 and June of 2006 have focused attention on the potential effects of storage volumes (voids) in major reservoirs within the Delaware River Basin on downstream discharges. Some of the major reservoirs were designed and built for flood control purposes while others were designed for water supply, hydropower, and recreation.

Evaluation of alternative operational scenarios for this complex reservoir system can be improved by use of a physically-based flood analysis model that simulates runoff and streamflow routing, incorporating the impact of storage in and discharge from major reservoirs.

DRBC Resolution 2006-20 authorizes the Executive Director of the Delaware River Basin Commission (DRBC) to develop a flood analysis model for the basin. Complex models that represent rainfall and snowmelt runoff, reservoir hydraulics, and flow routing are required and need to be combined into a single flood analysis model. The tool is needed to allow:

- The DRBC and others the capability to evaluate the potential for the basin's major reservoirs to be operated for flood mitigation;
- The DRBC and others to evaluate the feasibility of various reservoir operating alternatives;
- The DRBC and others to evaluate the effect of reservoir voids of different magnitudes on streamflow at locations downstream from the reservoirs;
- The DRBC and others the ability to examine, modify, and improve the model and datasets as new information and technology become available; and
- The DRBC and others to use the output from the tool as an educational instrument for demonstrating the operations of reservoirs and basin hydrology.

In cooperation with the Delaware River Basin Commission (DRBC), the U.S. Geological Survey (USGS), U.S. Army Corps of Engineers (USACE) - Hydrologic Engineering Center (HEC), and the NOAA's National Weather Service (NWS) are proposing development of an integrated flood analysis model for the Delaware River Basin to allow evaluation of flood operations at individual reservoirs and the reservoir system.

Purpose:

Develop a flood analysis model that will allow the evaluation of existing reservoirs for flood mitigation. The model will provide data to evaluate the effects of various reservoir operating alternatives on flooding at locations downstream of the reservoirs. The tool will incorporate rainfall/runoff processes, reservoir operations and flow routing components into a model for simulation of flood hydrographs at USGS stream gage locations and co-located NWS flood forecast points on the Delaware River and its tributaries.

Objectives:

1. Construct a rainfall/runoff and snowmelt model for the non-tidal Delaware River Basin to Trenton, New Jersey.

2. Construct a rainfall/runoff and snowmelt model for the non-tidal Schuylkill River Basin.

3. Construct rainfall/runoff and snowmelt model for the non-tidal Christina River Basin.

4. Construct reservoir simulation models for 15 reservoirs in the Delaware River Basin, as designated by the DRBC.

5. Construct a flow routing model for the Delaware River and major tributaries above Trenton, as well as for the non-tidal Schuylkill and Christina Rivers.

6. Integrate datasets for rainfall/runoff and snowmelt, reservoir simulation, and routing models into a common database structure and framework.

7. Integrate the rainfall/runoff, reservoir simulation, and flow routing models into a single operational tool. The tool will incorporate a graphical user interface for input parameters and datasets as well as output from the models. The modeling system will be modular and allow future incorporation of improved algorithms and improved datasets, such as higher-resolution digital elevation models (DEM's). As an initial step, the model components will first be applied to a pilot watershed to avoid incompatibility and integration issues, and to provide opportunities for reviewer inputs on the final model development approach. The pilot application will provide a test of model function and integration of features rather than calibration.

Approach:

The multi-agency project team will include participation of NWS, HEC, and USGS. Project coordination will be provided by the USGS Pennsylvania Water Science Center, with additional USGS contributions by the New Jersey and New York Water Science Centers, National Research Program, and Office of Surface Water. HEC will have lead responsibility for the reservoir and flow-routing models, and will contribute in all project products. USACE Philadelphia District will provide information on USACE reservoirs in the basin. NWS' Middle Atlantic River Forecast Center (MARFC), as well as Eastern Region Headquarters and Office of Hydrologic Development, will focus primarily, but not exclusively, on assisting with the flow-routing model components. Ongoing advisory input will be sought from staff of the Delaware River Basin Commission, the USGS Delaware River Master, and the Delaware River Basin Commission Flood Advisory Committee..

