NEW GENERATION WATER MANAGEMENT DECISION-SUPPORT SYSTEM, U.S. ARMY CORPS OF ENGINEERS

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Abstract

As part of its water resources mission, the U.S. Army Corps of Engineers (USACE) plans, designs, constructs and operates a variety of water resource projects. Projects include multi-purpose storage reservoirs, navigation dams and locks, and levee and bypass systems with closure and diversion structures. More than 700 reservoir and water control structures located throughout the U. S. are operated by USACE. In addition, emergency operations often include reinforcing or temporarily raising levees, sandbagging efforts, and evacuation during flooding. The Corps Water Management System (CWMS) is the new generation decision-support system that enables execution of the USACE water control management mission. This paper provides an overview of CWMS development, describes its capabilities, and briefly discusses implementation requirements.

1   BACKGROUND

Real-time Data and Water Control Management. Effective regulation of flow and storage in multipurpose projects must be based on timely and accurate information. During extreme events, such as floods, regulation decisions are often required in minutes to hours from the onset of rising river and lake levels. During drought conditions, storage and release decisions can affect water availability for months into the future. Continuous real-time data observations from the field, as well as reliable watershed, river, and reservoir operation modeling tools, are needed to provide appropriate response to changing hydrologic conditions.

Legacy System. The Water Control Data System (WCDS) provided USACE the information support services for water management from the late 1970's up through the early 1990's. WCDS was a system of dedicated mini-computers and data acquisition, management, and communications hardware and software. Although guided by USACE corporate policy, WCDS was not a centrally planned and developed system. Some standard data processing programs were used throughout USACE; others were developed regionally and locally. From a national perspective, it was a collection of individual systems that were locally managed and maintained. The system performed inconsistently and capabilities varied widely. Forecasting and decision-support modeling was performed on but a few of the most highly developed systems.

Need for Improvements. A large regional flood event, known as the Great Flood of 1993 (in the Mississippi River system), exposed the shortcomings of WCDS and prompted serious study of needs for system improvement. The flood affected the central third of the U.S. and involved more than 12 states and several USACE regional offices. The demand for collecting, storing and disseminating the real-time data was beyond the capability and computer processing power of the system. A here-to-fore not significant aspect was the unprecedented public demand for information. Different WCDS platforms in adjacent USACE offices further complicated region-wide monitoring and response as the flood progressed downstream. The outcome of the study was that USACE identified the need for a uniform water control management system that integrated communication networks, standard computer hardware, centrally developed and supported software, and state-of-the-art watershed, river, and reservoir system models.

2 OVERVIEW OF CWMS

USACE water control managers from around the U.S. convened to develop system requirements and adopt a process to enable their participation in system design and testing. Two USACE field office groups were formed and charged with providing oversight and guidance in the development of CWMS, the new name for the modernized system. The AG (senior water management Advisory Group - representing eight USACE regions) provided policy guidance and served as the overall project monitor. The CURG (CWMS Users Representative Group) composed of working-level water control managers, participated in system design and testing. Under the direction of a USACE headquarters program manager, the development, testing, and deployment of CWMS was performed by the USACE Hydrologic Engineering Center (HEC). HEC is also performing on-going support, maintenance, and improvements.
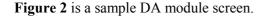
CWMS encompasses steps in the water control management process starting from the receipt and visualization of hydromet, watershed, and project status data, through the modeling of system response and decision-support analysis, ending with the dissemination of data and decision results. The incoming real-time data include river stage, reservoir elevation, gage precipitation, WSR-88D spatial precipitation, quantitative precipitation forecasts (QPF) and other hydro-meteorological parameters. These data are used to derive the hydrologic response for a watershed area, including short-term future reservoir inflows and local uncontrolled downstream flows. The reservoir operation model flows are then processed to provide proposed releases to meet operation goals. For flood periods, based on the total expected flows in the river system, river profiles are computed, inundated areas mapped, and flood impacts analyzed. CWMS allows evaluation of any number of operation alternatives before a final forecast scenario and release decision are adopted. For example, various alternative future precipitation amounts may be considered, hydrologic response may be altered, reservoir release rule changes may be investigated, and alternative downstream river conditions may be evaluated. During flood events, forecasting and decision-support analysis is focused on short interval events, on the order of hours to perhaps weeks. During low-flow and drought periods, forecasting and decision-support analysis is focused on long interval events, on the order of weeks, months, and seasonal time periods. The results of an operation decision, along with supporting hydromet, watershed, and project status and release data are disseminated to others via web technology. USACE water managers work in close coordination with other U.S. Federal (i.e. National Weather Service, Bureau of Reclamation, Federal Emergency Management Agency), state, and local water and emergency management organizations, to carry out their missions and responsibilities. Water management information is also provided to the media and the public. CWMS emphasizes visualization of information in time and space. The primary user interface is map based to provide clear spatial reference for watershed and modeling information. CorpsView, a USACE developed spatial visualization tool based on commercially available GIS software, provides a direct user interface to GIS products and associated spatial attribute information. The system is 'live' twenty four hours per day, seven days per week, continuously providing support during routine high and low flow periods, and during emergencies. CWMS monitors itself providing automated status information on components and processes, and alerting system managers to its service needs.
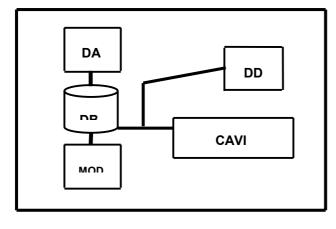
CWMS was developed and tested between 1997 and 2001. USACE-wide deployment was concluded in December 2002. An upgrade to Version 1.1 concluded in March 2003. Thus, CWMS is now in full-time use for day-to-day USACE water control management. The system in place in April 2003 is Version 1.1.

