WATER LEVEL FREQUENCY ANALYSIS IN COLD CLIMATES

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Introduction

Typically when one thinks in terms of problems/damages due to high water levels along a river reach the association is to a set of flood flow rates which caused such water levels. Recognizing that flood flows are of a variable size from time to time, a statistical analysis is performed on historic data in an attempt to associate expectancy or probability of occurrence with differing flood size (i.e., the 100-year flood is 10,000 cfs). These flows are then converted to associated river levels to explore potential damages and the effects and economies of various mitigations measures.

There are, however, other factors which may exist which have an effect on river level as well as the size of the flow rate. Certainly engineering works and encroachments on the flood plain may have a local hydraulic influence which alters previously existing relationships between flood size and associated river level. Such hydraulic influence may also exist on reaches of rivers which experience an ice cover and this paper addresses one aspect of this possibility.

River Levels and Ice

There are a number of situations which can develop from time to time and place to place on any given river system which effect river stage. Probably the most commonly referred to is the so called "Ice Jam". While this condition has been researched to a limited extent and several papers published there is still much that is unknown or uncertain. For the time being we will leave this area to others and concentrate our discussion on river level responses that may occur during the period associated with river freeze up and a later period which we will call the period of "stable ice control".

When a river reach begins to develop an ice cover an additional boundary is created (the ice cover) which increases the resistance to flow. This increased resistance causes the flow to be retarded and the depth to increase. The river level will also increase further due to buoyant effects as the ice cover thickens. There is also an additional hydraulic effect which takes place during freeze up due to the unsteady nature of the flow.

The analytics and mechanics of the items mentioned above may be found in papers by the authors. (See list of references).

Given the right set of circumstances the analytics suggest that river depth could increase with an ice cover by over thirty percent due to the ice resistance alone.

Many reaches of northern rivers form an ice cover in parts of the reach in the early winter and not in others. This allows for the production of frazil ice (fine spicule, plate or discoid ice crystals in super cooled turbulent waters) in the open water sections. Frazil ice tends to collect in the slower moving sections under existing downstream ice cover. These deposits can become quite large and act as an encroachment into the river cross section. This in turn can cause a "backwater" effect upstream of this "ice control" which increases the opportunity to form additional ice cover as the backwater deepens and slows the upstream flow. This, of course, also decreases the surface area available for the formation of additional frazil ice. Thus, in this type of situation, there is a progressive development of the ice cover in an upstream direction from the slower moving sections toward the faster zones. This is the freeze up period and once complete is followed by the period of stable ice control until such time as breakup occurs. The freeze up period generally lasts several days and the period of stable ice control may last for months. The combination of this backwater effect with the added resistance to flow and attendant buoyant displacement can cause rather large river level increases which can last for long periods of time.

Some Examples

In the course of pursuing a research effort dealing with the hydraulics of ice covered rivers in cooperation with the U.S. Geological Survey and U.S. Army Cold Regions Research and Engineering Laboratory the authors have had the opportunity to review published and unpublished data of the U.S. Geological Survey. This has uncovered numerous examples of the situations described above.

One such case is the U.S. Geological Survey gage located on the Brule River near Florence, WI. The gage has been in place for over 40 years and the flood of record is 4700 cfs. A log pearson type III analysis indicates this flood would be approximately the 100 year flood. Unpublished data for this gage indicates that almost every winter during the freeze up period river levels exceed that corresponding to the flood of record even though flow rates are relatively small. Further, during the period of stable ice control (about four months), water levels are such as to be indicative of 25 year flood levels (about 3000 cfs) even though the actual under ice flow is only 300 to 400 cfs. The conventional type of flood analysis applied to this gage history would in effect be working on a problem that doesn't exist.

Another example is the Lookingglass River near Eagle, Michigan. The flood of record is 2,860 cfs with a gage height of 7.70 ft. This would correspond to about the 100 year flood. The gage height corresponding to bank full stage is approximately 6 ft. Certainly this flood did cause some overbank flooding. A closer look at the record for this station indicates water levels are often over the 6 ft. gage height due to backwater from ice. In fact in 1956 gage height was 9.9 ft. from ice backwater which would correspond to something like the 10,000 year flood.

There are numerous other examples that one could site which are not so spectacular. These might be summed up by stating that it is not uncommon to find river levels with an ice cover which are indicative of the 10 to 20 year flood levels even though actual flow rates are relatively small. There were also several streams where backwater from ice caused the maximum water level in any given year.

Where Are We?

The previous section indicates that there is recorded evidence of ice related effects relative to abnormally high water levels. One should keep in mind that these exist only because the U.S. Geological Survey happened to have a gage at the right place to have recorded such effects. Certainly many more locations must exist on these river systems; there simply is no "formal" record.