Task 1 –Database Development and Maintenance:

A unified relational database will be constructed for the flood analysis model. The database will contain all data needed to simulate streamflow using the rainfall/runoff, reservoir, and flow-routing components described in following tasks. This database will provide a controlled system to quality assure input information and minimize redundancy in compiling input data that may be used in more than one model component. Many of the spatial GIS coverages needed have already been compiled for USGS projects in the Basin such as the ongoing National Water Quality Assessment (Fischer and others, 2004) and the SPARROW basin-scale nutrient transport

model (Chepiga and others, 2004). Streamflow routing model datasets are in use for current river forecasting by MARFC. Additional datasets will include USACE reservoir storage curves and operation rules, radar and gage precipitation, stream gage rating curves, digital elevation model, streams, hydrologic response units, streamflow-routing parameters and coefficients. USGS will lead this task.

In general the flood analysis model database will be developed by:

- Determining required data sets needed for model development;
- Acquiring available data sets including spatial datasets such as the 1:24,000 National Hydrography Dataset (NHD) and Delaware Basin NAWQA land use and other coverages, and simulating unavailable data, if necessary;
- Populating and updating the working database and spatial database;
- Quality assuring and maintaining the database;
- Incorporating new datasets from modeling tasks, or from outside efforts.

Task 2 – Rainfall/Runoff Model Development:

The USGS Precipitation Runoff Modeling System (PRMS) will be used for the rainfall/runoff model component (Leavesley and others, 1983). PRMS is a modular-design, deterministic, distributed-parameter modeling system developed to evaluate the impacts of various combinations of precipitation, climate, and land use on streamflow (Leavesley and others, 1983; Leavesley and Saindon, 1995). PRMS can simulate streamflow in both a daily mode and a shorter-time-interval storm mode during a model run. In the daily mode, streamflow and other hydrologic components are computed as daily averages or totals. In the storm mode, selected hydrologic components are computed as averages or totals over time intervals as short as one minute, as specified by the user. Continuity of mass is maintained as the model moves from daily mode to storm mode and back to daily mode. The daily mode component simulates the appropriate antecedent watershed conditions for each storm mode application. Thus PRMS can be used in a continuous simulation mode to evaluate the effects of various combinations of storm chronology, types, magnitudes, and frequencies on streamflow. PRMS is currently being used on river basins in the western United States to provide streamflow forecasts for major reservoir operations (Leavesley and others, 2002).

In general the rainfall/runoff/snowmelt model will be developed by:

- Constructing a rainfall/runoff component using the USGS Precipitation Runoff Modeling System (PRMS) for the Delaware River Basin. The model will:
    1. incorporate raster type (e.g.: NEXRAD) precipitation input data, and
    2. simulate snowmelt and runoff produced by snowmelt.
- Calibrate and verify the model by simulation of historic flood and high-flow events, using NWS archived precipitation and event datasets, USGS gage data, and USACE reservoir data. Data from recent floods in 2004, 2005 and 2006 will be used for calibration and verification.

Task 3 – Reservoir Simulation and Flow Routing – (HEC-ResSim):

HEC will lead development and application of HEC-ResSim for simulation of reservoirs and flow routing. HEC-ResSim (USACE, 2007) was developed to assist in planning studies for evaluating proposed reservoirs in a system and to assist in sizing the flood control and conservation storage requirements for each project recommended for the system. HEC-ResSim

will be used to determine the influence of major reservoirs on streamflow in the basin and evaluate selected alternative reservoir release rules to mitigate downstream flooding.

HEC will coordinate with the DRBC, USGS and NWS in the creation of a HEC-ResSim model of the Delaware River basin. Specific activities and approaches include:

1. Gather and analyze data required for flow-routing and reservoir modeling. This data includes:
   - time-series data (computed inflow and incremental local flow hydrographs from PRMS, observed flow hydrographs, observed reservoir pool elevations and releases and the associated computed reservoir inflows, etc.) for the three major events that have occurred within the last 4 years,
   - physical and operational reservoir data including reservoir pool definition (elevation-storage-area tables), outlet capacity curves, hydropower plant data (outflow and generation capacities, efficiency, losses, etc), operational zones, minimum and maximum release requirements, etc.,
   - rating curves at each stream gage location, and
   - routing reach parameters from existing NWS forecasting models.

   Other resources that will be needed include reservoir regulation manuals or other descriptions of the current reservoir operational objectives and constraints, and geo-referenced map files of the Delaware River basin including a rivers and streams map file, a lakes map file that identifies the reservoir locations and extents, and, if available, a watershed boundary map file that may include the sub-basin delineations, a stream gage locations map file, and a state boundaries map file.