3   CWMS COMPONENTS

Figure 1 shows the major components of CWMS (counter clockwise from upper left): Data Acquisition (DA), Database (DB), Modeling (MOD), Control and Visualization Interface (CAVI), and Data Dissemination (DD). These components have been developed in network client-server architecture, permitting each component of the system to be hosted on one or more separate computer platforms. The major portions of the system components are written in Java, with Fortran, and C++ used for certain of the model computations. The current server-side computer is a Sun Solaris machine(s) and the client (CAVI) side can be fielded on Windows 2000 or Sun Solaris computers. This design provides a centrally located database for each office to support the sharing of models and modeling results. The architecture allows users to access the system from their individual offices, or from remote locations should their office become inaccessible, or an off-hours emergency occur. The CWMS components shown are installed in a local area subnet within each of the thirty-five USACE field offices.

Data Acquisition. The Data Acquisition (DA) component is responsible for ingesting data from any of the supported data sources. Currently, the primary data streams processed in USACE are GOES Data Collection Platform (DCP) and National Weather Service SHEF. These and other formatted data may be processed as it is received via FTP or other file transfers, or via point-to-point network socket connections. Either type data is written directly to permanent storage and is then operated upon by the data acquisition software. Two levels of data screening may be performed. "On-the-fly" screening uses only simple magnitude and range checks. The second level of screening can perform tests that consider the rate-of-change of variables, comparison with neighboring stations, and other statistical tests. The DA component is also responsible for the derivation of secondary parameters. Typical derivations include: reservoir pool elevation to reservoir storage, river stage to flow, and accumulative precipitation to incremental precipitation. All data is stored in the database during its processing by the DA components. The data acquisition display is user configurable to depict data status via color bars positioned on a background map. These bars are time-scaled and reflect the data quality assigned during screening (e.g. green - OK, yellow - questionable, red - rejected). Graphic/tabular editing screens are available to correct data with quality problems.
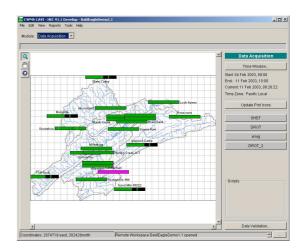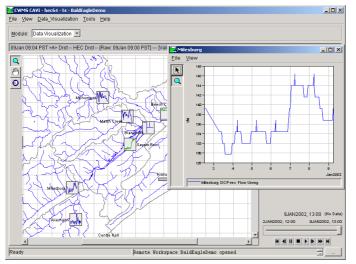
 Figure 2 is a sample DA module screen.

Figure 1. CWMS schematic and components.

Figure 2. Data Acquisition Screen.

Database. The Database (DB) component provides permanent data storage for the system. It is responsible for the management of time-series data received from the data system and time series data generated as derive and modeling operations are performed. The record database is an Oracle relational database designed for standard application in all USACE water management CWMS installations. The Database Interface (DBI) controls all data written to or read from the database. The DBI provides a single image view of data that is used in the many components of CWMS. All data in the database is stored in Coordinated Universal Time (UTC) in System International (SI) units. Activities requesting data from the DBI receive the information in U.S. Customary or SI units. In all cases time remains in UTC and the user interface then displays the time correctly in the users selected time zone. The consistent use of UTC resolves issues where data crosses time zones and the problematic semi-annual shifting between standard and daylight time. **Figure 3** shows thumbnail plots of river status for several locations with the Milesburg plot enlarged. This display is a live depiction of data as it flows in and is stored in the database.