A report to the National Science Foundation by the Illinois State Water Survey discusses a number of critical research needs relative to flood mitigation. In the section dealing with Hydrology and Hydraulics nine recommendations were listed for critical research. Four of the nine involve reliable predictions of water levels with appropriate related probability. These would include topics such as probability at ungaged locations, appropriate probability distributions, predicting stages from given flow rates and defining flood plain boundaries for various levels of probability.

There has been little research activity in these areas, relative to the effects of an ice cover, and much that does exist is very recent. We do feel at this time that there is reasonable evidence to suggest that the magnitude of the ice/water level effect is site (reach) specific and that collection and analysis of certain summer and winter data in the reach can be used to define coefficients for the reach which can be used in a predictive model. Such research is presently under way on three Michigan rivers with the present goal of establishing a predictive model for at least the period of stable ice control.

Summary and Conclusions

It should be evident that on certain reaches of ice covered rivers flood analysis should include statistical analysis of water levels caused by ice, especially for the more frequent events (say 10 to 20 years). This area should also be addressed from a design and planning point of view. For example, the design of a road/stream crossing (culvert) requires use of "water levels" with various expectancy (not necessarily flows with certain expectancy). Another example might be in assessing the effects of engineering works along the river and flood plain as they may effect future locations of "ice controls" and "frazil ice generators". These locations and the length of time a "frazil ice generator" are operative will dictate expected ice related river levels.

There is still much to do and to learn concerning the hydraulics of ice covered rivers. It is expected that research at Michigan Technological University will continue to address these problems in the future and that better analytical techniques and predictive capability will be developed.

References

Alger, G. R., and H. S. Santeford
1984 A Procedure for Calculating River Flow Rate Under an Ice Cover. Proceedings IAHR Ice Symposium, Hamburg, Germany, (August).

Bent, P. C.
1970 A Proposed Streamflow Data Program for Michigan. U.S. Geological Survey Open File Report, Lansing, Michigan.

Changnon, S. A., R. J. Schicht, and R. G. Semonin
1983 A Plan for Research on Floods and Their Mitigations in the United States. Report to the National Science Foundation by Illinois State Water Survey.

Santeford, H. S., and G. R. Alger
1984 Hydraulics of Freeze-Up. Proceedings of the Conference Water for Resource Development, ASCE, Coeur'd A'Lene, Idaho, (August).

Santeford, H. S., and G. R. Alger
1984 Predicting Flowrates in an Ice Covered Streams. Proceedings Third ISC Conference on Cold Regions Engineering, Edmonton, Alberta, (April).

Santeford, H. S., and G. R. Alger
1983 Effects of an Ice Cover - A Conceptual Model. Proceedings of the Conference on Frontiers in Hydraulic Engineering, ASCE, MIT, Cambridge, MA, (August).

Wiitala, S. W.
1965 Magnitude and Frequency of Floods in the United States. U.S. Geological Survey Water Supply Paper 1677.

MANAGEMENT OF FLOODPLAIN SAND AND GRAVEL MINING

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Introduction

Conflicting interests and issues surround the practice of floodplain sand and gravel mining. Because existing federal and state regulations fail to recognize several problems that are peculiar to floodplain operations, management which recognizes both environmental and industrial needs should be developed. In Louisiana, consequences from the lack of such policy are manifest and continue to intensify. Early assessment of the concerns expressed by the various users of floodplain resources is the first step toward balancing these diverse interests through management.

Regulations Affecting Sand and Gravel Mining

Several complex issues and problems pertaining to floodplain mining operations are often not addressed by federal, state, and local regulations. An overview of current regulations is required to understand the needs and concerns represented by diverse public interests. Gaps in representation can then be addressed by modifying existing legislation or by drafting new legislation if none exists.

No federal law directly regulates the sand and gravel mining industry (Banks and others, 1981). Some federal laws, however, may indirectly affect mining practices (Table 1). For example, in-stream mining could be affected by Section 404 of the Federal Water Pollution Control Act, which regulates the dredging and filling of navigable waters.

Most of the responsibility and authority for regulating sand and gravel mining is left to state and local government. About 30 states currently have laws affecting sand and gravel mining operations or reclamation (Fig. 1). Reclamation refers to the procedures, such as backfilling, landscaping, and revegetation, undertaken to achieve the land use desired after mining. Such requirements may vary considerably from place to place. Some states allow local jurisdiction to take precedence in

Table 1. Federal laws indirectly affecting surface mining (from Banks and others, 1981).