2. Develop a model schematic that identifies the key locations in the watershed. Key locations include reservoirs, gage locations, control points, forecast points, and any other locations that are needed as data transfer points between the PRMS model and the ResSim model or for information for the analysis of results. Geo-referenced map files (identified in step 1) will be used as the background of the model schematic and for delineation of the stream alignment (the framework or skeleton upon which the model schematic is created). The map files will be obtained from and/or shared with the PRMS modelers so that both models will use the same units and spatial transformation.

A coordination meeting of the USGS and HEC modelers and a DRBC representative will be held at the onset of the project to identify the key locations described above and to establish a naming convention for these locations and other model elements. Both the pilot basin and the overall watershed will be addressed.

3. HEC, in cooperation with USGS, and in consultation with NWS, will evaluate the use of several alternative approaches for flow routing in the main channel and major tributaries of the Delaware River. HEC-ResSim contains seven methods for routing streamflow (Coefficient, Muskingum, Muskingum-Cunge 8-pt Channel, Muskingum-Cunge Prismatic Channel, Modified Puls, SSARR, and Working R&D Routing), each method with its own set of routing parameters. In addition, the NWS variable lag & K routing method will be incorporated into HEC-ResSim so that existing operational parameters developed by NWS can be used, where applicable. To permit cross verification and allow use of the ResSim model as a NWS river forecast model, the routing parameters for the basin will be defined for a 6 hour computation interval. However, null routing and a daily timestep will be used for the “pilot basin”.

4. Define the physical and operational data for each major reservoir in the basin. Physical reservoir data includes: reservoir pool storage definition, dam elevation and length, outlets and their release capacities, and power plant data (if applicable). Defining the operational data includes specifying the operation zones or levels, the rules that constrain the releases for each zone, and a release allocation strategy that indicates how the releases will be allotted to the available outlets.

5. For each river junction that will receive incremental local inflow (i.e., subbasin runoff from hydrologic model), identify the source and an appropriate ratio (usually 1.0). In addition to key control point locations, the NWS forecast locations and USGS gage locations will be identified and included as junctions. Discharge to stage conversion at relevant locations will be computed if rating curves are available.

6. Calibration and verification of the model will be done by simulation of the three most recent high-flow events using observed (flow and reservoir elevation & releases) datasets from NWS, USGS, and/or USACE Philadelphia District..

Task 4 – Integration of the model components into the Modular Modeling System (MMS):

The Modular Modeling System (MMS) (Leavesley and others, 1996) is an open-source computer software system developed to (1) provide the integrated software environment needed to develop, test, and evaluate physical-process algorithms; (2) facilitate integration of user-selected algorithms into operational physical-process models; and (3) provide a common framework in which to apply historic or new models and analyze their results. MMS uses a library that contains modules for simulating a variety of physical processes (Leavesley and others, 1996). The MMS will be used to link all simulation models utilized in the system to a common database (Task 1) and to a graphical user interface (Task 5) for user interactions and the analysis of simulation results. This will provide a database-centered approach to support model applications and analysis. PRMS is currently incorporated in MMS, and interfaces will be developed to incorporate HEC-ResSim complete with the newly integrated flow routing algorithms into MMS, as needed. MMS is currently being used to provide database-centered system support for making complex operational decisions on selected multipurpose reservoir systems and watersheds in the western United States (Leavesley and others, 1996b) USGS will lead this task.

Task 5 – Graphical User Interface (GUI) Development:

A graphical user interface (GUI) that will enable a user to modify input data, apply the linked flood analysis model, and analyze the results will be developed by USGS. A user's manual explaining how to use the GUI and documenting the capabilities and functionality of the flood analysis model will be written. The GUI will:

- Package the rainfall/runoff, reservoir simulation, and flow routing model components into a single management tool to provide the technical support for evaluating potential flood operating scenarios.
- Have a pre-processor graphical user interface to facilitate alternative flood scenario simulations by incorporating the following;
    1. User friendly input for climatic data to facilitate simulation of historic flood events, snowmelt or other user defined scenarios.

2. The capability to simulate single or multiple storms over a 10-day period.
3. The functionality to allow the user to simulate flood events under varied reservoir pool void and operating conditions.
4. The functionality to allow the user to change predefined operating rules of existing reservoirs.

- Have post-processing capabilities to display:
  1. A selectable map of the basin showing the reservoirs and forecast points.
  2. Graphical display of the hydrograph for USGS gaging stations and co-located NWS flood forecast points.
- Provide other options, such as historic rainfall and snowmelt event hydrographs at gaging stations and NWS forecast points for selection by user to compare to user generated hydrographs using different reservoir operation scenarios.

