Integration of Hydraulic and Environmental Effects for Assessment of Systemwide Impacts of Navigation Traffic on the Upper Mississippi River and Illinois Waterway

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ABSTRACT

A feasibility study conducted by the U.S. Army Corps of Engineers (USACE) to accommodate projected increases in commercial navigation traffic on the Upper Mississippi River and Illinois Waterway over the next 50 years led to an extensive series of studies relating traffic effects to potential environmental impacts. Multidisciplinary teams were used throughout the study from different state and federal agencies, private consultants, and universities to develop scopes of work, execute experimental studies, develop and apply models, review reports and findings, and integrate study results. The integration team was responsible for the development and application of a systemic model that coupled the hydraulic and biological modeling components in an ecological risk assessment framework making extensive use of the data handling, analysis and pre- and post- processing capabilities of a GIS developed for the entire study area. The results included a 50-year assessment of impacts to fisheries, aquatic macrophytes, mussels, and sediment transport in the system, based on the physical effects produced by variable traffic conditions. Physical effects generated by commercial vessels were estimated on a reach-by- reach basis of the river (generally 0.5- to 1.0-mi intervals) in pools where geometric and characteristic riverine data existed by applying analytical approaches developed from more detailed studies and site-specific modeling applications. Extrapolation to areas and pools where data were less abundant was based on a hydraulic classification that subdivided the large study area into geomorphically similar areas and reaches. Environmental impacts were determined for incremental increases in traffic forecasts for each planning alternative.

INTRODUCTION

The Upper Mississippi River-Illinois Waterway System Navigation Study (UMRS) is tasked with evaluating the feasibility of navigation improvements to the Upper Mississippi River and Illinois Waterway to reduce delays to commercial navigation traffic, while maintaining the social and environmental qualities of the river system. The

Environmental Impact Statement accompanying the feasibility report will consider, among other environmental issues, the system wide impacts of navigation capacity increases. The UMRS Navigation Study is composed of planning, engineering, economic, environmental, and public involvement study plans. The system evaluation of ecological impacts due to incremental increases in traffic is part of the environmental study plans.

The Initial Project Management Plan (IPMP), based on recommendations from the Plan of Study for Navigation Effects of the Second Lock, Melvin Price Locks and Dam, identified environmental studies that were scoped by interagency technical teams in a series of workshops beginning in 1992 (USACE 1994). The environmental studies have been carried out by a number of agencies, universities, and contractors over the course of the study.

The environmental study had numerous multidisciplinary components related to biology and hydrodynamics. The studies included quantification of physical effects due to moving vessels; development of hydrodynamic and sediment models for prediction and transport of vessel-induced resuspension; identification of areas susceptible to vessel-induced bank erosion; biological sampling and modeling for prediction of impacts to fisheries, aquatic plants, and mussels; development of a hydraulic classification of aquatic areas for extrapolation of impacts; and a spatial database (GIS) for system analysis. Additionally, the physical forces and ecological impacts were driven by the traffic projections and the availability of data at a system level.

Due to the complexity of the study, a multidisciplinary team was needed to integrate technical study components and results, ensure continuity and focus through completion of the study, and coordinate efforts between working groups and management needs. The Modeling Integration Simulation Team (MIST) was created from technical team members of the key study tasks to 1) develop scenarios for assessment of impacts, 2) review study plans and scopes of work to ensure that study results could be effectively integrated upon completion, 3) integrate modeling components into a comprehensive system assessment tool, 4) apply or assist in the system modeling efforts, and 5) integrate components into a risk assessment framework.

STUDY APPROACH

The study was conducted using various levels of modeling, development of impact assessment tools, and integration of these tools into a system approach. To evaluate biological responses to physical effects and broadcast those effects to a system of 37 locks and 1,200 mi of navigable waterway for various traffic levels, a suite of models was needed to predict everything from micro-level responses to macro- or system-level impacts. The studies outlined in the IPMP suggested modeling approaches ranging from detailed laboratory experiments to field studies; numerical and physical model studies of effects at site-specific locations; and finally, screening and analytical approaches at the system wide level. The use of experimental models, field studies, site-specific models, screening and system models were all key components to the evaluation of environmental impacts.

