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IMPROVING REAL-TIME HYDROLOGIC SERVICES IN USA

PART II: INUNDATION MAPPING USING DYNAMIC STREAMFLOW MODELING

by

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1. INTRODUCTION

Since the first River Forecast Centers of the National Weather Service (NWS) were established in the mid-1940s, hydrologic forecasts of flood crests have been issued for a specific location (coincident with a stream gage) at a given point on a river or stream. The forecasts typically extended for 3 days into the future or until an expected flood crest was reached. The forecasts were deterministic and future precipitation was assumed to be negligible from the time the forecast was issued until the time the crest was forecast to occur. Each flood forecast was related to a pre-determined flood stage where damage would occur in the reach surrounding the forecast point. These forecast products were issued as single point values for an expected time when the crest might occur. The watershed areas affecting these forecast points were generally large, on the order of thousands of square kilometers. In later years, the number of hydrologic forecast points increased and the hydrologic (rainfall-runoff) forecast areas have become increasingly smaller, 500 to 1,000 square kilometers. End users of these forecasts have been seeking more detailed information, including probabilistic forecasts from days, to weeks, to months into the future. They are also asking for enhanced forecast information which provides additional information regarding the flow conditions between forecast points, especially within urban areas. In order to provide such enhanced forecast services the National Weather Service (NWS) is implementing an Advanced Hydrologic Prediction System (AHPS) which has been under development for several years (Day, 1985 and Fread, 1996, 1998) and was recently demonstrated (NWS, 1997 and Braatz, et. al., 1998).

Enhanced capabilities, via AHPS (Ingram, et. al., 1998), include: providing probabilistic river forecasts for risk-based decisions; utilizing precipitation and climate predictions to extend forecasts out to weeks and months; and providing real-time flood inundation mapping. The inundation mapping capabilities described in this paper build upon real-time probabilistic river

stages produced by an ensemble hydrologic prediction system utilizing a hydraulic/dynamic river routing feature.

2. DYNAMIC STREAMFLOW ROUTING

The NWS dynamic streamflow routing model, FLDWAV (pronounced "flood wave") is a sub-component of the NWS River Forecast System (NWSRFS) which is the basic component of AHPS. Inundation mapping capabilities, coupled with FLDWAV and Ensemble Streamflow Prediction, ESP (Day, 1985), provides for a spatial display of either inundation depths or probabilistic contours (zones) of inundation for a specified future window of time. An example product through the use of this coupled forecast system is an inundation map which reveals zones of 100 to 75 percent, 75 to 50 percent, 50 to 25 percent, and lower percent probabilities for inundation during the next 60 days (Figure 1). A hypothetical flood of sufficient magnitude to illustrate the extent of inundation resulting from levee overtopping flows is also shown in Figure 2.

FLDWAV provides many capabilities which are beneficial to the AHPS dynamic mapping system. The FLDWAV model (Fread and Lewis, 1988) is an unsteady flow, dynamic routing model which determines the water-surface elevation (h) and discharge (Q) at specified locations along the length (x) of a waterway (river, reservoir, etc.) when subjected to an unsteady flow event such as a flood wave or dam-break wave. The routing model is based on an implicit finite-difference solution of the complete one-dimensional Saint-Venant equations of unsteady flow coupled with an assortment of internal boundary conditions representing a wide spectrum of hydraulic structures. The flow may occur in a single waterway or a system of inter-connected waterways, including those having dendritic structures (nth order tributaries), in which sinuosity effects are considered. Additional capabilities of FLDWAV which are beneficial to the dynamic flood inundation mapping system include: 1) the ability to account for the effects of off-channel storage areas connected to the waterway or separated by levees and to compute the time-dependent water surface elevations of the storage areas; 2) the capability to dynamically model dam failures as well as flows which are affected by bridge constrictions; 3) the ability to simulate flows which overtop/breach levees located along either or both sides of a main stem and/or its principal tributaries; and 4) the provisions to handle flows in the subcritical and/or supercritical flow regime.

