A Coupled Hydrologic–Hydraulic Model for Flood Reduction Analysis in the Red River of the North Basin

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ABSTRACT

The Red River of the North borders North Dakota and Minnesota and flows north toward Lake Winnipeg in Manitoba, Canada. The river is susceptible to flooding because of the synchrony of its discharge with spring thaw and ice jams, its shallow and sinuous channel, its low gradient, and the decrease in its gradient downstream. As a result, the property adjacent to the river is subject to frequent, damaging inundation from minor and major flood events, with a truly devastating flood about every decade. To mitigate flooding, various structural and nonstructural measures have been employed. However, the extensive flooding in 1997 necessitated reexamination of these measures and exploration of innovative concepts to augment traditional approaches. Hydrologic and hydraulic models play a key role in evaluating and identifying economical and feasible measures for flood reduction in this complex river system. In terms of complexity and modeling objective, the models developed in the past two decades can be categorized as 1) explanatory analyses, 2) floodplain and floodway management analyses,

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The studies and results discussed in this paper are parts of an EERC project, “An Innovative Approach to Basinwide Flood Control: The Evaluation of the Waffle Concept,” funded by the Natural Resources Conservation Service of the U.S. Department of Agriculture. The positions expressed in this paper are solely those of the authors and do not represent official positions of the funding agency.

3) land planning and management analyses, 4) flood mitigation engineering design analyses, 5) flood forecasting, and 6) miscellaneous. While a few of these models were used for some initial flood reduction analyses, they were developed mainly for other purposes. In addition, the models insufficiently address inflows from ungauged areas and overland flows, which significantly affect their calibration, verification, and application. This paper discusses a conceptual model scheme to be applied to study the impacts of various storage scenarios on flood reduction in the Red River. Under this scheme, a coupled hydrologic–hydraulic model will be developed by integrating two decades of modeling achievements with new algorithms specially designed for this study, employing updated modeling techniques and utilizing improved spatial and temporal data. Furthermore, this model was used to analyze storage scenarios necessary to mitigate 1997-type floods and the probable maximum flood (PMF) in the Red River.

Keywords: hydro modeling, flood mitigation, nonstructural measures

BACKGROUND

The Red River of the North (the Red) originates in Minnesota, forms the boundary between North Dakota and Minnesota, and enters Canada at Emerson, Manitoba, and continues northward to Lake Winnipeg, Manitoba (Figure 1). It meanders approximately 548 mi (883 km) through the flat and fertile valley of the former glacial Lake Agassiz, forming the 45,000 mi^2 (116,500 km^2) Red River Basin. Both the channel and the basin are sectioned by the international border between the United States and Canada, with approximately 75% located in the United States. The basin is remarkably flat, with an overall gradient of around 0.5 ft per river mile

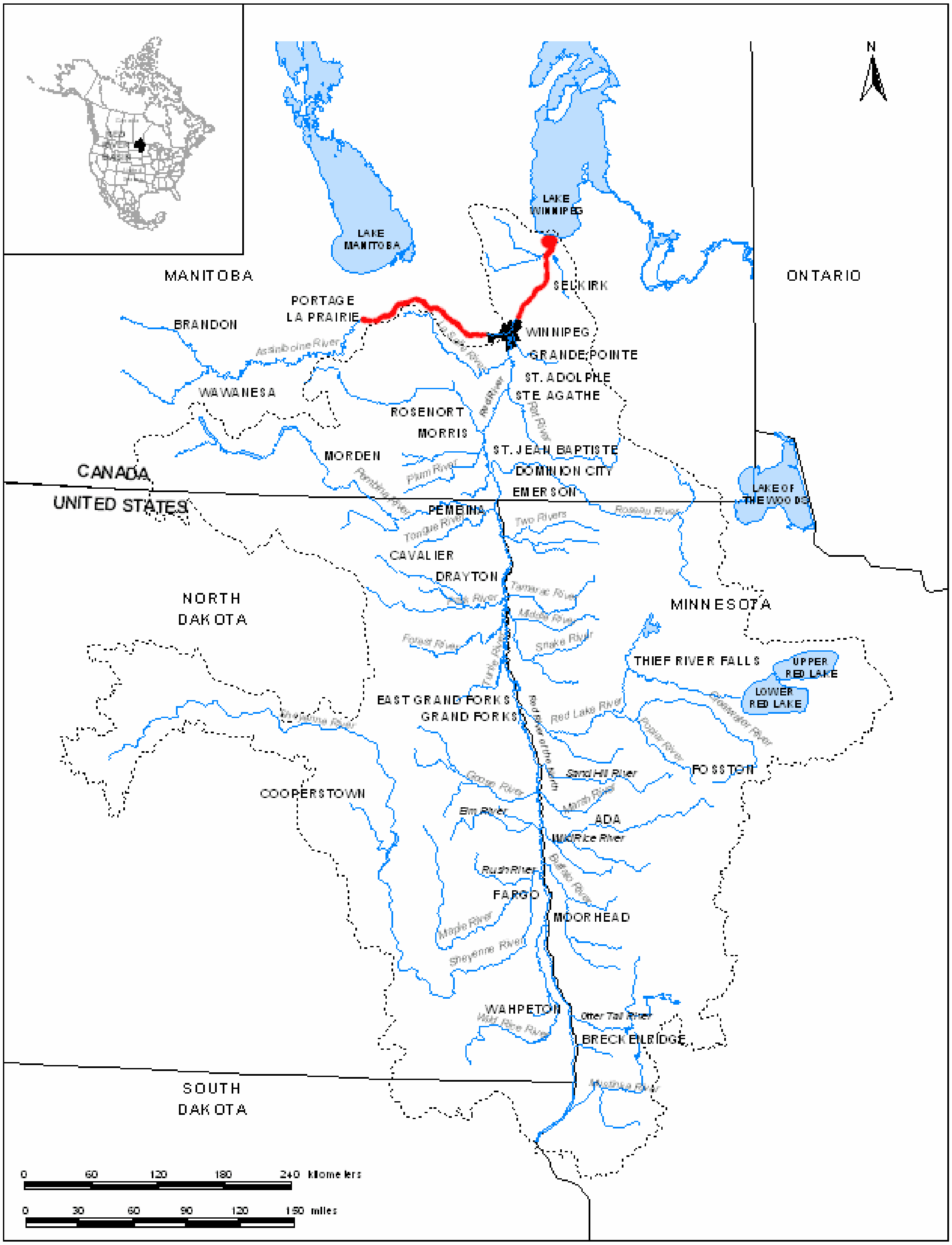

Figure 1. The Red River of the North Basin.

(International Joint Commission, 1997). While over 66% of the basin is conducive to agriculture and productive cropland due to the fertile, black, and fine-grained soils (Stoner et al., 1993), several major population centers (cities) are located on the banks of the Red, including Wahpeton–Breckenridge with a population of 12,000, Fargo–Moorhead of 100,000, Grand Forks–East Grand Forks of 60,000, Selkirk of 9,800, and Winnipeg of 670,000 (International Joint Commission, 2000).

The Red River Basin is subject to frequent damaging inundation from minor and major flood events. Since official record keeping began in 1882, major floods affecting large areas of the basin have occurred once in about every 4 to 6 years, with a truly devastating flood about every decade (LeFever et al., 1999; International Joint Commission, 1997). For description purpose, we define the latter as causal floods. The main historical causal floods occurred in 1826, 1897, 1950, 1966, 1969, 1975, 1978, 1979, and 1997. The 1826 flood is the worst flood known. Unfortunately, there is no detailed record on this flood. During the 1897 flood, a strip of land 30 mi (50 km) wide and 150 mi (240 km) long was inundated (Bavendick, 1952). While all of the other floods caused severe damages, the 1997 flood is the worst in the official record and forced the evacuation of many families in most of the cities mentioned above (International Joint Commission, 1997). To mitigate flooding loss, various measures have been taken (International Joint Commission, 1997, 2000; Red River Basin Board, 2000; Kingery et al., 1999; and Dyhouse, 1993). LeFever et al. (1999) described their possible means and analyzed their social and economic influences. They categorized these means as structural measures and nonstructural measures. Construction of levees and reservoirs, enlargement and straightening of channels, and installation of channel bypasses are structural measures, whereas nonstructural measures consist of regulating development, improving operation of the structures, establishing policies for emergency and loss protection, and employing new concepts such as mitigating flooding at its source. Control of runoff where it originates is the most effective and efficient solution to flooding (Hey and Philippi, 1994; McShane, 1996). One concept of mitigating flooding at its source, the Waffle solution originally, proposed by the University of North Dakota Energy & Environmental Research Center (EERC) in 1997, is to utilize both man-made and natural depressions scattered across a watershed to temporarily store and regulate water and reduce peak flows at its outlet. Although this concept is consistent with the integrated watershed-based approach recommended by the National Research Council (1999), it has been widely discussed and debated. This concept will be quantitatively evaluated for the Red River Basin in the following section. Compared with structural measures, nonstructural measures are cited as socially, economically, and environmentally sound.