The final impact assessment tools fell into three basic categories: GIS, biological response models, and physical effects tools. The biological and physical effects tools, along with economic projections of traffic characteristics and frequency, were used to assess impacts on fisheries, mussels, aquatic plants, and backwater/side channel sedimentation. The GIS was used to create coverages, store data inputs/outputs, and apply rules over the entire system. It is important to understand that the system model is not a single does-it-all model, but in fact, a complicated set of models that have hooks and intertwining inputs and outputs.

PHYSICAL EFFECTS

The cornerstone to understanding ecological impacts due to incremental increases in traffic was the thorough understanding of the physical effects produced by a moving vessel. A moving vessel generates forces due to displacement motion such as drawdown, currents, and shear stresses. These effects increase as channel size decreases. Drawdown (the long-period water- level response of the vessel's displacement) at side channels and backwaters openings adjacent to the navigation channel can propagate an exchange of water and suspended sediments into and out of these areas and generate oscillations or long-period seiche. Currents generated by the vessel can cause short-term changes in the ambient currents. As a vessel moves upstream, currents are temporarily increased above the ambient condition. As it moves downstream, ambient currents are reduced, and in the case of low ambient currents and high vessel-generated currents, the flow can be reversed as the vessel passes. Shear stress increases due to the changes in current, particularly in regions beneath the vessel, can, under certain hydrodynamic and substrate conditions, cause resuspension of sediment. The hull form of a moving object in water creates short-period waves that can propagate to the bank, disturbing near-shore sediments and aquatic plants and attacking exposed banks. These impacts increase with vessel speed and are not dependent on the channel size. The twin propellers on a commercial tow, often on the order of 8 to 9 ft in diameter, can generate highly turbulent changes in the flow regime and contribute to shear stresses and mixing. The proximity of the propellers to the channel bottom and the applied horsepower affect the magnitude of these impacts. The physical-effects studies were designed to quantify the hydrodynamic disturbances both near the vessel and in areas adjacent to the channel, and evaluate these effects on sediment resuspension and transport.

Using field studies, physical models, and numerical models, analytical approaches were developed to systemically quantify navigation effects for various planning alternatives. The fundamental system modeling tool developed for this study is an analytical program called NAVEFF (Maynord 1996). Outputs from this tool feed directly into a model for evaluation of main-channel and near-shore resuspension of sediments, biological response, and calculation of sediment exchanges into off-channel areas. NAVEFF, developed at the USAE Waterways Experiment, basically calculates drawdown, return current, shear stress, wave height, and scour depth at a given cross section for a given set of traffic characteristics and ambient river conditions. Flow diagrams outlining the interconnections between these models and the traffic and GIS inputs can be seen in Figures 1–3.

SYSTEM COMPUTATIONS AND ASSUMPTIONS

In order to step through the many economic scenarios, apply a risk-based approach, and evaluate impacts over the large spatial extent of the study, a sequenced computational approach was needed. System models were first applied in six reaches known as the Atrend pools. These included Pool 4, Pool 8, Pool 13, Pool 26, the open river from Cairo to St. Louis on the Mississippi River, and the LaGrange Pool on the Illinois River. Since the NAVEFF model takes data provided at a river cross section and computes effects laterally along that section, the main channel of the river was broken into reaches at 0.5- to 1.0-mile intervals. Furthermore, each cross section was divided into 10-m-wide cells where data were stored and computations were made. A typical pool, at 0.5-mi intervals, might have 50 cross sections, with approximately 40 to 60 cells per cross section. That means all required inputs and computational outputs are stored for 2,000 to 3,000 unique cells in each trend pool.

Inputs to the NAVEFF model regarding river conditions include the bathymetric data at the cross section, the ambient stage and velocity, and the type of sediment substrate. Vessel characteristics needed to run the model include configuration, draft, speed, direction, location laterally in channel (sailing line), applied horsepower, and whether the propeller is kort-nozzle or open-wheel. Since all those parameters are variable and can be combined in an infinite number of scenarios, the MIST was left with the task of assigning conditions and setting assumptions. It was not the purpose of the study to select the worst-case conditions, nor was it possible a priori to know what combinations of these parameters would produce those conditions. The purpose was to evaluate likely combinations and present probable outcomes.