The information necessary to execute FLDWAV includes: 1) an upstream time series of h or Q; 2) a downstream boundary condition (time series of h or a h(Q) relationship); 3) cross-section geometry (top width vs. elevation table); 4) information about hydraulic structures (dams, bridges, levees); 5) hydraulic roughness coefficients which may vary with h or Q and with location along the waterway; and 6) the initial water-surface elevation (h) and discharge (Q) at each cross-section location. Given this information, FLDWAV will simultaneously solve for the h and Q at each cross section location along the routing reach for each time interval during the specified simulation time period. The water surface profiles h(x) are essential for inundation mapping. Although FLDWAV generates water surface profiles at each time step which includes all computational points, a subset of the computational points (e.g., forecast points) only may be

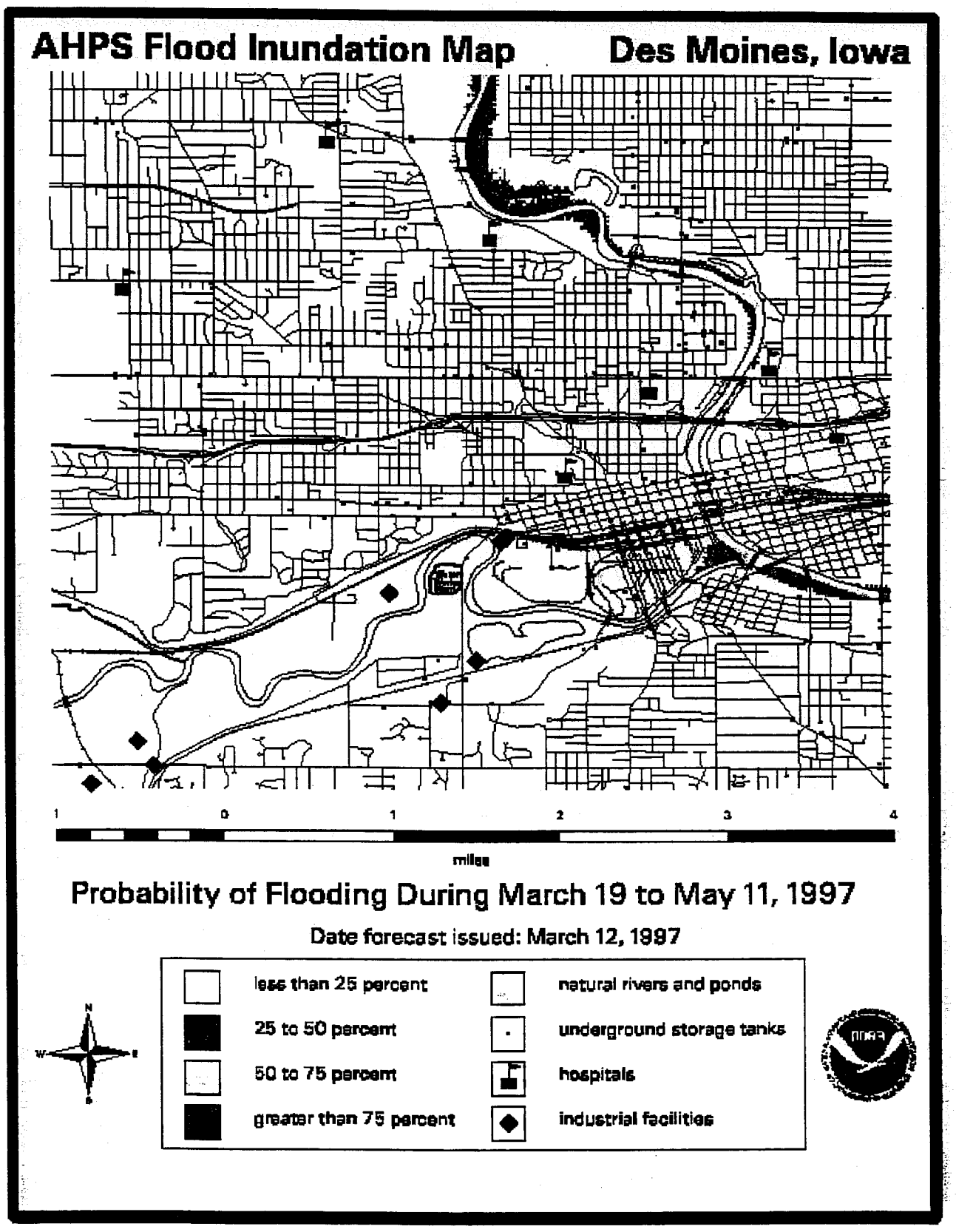

Figure 1. AHPS inundation map as demonstrated for the Des Moines and Racoon Rivers, Iowa.