Clean Air Act	Wild and Scenic Rivers Act
Federal Land Policy and Management Act	Fish and Wildlife Act
Federal Water Pollution Control Act	National Environmental Policy Act
Fish and Wildlife Coordination Act	Rivers and Harbors Act
Surface Mining Control and Reclamation Act (coal only)	Mine Safety and Health Act

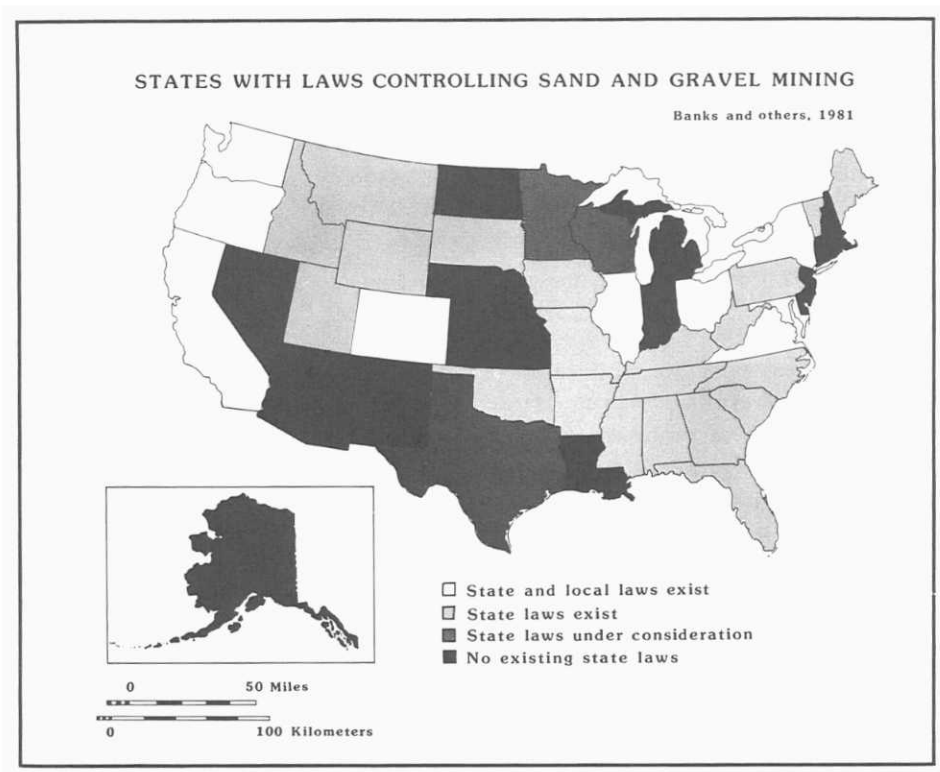

Figure 1. States with laws affecting sand and gravel mining operations or reclamation.

regulating operations whereas other states maintain the right to approve final mining permits (Banks and others, 1981). In addition, sand and gravel operations may be governed by local zoning ordinances, permits, plans, and variances.

Because the governing regulations cover a wide range of mineral extraction techniques, geographic settings, and commodities, floodplain sand and gravel mining practices are not often addressed in legislation. Issues other than operation and reclamation, such as industrial and environmental concerns, are often disregarded. States which lack mining policy, as exemplified by Louisiana, are more likely to experience greater environmental damage.

Issues of Floodplain Sand and Gravel Mining

Sand and gravel are vital commodities for urban growth and infrastructure, especially where hard rock aggregate is scarce. Public interests are best served if these minerals can be extracted at minimum cost with minimal environmental damage. Mineral conservation for the future and benefits to the local economy are also important considerations in planning. Management should attempt to balance the production and conservation of minerals while minimizing environmental, social, and other negative impacts associated with mining.

Environmental impacts associated with sand and gravel mining are probably the least significant compared to those associated with other types of surface mining, yet several problems may still develop. Channel instability and impacts on flood rates and patterns are two potential problems associated with mining operations in floodplains. Increased bank erosion and changing channel position and gradient may affect property and structures, causing legal problems regarding ownership, engineering liability, mining, and water rights. Stream aggradation resulting from the overloading of detritus, which increases flood stages and the amount of land being inundated, was described in early studies (Gilbert, 1917). Conversely, degradation attributable to several possible causes has also been observed (Scott, 1973; Bull and Scott, 1974; Graf, 1979; Lagasse and others, 1981; Storm, 1982). Gravel mining activities may also disturb water quality and floodplain habitat, thus affecting water resources, fisheries, and wildlife. Consequently, several problems unique to floodplain mining need to be incorporated into management plans in addition to reclamation.

Concerns in Louisiana

Because of economic considerations and limited construction materials, most gravel mining in Louisiana is confined to the valleys of rivers that transport coarse material. This presents problems regarding both economics and environment. For example, inundation of resources by dam construction must be considered an economic loss for local expanding urban areas. In addition, mining practices should attempt to minimize environmental impacts to the channel and floodplain. Several problems that are manifest in Louisiana reflect the failure to consider the dynamic nature of rivers, particularly when floodplain vegetation and character is disturbed.