However, both types of measures are generally needed for most of the watersheds as nonstructural measures may augment the flood mitigation capacities of structural measures, which is especially true for the Red River Basin (International Joint Commission, 1997, 2000). The extensive flooding in 1997 has raised awareness of the problem in the Red River Basin and necessitated the reexamination of the efficacy of the measures implemented. Besides creative structural measures, innovative concepts of nonstructural measures should be explored to augment the design capacities of structural measures planned to protect against future floods similar in scope to, or greater than, the 1997 flood. (International Joint Commission, 2000). Hydrologic and hydraulic models play a key role in these reexaminations and explorations (Halliday et al., 2000; International Joint Commission, 1997). In the past decade, numerous models relevant to flood mitigation in the Red have been developed. However, it is hard to directly use these models to evaluate the concept of the Waffle solution because 1) they were developed for other objectives; 2) they have a different modeling scope, making it impossible for accurate comparison; 3) their parameters were not correlated with land use and other watershed management practices; and 4) they were not basinwide. The following section provides an overview of these available models, followed by a coupled hydrologic–hydraulic basinwide conceptual model scheme. Finally, the simplest model consistent with this model scheme will be developed and used to evaluate the Waffle solution when applied to the 1997 flood and the probable maximum flood (PMF) in the Red River Basin. A more complex but easily used seamlessly coupled hydrologic–hydraulic model will be developed in the near future.

OVERVIEW OF FLOOD MITIGATION ANALYSES

In terms of the modeling objective, the analyses conducted in the past decade and relevant to flood mitigation efforts in the Red River Basin may be categorized as 1) explanatory analyses, 2) floodplain and floodway management analyses, 3) landscape planning and management analyses, 4) engineering design analyses, 5) flood forecasting, and 6) miscellaneous.

Explanatory Analyses

Explanatory analyses are based on a strong conceptual understanding of the basin and the appropriate engineering judgment. They are qualitative analyses and employ subjective speculations to provide a “big picture” of the basin’s hydrologic characteristics, the causes of the historical causal floods, and the possible means to mitigate flooding losses.

Bluemle (1997) attributed flooding in the Red River Basin to the interplay of constant factors and variable factors. The constant factors include the Red's northerly flow; its shortened time of concentration resulting from urbanization and over 28,000 mi (45,060 km) of man-made drainage ditches (Red River Basin Board, 2000); the randomized drainage manner due to the rural road system, low gradient, and thus low flow velocity; and the construction of impeding channel bypasses such as bridges, culverts, and dikes. Given these constant factors, five variable factors may combine to lead to a causal flood: 1) a wet fall; 2) a cold winter; 3) heavy winter snow accumulation; 4) a late, cool, wet spring followed by sudden warming; and 5) widespread, heavy, warm rainfall during the thawing period. He speculated that compared with the constant factors, these variable factors have a higher correlation with a causal flood in this basin. Guided by this analysis, LeFever et al. (1999) examined the contributions of these factors to each of the historical causal floods enumerated earlier. They stated, for example, that all of the constant factors and variable factors interactively contributed to the 1997 flood. Furthermore, they discussed some possible means to mitigate flooding by adjusting these constant factors. On the other hand, some geomorphologists cited the young age (8,200 to 7,800 radiocarbon years) of the Red as the main reason why it is vulnerable to flooding (http://sts.gsc.nrcan.gc.ca/hydro/redriver/geomorphology.asp). The Red is not old enough to cut a deep and developed channel with sufficient capacity to convey extreme flows (http://sts.gsc.nrcan.gc.ca/hydro/redriver/geomorphology.asp; Gosnold et al., 1997; Boss, 1999).

Floodplain and Floodway Management Analyses

In general, the floodplain and floodway management analyses were conducted to meet the requirements of the National Flood Insurance Program (NFIP), established by the National Flood Insurance Act of 1968 and further defined by the Flood Disaster Protection Act of 1973 (Federal

Emergency Management Agency [FEMA], 1995a). Taking the peak discharge values with a 1% chance of being equaled or exceeded in any given year (100-year flood or base flood), these analyses employ back-water steady-state hydraulic models to compute the corresponding water surface elevations (WSELs). The computed WSELs are superimposed on a topographic map with sufficient accuracy to delineate the base floodplain. Under certain circumstances, a floodway is determined and defined as the channel of a river or other watercourse and the adjacent land areas that must be reserved in order to discharge the base flood without cumulatively increasing the WSELs by more than a designated height such as 1.0 ft (0.3 m) (U.S. Army Corps of Engineers [USACE], 1992a, 2001a). With the available data, another three floods, termed as 10-, 50-, and 500-year floods with a 10%, 2%, and 0.2% chance, respectively, of being equaled or exceeded in any given year, were similarly analyzed. However, only a 500-year floodplain boundary was determined (FEMA, 2000). The peak discharge values used in these analyses were calculated either using a hydrologic rainfall-runoff model or a statistical computer program (USACE, 1998, 1992b, 2001b; Thomas et al., 1998; Interagency Advisory Committee on Water Data, 1982).

In the past decade, USACE conducted most of the hydrologic and hydraulic analyses to determine the base floodplain boundaries for both the main stem of the Red and its major tributaries (FEMA, 1987, 1995b). The method of the Interagency Advisory Committee on Water Data (1982) was used to establish the peak discharge-frequency relationships, and HEC–2 models were developed to compute the WSELs. With updated observed data, USACE (2001c) used the same method and completed a frequency analysis for the main stem of the Red from Wahpeton, North Dakota, and Breckenridge, Minnesota, through Emerson, Manitoba, (USACE, 2001c). The results will be used to update the Flood Insurance Studies (FIS) for the relevant communities and counties.

Landscape Planning and Management Analyses

Bengtson et al. (1999) developed HEC–1 models to evaluate the effects of restoring drained wetlands on peak flood flows in the 1,620 mi^2 (4,200 km^2) Maple River watershed and the 1,670 mi^2 (4,330 km^2) Eastern Wild Rice watershed. In these models, the wetland storage was represented by flow diversions (USACE, 1998a). The results indicated that restoring drained wetlands is highly unlikely to significantly affect the causal floods. For the base flood, the peak flood flows may be reduced 3%–6% resulting in only a 0.36%–0.85% lowered flood height. In parallel, Juliano (1999) employed an HEC–HMS model to investigate the role of drained wetlands in reducing flood volume and peaks in the 598 mi^2 (1,550 km^2) Rat River watershed, approximately 20 mi (30 km) southeast of Winnipeg. Rather than studying frequency floods, he simulated six historical causal floods that occurred in 1950, 1974, 1979, 1986, 1996, and 1997. In his model, the wetland storage was represented by flow diversions as well (USACE, 2001b). Like Bengtson et al., Juliano concluded that wetlands play a minor role in mitigating casual floods in this watershed and have a negligible impact on the main stem of the Red. Shultz (1999, 2000) made similar conclusions from an economic standpoint. However, pilot studies have shown the potential for wetlands to increase crop yield (Schroeder et al., 1990; North Dakota Wetlands Trust, 1992; BlueStem Incorporated, 1996).

