WATERSHED MODELING NEEDS ASSESSMENT, MODELING STRATEGY, AND MODEL RECOMMENDATIONS for SWAMP AND GREEN WQA PROJECTS

March 2002

King County

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KING COUNTY WATERSHED MODELING SERVICES WORK ORDER #2 TECHNICAL MEMORANDUM

March 2002

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King County
Department of Natural Resources and Parks
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EXECUTIVE SUMMARY

Introduction

The King County Department of Natural Resources, Water and Land Resources Division has retained AQUA TERRA Consultants to provide services to develop watershed water quantity and quality analysis models for the Sammamish-Washington Analysis and Modeling Program (SWAMP) and the Green-Duwamish Water Quality Assessment (Green WQA). The overall goal of both SWAMP and Green WQA projects is to provide the clients of the project team timely and scientifically justifiable water quantity and quality information for resource protection and for meeting the requirements of growth management and environmental legislation.

Modeling Purposes

The primary purpose of the watershed water quality and quantity models is to support the Green WQA and SWAMP teams by simulating surface and subsurface flow and associated physical, chemical, and biologic loads to the major receiving waters: the Green River and Duwamish Estuary for the Green WQA and the lakes for the SWAMP. These models will help to assess potential impacts of a range of future land use and infrastructure scenarios. Additional purposes of these models are to provide a general tool for watershed analysis, management and educational outreach components of SWAMP and Green WQA, King County's ESA response, aquatic resource protection, stormwater management programs, and ecological and human health risk assessment.

Model Selection

The model selection process was based on the needs of the watershed model applications required for SWAMP and Green WQA. Appropriate model selection criteria were established and used to evaluate a wide range of watershed models. Information from this process and other sources was used to short-list three candidate models: DHSVM (combined with a water quality model or algorithms), HSPF (and related modeling systems), and MIKE SHE.

Modeling Strategy

Three water quality modeling strategies were outlined. The three strategies reflect a range of monitoring data efforts from low to high to support a particular watershed model application. A strategy with low data requirements (Package 1) is implementable with currently existing data. A medium data requirement strategy (Package 2) requires a moderate amount of modification and augmentation of the current monitoring program. At the upper end is a high data requirement strategy (Package 3) that is based on significant modification and enhancement of the monitoring program to meet the needs of the associated level of modeling.

Recommendations

Based on the information provided in this report, we recommend the use of HSPF together with the medium modeling/data strategy to best meet King County's needs within its budget and time constraints. The development of a simulation plan is

recommended to implement the selected modeling strategy and provide a framework for the water quantity and quality modeling work.