Flow Conditions

Early on in the study, it was determined that physical effects should be evaluated over a range of flow conditions. Discharge and stage records were studied, and three flow conditions were selected. The 5, 50, and 95 percent duration-exceedence stages were selected for each reach of the river. Flows corresponding to these stages were taken from rating curves at gages, and profiles between gages were interpolated. Each cross section was assigned a low (95 percent), medium (50 percent), and high (5 percent) flow. The high and low flows were felt to be within the range of navigable conditions. Ambient velocities were computed for each trend pool at each of these flow conditions using a two-dimensional, depth-averaged hydrodynamic model. Outputs were saved at cell centers in the GIS. Since many of the biological impacts are seasonally related, monthly distributions of these three discharges were determined for each reach. In other words, annual probability of occurrence is distributed monthly based on the probability of each type flow (low, medium, or high) actually occurring during that month.

Sailing Line

The location of the vessel laterally in the channel, or the sailing line, affects magnitudes of impacts in each cell. Some of the factors that can affect the position of the tow in the channel are the direction of the tow (up or down), size of the vessel, horsepower of the vessel, straight and bendway reaches of the river, discharge and stage, and, in general, typical tow operations in any given pool. Rather than conduct detailed studies regarding sailing lines, the MIST decided that, for the purposes of a feasibility study, a workshop with tow pilots and district operations personnel would be used to identify sailing line locations. Using navigation charts, Coast Guard buoy locations, and the expertise of both operators and Corps employees, three sailing line positions were identified for each reach of river (left, center, and right). All centerline sailing locations were based on revisions to navigation charts distributed among the districts and to the operators. Left and right locations placed the edge of the barge on the outer edge of the nearest cell and were based on location of buoys, if available, or on distance from centerline, when not available. The probability distribution of vessels at each of the three locations was 5 percent left, 90 percent center, and 5 percent right. Exceptions to this rule were identified for several reaches in the system.

Traffic Configuration Characteristics

The physical effects produced by commercial vessels are related to configuration characteristics of the tow. The following information was needed to run the system model:

- Size of barge train: length and width,
- Draft of vessel,
- Direction of travel: up or down,
- Vessel speed relative to water,
- Type of propulsion system (kort-nozzle or open-wheel), and
- Applied horsepower.

The economics team evaluated the fleet characteristics of the 1996 traffic data from the Lock Performance Monitoring System (LPMS) and provided data to the environmental team on a pool-by-pool basis. After aggregating configuration characteristics, assignments were made to all data variables.

From the 1996 traffic data, economics generated three vessel sizes. Small was considered to be tows with 4 or fewer barges, and vessels in this class were assigned a 1-wide-by-3-long barge train (35 ft by 585 ft) for computations in NAVEFF. A medium-size vessel was 5 to 11 barges, and a vessel configuration of 2-wide-by-4-long (70 ft by 780 ft) was assigned to this variable. A big vessel was defined as 12 or more barges, and was assigned a 3-wide-by-5-long configuration (105 ft by 975 ft).

Three vessel speeds were chosen based on a combination of transit times from the LPMS database, discussions with pilots, and field data. The following speeds relative to water were assigned:

1. Upper Mississippi River
   a) Slow—5 mph
   b) Medium—6.5 mph
   c) Fast—8 mph

2. Illinois River
   a) Slow—3 mph
   b) Medium—5 mph
   c) Fast—7 mph

The drafts were assigned as loaded, mixed, and empty. Often the tows were configured with barges of variable draft, so the mixed category was included in the analysis. Since they tend to produce physical characteristics closer to loaded than empties, mixed tows were assigned a draft of 7 ft. The loaded was considered to be 9 ft and empty, 2 ft.

In summary, for each computational cell in a pool, physical effects were calculated based on three categories of size, draft, and speed; two directions; and two propulsion systems. This gives 108 possible combinations of traffic configuration characteristics at each cell. To determine the probability or likelihood that any given combination can occur in a given pool, the frequency of each of the 108 vessel types was provided on a pool-by-pool basis based on the relative frequency of occurrence of actual vessels from the 1996 traffic database. The 108 combinations, the variable assignments, and the probability that they could occur was assumed not to change over the life of the project or for different traffic forecasts. Assignment of these variables was made by the MIST and are subject to discussion. Trends in the fleet characteristics were assumed to be relatively constant, based on evaluation of historical trends by the economics team. The values selected represent currently accepted and reasonable values for these parameters. Future applications of the system model should investigate the sensitivity of the variables to the outputs.