Changes in channel morphology have been observed since the initiation of floodplain gravel mining in the Amite River in southeastern Louisiana (Fig. 2). Some changes are due to indirect effects of gravel mining, after floodwaters have reworked the alluvial valley. Removal of riparian vegetation and mining of point bars reduce the resistance of river banks to erosion during floods (Fig. 3). Also, during high stages, breaching and channel diversion into adjacent gravel pits may occur, especially where banks are not stabilized by vegetation. This results in a local change in base level, which influences aggradation and degradation patterns. Through these processes, channel pattern and meander geometry have been altered significantly after major floods (Mossa, 1983).

Direct environmental damages may also result from increases in sediment flux and channel dredging associated with in-stream mining. Concomitant hydrologic changes occur as the channel is shortened, widened, and altered in gradient; these changes may have aggravated local flooding on the Amite River in recent years (Mossa, 1983).

Although recognition of the adverse effects of floodplain mining is still in the early stages, practices causing the most severe environmental damage should be minimized. Removal of riparian vegetation and the mining of point bars and channel bottoms should be avoided, and buffer zones next to the channel should be established. Other guidelines developed for mining gravel in floodplains in arctic and subarctic regions (Joyce and others, 1980) may be applicable to rivers in Louisiana and elsewhere.

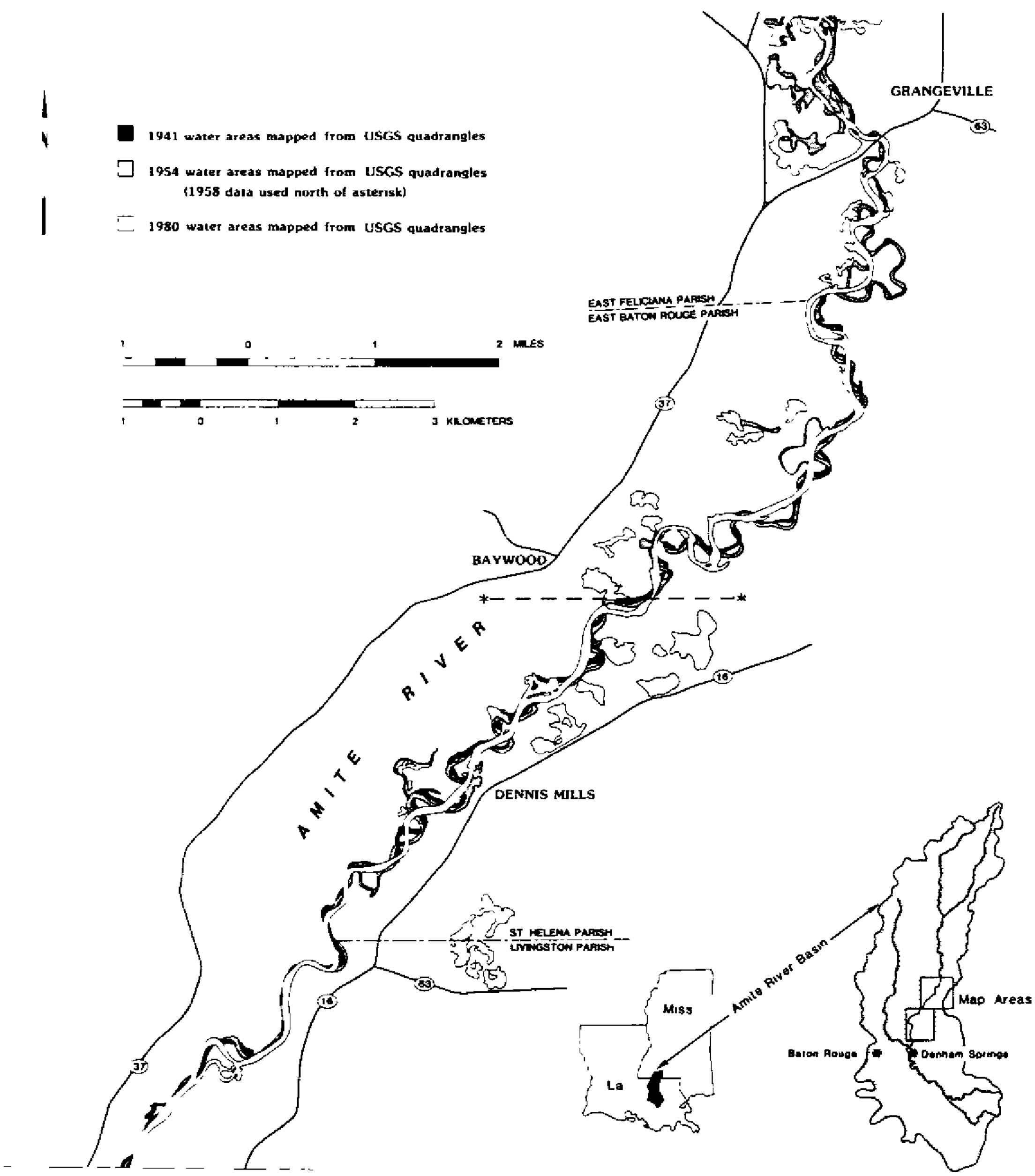

Figure 2. Historic channel positions of the middle Amite River show changes in the meander and channel geometry and an overall decrease in sinuousity through time. Channel diversion into the large pit north of Grangeville changed base level and is one factor that resulted in channel adjustment.

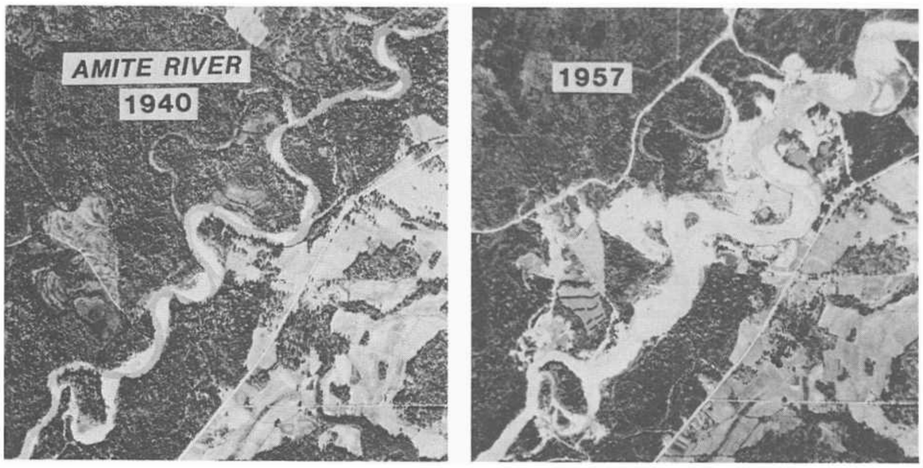

Figure 3. Removal of riparian vegetation and mining of the point bars and floodplains reduce the resistance of the banks during floods. Changes, including increased width, meander cutoffs, abandoned point bars, and an increased number of midchannel bars, have developed since the initiation of mining near Dennis Mills on the Amite River.

Minimal environmental damage and additional land use benefits are achieved with reclamation, which is particularly important near river channels where sediments and talus piles may be reworked in subsequent floods. These efforts are most successful if they are integrated into the total mining operation from the beginning and directed toward a desired post-mining land use (Dunn, 1982). Although this has not been the case in Louisiana, remaining landscapes can be left in a stabilized, nonhazardous, and useful condition if some planning measures are taken. Such plans should be developed promptly in states with severe flooding problems but no reclamation regulations, such as Louisiana.