1 INTRODUCTION

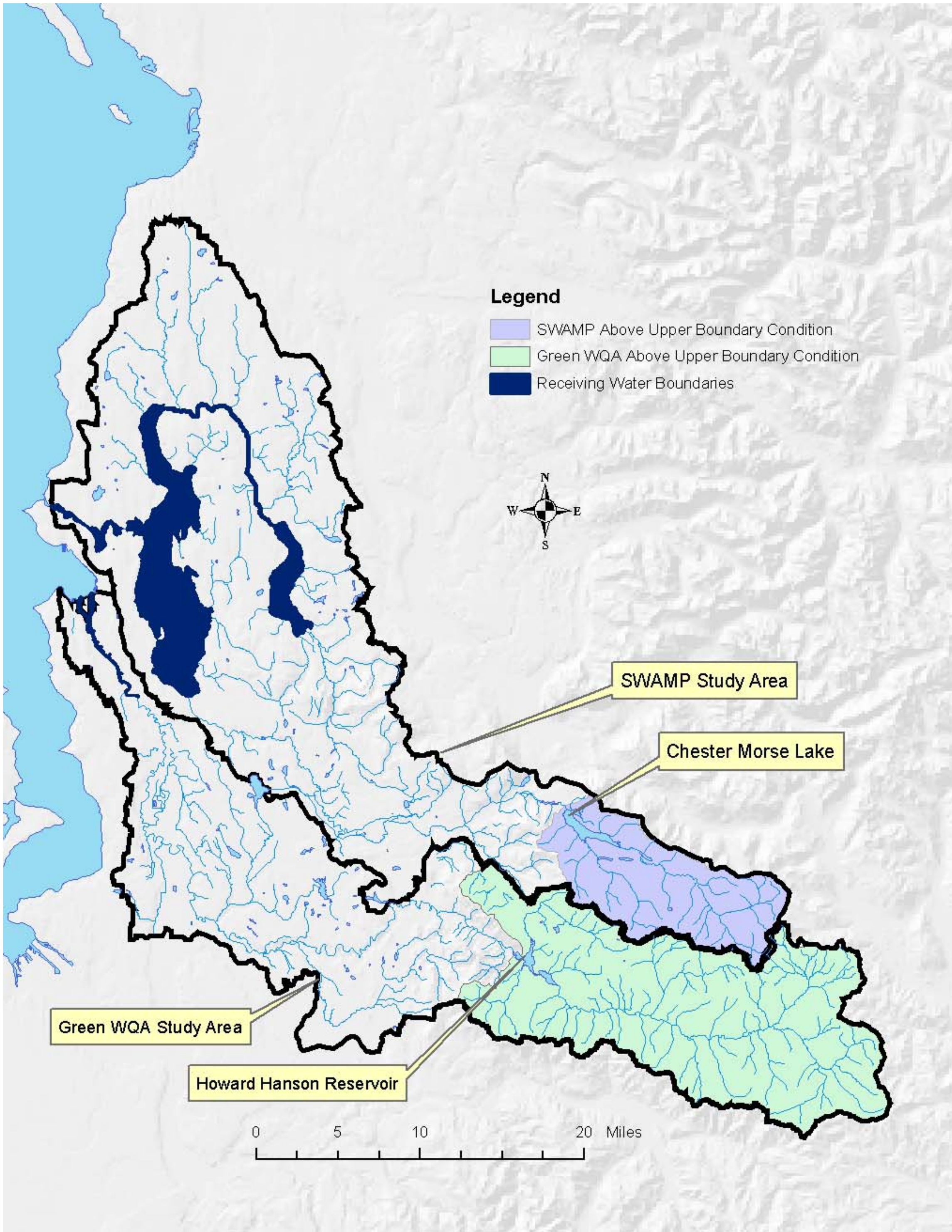
The King County Department of Natural Resources, Water and Land Resources Division has retained AQUA TERRA Consultants to provide water resources modeling services to develop watershed water quantity and quality analysis models for two topographic basins – the Green-Duwamish and the Lake Washington-Ship Canal watersheds (see Figure 1.1). These models will support the two major projects, the Green-Duwamish Water Quality Assessment (Green WQA) and the Sammamish-Washington Analysis and Modeling Program (SWAMP). They will be integrated components of an overall modeling system of both watersheds and major receiving water processes including hydrodynamics, water quality, and bio-dynamics within the Duwamish River and Lakes Sammamish, Washington, and Union.

The primary purpose of the watershed water quality and quantity models are to support the Green WQA and SWAMP teams by simulating at a tributary level, surface and subsurface flow and associated physical, chemical, and biologic loads to major receiving waters - the Green River (excluding areas above the Tacoma Public Works Division) and Duwamish Estuary for the Green WQA and the lakes for the SWAMP under a range of land use and infrastructure scenarios. Additional purposes of these models are to provide a general tool for watershed analysis, management and educational outreach components of SWAMP and Green WQA, King County's Endangered Species Act (ESA) response, TMDL determinations, groundwater-surface water assessments, aquatic resource protection, stormwater management programs, and ecological and human health risk assessment.

The watershed modeling services are being accomplished cooperatively by King County staff and AQUA TERRA Consultants through an on-call services arrangement through the issuance and completion of various work orders.

This technical memo covers the Work Order Number S-2 & G-2: Needs Assessment, Modeling Strategy, and Model Recommendation. This work order provides direction for completion of tasks for both SWAMP and Green WQA associated with model selection, modeling strategy, and model options development pursuant to the requirements and strategies for each of the projects.