To provide baseline and historical information for future research that will address specific water quality issues, Stoner et al. (1993) described the environmental setting of the Red River Basin, including its physical, chemical, and aquatic-biological characteristics. They comprehensively used field experiment and observed data to quantify these characteristics and tackle their interrelationships. The analysis revealed that a balance of the environmental setting may help to mitigate flooding and improve water quality in the Red.

Engineering Design Analyses

Hydrologic and hydraulic analyses were carried out to construct the six major dams along the Red, including Lake Traverse, Mud Lake, Orwell, Baldhill, Red Lake, and Homme (http://www.mvp-wc.usace.army.mil). USACE conducted most of these analyses and maintains inventories of the models and other documents. In addition, hydraulic analyses used to design other infrastructure such as channel bypasses and dikes may be available from USACE, the U.S. Department of Transportation (DOT) in North Dakota and Minnesota, Manitoba Water Resources, and other agencies and companies.

To protect Grand Forks–East Grand Forks from flooding similar in scope to the 1997 flood, USACE (1998b) completed a general evaluation report for a proposed project consisting of 29.6 mi (47.7 km) of levees and a 2.1 mi (3.4 km) floodwall set back from the Red, forming three “rings” around the two cities. An HEC–2 hydraulic model was used to determine the necessary length and height of the proposed levees and floodwall.

The structures in the Red River Basin were designed mostly using designated design floods determined by frequency analyses. However, due to insufficient observed data and violation of the assumptions made to develop the frequency analysis methods, the design floods did not always represent expected situations, which resulted in unsuccessful engineering. To be conservative, the PMF or the Standard Project Flood (SPF) were sometimes taken as the design flood (USACE, 1985; Lowing, 1995). The SPF is just a scaling down of the PMF (USACE 1960). Recognizing the inappropriateness of the PMF for the Red River Basin (World Meteorological Organization, 1973; Sellars et al., 1999a), Warkentin (1999) suggested the hydrometeorologic parameter routed flood (HPRT) to be the design flood.

Flood Forecasting

The National Weather Service maintains and provides Advanced Hydrologic Prediction Services (AHPS) for the Red (http://www.crh.noaa.gov/fgf). AHPS provides hydrologic forecasts with lead times from a few days to several months by not only accounting for precipitation already on the ground but also for probabilistic estimates of future precipitation. Both flow and stage hydrographs are predicted for 33 points on the Red and its Minnesota and North Dakota tributaries, as well as for Devils Lake.

As part of the Corps Water Management System (CWMS), West Consultants Inc. (2002) developed a flood forecasting system for the watershed upstream of the confluence of Bois de Sioux River and Otter Tail River by integrating the distributed snow process model (DSPM) with the HEC–HMS, HEC–ResSim, and HEC–RAS models. The DSPM generates inputs for the distributed HEC–HMS model, including grid precipitation, temperature, and initial snow water equivalent. Output flow hydrographs from the HEC–HMS model are taken as the inputs into the HEC–RAS and HEC–ResSim models to simulate the stage hydrographs for the reaches and reservoirs, respectively.

Miscellaneous

Using the gauged flow hydrographs for the 10 historical causal floods, McCombs-Knutson Associates Inc. (1984) developed an HEC–1 routing model to study the timing and volume contributions of a number of Minnesota tributaries to the main stem of the Red. The main purpose of this study was to provide the general basis for assessing the potential effects of the proposed tributary reservoirs on main-stem flood damage reduction from a flood timing perspective. The results showed that the contributions varied from flood to flood; i.e., each of the 10 historical causal floods was routed by an HEC–1 model with different routing parameters or even different routing methods. Thus it is difficult to directly extrapolate these results to other floods. In 1988, USACE utilized the straddle-stagger or average-lag hydrologic routing method within the HEC–1 software package (USACE, 1998) to route the same 10 historical flood hydrographs throughout the basin to points downstream. As with the McCombs-Knutson Associates Inc. study, this study revealed that the routing coefficients are flood-specific, and thus updating the model requires determination of new routing coefficients. In addition, to provide information on the 1997 flood to both public and the relevant agencies, Houston Engineering Inc. (1999) analyzed in detail the contributions and timing of tributary and main stem flows to points downstream. They inherited the 1988 study conducted by USACE and developed the routing coefficients appropriate for the 1997 flood. The analysis concluded that no single tributary is the source of large floods and no single dam will provide the solution to flooding of the Red.

Pairing with these hydrologic modeling efforts, several one-dimensional unsteady-state hydraulic models (hydrodynamic models) have been developed to simulate the flow and stage hydrographs along the main stem for the historical causal floods, especially the 1997 flood. Zien (1997) developed a UNET (Unsteady NETwork) model to improve the analysis of flood conditions and to provide a planning tool for evaluating future levee alignment and elevation proposals in the Red River Basin. He used the flow hydrograph at Lake Traverse as the upstream boundary condition and the stage hydrograph at Emerson as the downstream boundary condition. The data, including channel cross sections, bridges and culverts, and Manning's roughness coefficients used by USACE to conduct floodplain and floodway management analyses, were updated and used to develop the UNET model. Furthermore, Klohn–Crippen Consultants Ltd. (1999) developed a MIKE–11 hydrodynamic model to study the scenarios to operate the inlet control structure of the Red River Floodway, a man-made channel, approximately 30 mi (48 km) long, created to divert flood from upstream to downstream of Winnipeg. The scenarios were analyzed for two synthetic 1826 floods and the 1997 flood. Sellars et al. (1999b, c) elaborated on the model development and the analysis results. The upstream boundary condition of the model is the gauged flow hydrograph at Grand Forks, and the gauged stage hydrograph at Selkirk is used as the downstream boundary condition. This MIKE–11 model incorporated very detailed topographic data for the Canadian portion but used the same data as the UNET model for the U.S. portion. Both of these models were summarized by Halliday et al. (2000). They recognized that neither the UNET model nor the MIKE–11 model would be affected by insufficient topographic data, variation and uncertainty of the boundary conditions, and poorly defined inflows from the ungauged areas. Also, the results simulated by these two models for the overlap reach from Grand Forks to Emerson were comparable to each other, i.e., the performance of the UNET model matches the MIKE–11 model.

Like the UNET and MIKE–11 models, the FLDWAV (Flood WAVe) model is a one-dimensional unsteady-state flow model, originally developed by the National Weather Service to determine the water surface profile of the dynamic wave downstream of a dam failure (Fread et al., 1998). By 2000, the National Weather Service had completed a FLDWAV model for the Red from the headwater reservoirs of Lake Traverse on the Bois des Sioux River and Orwell Lake on the Ottertail River to Emerson. The model was designed for real-time flood routing and forecasting. It was calibrated using the 1997 and 1999 floods, and verified using the 1996 flood. The peak stages were simulated to within 0.5 feet of the observed peak crests, with corresponding flows simulated to within 5% (Halliday et al., 2000).