Once a river has changed its pattern and form, the problem becomes much more difficult to resolve. Whether reclamation should go beyond sculpturing and revegetating the floodplain and attempt to restore the previous channel character is a question that requires consideration. Although time will probably allow the river to restore itself, rivers are dynamic and little is known about how rapid or effective these modifications will be. Aggravated flood conditions could persist for years and intensify if unregulated mining continues. Establishing management guidelines prior to intensive mining is the better approach to minimizing environmental impacts.

Management should also encourage the sand and gravel industry to provide planning input to balance various local and regional, short- and long-term goals. Information regarding resource distribution should be provided to concentrate mining in preferable locations. Guidance and recommendations to facilitate reclamation should be given at the local and state level. The continued availability of resources depends upon the cooperation of the industry, whose input in decision-making and issues is important to balancing diverse economic and environmental interests.

Conclusions

Mitigation of impacts and restoration of mined landscapes in floodplains may entail either management or engineering measures or some combination of the two. Although some measures will result in a direct and noticeable improvement of the environment, others may take several years to produce visible results, and in some cases, time may be the only solution to recovery. The recommendations stated here and the guidelines developed for mining in other floodplains should be considered prior to mining because environmental problems become much more complicated and harder to resolve after mining operations have begun. Floodplain managers can help to balance diverse interests by considering input from various sectors early in the decision-making process. In states without legislation, such as Louisiana, floodplain management may be the most immediate solution to addressing environmental and industrial interests.

References

Banks, P.T., R.E. Nickel and D.A. Blome
1981 Reclamation and Pollution Control: Planning Guide for Small Sand and Gravel Mines. Washington, D.C.: Department of the Interior, Bureau of Mines.

Bull, W.B. and K.M. Scott
1974 "Impact of Mining Gravel from the Urban Stream Beds in the Southwestern United States." Geology 4: 171-174.

