2 LITERATURE REVIEW

As nonpoint source pollution has garnered more attention in recent years, governmental agencies, academic and research institutions, and commercial consulting firms have developed methods of assessing pollution from nonpoint sources. Many of these methods have involved the development of computer-based models for automated, reliable, and repeatable analyses. More recently, some of these models have been linked with geographic information systems (GIS) for ease of data management or for the apportionment of processing tasks.

This chapter provides a review of some of the more well-known nonpoint source pollution models. An investigation of some of the more recent integrated GIS/nonpoint source modeling efforts is also included. Finally, a discussion is provided of previous water quality analyses performed in the study area.

2.1 Nonpoint Source Pollution Models

Ever since the EPA created the Stormwater Management Model (SWMM) in the early 1970's as the first urban runoff quality model (Donigian and Huber, 1991), researchers worldwide have continued to develop computer-based models to simulate runoff hydraulics and water quality in urban and non-urban environments. The role of GIS in these modeling efforts has also grown from that of a pre-processor for spatially oriented input data (Evans and Miller, 1988) to that of a stand-alone system through which runoff hydraulics and water quality are directly simulated (Newell et al., 1992).

This section describes some of the most commonly used nonpoint source pollution models and some successful GIS links to them. All of the models included in this section are written in standard FORTRAN 77 and are executable under the MS/DOS environment.

HSPF

The Hydrological Simulation Program-FORTRAN (HSPF) was developed by the EPA-Athens laboratory (Johanson et al., 1984). It is executable under either

DOS-based or VAX VMS systems. HSPF simulates both watershed hydrology and water quality for conventional and toxic organic pollution. The model provides estimates for these parameters on a one-dimensional stream network basis. HSPF is the only water quality model that provides for integrated simulation of land and soil contaminant runoff processes with instream hydraulic and sediment-chemical kinetics (Donigian and Huber, 1991).

HSPF requires continuous rainfall records to drive the agricultural runoff routine embedded in the program. Additionally, records of evapotranspiration, temperature, and solar radiation are input to the model. HSPF simulates the transfer and reaction processes of hydrolysis, oxidation, photolysis, biodegradation, volatilization, and sorption. Settling and resuspension of silts and clays are also modeled (Johanson et al., 1984).

The outputs of the HSPF model include time histories of the runoff flow rate, sediment load, and nutrient and pesticide concentrations. These time histories can be produced for any point in the stream network of a watershed (Donigian and Huber, 1991).

In 1995, Donigian et al. used HSPF, along with its more recently developed Agrichemical (AGCHEM) soil nutrient submodel, to estimate nutrient loadings to Chesapeake Bay. For this study, the AGCHEM modules were used to establish typical nutrient balances for each of the major agricultural crop categories in the Chesapeake Bay watershed. The analysis was the first extension and detailed application of HSPF/AGCHEM on a large (176,000 km^2) drainage area (Donigian et al., 1995).

Also in 1995, Al-Abed and Whiteley used the Arc/Info GIS, along with HSPF, to simulate the effects of changes in land use and in resource management strategies on the quality and quantity of irrigation water in the lower portion of the Grand River watershed, in southwestern Ontario, Canada. In this study, Arc/Info was used to establish watershed segments based on soil classification and land use/crop type. For each segment in the watershed, water holding capacity, soil infiltration capacity, surface slope, and initial soil water storage were calculated and provided as inputs to the HSPF model (Al-Abed and Whiteley, 1995).

CREAMS/GLEAMS

The U.S. Department of Agriculture-Agricultural Research Service developed the Chemicals, Runoff, and Erosion from Agricultural Management Systems (CREAMS) model (Knisel, 1980) to aid in the assessment of agricultural best management practices for pollution control. Like HSPF, CREAMS is a continuous simulation model requiring continuous precipitation data and monthly values of air temperature and solar radiation. Soil and crop type data are also provided as inputs. In order to assess best management practices, the user of CREAMS can simulate various management activities, such as aerial spraying or ground application of pesticides, animal waste management, tillage operations, or terracing (Knisel, 1980).

CREAMS calculates runoff volume, peak flow, infiltration, evapotranspiration, soil water content, and percolation on a daily basis. Daily erosion and sediment yield are also estimated and average concentrations of sediment-associated and solute chemicals are calculated for the runoff, sediment, and percolating water (Knisel, 1980).

By incorporating a component for vertical flux of pesticides in the root zone, the Groundwater Loading Effects of Agricultural Management Systems (GLEAMS) model (Leonard et al., 1987) was established. GLEAMS is partitioned into three components, namely hydrology, erosion/sediment yield, and pesticides. Rainfall is partitioned into surface runoff and infiltrating water using the Soil Conservation Service (SCS) Curve Number Method (Chow et al., 1988). Soils are divided into multiple layers of varying thickness for water and pesticide routing (Leonard et al., 1987).

A watershed version (Opus) of CREAMS/GLEAMS has also been created. Opus is a comprehensive model that simulates the processes of sediment transport, chemical transport, carbon and nutrient cycles in soil microbial decay, flow of heat in soil, and growth of crops (Smith, 1992). Opus relies heavily on algorithms from other models: weather conditions are simulated by a daily weather generation model (WGEN), daily runoff is calculated from a modified SCS Curve Number approach, and soil erosion is modeled using the Modified Universal Soil Loss Equation (MUSLE) (Williams, 1975).