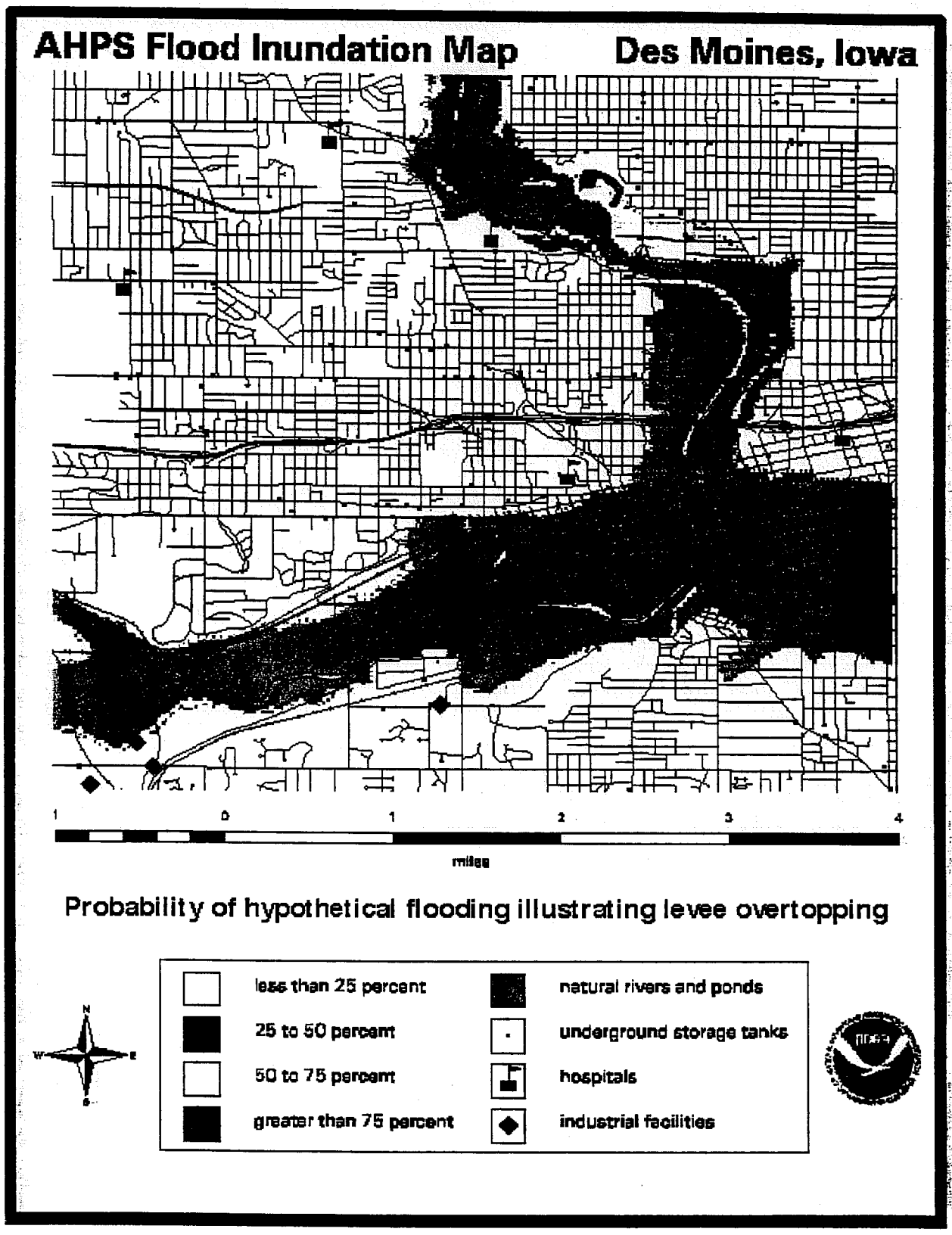

Figure 2. AHPS inundation map depicting the probability of hypothetical flooding with levee overtopping.

used for the profiles. The time series at each point used for the profile is stored and later passed to the inundation mapping component of the AHPS.