Traffic Forecast

Economic scenarios are based on the forecast of traffic increases over the projected life of the project. Economics provided traffic forecasts for the system models based on the projected number of tows per day, by pool, by month, per alternative. Forecasts were provided at 5-year intervals for the 50-year project life. Base traffic conditions were based on 1996 data, and alternatives provided were based on incremental increases above this baseline. Sequencing of vessels, or interarrival times, was important in the evaluation of biological impacts. So in addition to knowing the number of vessels and their most probable configuration characteristics, it was necessary to predict their arrival through a computational reach. An exponential decay function and random sampling routine were used to pick the time and order of tows arriving per day. To conduct the impact analysis, the system model will be evaluated for the future without project conditions, the National Economic Development plan, and other plans defined as the study progresses. Figure 4 is a flow chart summarizing traffic information. Figures 1–3 show where these traffic data fit into the computation of the physical effects.

Spatial Integration and Modeling Using GIS

The GIS was an invaluable tool for storing and retrieving data and identifying relational information between coverages. It was absolutely essential in the delivery of products and information regarding the study. Coverages developed for the study and used in the impact analysis included the bathymetric data, the left/center/right sailing locations, the location of existing mussel beds, the location of existing macrophyte beds, the hydraulic classification, a map identifying classification categories of bottom sediments or substrate, and the velocity magnitudes of ambient currents (trend pools only). All attributes used as inputs to NAVEFF or the biological models were stored by cross section and cell. Outputs of the physical effects or biological impacts can be mapped on a pool basis or cell basis. The GIS was used in conjunction with NAVEFF output to perform screening calculations such as identifying potential locations of macrophyte beds based on depth, substrate and hydraulic characteristics. Figures 1–3 and Figure 5 (flow diagram for the fish-spawning model) show where GIS inputs are used in these respective system model tools.

BIOLOGICAL MODELING AND IMPACT ASSESSMENT

Biological impacts were assessed by various types of models, including threshold/rule-based models for screening impacts, habitat suitability models, proportional mortality models, growth models, and bioenergetics models. Ecological impacts were assessed for submerged aquatic vegetation, freshwater mussels, and fish. Impacts concerning submerged aquatic vegetation included physical disruption, reduced growth, reproductive impairment, and habitat degradation. Impacts to mussels included physical impacts, reduced filtration, fecundity, and habitat degradation. Fish impacts from traffic can be assessed by entrainment mortality, equivalent adults lost, recruitment forgone, production forgone, drawdown mortality (stranding), and spawning-habitat degradation. Figure 5 is an example of how one of the biological models, the fish-spawning model, is proposed to be integrated with the traffic and physical effects for evaluation of impacts in trend pools.

EXTRAPOLATION

Due to the spatial and temporal extent of the study effort and the detailed computational intensity of some of the models (such as the plant growth model or the sediment transport model), a need was recognized early in the study to have a means of extrapolation. The hydraulic classification was developed with that purpose in mind. It was conceived that physical effects and characteristic attributes of each classification type could be linked to ecological impacts in areas where time or data were insufficient to make calculations of impacts. Three general classification types were identified, and GIS coverages were made of the entire system. These were main channel, side or secondary channels, and backwaters. The main channel was subdivided into the navigation channel and channel border areas. Backwaters were separated into contiguous and isolated backwaters. Details of extrapolation are still being decided by the MIST.

SUMMARY

The successful integration of physical effects and ecological impacts on the UMRS study is largely due to the vision and careful planning of study tasks outlined in the IPMP and the dynamic role of the MIST to piece together the experimental, numerical, and field study results into a set of system evaluation tools. Concurrent development of models would not have been possible without the continued feedback of the technical team and the common goal of ultimately hooking together the study components. The nucleus of the final system tool was the GIS, and the engine that drove the computations was NAVEFF. Not only the tools developed from this study, but also the integration process itself should be repeated on future large-scale studies.