Zhang et al. (1995) used CREAMS-WT, a modified field scale version of CREAMS, for simulating runoff and nutrients under high water table conditions, along with the Enhanced Stream Water Quality Model (QUAL2E) (Brown and Barnwell, 1987) and the GIS-based Lake Okeechobee Agricultural Decision Support System (LOADSS), to simulate phosphorus transport processes in the watersheds draining to Lake Okeechobee in south Florida. For this study, the LOADSS GIS was used to provide spatially distributed land use data to the CREAMS-WT model. Using soils associated data for the land uses, the CREAMS-WT calculates phosphorus concentration values throughout the watershed. This data, along with surface runoff data, is provided to QUAL2E, which simulates the phosphorus transport and retention in wetlands and stream channels. The South Florida Water Management District continues to use this modeling framework for assessment of eutrophication problems in the lake (Zhang et al., 1995).

AGNPS

The Agricultural Nonpoint Source Pollution Model (AGNPS) was created by the U.S. Department of Agriculture-Agricultural Research Service (Young et al., 1986) in order to compare the effects of different watershed pollution control management practices. AGNPS simulates sediment and nutrient loadings from agricultural watersheds for single storm events or for continuous data input. Watersheds in the model are discretized into series of square cells, for which homogeneous characteristic parameters are assigned.

AGNPS is partitioned into two submodels. The erosion portion of the model provides estimates of upland erosion, channel erosion, and sediment yield. The model uses the Modified Universal Soil Loss Equation (Williams, 1975) for soil erosion calculations and distributes predicted erosion into five particle size categories: sand, silt, clay, small aggregates, and large aggregates. The pollutant transport portion of AGNPS is subdivided into one part addressing soluble pollutants and one part handling pollutants adsorbed onto solids. Nitrogen and phosphorus loads are determined using relationships between chemical concentrations, sediment yield, and runoff volume (Young et al., 1986).

Input data for AGNPS are classified into two categories: watershed data and cell data. Watershed data includes information applicable to the entire watershed, while cell data is based on land use practices and soil type data within each cell. Output of the model includes a hydrology component, with runoff volume and peak runoff rate, and a sediment component, which includes the erosion data described above and estimates of pollutant loadings. Volumes and loadings can be determined on a watershed scale or for each receiving cell (Young et al., 1986).

AGNPS has proven to be a quite popular model with researchers and there have been significant numbers of studies coupling AGNPS to other models and GIS. Evans and Miller (1988) used a grid cell-based GIS known as ERDAS (Earth Resources Data Analysis System) integrated with AGNPS. In their study, Evans and Miller used an ERDAS algorithm called AGNPSIN to compute average AGNPS cell values for land slope, channel slope, curve number, roughness coefficient, surface condition constant, soil texture, chemical oxygen demand, and cropping factor. The calculated average cell values were then written to a data file, which supplied direct input to AGNPS during execution of the model.

Vieux and Needham (1993) studied the sensitivity of AGNPS to variations in Arc/Info grid-cell sizes. A 282-hectare agricultural and forested watershed near Morris, Minnesota was used as the test case. By varying the Arc/Info grid-cells between one hectare and 16 hectares, simulated flow path lengths were seen to decrease with increasing grid-cell size. This shortening of flow paths is attributed to stream meander short-circuiting at the larger grid-cell sizes. A corresponding variability in AGNPS sediment yield, which is dependent on flow-path length, was also observed. Sediment delivery ratio, when using the one-hectare grid-cells, was 71% greater than for the 16-hectare grid-cells. This variation was due solely to the cell size selected to represent the watershed. This research showed that cell size selection for a discrete watershed analysis should be based on the scale necessary to capture the spatial variability of parameters in the watershed.

Mitchell et al. (1993) used the Geographic Resources Analysis Support System (GRASS) GIS (U.S. Army, 1987), integrated with AGNPS, to perform a validation of the model for small mild topography watersheds in East Illinois. Using GRASS, all 22 input parameters for the AGNPS model were obtained from just four GIS layers. These input parameters were established either by using internal GRASS routines or by reclassification of the original GIS layers. For example, the Universal Soil Loss Equation K factor, the percent sand, percent clay, and the hydrologic soil group are AGNPS parameters which are associated with GIS polygons on the soils map. Reclassifications of the soils map with values for these parameters resulted in four input parameter layers for the AGNPS model.

Other AGNPS links with Arc/Info have also been investigated. A study of the impact of changing agricultural management practices on predicted water quality of the 1465 km^2 Bedford-Ouse catchment in England (Morse et al., 1994) showed that AGNPS input parameters could be effectively processed and provided through an interface with Arc/Info. Also, an evaluation of the effectiveness of different management strategies in reducing sediment loads was performed for the 417-hectare Bluegrass watershed in Audubon County, Iowa (Tim and Jolly, 1994). The integrated AGNPS-Arc/Info system proved to be an effective framework for assessing sediment load reductions through the management practices of vegetation filter stripping and contour buffer stripping.

ANSWERS

The ANSWERS (Areal Nonpoint Source Watershed Environment Response Simulation) model was developed in the Agricultural Engineering Department of Purdue University in the late 1960's. It is a distributed parameter, event-based model for predicting the hydrologic and erosion response of agricultural watersheds. The distributed parameter approach allows the user to account for spatial variability of input variables. ANSWERS also allows for selective evaluation of output within the watershed instead of being limited to the basin outlet (Donigian and Huber, 1991).