Dunn, J.
1982 "COSMAR (Committee on Surface Mining and Reclamation)." Pages 9-12 in P.Y. Amimoto, Ed. Proceedings of Mined Land Reclamation Workshop. Davis, California, June 11-12, 1980. Sacramento: State of California, Department of Conservation, Division of Mines and Geology, Special Publication 59.

Gilbert, G.K.
1917 "Hydraulic-Mining Debris in the Sierra Nevada." U.S. Geological Survey Professional Paper 105. Washington, D.C.: Department of the Interior.

Graf, W.F.
1979 "Mining and Channel Response." Annals of the Association of American Geographers 69: 262-275.

Joyce, M.R., L.A. Rundquist, and L.L. Moulton
1980 Gravel Removal Guidelines Manual for Arctic and Subarctic Floodplains. Report No. FWS/OBS 80/09. Washington, D.C.: U.S. Department of Interior, Fish and Wildlife Service.

Lagasse, P.F., B.R. Winkley and D.B. Simons
1981 "Impact of gravel mining on river systems stability." American Society of Civil Engineers. Journal of the Waterway, Port, Coastal and Ocean Division: 389-404.

Mossa, J.
1983 "Morphologic Changes in a Segment of the Amite River, Louisiana." Abstracts with Programs, Geological Society of America, 96th Annual Meeting 15: 648.

Scott, K.M.
1973 "Scour and Fill in Tujunga Wash--A Fanhead Valley in Urban Southern California, 1969." U.S. Geological Survey Professional Paper 732-B. Washington, D.C.: Department of the Interior.

Storm, D.
1982 "In-stream Mining." Pages 73-76 in P.Y. Amimoto, Ed. Proceedings of Mined Land Reclamation Workshop. Davis, California, June 11-12, 1980. Sacramento: State of California, Department of Conservation, Division of Mines and Geology, Special Publication 59.

LOCAL FLOOD WARNING SYSTEMS--WHERE ARE WE?

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Common sense suggest that people vulnerable to floods ought to be warned so that response can be taken to protect lives and property. The National Weather Service is responsible for warning individuals of approaching floods. Generally, for rivers which crest greater that 18 hours after rainfall occurs, the conventional flood forecast operations of the National Weather Service provide timely and accurate flood forecast service for threatened communities. In rivers which crest less than 18 hours after rainfall occurs, time is short, data is scarce, and development of timely, accurate and specific flood predictions is difficult, if not impossible. One solution to this short-fused flood problem is the development of an integrated local flood warning and response system for a community vulnerable to floods.

Recently, the Federal Interagency Work Group on Local Flood Warning Systems has produced a report titled, "Guidelines on Local Flood Warning and Response Systems for Communities." This document defines a local flood warning system to consist of four steps. These four steps include: 1) Data Collection; 2) Data Transmission; 3) Flood Forecast; and 4) Inform Local Officials. These four basic steps offer the threatened community recognition of the magnitude and extent of the flood threat. However, providing a timely and accurate warning will not reduce flood losses unless an effective response system is in place. A flood warning is useless unless people know what actions to taken when they receive the warning. The response system consists of three steps: first, warn local residents who will be affected by the flood; second, threatened residents should be evacuated; and the last step is re-rentry, or return of residents into the flood plain.

Local flood warning systems are flood recognition or forecast systems that determine the magnitude and extent of flooding. These systems are categorized as manual or automatic. Manual systems primarily consist of volunteer observers who read plastic rain gages, a volunteer community flash flood coordinator, and a simple flood forecast procedure provided by the National Weather Service. Most local flood warning systems are manual systems and are quite effective in providing basic flood recognition. Automated systems consist of a volunteer community flash flood coordinator, automatic self-reporting hydrologic sensors, radio transmission and receiving equipment, a continuously operating microprocessor, river and rainfall data analysis software, and a hydrologic simulation model. The National Weather Service and or private hydrologic consulting companies provide hydrologic expertise in providing automated local flood warning systems to communities.

There are basically three types of automated local flood warning systems in operation. These systems vary in functional capability and cost. The flash flood alarm gage, the most basic type, consists of water level sensors connected to an alarm or light located at a community agency which operates 24 hours a day. River stages exceeding a pre-set level trigger the alarm. The distance the alarm is located upstream from the community determines the amount of warning time available. There are approximately 65 flash flood alarm gages in operation around the country. The flash flood alarm gage provides the least capability of all the automated systems and is also the least expensive.