Modeling. The modeling component is responsible for the specification of model alternatives, the execution of model runs, and the display and interpretation of analysis results. The model suite includes precipitation input preparation, hydrologic response modeling, reservoir operation modeling, steady and unsteady flow river profile analysis, inundated area determination, and flow impact analysis. The models that are implemented in CWMS include the HEC suite of NexGen programs
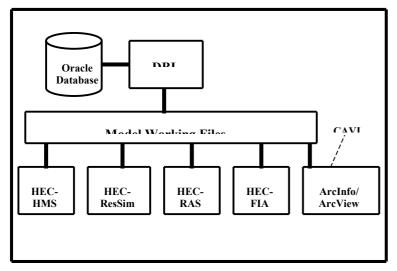
Figure 3. Live database thumbnail plots

(USACE 2001a), with the addition of GIS processing and viewing via Environmental Systems Research Institute products of ArcInfo and ArcView (ESRI 2001). The model functions are: HEC-HMS (USACE 2001b) - precipitation runoff; HEC-ResSim (USACE 2002b) - reservoir system; HEC-RAS (USACE 2001c)- river profile analysis; HEC-FIA (USACE 2002a)- flood impact (damage); and ArcInfo/ArcView - inundation boundary computation, and GIS information viewing. Access for set up, seamless model execution as an integrated suite, and viewing is via the CAVI. The integration schema permits other supplementary models (than those presently implemented) to be substituted or added so that they would function in a similar transparent and seamless manner.

Figure 4 shows the models as integrated in CWMS, and **Figure 5** is the CAVI dialogue for specifying a forecast alternative. At a user specified forecast time, data pertinent to a watershed area is extracted from the database and placed in a modeling sub-database. This sub-database is then the source and destination for all model runs and all the alternatives that are evaluated. At completion of the analysis the final operation alternative results are posted back to the Oracle database for dissemination. The sub-database, the related model parameters, and specific model output and log files can be saved to off-line storage to serve as a complete record of the analysis performed to support the decision process. **Figure 7** (included later) is an example of the model interface for the test watershed in Bald Eagle Creek, Pennsylvania. The depiction is a zoomed window displaying the model layer for reservoir analysis. Other model layers of watershed basins/flow, flood impact, and stage can be displayed separately or as multiple overlays depending on user preference.

4   HYDROLOGIC MODELING.

The hydrologic response of the watershed is modeled using spatially distributed precipitation. HEC-HMS accepts gridded precipitation from both radar and point precipitation gage sources. Runoff excess from each grid cell is determined and is routed using the Modified Clark procedure to provide runoff at the sub-basin outlet. Sub-basin hydrographs are then routed down through the channel network to develop flow into reservoirs, and local flow at downstream locations. The HMS model is set up and calibrated for a base forecast condition outside of the CWMS environment and inserted into the CWMS system - a one time (or occasional) set up. Digital Elevation Model (DEM) data is used to develop model basin boundaries and parameters. Within CWMS, selected model adjustments are permitted in the forecast mode, for example, general wetness condition (loss rates) by watershed region, and this capability is operated via the CAVI. **Figure 6** depicts the HEC-HMS model layout.
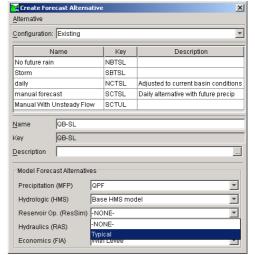

Figure 4. CWMS models integration schematic.

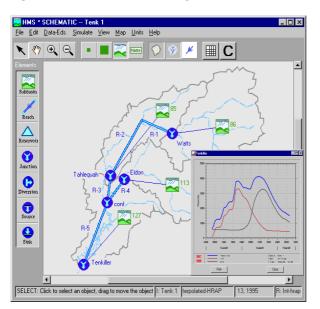**Figure 5.** Forecast setup dialogue.
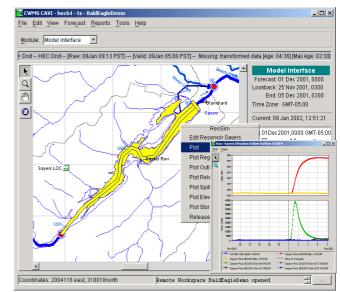

Figure 6. Typical HEC-HMS model.

Figure 7. HEC-ResSim reservoir display.