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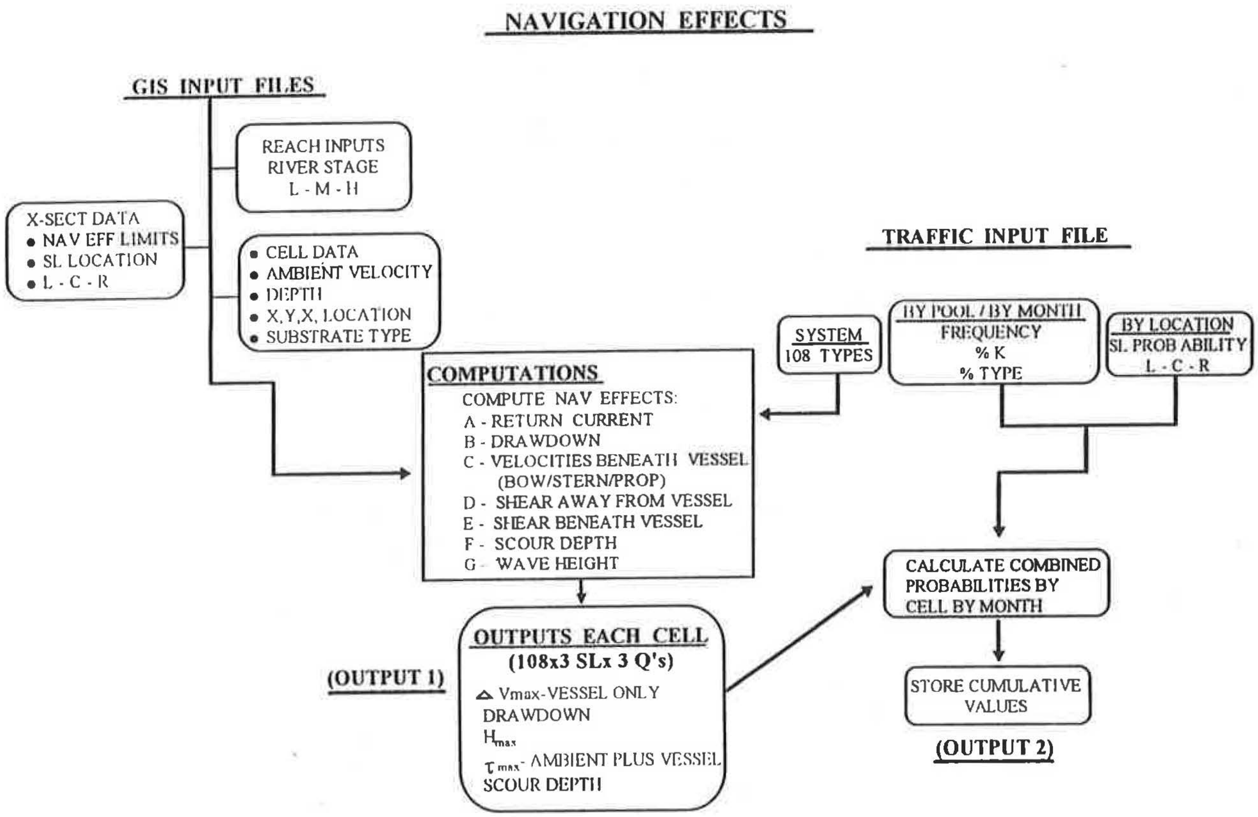

FIGURE 1 Flow diagram for computation of navigation effects in system model.