Figure 1.1 SWAMP and Green WQA Study Areas



1.1 Purpose and Scope

The primary purpose of this work order is to create products that provide a foundation, documentation, and process that will result in timely selection of watershed modeling strategies for each project that are both appropriately coordinated and customized.

A second purpose is to develop strategies, protocols, and timelines for coordination and cooperation of watershed modeling work with separate but related project components currently underway in other organizations and agencies.

Key work order elements are:

- Review of Modeling Needs for both SWAMP and Green WQA projects
- Strategic Review of Modeling Approaches
- Development and Detailing of Modeling Alternatives
- Coordination/Cooperation Strategy

1.2 Report Structure

The report contains the following additional sections:

Section 2 summarises the modeling needs for the SWAMP and Green WQA projects.

Section 3 presents the water quantity and quality data available in the SWAMP and Green WQA study areas and discusses model data needs.

Section 4 identifies a range of different watershed model types that are potentially applicable to meet the SWAMP and Green WQA project needs, goals, and objectives. A short-list of acceptable models for the SWAMP and Green WQA study areas is presented.

Section 5 details the relationship of modeling alternatives to data availability and current monitoring program, and recommends a preferred modeling plan.

Section 6 gives a proposed modeling implementation plan which encompasses the scope, feasibility, protocol and schedule for cooperation among various project components and parties.

Section 7 provides a summary of the model needs, approaches, alternative strategies, and coordination and cooperation issues.

1.3 Definitions

Prior to reviewing watershed needs and modeling approaches it is important to define some terms that are used in this report.

Watershed Model: a computer software program that simulates the conversion of rainfall to runoff and may include water quality and streamflow routing components. The routing algorithms for both water quantity and quality are instream processes. HSPF, MIKE SHE, and DHSVM are watershed models.

Receiving Water Model: a computer software program that simulates dynamic movement of water and water quality constituents in a major river, lake, or estuary. EFDC, CH3D-ICM, and CE-QUAL-W2 are receiving water models. It is expected that all of the lakes will use CH3D-ICM. The Sammamish River will use CE-QUAL-W2 and the Duwamish/Lower Green will use EFDC, based on information provided by King County staff.

Boundary Conditions: input to a model at a space and/or time boundary. Watershed models provide water quantity and water quality input to receiving water models at the inflow boundaries to the major rivers (Sammamish, Green, and Duwamish) and lakes (Lake Sammamish, Lake Washington, and Lake Union).

2 REVIEW OF WATERSHED MODELING NEEDS

The purpose of the watershed modeling needs assessment is to provide review, refinement, clarification, and summarization of modeling needs with regard to what, when, where, how, and why water quality and quantity parameters need to be modeled in each watershed. The results of the needs assessment provides the assessment of requirements to help define the modeling goals, objectives, and schedule, and to recommend needed adjustments to the project team.

2.1 Project Goals and Objectives

2.1.1 Goals

The overall goal of both SWAMP and Green WQA projects is to provide the clients of the project team, both internal and external, timely and scientifically justifiable water quantity and quality information for resource protection and with respect to the requirements of growth management and environmental legislation.

Water quantity and quality information are obtained through a mixture and collaboration of monitoring and modeling activities for the watersheds in the SWAMP and Green WQA study areas. The results of these activities are then used to assess the impacts of land use and legislative changes on King County land and water resources.

The evaluation of land use changes is done through model representation of different land use configurations or scenarios that can be represented in an appropriate watershed model. Mitigation strategies can be evaluated and then initiated through the legislative process.

Development of an appropriate watershed model that meets King County's needs and provides timely answers requires a broad range of expertise from land use to hydrology to water quality specialists. Close coordination with researchers at the University of Washington together with other leading experts in these fields maximizes King County's ability to achieve these goals and objectives.

2.1.2 Objectives

The primary objective of the SWAMP and Green WQA is to assist wastewater capital planning, habitat conservation planning, and salmon recovery and watershed planning efforts by collecting information, developing a set of scientific tools to better understand the Sammamish/Washington and Green watershed systems, and using the tools to evaluate resource management options. These tools and information make use of water and sediment quality monitoring results, and water quality and quantity modeling to provide input to the ecological and human health risk assessments, and habitat and biological assessments. The models also will be used to support development of Total Daily Maximum Loads (TMDLs) required by the Clean Water Act.