5   RESERVOIR MODELING.

The analysis of reservoir operations is performed using HEC-ResSim. This newly developed reservoir simulation program determines project releases based on a set of user supplied operation rules. A reservoir model is defined over a stream alignment, which shows the river network underlying the system model. Model objects representing reservoirs and channel reaches, are drawn by selecting an object tool from the tool list and locating the upstream and downstream ends of the object on the stream alignment. Operational data are defined and stored separately for each reservoir. Each reservoir "owns" one or more sets of data that define the operational storage zones and associated release rules. Rules can be defined to control individual outlets within the outlet works or groups of outlets. Rules are also available to control operation for downstream goals or constraints. Reservoirs operating as a system are guided by implied, or specified, relative storage levels.
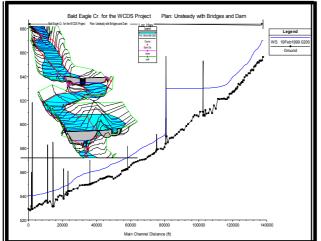
This rule-based approach allows good flexibility in describing desired behavior for individual reservoirs operating for multiple local and downstream goals, as well as when reservoirs must operate as a system. The reservoir model uses inflows generated from the hydrologic model. Initial pool elevation, its corresponding reservoir storage and known project releases must be available to properly initialize the model. In cases where different rules lead to a conflict in determining releases, a rule priority is used to resolve the conflict. The determined releases are then combined with local uncontrolled flows from the hydrologic model to provide total flows throughout the watershed. **Figure 7** depicts the reservoir layer in the model interface of the CAVI. Note that the display panel with an array of display choices is activated by selecting the control point of interest on the stream alignment shown in the reservoir layer.

6   RIVER PROFILE MODELING.

The total river flow for each of the alternatives is used to determine the water surface profiles before, through, and downstream of the reservoirs. The HEC-RAS model is capable of computing both steady and unsteady flow profiles. Each of these determinations is based on a stream model that includes bridges, in-line structures (including culverts, dams, weirs, and navigation lock and dams) and cross section geometry. Geo-spatial tools may be used outside CWMS to assist in generating the necessary cross sections from triangular irregular network (TIN) files. Because the profile analysis can be performed with spatially registered cross sections, the resulting water surface profiles can be used to map inundated areas. **Figure 8** shows output displays from the river profile analysis with HEC-RAS. The inset is a quasi- 3D representation of the stream; this display can be animated to show the rise and fall of the profile during passage of a forecast flood event.

7   FLOOD IMPACT ANALYSIS.

Based on the information available from the preceding model steps the impacts of flows and stages may be evaluated. This evaluation is based on relationships between flow and/or stage and various evaluation functions, such as damage, area/properties impacted, and emergency response table. The damage functions may reflect urban, suburban, and agricultural conditions. Impacts are evaluated for any number of impact areas as defined by the user. Impact results may be aggregated by county, state, Congressional district, or other desired spatial entity. The relationships used for computing impact analysis in real-time are separately prepared in a one time, or occasional, set-up step. A number of GIS-based and other utilities are available to assist in function development. **Figure 9** is the CAVI display for the flood impact layer of the model interface. Selecting the impact area of interest brings up a number of displays and tabulations for viewing by the user.
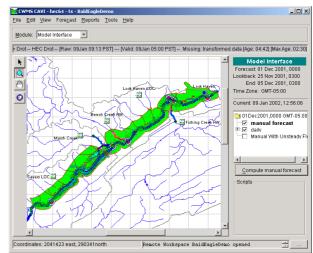
Figure 8. River profile display.

Figure 9. Flood impact model layer.

Data Dissemination. Internet Web and other automated technology are used to provide information from the CWMS to interested parties. Data received from the data acquisition components, derived data, and final project operation data are available for dissemination to other USACE offices, cooperating Federal, state and local agencies, and other public and private interests. A close working relationship exists between USACE and the National Weather Service (NWS). Information that USACE disseminates is solely associated with its mission to operate water projects, and to perform emergency flood fight activities. Public dissemination of flood alerts, flood warnings, and other weather information is the responsibility of the NWS. **Figure 10** is a depiction of a sample Web-accessible display automatically generated via selecting a 'posting' option from the CAVI.
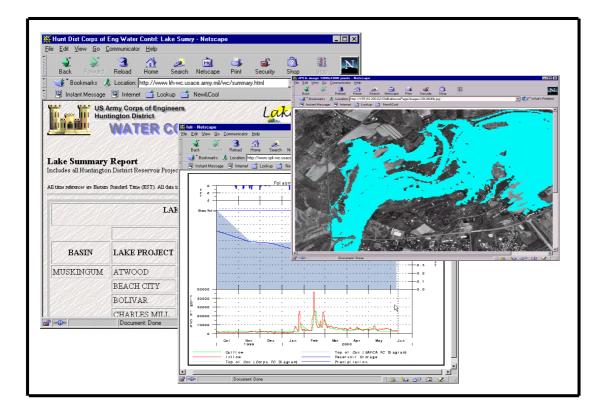

Figure 10. Sample Web postings of forecast results.