The FLDWAV model is applied to the Des Moines River system as shown schematically in Figure 3. The area within the box represents that portion of the system (the city of Des Moines, IA) for which inundation mapping will be done. The river system consists of a 10.7 mile reach of the Des Moines River (Saylorville Reservoir to the 14th Street Bridge) with three gaging stations; and 29 miles of the Raccoon River (Van Meter, IA to its confluence) with two gaging stations. The Des Moines River has 21 cross sections with an average distance interval of 0.5 miles (0.9 km); and the Raccoon River has 32 cross sections with an average distance interval of one mile (1.6 km). A discharge time series is specified at the upstream end of each river; and an empirical h(Q) rating curve is specified at the downstream boundary location on the Des Moines River. Initial water-surface elevations (h) and discharges (Q) are specified at each cross section in the river system. The h and Q time series are generated by the FLDWAV model for the river system. Although the computational time step is 0.5 hours, computed information (h and Q) at specified cross-section locations are stored in the database at 6-hourly increments. This information is used by the inundation mapping software.

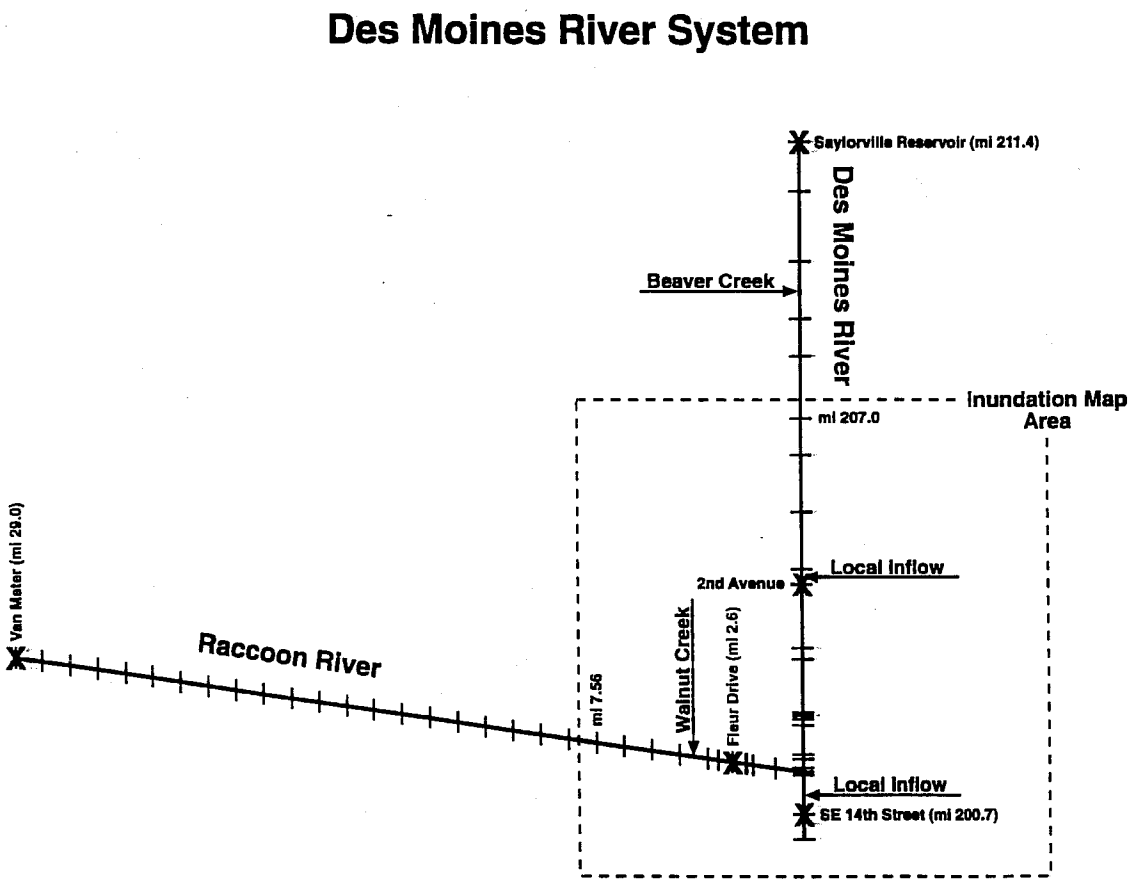

Figure 3. Schematic diagram locating x-sections of Des Moines system.

3. ENSEMBLE STAGE HYDROGRAPHS

In order to spatially display a range of inundation probabilities for a specified future window of time, ESP is run to produce an ensemble of stages for each forecast point. ESP is the portion of the NWS River Forecast System (NWSRFS) which enables a hydrologist to make extended probabilistic forecasts of streamflow and other hydrological variables. ESP assumes that historical meteorological data are representative of possible future conditions and uses these as input data to hydrologic models along with the current states of these models obtained from the forecast component of the NWSRFS. A separate streamflow time series is simulated for each year of historical data using the current conditions as the starting point for each simulation. The streamflow time series for each year's simulation can be analyzed statistically