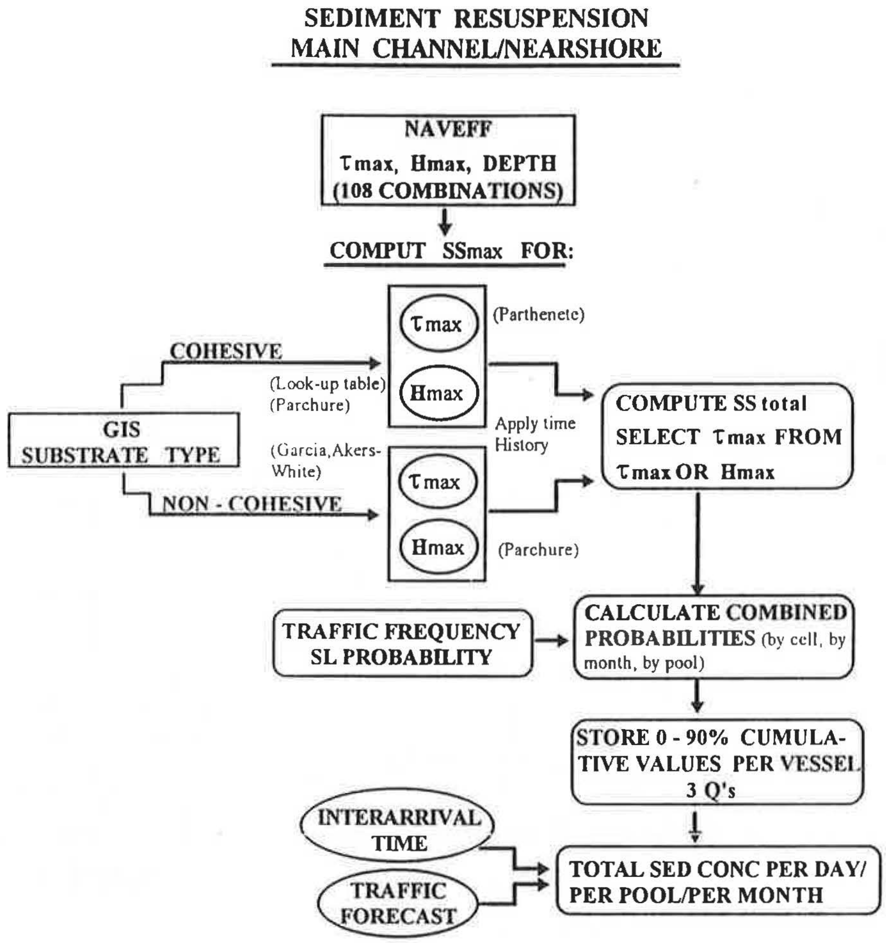

FIGURE 2 Flow diagram for computation of main channel sediment resuspension in system model.