Within ANSWERS, an entire watershed is discretized into square cells within which input variables are constant. Principal inputs to the model are the rainfall hyetograph, antecedent soil moisture, and the soil, crop, and physical characteristics of each discrete cell. The model calculates amount of infiltration and then simulates surface storage, surface detention and overland flow. Soil detached from rainfall or runoff is also available for transport by overland flow. ANSWERS outputs an event hydrograph and an event sedimentgraph, from which net sediment yield may be determined (von Euw et al.. 1989).

ANSWERS has been found to be extremely sensitive to rainfall input, indicating that care must be taken for temporally and spatially variable events. The model is also sensitive to infiltration variables for small events (von Euw et al., 1989).

In a comparative study of various water quality models, Engel et al., (1993) used GRASS, linked with ANSWERS, to assess model accuracy of predicted hydrologic responses and sediment loads from single rainfall events in an 830-acre agricultural watershed near West Lafayette, Indiana. GRASS tools, written in the C programming language, were used to calculate flow direction and slope lengths from digital elevation model data, determine SCS curve number values for each ANSWERS cell, and develop soil property data layers from soil series data layers.

For four separate rainfall events, the simulated (ANSWERS) hydrologic responses were found to correlate closely with actual hydrograph responses in the watershed. Predicted sediment loads from ANSWERS, however, were significantly and consistently less than actual measured loads. This research showed that rough estimates for ANSWERS input parameters, as calculated in GRASS, were sufficient for the prediction of hydrologic response, but not for predicting sediment loads (Engel et al., 1993).

SWAT

The Soil Water and Assessment Tool (SWAT; Arnold et al., 1993) was developed as an extension to the Simulator for Water Resources in Rural Basins (SWRRB; Williams et al., 1985) at the Texas Water Resource Institute in College Station, Texas. SWAT is a continuous spatially distributed watershed model operating on a daily time step. It simulates runoff, sediment, nutrient, and pesticide movement through a watershed and aids in assessing water supplies and nonpoint source pollution in large basins (Arnold et al., 1993).

SWAT was one of the nonpoint source pollution water quality models assessed in the comparison of Engel et al. (1993). As with the ANSWERS model, input parameters were calculated in GRASS and provided to the SWAT model. SWAT estimates for total runoff and nutrient and sediment loads were less accurate than the ANSWERS simulated values.

Jacobson et al. (1995) also used a coupling of GRASS and SWAT in their evaluation of water quality impacts of diverse crops and management practices in the Herring Marsh Run Watershed in the North Carolina Coastal Plain. For this study, GRASS was used to input data for the SWAT model. The resultant monthly stream flows predicted by SWAT were seen to be adequate, but nitrate-nitrogen loading values were not.

Other Models

Other water quality models have been coupled with GIS for a variety of purposes. Kern and Stednick (1993) used Arc/Info with a metal speciation model (MINTEQA2) to develop the Chemical-Hydrologic Resource Information System (CHRIS). CHRIS was then used in the Upper Arkansas River catchment to identify heavy metal species concentrations in specified stream reaches and to associate water quality analyses with landscape elements in the basin.

The GRASS GIS has also been used extensively in combination with other water quality models. In an effort to provide for easier assessment of downstream hydrologic and sedimentation impacts, Hodge et al. (1988) linked GRASS with the ARMSED model of the U.S. Army Construction Engineering Research Laboratory (USA-CERL). ARMSED is an adapted version of the Multiple Watershed Sediment Routine (MULTSED) model, which was developed jointly by Colorado State University and New Mexico State University personnel.

Matlock et al. (1995) used GRASS as a data storage and display medium in the development of the Spatially Integrated Model for Phosphorus Loading and Erosion (SIMPLE). SIMPLE was then used to characterize nonpoint source contributions of phosphorus at a watershed scale.

Less recognized GIS programs have also been used for nonpoint source pollution modeling. Klaghofer et al. (1993) linked AGNPS and the Erosion Productivity Impact Calculator (EPIC; Williams et al., 1993) to Clark University's IDRISI GIS (Eastman, 1990) to estimate sediment and nutrient transport resultant from runoff processes. In The Netherlands, Molenaar et al. (1993) used data layers from an unnamed GIS, integrated them into a system called the Integrated River

Information System (IRIS), and used IRIS for the identification and quantification of transboundary pollutant sources and loads.

2.2 GIS-Based Nonpoint Source Pollution Models

In their investigation of alternative management strategies for reduction of sediment pollution using the combined AGNPS-Arc/Info model, Tim and Jolly (1994) refer to three potential levels of integrating GIS with hydrologic/water quality models. For the first level of integration, known as Ad-hoc integration, the GIS and the Model are developed separately and are executed independently. The GIS serves only as a pre-processor of the input data for the model. Most of the studies discussed in section 2.1 fall into this category.

The second level of integration - partial integration - is the result of establishing an interactive interface between the GIS and the model. In this level of integration, the GIS provides input data to the model, but also accepts modeling results from the model for further processing and/or presentation.