BASINWIDE CONCEPTUAL MODEL SCHEME

The U.S. Geological Survey (USGS) subdivided the U.S. portion of the Red River Basin into twenty-eight 8-digit hydrologic units (HUCs), listed in Table 1. Except for the Devils Lake unit (09020201), an isolated HUC without direct hydrologic connection to the Red, and the Roseau unit (09020314), which drains into the Red downstream of the international gauging station at Emerson (Figure 1), the other 26 HUCs drain into the Red upstream of the international border between the United States and Canada. Three HUCs, Elm–Marsh (09020107), Sandhill–Wilson (09020301), and the Lower Red (09020311), are territorial to both North Dakota and Minnesota. The USGS inventoried 40 to 100 years of records of daily stream flow data for the five gauging stations along the Red from downstream to upstream at Drayton, Grand Forks–East Grand Forks, Halstad, Fargo–Moorhead, and Wahpeton–Breckenridge. Upstream of Wahpeton–Breckenridge, two reservoirs in series, Mud Lake and the Lake Traverse, were constructed to prevent flooding

Table 1. USGS Hydrologic Units of the Red River Basin

Code	Name	Drainage Area (mi^2)	Drainage Area (km^2)
09020101	Bois de Sioux	1,140	2,952
09020102	Mustinka	825	2,137
09020103	Otter Tail	1,980	5,128
09020104	Upper Red	594	1,538
09020105	Western Wild Rice	2,380	6,164
09020106	Buffalo	1,150	2,978
09020107	Elm–Marsh	1,150	2,978
09020108	Eastern Wild Rice	1,670	4,325
09020109	Goose	1,280	3,315
09020201	Devils Lake	3,700	9,582
09020202	Upper Sheyenne	1,940	5,024
09020203	Middle Sheyenne	2,070	5,361
09020204	Lower Sheyenne	1,640	4,247
09020205	Maple	1,620	4,196
09020301	Sandhill–Wilson	1,130	2,927
09020302	Red Lakes	2,040	5,283
09020303	Red Lake	1,450	3,755
09020304	Thief	994	2,574
09020305	Clearwater	1,350	3,496
09020306	Grand Marais–Red	482	1,248
09020307	Turtle	714	1,849
09020308	Forest	875	2,266
09020309	Snake	953	2,468
09020310	Park	1,080	2,797
09020311	Lower Red	1,320	3,419
09020312	Two Rivers	958	2,481
09020313	Pembina	2,020	5,231
09020314	Roseau	1,230	3,186

Note: From EERC, University of North Dakota, The Red River Drainage Basin, May 2001

and improve water quality downstream. Figure 2 shows the hydrologic connections between the Red and the HUCs.

While the various analyses mentioned above have been conducted in the past decade, because of their inconsistent modeling objectives and scopes and indirect linkage to land use, land cover, and watershed management practices, a conceptual model scheme shown in Figure 3 is needed to guide the future modeling efforts for the basinwide flood reduction studies in the Red River Basin. First, this scheme has an open structure. The available existing hydrologic–hydraulic models relevant to flood mitigation may be integrated into this scheme with necessary

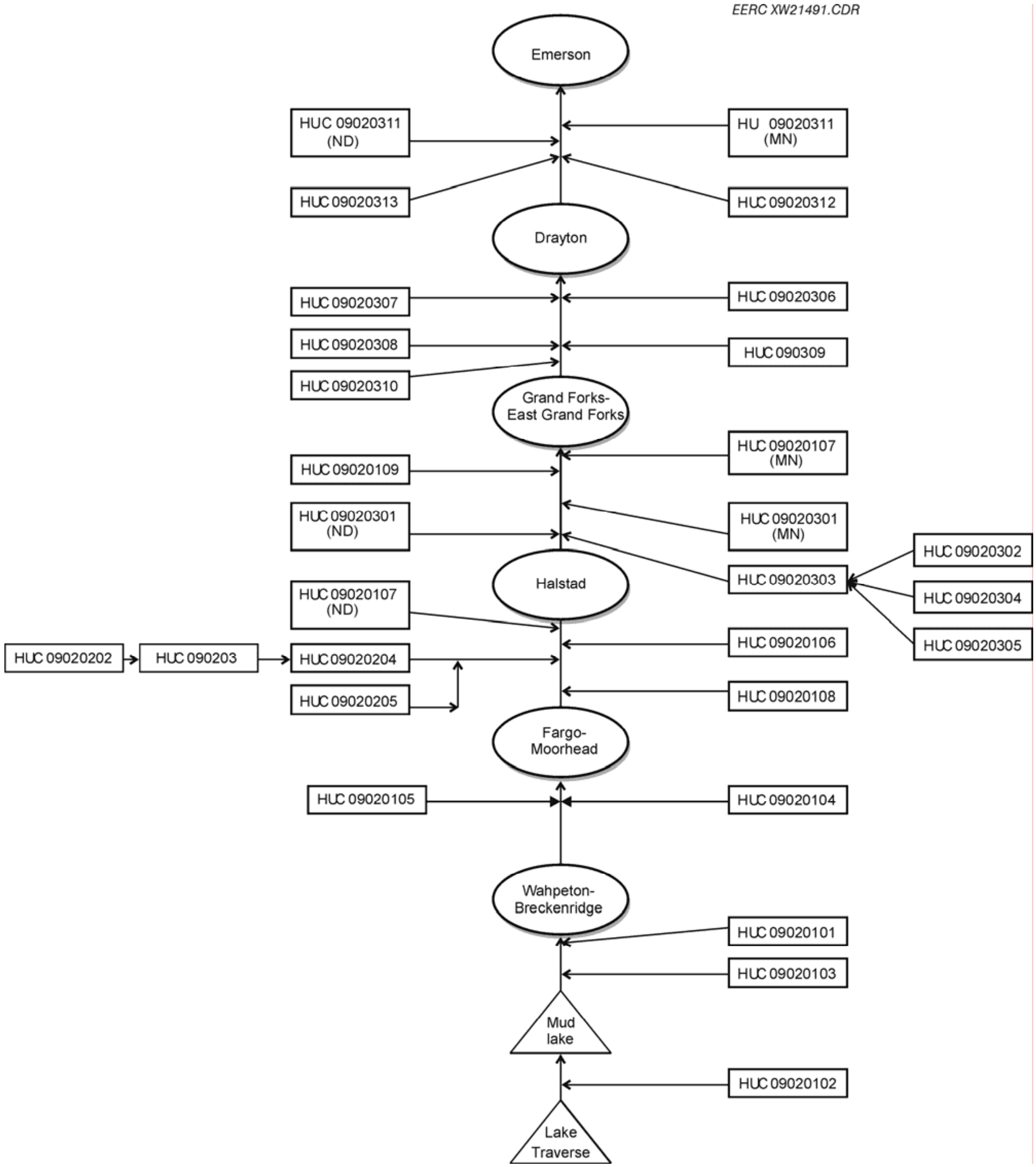

Figure 2. Hydrologic/hydraulic connectivity in the U.S. portion of the Red River Basin.