2.2 Watershed Modeling Goals and Objectives

The watershed modeling goals and objectives are a subset of the project goals and objectives described above. The goal of the watershed water quality and quantity modeling is to support the SWAMP and Green WQA teams in meeting the water quality assessment needs from various on-going and anticipated future programs mentioned above. It is to be accomplished by filling a subset of the void of measured data and analysis through interpolations and extrapolations of measured data (i.e., model calculations) following model calibration to available measured data. For example, a synthetic dataset will be generated by performing a watershed model simulation at a tributary level, producing surface and subsurface flow and associated physical, chemical, and biologic loads to major receiving waters under a range of land use and infrastructure scenarios.

Additional purposes of watershed modeling are to provide a general tool for watershed analysis, management and educational outreach, King County's ESA-response, aquatic resource protection, stormwater management programs, and ecological and human health risk assessment.

2.2.1 General Objectives

A complete understanding of the watershed model objectives is important in assessing the needs of the Green WQA and SWAMP projects. These objectives are multi-disciplinary and multi-directional. For habitat conservation planning requirements there is the objective of maintaining appropriate flows for fish. For King County's Clean Water Act NPDES permit there is the objective of maintaining or improving water quality of the streams, rivers, and lakes of King County. For the Growth Management Act there is the objective of providing appropriate water supplies to urban areas and providing the stormwater control infrastructure for new land development and growth.

Another important objective is to satisfy the needs for the boundary conditions with upstream inflows and downstream receiving water models. Both the Green WQA and SWAMP study areas have upstream and downstream boundary conditions that will play a role in the assessment and selection of an appropriate model. The Green WQA has an upstream boundary condition on the Green River at the City of Tacoma Public Utility Diversion. The river flow, and associated water quality, becomes the inflow to the Green River model. The availability of water quality data for this flow was important to assess. The same situation is true for the upstream boundary condition on the Cedar River at the City of Seattle's Landsburg Dam. The downstream boundary conditions define where the watershed model will need to provide information to the receiving water models. For the Green WQA this is near the I-405 crossing of the Duwamish River plus tributary inflows from the Longfellow and Hamm watersheds and other direct drainages to the Duwamish River Estuary. The assessment includes the data requirements of the EFDC model at this location. The downstream boundary condition for the SWAMP study area is the Lake Washington Ship Canal, the Sammamish River, plus the direct drainage to

Lake Sammamish, Lake Washington, and Lake Union. At the inflow locations to these water bodies we have assessed the needs of the CH3D-ICM model, as it relates to the watershed quantity and quality models.

These assessments provide critical information in the formulation of the water quantity and quality modeling strategy (Section 5).

2.3 Watershed Modeling Applications and Clients

King County watershed modeling needs are derived from a number of urban development, environmental legislation, and management programs or plans. These programs and plans can be thought of as clients for obtaining information from the watershed modeling program. Following are brief descriptions of these clients.

2.3.1 Wastewater Program (WTD)

The major sponsor of the SWAMP and Green WQA projects is the King County Wastewater Treatment Division (WTD) (formerly Metro) of King County Department of Natural Resources. WTD projects, such as Brightwater Wastewater Treatment Plant (WTP) Siting Planning, Combined Sewer Overflow (CSO) Control Study, CSO Water Quality Assessment Study, Infiltration and Inflow Control Study, and Sediment Study in the Duwamish basin, all require some kind of water quality monitoring and assessment to establish environmental baseline conditions, assess water quality impacts and human health and ecological risk potentials, and identify mitigation options.

2.3.2 Administration of the NPDES Permit Program

Water pollution degrades surface waters making them unsafe for drinking, fishing, swimming, and other activities. As authorized by the Clean Water Act, the National Pollutant Discharge Elimination System (NPDES) permit program controls water pollution by regulating point sources that discharge pollutants into waters of the United States. Point sources such as King County WTP outfall discharge are subject to NPDES permit requirements.