The third level of integration is typically referred to as complete integration or "modeling within GIS". For this level of integration, the functionality of the hydrologic/water quality model is implemented or programmed directly into the GIS, so that data pre-processing and analytical functions are performed under the same operating system. This level of integration is technically preferred by most modelers, but is often difficult to implement, due to incompatibilities in the data structures of the model and the GIS, or due to proprietary rights of commercial GIS software limiting the introduction of additional processing routines.

Figure 2.1 shows schematic illustrations of the three potential levels of integration for GIS and hydrologic/water quality models. This section describes some hydrologic and nonpoint source pollution modeling efforts employing either partial or complete integration with a GIS.

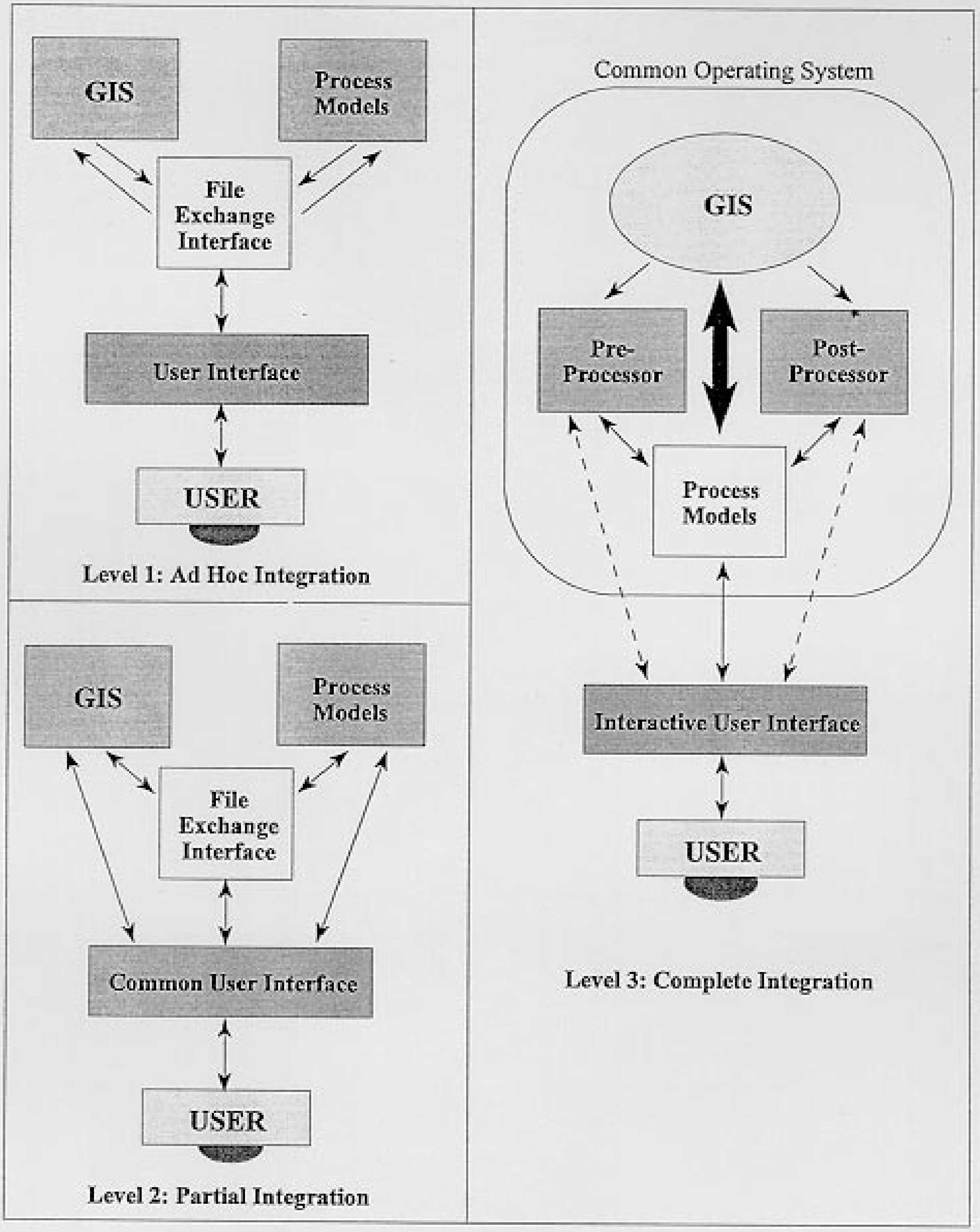

Figure 2.1 : Levels of Integration of GIS and Simulation Models
(Source: Tim and Jolly, 1994)

Partial Integration

Tim and Jolly (1994) refer to their own investigation as a partial integration of the Arc/Info GIS with AGNPS. For this study, the AGNPS input data was created in Arc/Info through manipulation of topography, hydrography, soil, land cover, land management and climate data coverages. These vector data sets were converted into raster data units corresponding to the AGNPS cell size. Once the data was provided to AGNPS and execution of the model was performed, the output was fed back into Arc/Info for subsequent analysis and presentation.

Kim and Ventura (1993) used an unnamed GIS, along with the Source Loading and Management Model (SLAMM), to identify critical areas of excessive nonpoint source pollutant loadings in the urban portion of southern Milwaukee County, Wisconsin. Contrasting with most of the studies discussed in section 2.1, most of the analytical processing in this study was performed in the GIS, with SLAMM used to estimate runoff volumes and pollutant loadings from individual rainfall events for each land use polygon in the study area. The GIS was then used to accumulate the calculated loads of phosphorus, zinc, copper, lead, cadmium, and sediment for each digitally delineated sewer sub-basin in the watershed.