for peak flows, minimum flows, flow volumes, etc., for any period in the future to produce a probabilistic forecast for the streamflow variable. This analysis can be repeated for different forecasts periods and additional streamflow variables of interest. Short-term quantitative forecasts of precipitation and temperature can be used to weight the years of simulated streamflow based on the similarity between the climatological conditions of each historical year and the current year. ESP allows flexibility in the streamflow variables which can be analyzed, the capability to make forecasts over both short and long time periods, and the ability to incorporate forecast meteorological data into the procedure.

For each streamflow hydrograph, FLDWAV is run in order to route the flow and determine the associated river elevations occurring at the cross sections specified between the forecast points. An analysis of this array of water surface elevations is then performed using ESP, resulting in a data set which provides predicted river elevations for each cross section and for multiple probabilities of exceedance (Figure 4).

4. OPERATIONAL FORECASTS DISPLAYED VIA INUNDATION MAPPING

The AHPS inundation mapping capabilities have been demonstrated during the snowmelt/spring-runoff season of 1997 for the Des Moines River basin, Iowa. The site which as mapped includes downtown Des Moines, Iowa, a location which experienced severe flooding during "The Great Flood of 1993" (NWS, 1994).

A Geographic Information System (GIS) application was developed by the NWS Office of Hydrology (OH) for visualizing the areal extent of flood inundation by combining outputs from ESP with Digital Elevation Model (DEM) and Reach File Version 1 (RF1) geospatial data sets. Within the limitations of the data, the inundation mapping algorithm adheres to sound hydrodynamic/ hydrologic principles to produce accurate portrayals of flood forecasts or events. In the Des Moines demonstration, the flood inundation mapping system was used to generate predicted areas of inundation based on ESP-generated probabilistic levels of exceedance forecasts. The mapping system can also be used to produce inundation maps from near-term forecasts and now-casts.