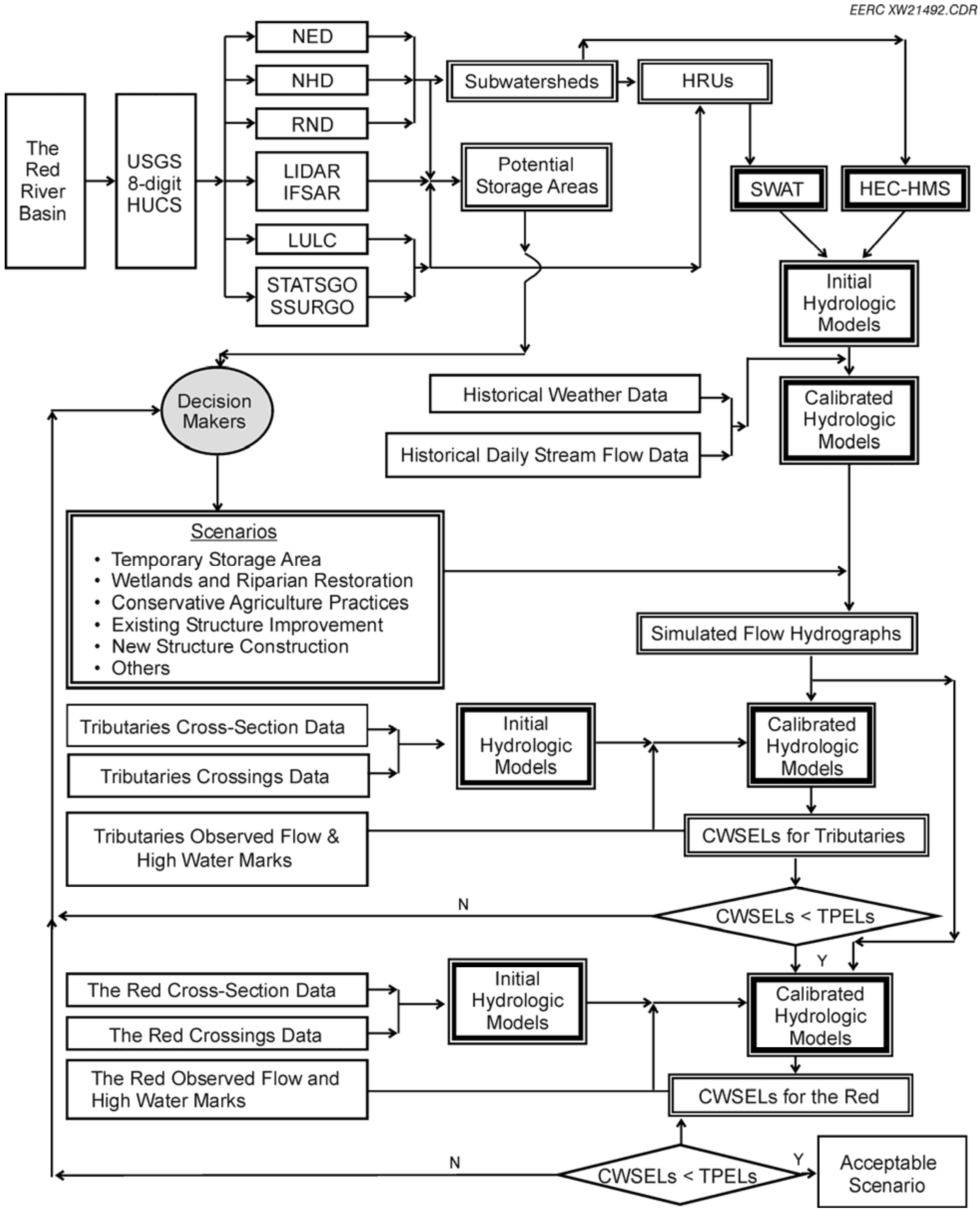

Figure 3. The conceptual model scheme for the Red River Basin.

modifications. The integration is not a motley collection of but a systematic assembly of these models. As a result, a series of useful modeling tools to be used for either simple or sophisticated, comprehensive flood reduction analyses will be developed. Second, this scheme is comprehensive but practicable. The users can freely combine the models needed to address their specific issues. For example, when the flow hydrographs are gauged or estimated by other methods, the users can just simulate the WSELs by using the hydraulic models. Finally, this scheme has great flexibility. In terms of the study needs and data availability, the functionality and complexity of the hydrologic models may vary by the HUCs. For example, the hydrologic model may simulate water quantity only for one HUC but both water quantity and water quality for another HUC.

The flow hydrographs simulated by these hydrologic models will be fed into either the steady-state (hydrostatic) or unsteady-state (hydrodynamic) HEC–RAS or MIKE–11 models to simulate the WSELs along the Red and its tributaries. Two software packages, HEC–HMS, developed by the Hydrologic Engineering Center (HEC) of USACE (2000, 2001b), and SWAT, developed by the Agricultural Research Service (ARS) of the U.S. Department of Agriculture (USDA) (Neitsch et al., 2002a), will be used to develop the hydrologic models for these HUCs in the Red River Basin. HEC–HMS, (Hydrologic Engineering Center Hydrologic Modeling System) was designed to simulate the precipitation-runoff processes of dendritic watershed systems (USACE, 2001b), whereas SWAT (Soil and Water Assessment Tool) is a physically-based river basin scale model developed to predict the impacts of land management practices on water, sediment, and agricultural chemical loadings in large, complex watersheds with varying soils and land use and management conditions over long periods of time (Neitsch et al., 2002a, b).

While HEC–HMS needs less data and has been widely used to study water quantity, SWAT may be utilized to address a wider range of issues, from water quantity to water quality. Therefore, the SWAT model is preferred and will be developed for the HUCs where sufficient data are available. In addition to the comparable hydrologic component with HEC–HMS, SWAT has several advantages for flood reduction studies in the Red River Basin: 1) SWAT incorporates hydrologic response units (HRUs), portions of a subwatershed that possess unique land use–management–soil attributes. HRUs may more accurately reflect the hydrologic characteristics of the study watershed and quantify the hydrologic responses to alternative agricultural practices; 2) SWAT has effective components to simulate the effects of small ponds and wetlands. These components are perfectly appropriate for evaluating the Waffle solution, which would use both man-made and natural depressions scattered across a watershed to temporarily store and regulate water to reduce peak flows at its outlet. These depressions may be simulated as ponds or intermittent wetlands. On the other hand, HEC–HMS has been traditionally used to simulate big dams; 3) SWAT simulates runoff produced both by rainfall and snowfall in one run. Its snowfall component simulates snow accumulation and snow thaw, which is very convenient when studying the snow-melt-dominated flooding in the Red River Basin. Conversely, another snow model is needed to convert the snowfall to the equivalent rainfall hyetographs to be fed into the HEC–HMS model (Shutov, 2000; Socolofsky et al., 2001); 4) SWAT subdivides the vadose zone into several sublayers. The soil moisture and permeability affecting the infiltration into the vadose zone may be specified for each of the layers to more accurately consider the antecedent condition, one of the five constant factors leading to a casual flood (Bluemle, 1997). The recharge from the vadose zone into groundwater may be accurately simulated by the SWAT model; 5) SWAT includes a water quality component. In addition to water yield, SWAT can simulate sediment and chemical loading, as well as the crop yields corresponding to various weather conditions and alternative agricultural practices; 6) SWAT has been seamlessly integrated with the databases developed and maintained by several federal agencies including the USGS, USDA, and the U.S. Environmental Protection Agency (EPA), which will undoubtedly expedite model development, standardization, usage, and upgrading. For example, the model parameters initially can be automatically extracted from these databases and then adjusted for the study watershed to develop a calibrated and verified model.

The data needed to develop the hydrologic models can be obtained from the relevant agencies. As a result of the maturation of the USGS effort to provide 1:24,000-scale digital elevation model (DEM) data for the conterminous United States, the national elevation dataset (NED) for the U.S. portion of the Red River Basin has been developed by merging the highest-resolution, best-quality elevation data available into a seamless raster format (http://gisdata.usgs.net/NED/default.asp). Where available, LIDAR, light detection and ranging, and IFSAR, interferometric synthetic aperture radar, will be used to amend NED. In cooperation with EPA and other organizations, the USGS also developed the 1:10,000-scale national hydrography dataset (NHD), a comprehensive set of digital spatial data that contains information about surface water features such as lakes, ponds, streams, rivers, springs, and wells (USGS 2000a, b). The NHD is based upon the content of the USGS digital line graph (DLG) hydrography data integrated with the reach-related information from the EPA reach file version 3 (RF3) (USGS, 1999a, b; 2000c, d). The NHD, which has been expanded and refined, supersedes DLG and RF3 by incorporating, not just replacing, them. (USGS, 2000b). Moreover, as a part of its national mapping program, the USGS provides the land use and land cover

(LULC) data sets and associated 1:250,000-scale maps for the conterminous United States (http://edcwww.cr.usgs.gov/glis/hyper/guide/1_250_luk). These data sets describe the vegetation, water, natural surface and cultural features on the landscape. Also, the USGS developed the state soil geographic database (STATSGO), organized according to the 2-digit hydrologic codes, for the conterminous United States. The STATSGO of the Red River Basin is in Region 09, Souris-Red-Rainy (http://water.usgs.gov/lookup/getspatial?ussoils). Currently, the Natural Resources Conservation Service (NRCS) of USDA is developing the soil survey geographic database (SSURGO). Compared with STATSGO, SSURGO is more detailed and has scales from 1:12,000 to 1:63,360 (http://www.ftw.nrcs.usda.gov/SSURGO.html). SSURGO has been available for most of the Red River Basin, so it will be utilized where available rather than STATSGO.

In addition to the data from these agencies, a road network dataset (RND) will be developed by compiling the existing scattered paper-format and digital data and the additional newly surveyed data. The RND will contain the typical attributes of the roads, including name, length, surface elevation, surface slope, side slope, construction materials, and dimensions and features of the underneath culverts. Furthermore, using Landsat 5 and Landsat 7 multitemporal images, the National Agricultural Statistics Service (NASS) of USDA developed a very detailed LULC dataset for the North Dakota portion of the Red River Basin (http://www.usda.gov/nass/aggraphs/cropmap.htm). This dataset will be used to improve the LULC datasets provided by the USGS.