Complete Integration

Stuebe and Johnston (1990) modeled rainfall runoff directly into the GRASS GIS for six watersheds in Lawrence County, South Dakota. Starting with elevation, soils, and land cover data, GRASS was used to connect the soils and land use data layers to 30-meter resolution raster map layers corresponding to the digital elevation model grid cells. The soils grid was reclassified to create a grid of hydrologic soil group values and the land use grid was reclassified to assign Soil Conservation Service (SCS) curve number values to each discrete 30-meter grid cell.

Then, using the SCS curve number model, map layers of potential abstraction and runoff from each 30-meter grid cell were established. The watersheds of the region were digitally delineated using GRASS’s internal Gwatershed program. Finally, the grid cell-based surface runoff values determined from the curve number method were accumulated throughout the digital basin to establish values of runoff at each watershed outlet point (Stuebe and Johnston, 1990).

Completely integrated GIS models of the Universal Soil Loss Equation (USLE) have also been created. Hession and Shanholtz (1988) created the Virginia Geographic Information System (VirGIS), incorporating the USLE and a sediment delivery ratio, for the estimation of potential sediment loadings to streams from agricultural lands. Separate land use-based map layers were created for rainfall erosivity factor, soil erodibility factor, slope length, cover and management factor, and conservation practice factor. Each of these parameters are components of the USLE, and a value for soil loss per unit area was determined by combining them. Sediment delivery ratio for each land use cell was also determined as a function of the relief and slope in each cell.

Potential sediment loading from each cell was determined as the product of the soil loss per unit area and the delivery ratio. Finally, a Pollution Density Index for each modeled watershed was calculated as the sum of all cell-based potential sediment loadings in the watershed divided by the number of cells there (Hession and Shanholtz, 1988).

Heidtke and Auer (1993) also modeled the USLE in a GIS developed and maintained by the Cayuga County Planning Board in Upstate New York. The GIS was used to build a matrix of land use areas, specified by soil texture and surface slope, for six sub-basins draining to Owasco Lake. The USLE was used, with the appropriate factors indexed by the soil and slope data, to calculate annual soil erosion from each sub-basin. Unit area phosphorus load from each sub-basin was determined by multiplying the annual soil erosion by typical phosphorus concentration values obtained from in situ soil chemistry measurements for each soil type. As a result of this implementation, a simple GIS-based model for prediction of annual phosphorus loads to Owasco Lake was established.

Zollweg et al. (1995) created another GIS-based phosphorus loading model for the 25.7-hectare Brown Watershed near Harrisburg, Pennsylvania. For this study, the Soil Moisture-based Runoff Model (SMoRMod) was rehosted within the GRASS GIS. SMoRMod is an event-based, distributed model of watershed processes, including infiltration, soil moisture redistribution, groundwater flows, and surface runoff. SMoRMod also accounts for variable source areas, which are defined as runoff contributing regions within a watershed that expand and contract during storm events, providing variable amounts of runoff over the length of the event (Ward, 1984).

Through use of the GRASS GIS, aerial distributions of simulated runoff and phosphorus losses were produced, allowing for the identification of zones of runoff and phosphorus production. The GRASS-hosted SMoRMod algorithm was also modified to implement various land management practices throughout the watershed. This allowed for an assessment of the phosphorus load reducing capabilities of each practice (Zollweg et al., 1995).

Newell et al. (1992) performed an assessment of nonpoint sources and loadings to the Galveston Bay in Texas, as part of a Galveston Bay National Estuary Program study. The assessment was done completely within the Arc/Info GIS and was executed for a list of 15 pollutant constituents, including heavy metals, nutrients, total suspended solids, biochemical oxygen demand, and fecal coliform. For this study, subwatersheds within the study area were manually digitized from USGS 7.5-minute quadrangle maps. Annual runoff values were then established for each subwatershed, using the GIS-modeled SCS curve number method, with precipitation, soil type, land use, and curve number data as inputs to the model. Annual runoff values were calculated for typical wet, average, and dry years.

Typical pollutant constituent loadings for all three categories of runoff were calculated by associating pollutant event mean concentrations with land use polygons in each subwatershed. For each pollutant of interest, an average weighted event mean concentration was established in each subwatershed and multiplied by the annual runoff in that subwatershed to establish total nonpoint source loads of the pollutant (Newell et al., 1992).

The nonpoint source pollution assessment method described by Newell et al. (1992) resembles the method applied in this report more closely than do the approaches of the other studies cited in this section and section 2.1.

2.3 Earlier studies in the San Antonio-Nueces Coastal Basin

The modeling efforts discussed in sections 2.1 and 2.2 represent a diverse cross-section of approaches for simulating hydrologic and water quality parameters. Those investigations also represent a wide variety of study areas where the models have been implemented. These regions are chosen for various reasons, ranging from ease of implementation at the location to availability of an abundance of measurement data with which to compare model results. Frequently, however, study areas are chosen, not for the convenience of model implementation, but because a particular hydrologic or water quality problem exists there.