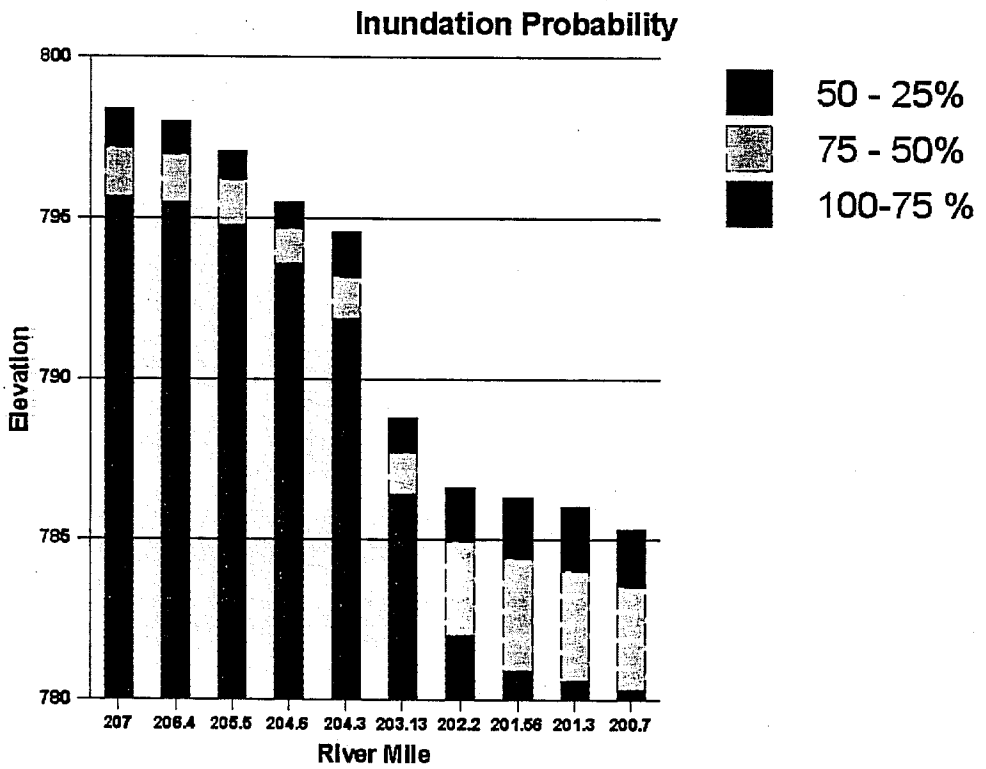

Figure 4. Probabilities of exceedance as predicted for maximum water surface elevation to occur during the specified time period (March 12 - May 4, 1997) at each river cross section for the Des Moines River, River Mile 207.0 - 200.7 .

The flood mapping software places forecasted river elevations into a digital representation of the landscape. Points along the river that were not forecasted are estimated by interpolating between forecasted points. The forecasted and interpolated river elevations are then extended into the landscape, perpendicular to the river channel, until they are impeded by the terrain. The resulting, predicted areas of inundation are then merged with GIS overlays (roads, hospitals, schools, etc) to produce a flood inundation map easily interpreted by the general public.

4.1 Inundation Mapping Software Components

The flood inundation mapping software consists of four major components: (1) forecast data management, (2) flood inundation mapping, (3) interactive flood inundation mapping display, and (4) flood inundation mapping product generation. The first three components are non-proprietary software and are integrated into an OH-developed GIS software and data environment. The fourth component relies on an Arc/Info Macro Language (AML) application. The forecast data management component keeps track of both forecast region parameters and forecast data required to interpolate river elevations between river forecast points. A one-time-only execution requires the user to provide basic information on each river and forecast

point within the forecast region. River and forecast point parameters are stored in Informix database tables. As new forecasts are generated within the forecast region, their data are related to the river and forecast point parameters stored in the database. These relational database tables provide river forecast data that are spatially correlated with a digital representation of the landscape. The mapping software accepts (as inputs) hydrologic model outputs in a specified format. While the Des Moines demonstration project focused on ESP output as inputs into the mapping system, any NWS system capable of generating output in the required format can use this mapping system as a visualization tool.

After a forecast is entered into the forecast data management component, the second major component (the flood inundation mapping component) operates upon regular grid cells (23m x 31m) that contain elevation information derived from a Digital Elevation Model (DEM) and point elevations associated with levees to generate inundated areas as follows:

1. For each DEM cell along each river in the inundation mapping domain, the river surface elevation is estimated by interpolating between probabilistic river elevations produced by FLDWAV and ESP at selected cross-sections along each river.

2. Inundation of a cell is determined (marked) by systematically inspecting all DEM values contained within succesive layers of cells adjoining the river on both banks; if a given cell's elevation is (a) lower than the river elevation and (b) has a flow path back to the river, the cell is determined (marked) as being inundated. Each DEM cell is systematically inspected layer by layer extending in both directions outward from the river.