The Automated Local Evaluation in Real Time (ALERT) system is an automated local flood warning system developed by hydrologists at the NWS California/Nevada River Forecast Center. The ALERT system has rapidly gained popularity in the United States with about 50 communities now operating or installing these systems. ALERT consists of automatic reporting river and rainfall gages, a radio communications system and a base station consisting of radio receiving equipment and a microprocessor. Various types of software are available for the ALERT system from data analysis software to hydrologic forecast model. Basic software is available from the NWS, while more special-needs software is available through private firms.

In a 6-state region of Appalachia, the Integrated Flood Observing and Warning System (IFLOWS) is implementing an automated prototype networked local flood warning system that links the county emergency operations center (EOC) to the state EOC and to the NWS forecast office. Over 100 counties will be operating nearly 600 automatic reporting rain gages to 100 county-based stations (radio communication, receiving equipment, DEC microcomputers which collect, display and relay rainfall data and flood warning information). The IFLOWS program uniquely distributes flood related information to Federal, State, and local offices.

Local Flood Warning System Standards

The NWS Technical Working Group on Local Flood Warning Systems (LFWS) has developed standards for automated local flood warning systems. These standards are currently under review by the NWS and will then be sent to all interested Federal agencies for review. The Hydrology Subcommittee of the Interagency Advisory Committee on Water Data is investigating the need for a standing committee on local flood warning systems to address LFWS problems and issues and to continue modification of LFWS standards as technology continues to advance. The purpose of establishing LFWS standards are:

1) To ensure that basic flood forecast capability is made available to communities ranging from poor and technically unsophisticated, to wealthy and professionally talented.
2) To ensure that LFWS data can be made available to all NWS Offices responsible for flood warnings. This assures coordination which is vital to warning the population of a flood event.
3) To promote competition between private sector firms who wish to develop "enhanced" LFWS software.

We anticipate LFWS standards will be available in late summer for distribution to communities.

Where are We Going?

As the proliferation of LFWS continues, various issues begin to surface concerning the type and distribution of data and forecasts. As more and more communities continue to install automated systems, a high volume data base will be created. If an upstream community develops an automated flood warning system, who is responsible to warn the next downstream community-based, or the upstream community system operation? What Federal, State, and local agencies require LFWS data? What specific data?

FLASH

The NWS is developing a project known as FLASH (Flood Local Analysis System for Hydrometeorology) which will provide the Weather Service Forecast Office (WSFO) with two basic capabilities. The first capability is to establish a hydrometeorology data base which will contain up-to-date river and precipitation data (including automated LFWS data), and secondly, simplified hydrologic models to provide site-specific forecasts for flash-flood-prone communities.

UTILIZATION OF THE SEA, LAKE AND OVERLAND SURGES FROM HURRICANES (SLOSH) MODEL IN HURRICANE EVACUATION STUDIES

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Introduction

The coastal population of the United States has increased sharply over the past twenty years and in many locations the rate of growth has accelerated. This tremendous growth and development has presented emergency management officials with the difficult task of developing hurricane evacuation plans which can reasonably assure safe and effective hurricane evacuations for the vulnerable population. The critical data necessary for the development of these plans often require comprehensive and specialized analyses. In an effort to assist state and local governments develop the needed technical information, the U. S. Army Corps of Engineers, Federal Emergency Management Agency and the National Oceanic and Atmospheric Administration have joined state and local emergency management agencies in conducting hurricane evacuation studies for certain Gulf and Atlantic coastal basins. These studies consist of several related analyses to develop technical data concerning hurricane hazards, vulnerability, public response, timing of evacuations and sheltering needs for various hurricane threat situations.

The hazards analysis quantifies the still-water surge heights, waves and windspeeds for various categories, tracks, directions and forward speeds of hurricanes considered to have a reasonable probability of striking a particular coastal basin. Potential freshwater flooding from rainfall accompanying hurricanes is also considered; however, due to the wide variation in amounts and times of occurrence from one hurricane to another, rainfall can only be addressed in general terms. The purpose of this manuscript is to describe the utilization of the Sea, Lake and Overland Surges from Hurricanes (SLOSH) Model in the hazards analysis of hurricane evacuation studies.

Hazards Analysis

The Sea, Lake and Overland Surges from Hurricanes (SLOSH) numerical model, developed by the National Weather Service, is commonly utilized in the hazards analysis of hurricane evacuation studies to determine the still-water surge heights and windspeeds associated with various simulated hurricanes modeled for a study. Developed for selected Gulf and Atlantic coastal basins, the SLOSH model incorporates a curvalinear polar coordinate grid scheme (a fan-shaped grid) in which a basin's bathymetry, topography and natural and man-made barriers are mathematically represented. The grid configuration of the model has a resolution of approximately one-half square mile for inland areas at the focus to 1 1/2 square miles at the coastline. The grid squares become progressively larger as the grids extend outward from the coastline where storm effects are of secondary interest.