Implementation Strategy

The implementation strategy includes an initial focus on a flood analysis model for a major tributary to the Delaware River above Trenton. This "pilot basin" approach will avoid late-stage incompatibility and integration issues between model components and provide DRBC and advisors with an opportunity for timely input on the final basin-wide approach.

Project progress and plans will be communicated via scheduled monthly teleconferences and project milestones which will involve face-to-face meetings among project participants.

- **Milestone 1** will occur about 4 months after the agreement is signed and will involve a presentation of the integrated model, including rainfall and snowmelt runoff, reservoir simulation, and flow routing for the selected "pilot" basin. After successful completion of this milestone, including an advisory peer review, the model will be expanded to the entire study area.
- **Milestone 2** will be 11 to 13 months into the project. It is anticipated the Delaware Basin model will be completed and discussion will focus on calibration and operation of the model and details associated with the products.
- **Milestone 3** will occur 18 months after the project start and will include presentation of model results and product deliverable.

Products:

A joint USGS/HEC Report will be written that will document the flood analysis model development, including the rainfall/runoff, reservoir simulation, and flow routing components. This final report will also present results of selected applications to evaluate the impact of reservoir operations on flood mitigation. A users' guide will be written and included as an appendix of the joint final report. USGS will prepare an Open-File report on development of the rainfall/runoff model and documentation of the model database. HEC will prepare a report on the reservoir modeling and flow routing, focusing primarily on the aspects or features that subsequent modelers will need to be aware of as further alternatives are developed. At least one journal article or technical conference presentation will be written describing the integrated model of runoff, stream flow routing, and reservoir storage and releases in the Delaware River Basin.

USGS and HEC will deliver and install the flood analysis model, with all necessary input files and software components, on DRBC computer systems, and train DRBC staff in its operation. USGS and HEC will prepare presentations suitable for delivery to the public that describe model development, calibration, verification, and results of simulation of historic high flow events such as the floods of September 2004, April 2005, and June 2006.

In summary, project products will include:

- Documentation of the model development, model assumptions, model database, and model calibration and verification in a joint USGS/HEC report.
- A user's manual for running the flood analysis model. The user's manual will document the capabilities and functionality of the tool. The user's manual will be included in the final report.
- A USGS Open-File report on details of rainfall/runoff modeling and the model database
- A HEC report on reservoir modeling and flow routing
- Journal article or technical conference presentation
- Delivery of the model in a package that will allow modification, additional simulation, expansion, and distribution by DRBC. USGS products are generally public domain. HEC-ResSim software is free and models developed using these tools can be used by anyone.
- Development and, if requested, delivery of public presentations for DRBC on modeling results.

References:

Chepiga, Mary; Colarullo, S.J.; and Fischer, J.M., 2004, Preliminary analysis of estimated total nitrogen and total phosphorus loads and factors affecting nutrient distribution within the Delaware River Basin [abs.], in Proc. of the American Water Resources Assoc. 2004 Spring Specialty Conf. - Geographic Information Systems (GIS) and Water Resources III: American Water Resources Assoc., May 17-19, 2004, Nashville, Tenn.

Fischer, J.M., Riva-Murray, Karen, Hickman, R.E., Chichester, D.C., Brightbill, R.A., Romanok, K.M., and Bilger, M.D., 2004, Water quality in the Delaware River Basin, Pennsylvania, New Jersey, New York, and Delaware, 1998-2001: USGS Circular 1227, 38 p.

Flippo, H. N., Jr. and Madden, T. M., Jr., 1994, Calibration of a streamflow-routing model for the Delaware River and its principal tributaries in New York, New Jersey, and Pennsylvania: U.S. Geological Survey Water-Resources Investigations Report 93-4160, 54 p.

Hydrologic Engineering Center, 2003, HEC-ResSim, Reservoir System Simulation, User's Manual Version 2.0: U.S. Army Corps of Engineers, Report CPD-82, Davis, Calif., 426 p.

HydroLogics, Inc., 2002, Modeling the Delaware River Basin with OASIS, Prepared for the Delaware River Basin Commission.

Leavesley, G.H., Lichty, R.W., Troutman, B.M., and Saindon, L.G., 1983, Precipitation-runoff modeling system--User's manual, USGS Water Resources Investigation Rep. 83-4238, 207 p.