SIDE CHANNELS/BACKWATERS – SYSTEM MODEL

TREND POOLS

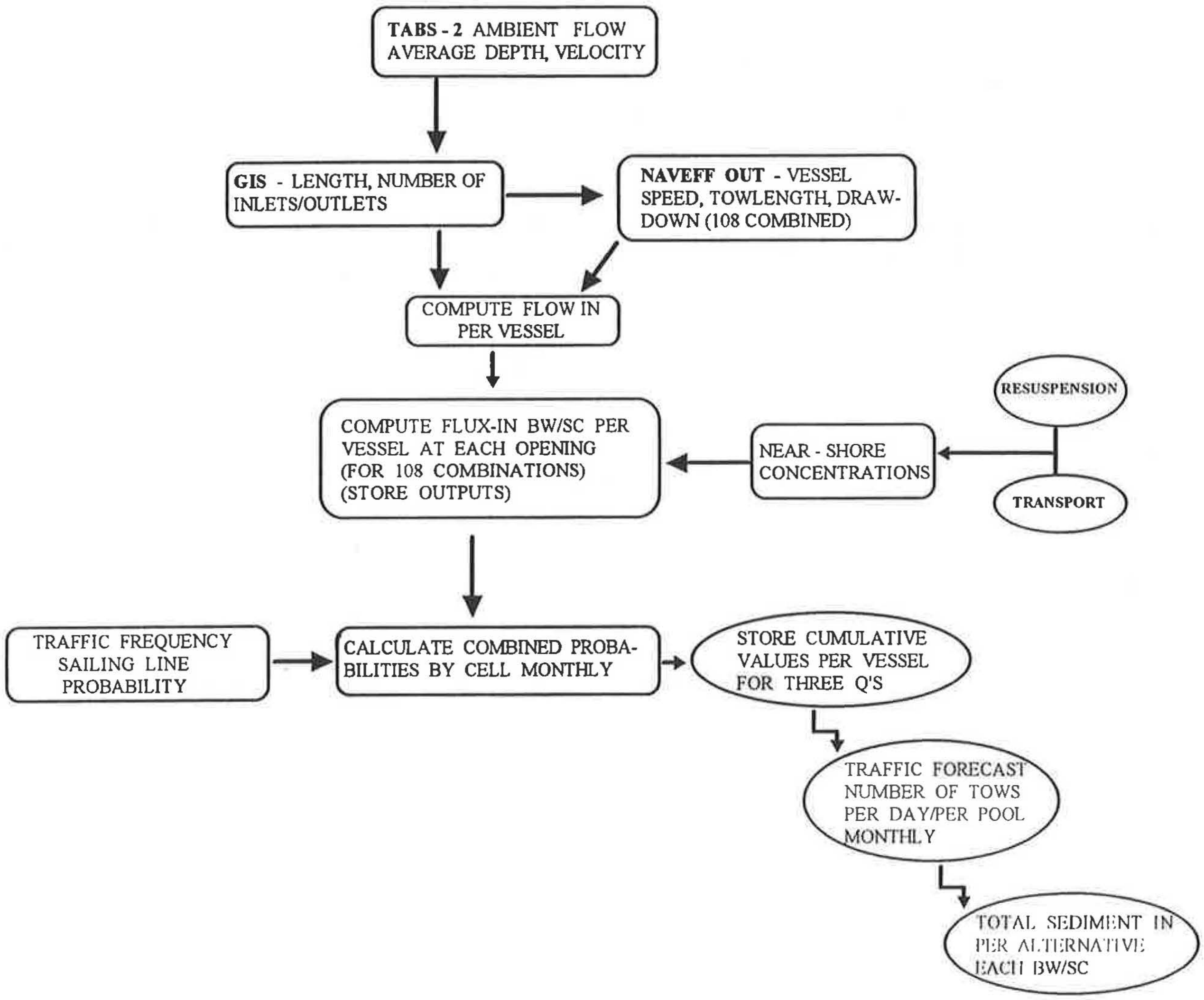

FIGURE 3 Flow diagram for computation of sediment into side channels and backwaters for UMRS system.

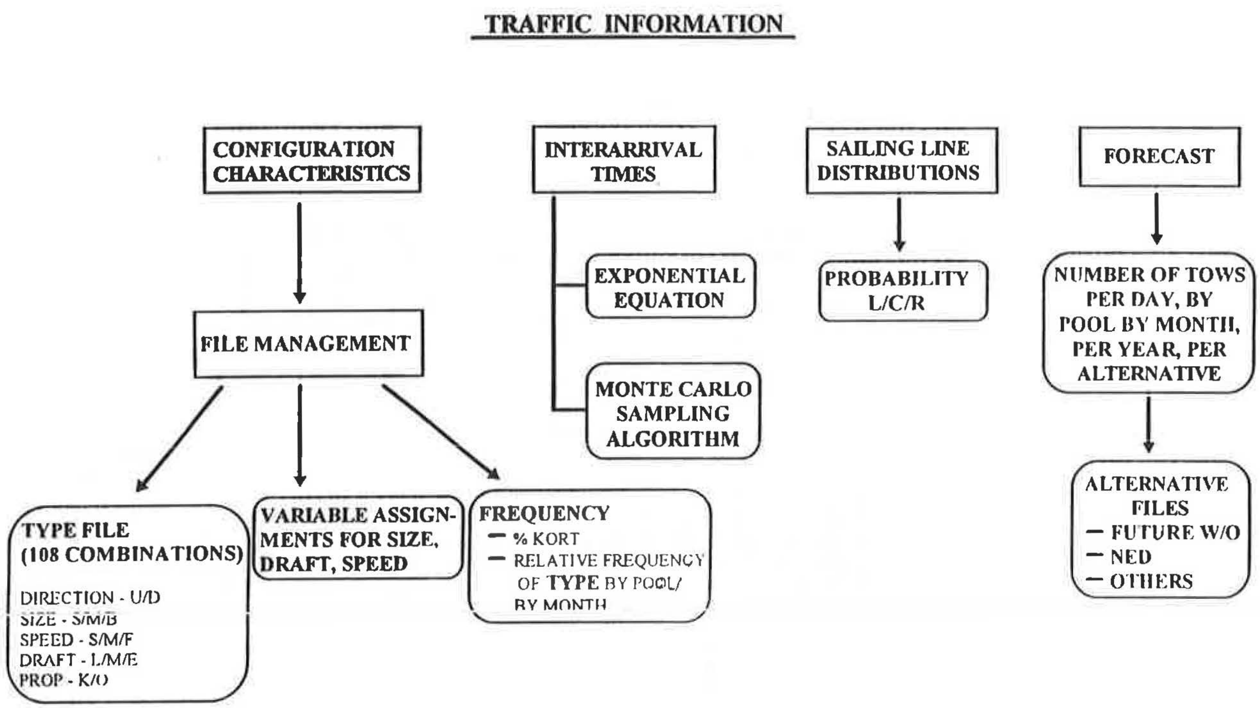

FIGURE 4 Flow diagram of traffic data used in system modeling approach.