Overlaid with NED, NHD, and RND, each of the USGS 8-digit HUCs will be further subdivided into smaller subwatersheds, with appropriate sizes varied according to study needs. The smallest subwatershed area depends on the NED resolution. The 30-m NED has a grid area of approximately 900 m^2 (0.22 ac). Therefore, the smallest subwatershed area that can be reasonably simulated by HEC–HMS and SWAT may be 90,000 m^2 (22.23 ac) (Seybert and Kuo, 1996; Garbrecht and Martz, 1999; and Tucker et al., 1999). These subwatersheds will be used to develop the Red River Basin Model for the HEC–HMS model (USACE, 2000 and 2001b) or may be further subdivided into the HRUs by considering the land use–management–soil attributes when the SWAT model is developed. The HRUs are portions with unique land use–management–soil attributes and thus do not physically subdivide their parent subwatershed. The subwatershed and its HRUs will be used to develop the SWAT model.

The hydrologic models, HEC–HMS and SWAT, will be calibrated and verified using historical weather data and daily stream flow data. Fed into these calibrated hydrologic models, the potential scenarios to reduce flooding, as specified by decision makers, can be evaluated. The scenarios may include structural measures such as improvements to existing detention ponds and culverts or the construction of new ones; nonstructural measures such as adaptation of conservative agricultural practices, restoration of wetlands, creation of riparian zones, and use of the existing temporary storage areas; or a combination of these measures (De Laney, 1995; Napier et al., 1995). For example, the existing temporary storage areas can be identified by using a geographic information system (GIS) to manipulate the datasets discussed above, including NED, LIDAR, IFSAR, NHD, RND, LULC, STATSGO, and SSURGO (Manale, 2000; Jenson and Domingue, 1988). The flow hydrographs simulated by the hydrologic models will be fed into the hydraulic models to compute the corresponding WSELs along the Red and when possible its tributaries.

The hydraulic models may be either hydrostatic or hydrodynamic. During a decade-long effort and in collaboration with FEMA, USACE (2003) developed a HEC–RAS hydrostatic model for the Red from just upstream of Emerson to just downstream of Wahpeton–Breckenridge by compiling and improving the previous HEC–2 models. While HEC–2 or HEC–RAS hydrostatic models have been developed for a few of the tributaries, appropriate modifications must be made to make them usable. In addition, two hydrodynamic models, UNET and FLDWAV, have been developed for the Red (Zien, 1997; Lewis, 1998; and Buan et al., unpublished). An effort is being made to develop MIKE–11 and HEC-RAS hydrodynamic models for the Red (Red River Basin Commission, 2002; Water Management Consultants, 2002). The Phase I basic model was planned for delivery by May 2003, but it is unknown when and how the Phase II refined and usable model will be developed (Water Management Consultants, 2002). These hydrodynamic models, reviewed carefully and modified necessarily, will be incorporated into the conceptual scheme. Because these models are limited by such things as their different modeling objectives (the FLDWAV model, for example, was mainly designed for forecasting), a HEC–RAS hydrodynamic model that is more efficient for flood reduction studies may be developed for the Red by improving the model developed by the Water Management Consultants. Furthermore, when needed, HEC–RAS hydrodynamic models will be developed for the tributaries. These existing or newly developed hydrostatic and hydrodynamic models will be calibrated and verified using historical major floods such as the 1976 and 1997 floods. Using the flow hydrographs corresponding to the study scenario simulated by the hydrologic models, the hydraulic models will compute the WSELs along the Red and its tributaries. When the computed WSELs (CWSELs) are less than the targeted protection elevations (TPELs) (USACE, 2001c), the scenario may be acceptable; when the CWSELs are greater than the TPELs, another scenario should be explored and evaluated. It is possible that there will be several acceptable scenarios. The feasible scenarios will be formulated from these acceptable scenarios by further considering their jurisdictional constraints and economic effects.

AN EXAMPLE APPLICATION OF THE CONCEPTUAL MODEL

As a preliminary effort to apply this conceptual model scheme to study reducing 1997-type flooding in the Red River Basin, a simple model shown in Figure 4 was developed by integrating the existing hydrologic and hydraulic models with a new twin algorithm. The existing HEC–2 and HEC–RAS models, developed by USACE (http://www.mvp-wc.usace.army.mil/org/RRN), were calibrated using the 1997 high water marks data provided by USACE and FEMA (2003). Taking the TPELs at the targeted protection locations along the Red (USACE, 2001c), these models were used to determine the maximum allowable discharge values (Q_{max}). By shaving the peaks with Q_{max}, the daily stream flow hydrographs observed by the USGS in 1997 (http://waterdata.usgs.gov/nwis/discharge) were manipulated to compute the water volume that needs to be regulated upstream of these targeted protection locations. The flow hydrographs from the ungauged drainage areas, the areas uncontrolled by the USGS gauging stations, were estimated using an existing HEC–1 model with extensive subjective engineering judgments (Houston Engineering Inc., 1999). The twin algorithm, a storage-release algorithm, was developed and utilized to allot the computed water volumes to the subwatersheds upstream of the targeted protection locations.

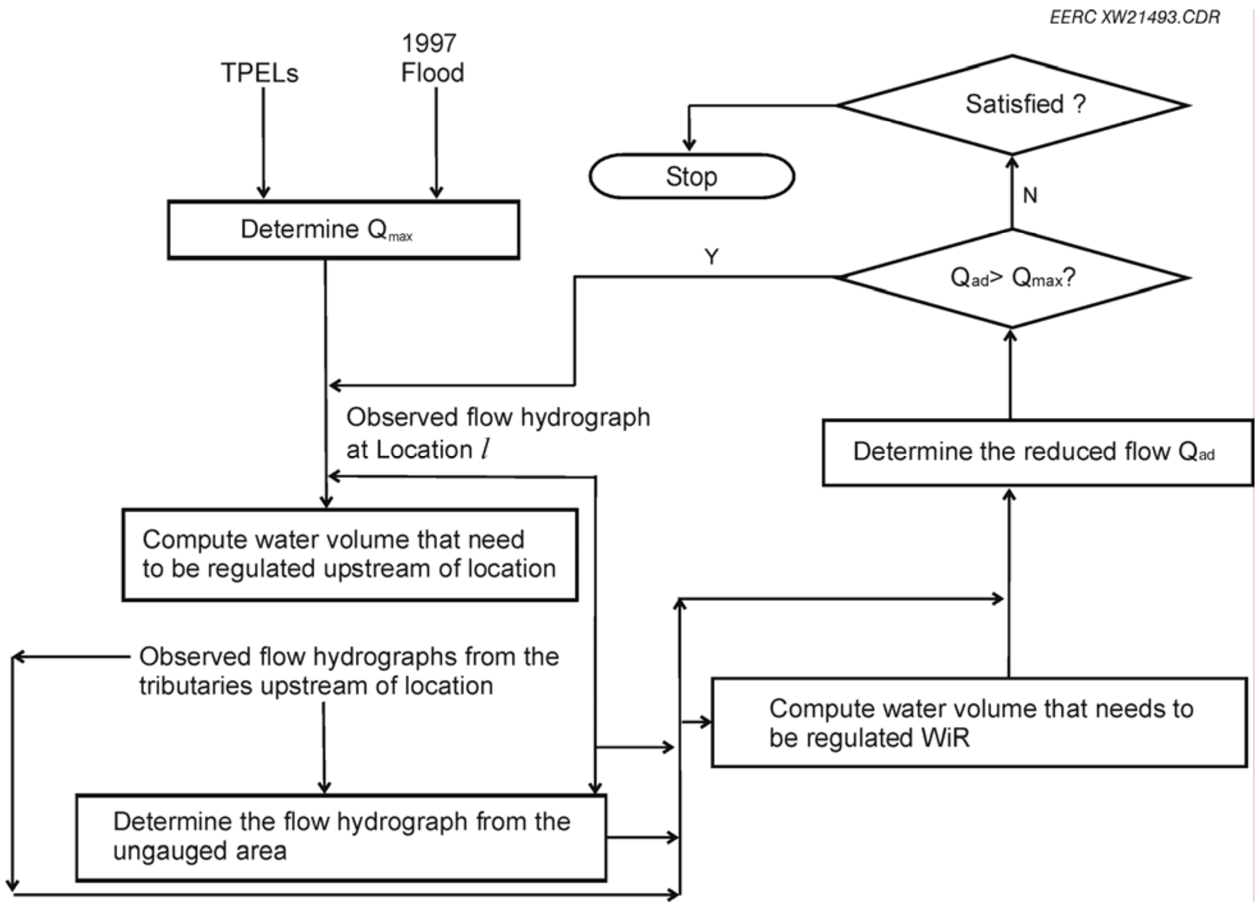

Figure 4. A simple model to study reducing 1997-type flooding in the Red.