Complex natural hydrologic systems that are placed under some additional manufactured or man-made burden typically encounter such problems. The Texas Intracoastal Waterway, with its elaborate network of bays, estuaries, marshes, and barrier islands, is a complex hydrologic system made more complicated by the encroachment of industry, agriculture, and shipping throughout its length. In accordance with the greater potential for the occurrence of water quality problems, many hydrologic and water quality analyses have been conducted throughout the waterway. This section focuses on water quality modeling studies that have been performed in close proximity to the San Antonio-Nueces Coastal Basin, particularly in the estuarine regions near Copano Bay, Aransas Bay, and Corpus Christi Bay.

Estuarine water quality modeling of the Corpus Christi Bay dates back to at least the mid 1970’s. In 1974, Penumalli et al. applied a model developed by the Texas Water Development Board (TWDB) called the Corpus Christi-Aransas-Copano Bay System Model. This model simulated the aerial shape of the bay network with a series of one square nautical mile grid cells (Figure 2.2). Hydraulic flow throughout the bay network was simulated using a finite difference method to model flow between cells, or segments.

For the same study, a mathematical water quality model was also created to represent conservative constituent transport between grid cells. A finite difference implementation was also employed for this model, accounting for spatial and temporal distributions of the mass concentration of a constituent (Penumalli et al., 1974).

Using these models, with boundary conditions implemented for all boundary cells in the discrete network, simulated phosphorus and nitrogen concentrations were

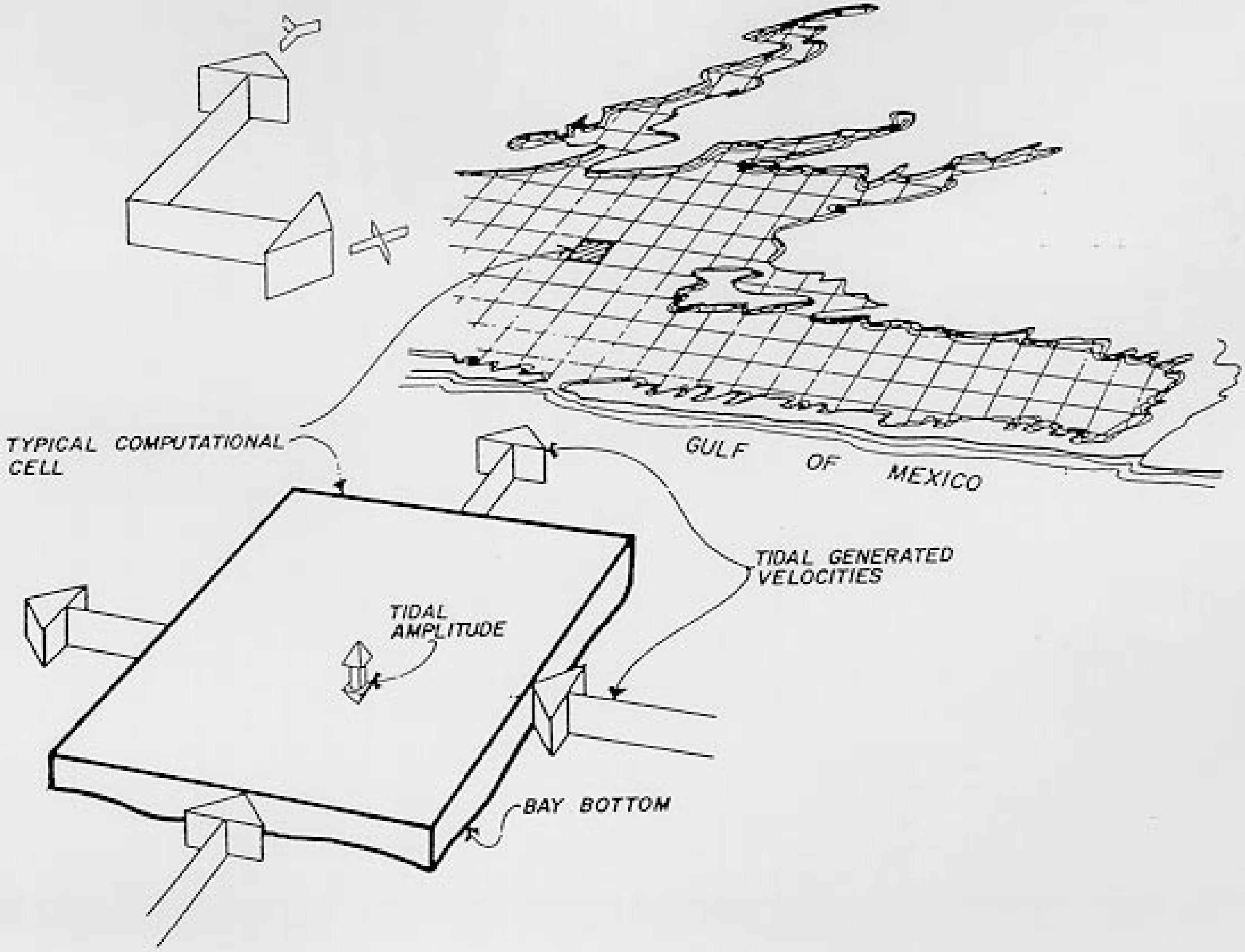

Figure 2.2 : Conceptual Illustration of Discretization of a Bay
(Source: Texas Department of Water Resources, 1981)

established for each grid cell. These concentrations were determined using estimated loadings of the nutrients for the year 1972. The results were compared with observed concentrations measured at various locations throughout the bay network and the models were adjusted for better agreement with the observed measurements. The final adjusted models were used to estimate nitrogen and phosphorus concentration profiles throughout the bay network for the years 1980 and 1990, using anticipated nutrient loadings for those years (Penumalli et al., 1974).