FISH SPAWNING (PER SPECIES)

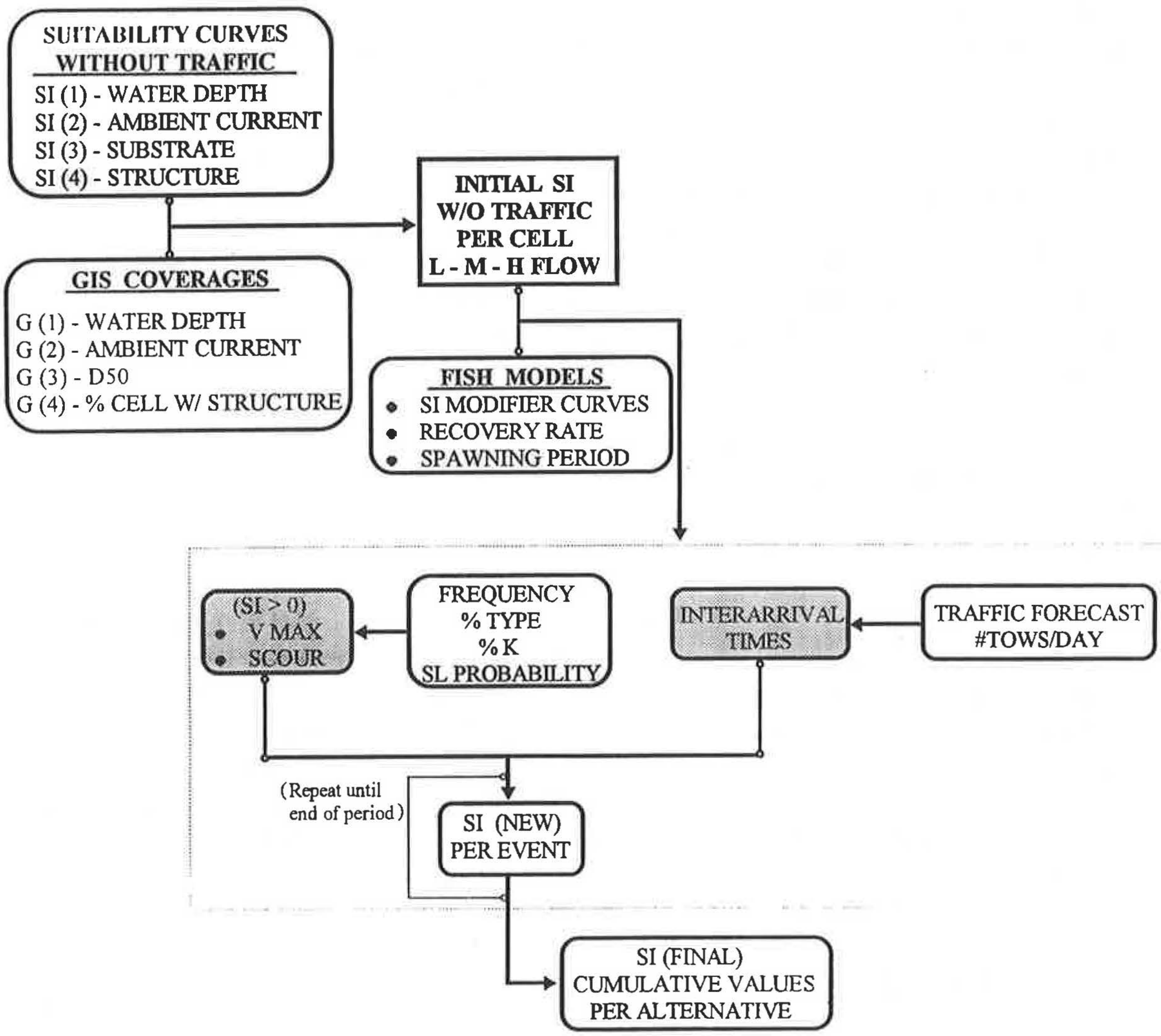

FIGURE 5 Sample flow diagram for integration with ecological model (fish-spawning model).