8 CWMS IMPLEMENTATION

System Requirements. When fully deployed, CWMS is a powerful system, providing a rich suite of data management, visualization, and analytical tools to assist in real-time water control management. To arrive at a fully deployed system requires substantial effort and considerable resources. Users must gather, organize, and put to use, watershed, river system, and water control management information in a manner compatible with CWMS. Successful implementation also requires acquisition, populating, and maintaining a computer and electronic network for acquiring, managing and using large amounts of data. CWMS requires:

- A field network of field observations gages for collecting and reporting hydro-meteorological and water control system status data in real time;

- Extensive static information about watersheds, rivers and projects, operation rules;

- Modeling expertise to develop the watershed, river, reservoir and impact models so that the decision-support analysis is based on accurate representation of watershed conditions;

- For automated flood inundation mapping, accurate hydrographic and topographic data in electronic form;

- A fast, reliable local computer network equipped with modern but modest workstations and personal computers;

- Professional staff to ensure maintenance of hardware and software for 24/7 operations.

To achieve successful implementation requires up-front commitment of funding and resources, including specially trained personnel. While the initial investment required for CWMS implementation is substantial, the benefits to be derived are proving to far outweigh the costs. Now that the system is operational in USACE offices, it is expected to take several more years to fully implement CWMS for all watersheds and projects within USACE's jurisdiction.

Implementation of CWMS Outside USACE, Including International. CWMS architecture, software components, data processes, geographic coordinate system, and time management features are designed for system portability. The client-server architecture is based on industry standard protocols and telecommunications software; the software executes on standard SUN Solaris and Microsoft Windows platforms; native data unit system is SI, with conversion to U.S. Customary at users discretion; geographic coordinates are Latitude - Longitude based; and time is with reference to Coordinated Universal Time (UTC) - reporting in local time is at users discretion. CWMS can thus be implemented anywhere in the world and function as intended. At present, the dialogue text and output displays and reports are in English. Preliminary work has been undertaken to provide for language adaptation, for example to enable dialogue text and reports to be in Spanish, French and other alphabet-based languages, but accomplishment awaits interest and participation by the international community.

CWMS is an official Automated Information System of USACE and as such, is designed and developed to meet stringent corporate robustness and security requirements. Because of its status as an official USACE system, users are assured that CWMS will be maintained, supported, and improved over the normal life cycle - a minimum of ten years. An effort is underway that will replace the corporate security and other such USACE-specific features with equivalent industry-standard features enabling appropriate implementation outside USACE. CWMS software is considered to be U.S. public domain. This means that the software was developed with U.S. Federal resources and is thus to be provided to the public free of copyright restrictions or proprietary license fees. That said, for the near term, CWMS would not be

publicly posted for free acquisition or download. However, the individual models integrated in CWMS are available for download at: http://www.hec.usace.army.mil. CWMS is a sophisticated, complex system such that successful implementation would require a high-degree of CWMS-specific computer system and engineering modeling expertise in order to be successful. Since significant assistance by an organization trained and familiar with CWMS would be required, a mechanism to provide access to those resources is being devised.

9 ACKNOWLEDGMENTS

Planning, design, development, testing, and deployment of CWMS has been a model of teamwork among HEC staff and the extended community of other participants across USACE and in the private sector. HEC is the responsible 'materiel developer' under the HQUSACE program manager; USACE field office teams developed the system requirements; HEC staff led the software development with assistance by a private contractor; selected field offices served as test sites throughout the development process; and a senior water management group provided oversight. Principal HEC staff with leadership roles in CWMS development include, besides the author: Art Pabst - Technical Director; Dan Barcellos - database system; Bill Charley - CAVI and models team leader; Carl Franke - data acquisition and data dissemination; Matt McPherson - data validation/transformation; Tom Evans - runoff forecasting and deployment coordinator; Gary Brunner - river profile modeling; Joan Klipsch - reservoir system modeling; and Penni Baker - flood impact modeling. The GIS-related activities team member is Tim Pangburn, USACE Remote Sensing and GIS Center. John DeGeorge and his team at RMA Associates, Fairfield, CA contributed substantially to software development for the DBI, flood impact and reservoir models, and overall system integration.

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