Lambert and Fruh (1976) used a modified version of a hydrodynamic mathematical model called HYDTID, along with a salinity transport model called LOTRAN, to help in the determination of minimum fresh water inflow requirements to Corpus Christi Bay. For the grid-cell representation of the bay, HYDTID and LOTRAN account for hydrodynamic circulation patterns, tidal effects, and vertical mixing, when provided with a varying fresh water inflow profile and a tide cycle period as inputs.

The combined HYDTID/LOTRAN model also accepts, as input parameters, aerial locations and magnitudes of return flows and diversion sources, average rainfall and gross evaporation, average wind speed and direction, aerial locations and magnitudes of excitation tides, and typical boundary condition salinity concentrations. Each of these parameters are provided as average values for a chosen time interval (typically monthly) of the model (Lambert and Fruh, 1976).

For this analysis, various model runs were performed, using monthly values of the input data parameters and fresh water inflow data from the period 1913-1962. By using the historical health profiles of certain aquatic indicator organisms local to Corpus Christi Bay for the same time period, assessments of the adequacy of the documented fresh water inflows were made. Finally, determinations of the minimum fresh water inflows required to maintain organism health were established (Lambert and Fruh, 1976).

Another study of fresh water inflows to the bay network was performed in 1981 by the Texas Department of Water Resources (TDWR). For this analysis, the TDWR used the same hydrodynamic and salinity transport mathematical models to assess the effects of fresh water inflows to the Nueces and Mission-Aransas estuaries. For the purposes of the investigation, this estuary system was defined as the portion of the Texas Intracoastal Waterway including Nueces Bay, Corpus Christi Bay, Oso Bay, Redfish Bay, Aransas Bay, Copano Bay, and Mission Bay (Figure 2.3).

Annual and monthly average values of fresh water inflows over the period from 1941 to 1976 were used as inputs to the model. Water quality of these inflows was determined by comparison with measured data from USGS gauging stations on Copano Creek, Mission River, Chiltipin Creek, Nueces River, and Oso Creek. As a result of this modeling effort, simulated salinities were generally seen to be within five parts per thousand of observed salinities. Exceedences of this value were consistently seen for the Nueces Bay area, where additional unmodeled industrial brine discharges were suspected of contributing to elevated salinities during periods of low flow (TDWR, 1981).

The TDWR study also included a fresh water inflow/salinity regression analysis in an attempt to determine mathematical relationships applicable at different points within the bay network. The regression analysis resulted in the establishment of two geometric series relationships for monthly average salinity and monthly gauged flow. Using these relationships, salinities were estimated for gauged streamflow into the Nueces Bay and Copano Bay (TDWR, 1981).

The Texas Natural Resource Conservation Commission (TNRCC) published a study of water quality in the Nueces Coastal Basins in 1994. In an effort to identify areas with a high potential risk of nonpoint source loadings, the TNRCC used Arc/Info for the establishment of a nonpoint source pollution potential index. This index was determined by considering components related to soil type, land use, and landscape features such as soil permeability, slope, and soil erodibility.

Components of the nonpoint source pollution potential index are based on the Revised Universal Soil Loss Equation (RUSLE; Renard et al., 1993). For each of the elements of this equation, a separate Arc/Info layer was created with element values assigned to the reclassified polygons from the original source map. For example, values for the soil erodibility an slope steepness layers were assigned to polygons from the initial soils map. In addition to the elements from the RUSLE, the nonpoint source pollution potential index also includes factors accounting for land use potential to permanently degrade receiving waters and land use potential to supply non-sediment related hazardous pollutants, such as pesticides or heavy metals. Separate Arc/Info layers for each of these factors were also created (TNRCC, 1994).