The storage algorithm, the first part of the twin algorithm, assumes that the subwatersheds contributed more runoff and will regulate more water. Thus, the water to be regulated by subwatershed i upstream of the targeted location *l*, W_{iR} , may be estimated by Equation (1):

$$W_{iR} = \frac{W_{ic}}{W_{lp}} \times W_{lpR} \qquad (1)$$

where, W_{ic} – Observed runoff volume from subwatershed i

W_{lp} – Observed total runoff volume at location *l*

W_{lpR} – Computed water volume that needs to be regulated upstream of location *l*

On the other hand, the release algorithm, the second part of the twin algorithm, is based upon shaving the peak at the latest possible high-flow period but releasing the water at the earliest possible low-flow period. Thus the reduced flow hydrograph, Q_{ad}, at location *l* and the outlet of subwatershed i may be estimated by Equation (2):

$$Q_{ad} = \begin{cases} Q_{ob}(1 - \frac{W_R}{W_{ob}}) & \text{Storage period} \\ Q_{ob} + \frac{1}{\frac{Q_{ob}}{W_{ob}}} W_R & \text{Release period} \end{cases} \qquad (2)$$

where, Q_{ob} – Observed daily stream flow

W_{ob} – Observed runoff volume

W_R – Computed water volume that needs to be regulated, equal to W_{lpR} or W_{iR}

The results simulated by this simplest model are given in Table 2. Under the existing conditions, to reduce the 1997 flood crests below the major flood stages along the Red, approximately 1.4×10^6 ac-ft ($1.68 \times 10^9 m^3$) water will need to be regulated upstream of Drayton, including 0.18×10^6 ac-ft ($0.22 \times 10^9 m^3$) upstream of Wahpeton–Breckenridge, 0.13×10^6 ac-ft ($0.16 \times 10^9 m^3$) between Wahpeton–Breckenridge and Fargo–Moorhead, 0.17×10^6 ac-ft ($0.21 \times 10^9 m^3$) between Fargo–Moorhead and Halstad, 0.6×10^6 ac-ft ($0.7 \times 10^9 m^3$) between Halstad and Grand Forks–East Grand Forks, and 0.32×10^6 ac-ft ($0.39 \times 10^9 m^3$) between Grand Forks–East Grand Forks and Drayton. With such volume of water regulated upstream of Drayton, the WSEL at Emerson will be below its major flood stage. This volume of water was allotted to the subwatersheds using the twin algorithm. The equivalent water depths, averaged by the contributing areas of the subwatersheds, vary from 0.0 to

Table 2. Flood Reduction Analysis in the Main Stem of the Red River of the North for the 1997 Flood

Control Location	Vertical Datum, ft – NGVD 29	Geographic Coordinates: Latitude	Geographic Coordinates: Longitude	Drainage Area[a], mi^2: Contributing	Drainage Area[a], mi^2: Non-contributing	Peak Discharge[b]: Peak, cfs	Peak Discharge[b]: Date, mo./day	High Mark, ft	Volume from March 1 to May 31[c], ac-ft	Water That Needs to be Regulated Upstream, ac-ft: Existing Condition	Water That Needs to be Regulated Upstream, ac-ft: Post Project in GF & EGF	Average Water Depth by the Contributing Area, in.: Existing Condition	Average Water Depth by the Contributing Area, in.: Post Project in GF & EGF	Reduced Peak Discharge, cfs: Existing Condition	Reduced Peak Discharge, cfs: Post Project in GF & EGF	Expected High Mark, ft: Existing Condition	Expected High Mark, ft: Post Project in GF & EGF
Wahpeton (05051500)	942.97	46.265278	96.594444	2,425	1,585	12,700	4/15	962.39	782,257	180,000	180,000	1.4	1.4	6,100	6,100	958.97	958.97
Doran (05051300)		46.152222	96.578889	1,880		11,500	4/16		490,107	112,775	112,775	1.1	1.1				
Fergus Falls (05046000)	1,029.65	46.209722	96.184722	1,740		1,480	4/16		191,177	43,990	43,990	0.5	0.5				
Ungauged Area				390					100,973	23,234	23,234	1.1	1.1				
Hickson (05051522)	877.06	46.659722	96.795556	2,715	1,585	8,920	4/1	914.66	883,237	186,229	186,229	1.3	1.3				
Wahpeton (05051500)	942.97	46.265278	96.594444	2,425	1,585	12,700	4/15	962.39	782,257	180,000	180,000	1.4	1.4				
Ungauged Area				290					100,980	6,229	6,229	0.4	0.4				
Fargo (05054000)	861.80	46.861111	96.783333	4,625	2,175	25,800	4/19	901.52	1,454,940	306,772	306,772	1.2	1.2	20,000	20,000	893.75	893.75
Hickson (05051522)	877.06	46.659722	96.795556	2,715	1,585	8,920	4/1	914.66	883,237	186,229	186,229	1.3	1.3				
Abercrombie (05053000)	907.94	46.468056	96.783333	1,490	590	9,450	4/16	935.24	374,132	78,885	78,885	1.0	1.0				
Ungauged Area				420					197,571	41,658	41,658	1.9	1.9				
Halstad (05064500)	826.65	47.351944	96.843333	15,205	6,595	69,900	4/19	867.39	3,364,385	473,146	473,146	0.6	0.6	55,000	55,000	865.50	865.50
Fargo (05054000)	861.80	46.861111	96.783333	4,625	2,175	25,800	4/19	901.52	1,454,940	306,772	306,772	1.2	1.2				
West Fargo Diversion (05059480)	876.78	46.887500	96.919167	0		4,800	4/19		377,077	32,856	32,856						
West Fargo (05059500)	877.19	46.891111	96.906667	3,090	5,780	4,800	4/19	899.98	415,259	36,182	36,182	0.2	0.2				
Enderlin (05059700)	1,056.72	46.621667	97.573611	796	47	3,890	4/18	1070.82	151,495	13,200	13,200	0.3	0.3				
Amenia (05060500)	943.00	47.016667	97.213889	116		1,450	4/16		36,117	3,147	3,147	0.5	0.5				
Dilworth (05062000)	878.31	46.961111	96.661111	975		8,370	4/6	905.41	232,880	20,291	20,291	0.4	0.4				
Hendrum (05064000)	836.75	47.268056	96.797222	1,560		10,300	4/18		383,061	33,377	33,377	0.4	0.4				
Ungauged Area				2,636					313,556	27,321	27,321	0.2	0.2				
Grand Forks (05082500)	779.00	47.927222	97.026111	21,445	8,655	127,000	4/18	833.35	5,016,820	1,070,000	473,146	0.9	0.4	110,000	127,000	830.88	833.35

[a] Data for the main stem from ACE (Table 2 included in Regional Red River Flood Assessment Report, Wahpeton, North Dakota/Breckenridge, Minnesota, to Emerson, Manitoba, January 2003), but others from the USGS.
[b] From the USGS. The values are the maximum discharges presented in the daily stream flow data.
[c] Computed based on the flow hydrographs from the USGS.

continued . . .