Other computer models have reliably calculated surge heights for the open coastline; however, the SLOSH model has the added capability to simulate the routing of storm surge into bays, estuaries, coastal rivers and overland. Significant natural and man-made barriers such as dunes, roadbeds or levees are also represented in the model and their effects considered in the calculations of surge heights for a location. This capability results in more accurate and realistic simulations of the impacts an area can expect from potential hurricanes. Simple time-dependent input parameters for the desired hurricanes to be modeled are supplied by the user and from which calculations of surge heights and windspeeds are made. These parameters, entered at six-hour intervals for a simulated 72-hour hurricane track, are storm position by latitude and longitude, central barometric pressure in millibars and the radius of maximum winds.

Simulated hurricanes varying in intensity, direction of movement, forward speed and landfall location are modeled for a study. For example, in the Tri-State Hurricane Evacuation Study for the central Gulf Coast, a total of 964 simulated storms were modeled for the study area. These simulated hurricanes represented the five categories of hurricane intensity as described by the Saffir-Simpson Hurricane

Scale, five directions of storm movement for landfalling and paralleling hurricanes (N, NW, NE, W, E), two forward speeds of 5 and 15 miles per hour and numerous landfall or nearest approach locations spaced approximately 20 miles apart along the coastline. The characteristics of the simulated hurricanes modeled for a study are predicated upon the meteorological history of the basin; therefore, variation in selected storm parameters between study areas is likely to occur.

The model output for each simulated storm run consists of a surface envelope of water which represents the maximum surge values calculated for each grid point irrespective of the time during the simulation that the maximum height occurred. These values are displayed on printouts on which the grid points are referenced by a system of coordinates. The coordinates, through the use of grid overlays, allow the surge heights to be transferred onto transverse mercator maps of any desired scale. Time-history tabulations for sixty (60) pre-selected grid points are also furnished with each run.

Prior to modeling the desired hurricanes, a maximum of sixty (60) model grid points are selected for which time-histories of surge heights, windspeeds and wind directions are tabulated for at least a 30-hour segment of a simulated storm track. The selected grid points normally represent the locations of critical roads and bridges of low elevation, potentially vulnerable population centers or areas adjacent to significant natural or man-made barriers. The time-history information for each selected grid point lists values at ten-minute intervals for still-water surge heights in feet above National Geodetic Vertical Datum (NGVD), windspeeds in miles per hour and wind directions as azimuths from which the wind is blowing. The time-history information is utilized to determine the pre-landfall hazards times expected in advance of an approaching hurricane. The arrival time of gale-force winds (sustained 40 miles per hour) and/or the time that critical roads or bridges needed for evacuation may be inundated by rising storm surge are commonly the thresholds used to determine the pre-landfall hazards times. The pre-landfall hazards times represent the time period, in advance of expected hurricane landfall, that evacuees will likely be exposed to hazardous wind or storm surge conditions. The time-history data allow emergency management officials to more accurately judge the time at which evacuees may be exposed to storm hazards and permit the timing of evacuations to avoid those hazards.

Due to the large number of simulated storm runs required for a study, the results of the individual simulations are combined into Maximum Envelopes of Water (MEOW), which display the maximum surge value for each grid point in the model for any storm parameter or combination of parameters desired. Variations in category, forward speed, direction of movement and landfall location, individually or collectively, result in differing surge heights calculated for a location. Normally, the MEOWs are prepared by category of storm and combine all other storm parameters to determine the maximum surge heights possible for a location. The MEOWs are utilized in order to simplify the data and because present technology cannot assure precise forecasting of hurricane landfall location to permit confident use of individual storm runs in emergency management planning. The average radii of forecast error for hurricanes with an expected landfall time of 24 hours are 105 miles for the Gulf of Mexico and 125 miles for the Atlantic Ocean. Considering the average radii of forecast error and the clearance times required to evacuate the threatened population of many coastal locations, each jurisdiction under a hurricane threat must prepare for the worst probable effects from approaching storms. The MEOWs allow this data to be generated and presented in an efficient and uncomplicated manner.

The SLOSH model does not provide data concerning the additional heights of waves generated on top of the still-water storm surge. Generally, waves do not add to the areal coverage of the storm surge in a basin and can usually be ignored except for locations immediately along the open coastline or the shorelines of very large bays where significant fetch lengths and water depths are possible. Due to the presence of structures, dunes or vegetation, the waves break and their energy dissipates within a few hundred yards of the coastline.

The data developed from the hazards analysis and other related analyses conducted for a hurricane evacuation study are presented in a technical data report. Local implementation guides are normally prepared for each county within a study area and include the technical data and operational information pertinent to a particular jurisdiction. The technical data allow emergency management agencies to more accurately determine the vulnerable areas and to estimate the time required to safely evacuate the threatened population for a wide range of potential hurricane threats.