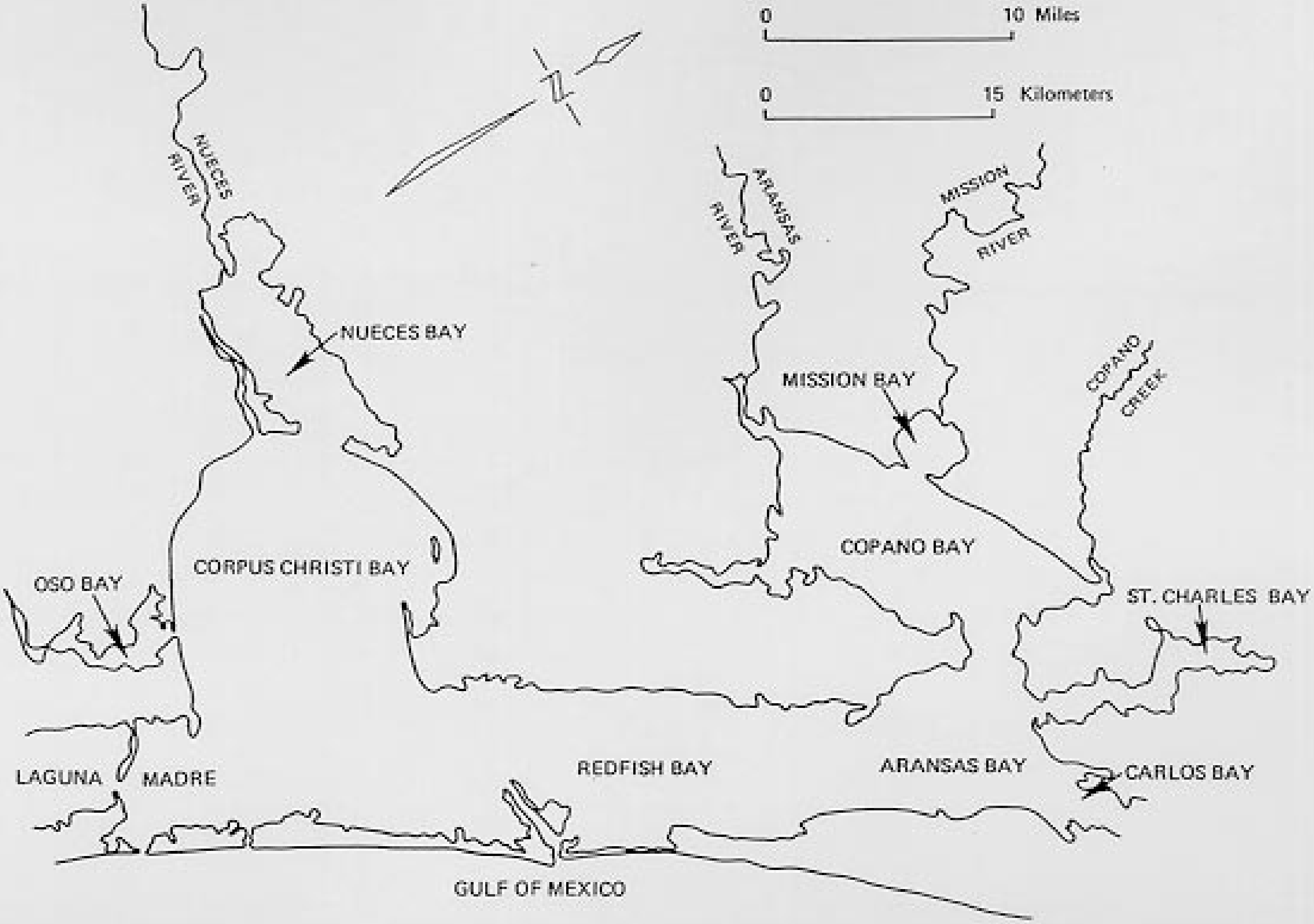

Figure 2.3 : Nueces and Mission-Aransas Estuaries (Source: Texas Department of Water Resources, 1981)

The product of the RUSLE elements and the other factors provided values for the nonpoint source pollution potential index. Through application of this index to the study areas of the San Antonio-Nueces and Nueces-Rio-Grande Coastal Basins, the TNRCC concluded that the region generally had a moderate potential for nonpoint pollutant sources, but that areas of higher potential existed for agricultural land uses in regions of maximum slope and erodible soils (TNRCC, 1994).

Most recently, Baird et al., (1996) used SWAT and HSPF in a comparison of each model's effectiveness in the assessment of nonpoint source pollution. This comparison was performed on the Oso Creek watershed in southern Nueces County, as part of a Corpus Christi Bay National Estuary Program study. Both models were calibrated for the period of 1987 through 1992, using rainfall data from three gauges in the watershed and streamflow data from the USGS Oso Creek gauge, which drains the upper 39% of the watershed.

The SWAT model was used to simulate streamflow at the Oso Creek gauge, with rainfall data from two of the three precipitation gauges used as input. Agricultural cropping profiles, along with tillage management practices for the fallow period, were also applied as inputs. As a result of this modeling effort, average annual predicted streamflow was determined to be approximately 10% less than the average observed streamflow over the period between 1987 and 1992. Predicted streamflow values for each individual year between 1986 and 1993 showed errors in excess of 80%, when compared with observed annual streamflow values (Baird et al., 1996).

HSPF was used to model both streamflow and loadings of nutrients and sediments. Model parameters were calibrated for the upper portion of the watershed and then applied to the entire watershed for the estimation of runoff and loadings to Corpus Christi Bay. Rainfall data from the most central of the three precipitation gauges was applied across the watershed. The average annual predicted streamflow calculated by HSPF was within 0.4% of the average observed value over the period from 1987 to 1992. As with the SWAT model, however, predicted stream flow values for individual years showed more significant errors of up to 68% (Baird et al., 1996).

Nutrient and sediment loadings were predicted by the HSPF model by applying expected mean concentration values to land uses in the Oso Creek watershed, determining the percentage of each land use within the watershed, calculating the corresponding percentages of the total runoff from each land use type, and multiplying the pollutant expected mean concentration values by the land use-based runoff values. This process resulted in sets of land use-based loads for each month in the eight year modeling period. Summation of the land use-based loads resulted in a total load of pollutant from the watershed. Variability of the loadings from year to year naturally corresponded to the observed variability of streamflows from year to year (Baird et al., 1996). Overall, the HSPF model was seen to be more robust and to provide more accurate results than the SWAT model.