3. When a particular DEM cell's elevation exceeds the river's elevation associated with the flow path of the cells emanating outward from the river, that cell is not marked as inundated.

4. Cells behind islands or behind higher overbank terrain such as levees are also checked for inundation resulting from connectivity with other upstream or downstream cells already determined to be inundated; thus in addition to Step 2, a cell is determined (marked) as inundated if any of its 8 adjoining cells have already been determined as inundated.

ESP produces a predicted river elevation for each forecast point for multiple probabilities of exceedance. The inundation mapping software cycles through each probability in ascending order; e.g., 25 percent, 50 percent, and 75 percent probability of exceedance (Figure 3). The result for each probability level is successively superimposed to produce a single inundation map.

Interactive visual GIS tools are used to query the resultant product in the context of other geospatial data stored as GIS data layers. In addition to the probabilistic flood inundation map products, the flood mapping system provides a georegistered raster that represents flooded areas and depth of flooding. The flood rasters can be imported into many digital image processing systems or geographic information system used by disaster emergency services personnel, county planning offices, or other federal or state agencies with an interest to further enhance or display the flood raster analysis.

Currently, the flood inundation mapping system relies on an Arc/Info AML to generate soft and hardcopy map products. The AML is designed to generate both GIF and Postscript files depicting areal extent of inundation with hardcoded GIS overlays. Arc/Info was used in this demonstration to display the flood raster with the cultural data layers.

The accuracy of the mapping system depends on the accuracy of the input data. Additionally, the output from ESP assumes a constant elevation perpendicular to the course of the river which, under certain circumstances, may be an unrealistic representation of the volume of water available for inundation.

4.2 Spatial Data Sets

The mapping algorithm uses two geospatial data sets: (1) RF1, and (2) DEM. The RF1-River Reach data are used to interpolate river elevations between forecast points. The DEM is used to contain the areal extent of flooding. Both data sets required manual preparation to ensure consistency of quality and georegistration. The presence of federal, local, and private levees posed a special problem. Levee location and height information was incorporated into the DEM data to model the effect of levees on floodwater distribution. The levee information was superimposed on the DEM used by the mapping algorithm.

Dozens of GIS coverages were examined for possible map overlays onto final product images, including a digital orthophoto of the demonstration area. The orthophoto was not used because it contained too much detail and detracted from the focus of the final map product. Instead, a vector representation of the area from the Iowa Department of Transportation was selected as the primary overlay feature. This gives the product the appearance of a city map, with easily recognizable features and layout. Three significant point-feature overlays were also selected for representation: (a) underground storage tanks that can leak or be dislodged during flooding, (b) critical industrial facilities located in the Raccoon River floodplain, and (c) all hospitals within the demonstration area.

Arc/Info, a commercial GIS software package, was used to display the output products. Additionally, Arc/Info was used initially during the development phase to create the DEM/levee raster, to evaluate all candidate overlay coverages, and operationally to create the final map product graphic file and hardcopy. The gridded flood inundation raster was converted to an Arc/Info-compatible format and used as a map object along with the overlay coverage to create the final product.

5. SUMMARY

The one-dimensional implicit unsteady flow dynamic routing model, FLDWAV, was used on local reaches in the City of Des Moines, Iowa on the Des Moines River during the March 1997 demonstration of the Advanced Hydrologic Prediction System (AHPS). FLDWAV was used to compute stage and flow at various cross sections throughout the local reach, and the stages were used for the demonstration of flood inundation mapping. Though the lack of

significant flooding minimized the evaluation of this display technique, the demonstration of the feasibility to provide flood inundation probabilities in a spatial display for a specified time window was successful. Benefits of providing these advanced hydrologic services include the enhanced protection of life and property from the adverse impacts of floods; however, these services may also provide beneficial information to the requirements for real-time decisions made by water resource managers and water resource users.

The flood mapping system is intended to be deployed in high risk areas (large urban areas on major rivers) where sufficient quality DEM data are available. The deployment is dependent upon the phasing of AHPS implementation (Ingram, et. al., 1998).

6. REFERENCES

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