Table 2. Flood Reduction Analysis in the Main Stem of the Red River of the North for the 1997 Flood

Control Location	Vertical Datum, ft – NGVD 29	Geographic Coordinates: Latitude	Geographic Coordinates: Longitude	Drainage Area[a], mi^2: Contributing	Drainage Area[a], mi^2: Non-contributing	Peak Discharge[b]: Peak, cfs	Peak Discharge[b]: Date, mo./day	High Mark, ft	Volume from March 1 to May 31[c], ac-ft	Water That Needs to be Regulated Upstream, ac-ft: Existing Condition	Water That Needs to be Regulated Upstream, ac-ft: Post Project in GF & EGF	Average Water Depth by the Contributing Area, in.: Existing Condition	Average Water Depth by the Contributing Area, in.: Post Project in GF & EGF	Reduced Peak Discharge, cfs: Existing Condition	Reduced Peak Discharge, cfs: Post Project in GF & EGF	Expected High Mark, ft: Existing Condition	Expected High Mark, ft: Post Project in GF & EGF
Halstad (05064500)	826.65	47.351944	96.843333	15,205	6,595	69,900	4/19	867.39	3,364,385	473,146	473,146	0.6	0.6				
Goose (05066500)	879.52	47.409444	97.060833	1,039	164	8,060	4/5		228,240	82,440		1.5	0.0				
Shelly (05067500)	841.14	47.412500	96.763889	220		4,100	4/18	866.84	82,896	29,942		2.6	0.0				
Sandhill (05069000)	820.00	47.611944	96.814444	420		4,360	4/20	902.50	105,608	38,145		1.7	0.0				
Crookston (05079000)	832.72	47.775556	96.609167	5,270		27,500	4/18	861.12	1,012,892	365,853		1.3	0.0				
Ungauged Area				1,187					222,799	80,474		1.3	0.0				
Drayton (05092000)	755.00	48.572222	97.147222	26,085	8,715	124,000	4/24	800.56	5,707,269	1,317,629	1,317,629	0.9	0.9	50,000	54350	795.00	795.95
Grand Forks (05082500)	779.00	47.927222	97.026111	21,445	8,655	127,000	4/18	833.35	5,016,820	1,070,000	473,146	0.9	0.4				
Turtle (05082625)	980.00	47.931944	97.514167	311		930	4/2		40,580	14,554	40,580	0.9	2.4				
Minto (05085000)	806.95	48.269444	97.369444	620	120	2,100	4/20		81,850	29,355	81,850	0.9	2.5				
Grafton (05090000)	811.11	48.424722	97.411667	695		5,150	4/21	826.37	131,965	47,329	131,965	1.3	3.6				
Argyle (05087500)	828.53	48.340833	96.817222	255		3,800	4/19		66,930	24,004	66,930	1.8	4.9				
Ungauged Area				2,699					369,124	132,386	369,124	0.9	2.6				
Emerson (05102500)	700.00	49.00833	97.211111	31,445	8,755	129,000	4/26	792.56	6,339,660	794,580	794,580	0.5	0.5	80,000	80,000	789.52	789.52
Drayton (05092000)	755.00	48.572222	97.147222	26,085	8,715	124,000	4/24	800.56	5,707,269	1,317,629	690,449	0.9	0.5				
Akra (05101000)	930.00	48.778333	97.745278	160		675	4/22		37,908		5,589	0.0	0.7				
Neche (05100000)	809.69	48.989722	97.556667	3,410		14,300	4/27	834.44	558,232		82,300	0.0	0.5				
Lake Bronson (05094000)	928.53	48.730556	96.663889	422		4,100	4/20		110,170		16,242	0.0	0.7				
Ungauged Area				1,408					-73,919			0.0	0.0				

[a] Data for the main stem from ACE (Table 2 included in Regional Red River Flood Assessment Report, Wahpeton, North Dakota/Breckenridge, Minnesota, to Emerson, Manitoba, January 2003), but others from the USGS.
[b] From the USGS. The values are the maximum discharges presented in the daily stream flow data.
[c] Computed based on the flow hydrographs from the USGS.

approximately 3.0 inches, with the maximum depth occurring in the Elm-Marsh subwatershed (09020107) upstream of the USGS Shelly gauging station. In addition, a similar simulation under the existing conditions was also analyzed with the Grand Forks–East Grand Forks levee project completed (post-project conditions). Under the post-project conditions, Grand Forks–East Grand Forks will not need to regulate water upstream. However, under existing conditions, the same volume of water will have to be regulated upstream of Wahpeton–Breckenridge, Fargo–Moorhead, and Halstad to protect these locations to their major flood stages. It will be impossible to protect Drayton to its major flood stage, even with the gross runoff from the subwatersheds between Grand Forks–East Grand Forks and Drayton regulated. Additionally, approximately 0.11×10^6 ac-ft ($0.14 \times 10^9\, m^3$) of water will have to be regulated between Drayton and Emerson to protect Emerson to its major flood stage. The average depths of water allotted to the subwatersheds will be from 0.0 to approximately 5.0 inches, with the maximum depth occurring in the subwatershed upstream of the USGS Argyle gauging station. For both the existing conditions and the post-project conditions, when the above estimated volumes of water can be regulated, the 1997 flood crests along the Red will be lowered 3.0–7.0 ft (0.9–2.0 m).

DISCUSSIONS AND CONCLUSIONS

The Red River of the North Basin is a complex river system. The basin incurred major floods about every 4 to 6 years, with truly devastating floods about every decade. While various structural and nonstructural measures have been taken, the extensive flooding in 1997 necessitated reexamination of these measures and exploration of innovative concepts to augment the traditional approaches. The most effective and efficient solution to flooding is to control runoff where it originates, i.e. to mitigate flooding at its source. Flooding along the Red has occurred for hundreds of years, but did not become a "problem" until humans decided to build settlements in the midst of the floodplain. Now that those settlements have grown into towns and cities, much time and money has been spent trying to keep the floodwater of the Red River from impacting people and communities. Costly lessons from traditional flood control practices have led humans to explore innovative approaches to augment conventional flood protection measures . Innovative solutions that address runoff before it becomes a problem are especially crucial to the Red River of the North Basin because of its low relief and intensive agricultural activities. However, there is no single solution for flooding in this basin. Comprehensive solutions should be evaluated and implemented in the near future, including existing hydraulic structure improvements, new hydraulic structure construction, wetland and riparian restoration, conservative agricultural practices implementation, and temporary water storage in potential storage areas. Hydrologic and hydraulic models play a key role in evaluating these solutions. While several models have been developed in the past decade, it is difficult to use them for these evaluations due to their different modeling objectives.

A coupled hydrologic-hydraulic model is lacking for these evaluations. To fill this gap, a conceptual model scheme was developed in this paper. The scheme has an open structure and great flexibility but is comprehensive and practicable. The modeling achievements in the past decade will be incorporated into this scheme. In addition, more detailed models will be developed by employing updated modeling techniques and utilizing improved spatial and temporal data sets to meet the evaluation needs. While the ideal situation of this scheme is to develop an HEM–HMS or SWAT hydrologic model for each of the HUCs and an HEC–RAS hydrodynamic model for the Red and each of its tributaries, and then to seamlessly couple these models together, various simplified runs may also be executed. For example, as a preliminary application of the scheme, a simple model was developed by integrating the existing HEC–1, HEC–2, and HEC–RAS models with the twin algorithm. Using this simple model, the volume of water that needs to be regulated to offer protection from 1997-type flooding to the major flood stages along the Red was estimated to be approximately 1.4×10^6 ac-ft ($1.68 \times 10^9\ \mathrm{m}^3$). Averaged by the subwatershed contributing areas, this volume is equivalent to a maximum water depth of 3.0 inches for the existing conditions and 5.0 inches for the conditions with the Grand Forks–East Grand Forks Project.

It should be emphasized that the current models and results are very preliminary. More detailed hydrologic and hydraulic models essential to the flood reduction study in the Red River Basin will be developed under this scheme. The potential scenarios studied to reduce 1997-type flooding will be designed and evaluated using this more detailed coupled hydrologic–hydraulic model. Greater floods such as the PMF will be generated and the model will be utilized to verify the accuracy of the acceptable scenarios.

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