Leavesley, G.H., and Stannard, L.G., 1995. The precipitation-runoff modeling system—PRMS, *in* Singh V.P. (ed.), Computer Models of Watershed Hydrology, Water Resources Publications: Highlands Ranch, CO; p. 281–310.

Leavesley, G.H., Restrepo, P.J., Markstrom, S.L., Dixon, M., and Stannard, L.G., 1996a, The Modular Modeling System (MMS): User's Manual, USGS Open-File Report 96-151, 142 p.

Leavesley, G.H., Markstrom, S.L., Brewer, M.S., and Viger, R.J., 1996b, The modular modeling system (MMS)—the physical process modeling component of a database-centered decision support system for water and power management. *Water, Air, and Soil Pollution* **90**: 303–311.

National Weather Service-Middle Atlantic River Forecast Center, 2006, Model simulations for the Upper Delaware River Basin flooding, 7 p. <http://www.state.nj.us/drbc/Flood_Website/NWSResSimRPTAug2006.pdf>

National Weather Service, 2007 (accessed online), National Weather Service River Forecast System (NWSRFS) User Manual: <http://www.nws.noaa.gov/oh/hrl/nwsrfs/users_manual/htm/xrfsdocpdf.php>

Quinodoz, H.A., 2006, Reservoir operations and flow modeling to support decision making in the Delaware River Basin: Eos Trans. AGU, 87(52), Fall Meet. Suppl., Abstract H41D-0441.

U.S. Army Corps of Engineers, 1984, Delaware River Basin Survey Report, 83 p., appendices.

U.S. Army Corps of Engineers, 2007 (accessed online), HEC-ResSim: <http://www.hec.usace.army.mil/software/hec-ressim/hecressim-hecressim.htm>

Watson, K.M., Reiser, R.G., Nieswand, S.P., and Schopp, R.D., 2005, Streamflow characteristics and trends in New Jersey, water years 1897-2003: U.S. Geological Survey Scientific Investigations Report 2005-5105, 131 p.

Zagona, E.A., Fulp, T.J., Goranflo, H.M., and Shane, R.M., 1998, RiverWare: A general river and reservoir modeling environment: Proceedings of the First Federal Interagency Hydrologic Modeling Conference, Las Vegas, Nevada, April 19-23, 1998, pp. 5-113-120.

Budget:

Total (gross) costs by Task are shown in Table 1.

Table 1: Summary of estimated budget (in gross dollars) by Task.

Tasks	Total Cost
Database Development	$80,000
Rainfall/Runoff Model Development	$220,000
Reservoir Simulation and Flow Routing ModelDevelopment	$209,000
Model Integration and GUI Tool Development	$35,000
Products & Management	$191,000
NOAA-NWS In-kind services (divided among proj. tasks)	$30,000 (estimated value)
Total	$765,000

Funds to conduct the proposed work will be provided by DRBC with additional funds and in-kind support from USGS and USACE, and in-kind support by NWS. USGS funds would come from the Federal-State Cooperative Program and are subject to the availability of funds. NWS staff availability may be affected by operational needs during hydrologic events. Funding sources for the project are listed in table 2.

Table 2: Summary of estimated funding (in gross dollars) (*[1]USGS contribution is subject to availability of Federal-Cooperative Program funds; [2] scheduling of NWS in-kind support is subject to staff availability due to hydrologic events; [3]Estimated monetary value for NOAA NWS's in-kind services provided; [4]Proposed cost-sharing agreement between DRBC and USACE)*

Agencies	Total
DRBC	**$500,000**
USGS Match[1] & in-kind	**$100,000 $35,000**
NOAA's NWS in-kind [2] (about ⅓ FTE)	**$30,000[3]**
USACE[4]	**$100,000**
Total contribution	**$765,000**

Project Timeline

The project will be completed 18 months from the signing of the Joint Funding Agreement.

Table 3: Timeline for project (indicates approximate timing of review meetings w/ DRBC, USACE, and USGS)

TASKS	Months after agreement is signed																	
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Database Development																		
Rainfall/Runoff Model Development																		
Reservoir Simulation Model Development																		
Flow Routing Model Development																		
Review/Presentation of results (progress)				"PILOT"														
Model Integration																		
GUI Tool Development																		
Report Writing and Presentation																	draft due	

Figure 1: Map of Delaware River Basin showing major reservoirs (DRBC, 2007)