In 1987, Congress changed the federal Clean Water Act by declaring the discharge of stormwater (traditionally considered a nonpoint source) from certain industries and municipalities to be a point source of pollution requiring NPDES permits. The State of Washington is delegated authority by the U.S. Environmental Protection Agency (EPA) to implement the NPDES water quality permit.

The EPA stormwater regulations establish two phases for the stormwater permit program. Phase I stormwater NPDES permits have been issued to cover stormwater discharges from certain industries, construction sites involving five or more acres, and municipalities with a population of more than 100,000.

King County is one of seven public entities in Washington that are covered under Phase I Municipal Stormwater NPDES permits. The municipal stormwater permits require the implementation of a Stormwater Management Program. The Stormwater Management Program is a plan for the term of the permit to reduce the discharge of pollutants, reduce impacts to receiving waters, eliminate illicit discharges, and make progress towards compliance with surface water, ground water, and sediment standards.

2.3.3 Habitat Conservation Plans (HCPs)

The National Marine Fisheries Services (NMFS) and the U.S. Fish and Wildlife Service (USFWS) listed Puget Sound chinook salmon and coastal and Puget Sound bull trout as "threatened" species under the Endangered Species Act in 1999. Soon after their listing, these agencies will prohibit the *take* of these species (i.e., killing or harming them, including degradation of their essential habitat), though this is not guaranteed. The *take* prohibitions are already in effect for the listed species, unless an operation or entity has an "incidental take permit."

The King County WTD is preparing an HCP to obtain an incidental take permit for chinook salmon and other species under the Endangered Species Act. The permit will cover discharge, operations, construction, and maintenance related to the regional collection and treatment of wastewater. The WTD's North Treatment Facility (NTF) Team is beginning a multiyear process to site and construct a wastewater treatment plant and an outfall in northern King County or southern Snohomish County. The NTF team is working on the programmatic environmental impact statement (EIS) for this project that will document the selection of a preferred treatment plant location and system configuration. It is anticipated that the Cedar River-Lake Washington watershed model will support the analysis of impacts to aquatic resources related to construction and operation of the new plant such as high flow bypass and emergency overflows.

2.3.4 Salmon Recovery and Conservation Plans

The Washington Department of Fish and Wildlife and Treaty Indian tribes co-manage the state's salmon populations, and are joining with the National Marine Fisheries Service and U.S. Fish and Wildlife Service to define recovery goals for listed stocks. King County is making a long-term commitment to salmon recovery and conservation in both WRIA8 (Lake Washington/Cedar River/Sammamish Watersheds) and WRIA9 (Green-Duwamish Watershed). The effort includes identifying, evaluating, and prioritizing actions to protect and restore salmon populations, especially actions related to habitat. The WRIA salmon recovery and conservation plan is based on future monitoring.

2.3.5 Total Maximum Daily Load (TMDL)

The Clean Water Act requires states to identify waters not meeting water quality standards and to develop plans for cleaning them up. The framework for these plans is the Total Maximum Daily Load (TMDL) program. A TMDL is essentially a prescription

designed to restore the health of the polluted body of water by indicating the amount of pollutants that may be discharged to the water body and still meet water quality standards.

In accordance with Section 303(d) of the federal Clean Water Act, every four years each state must identify its polluted water bodies and submit this list to EPA. These are water quality limited estuaries, lakes, and streams that fall short of state surface water quality standards, and are not expected to improve within the next four years.

EPA requires the states to set priorities for cleaning up threatened waters and to establish a Total Maximum Daily Load (TMDL) for each. A TMDL, or water cleanup plan, entails an analysis of how much pollution a water body can assimilate and still remain healthy for its intended uses. The cleanup plan also includes recommendations for controlling the pollution and a monitoring plan to test the plan's effectiveness.

Washington State Department of Ecology (WDOE) has tentatively chosen a list of priority water bodies for water cleanup planning. The water bodies in SWAMP and Green WQA study areas that are on the list are shown in Table 2.1. The TMDL plan tells which quality standards each water body exceeds, and by how much. The primary water quality problems in the two basins are fecal coliform and water temperature. Other cited problem water quality parameters are pH, dissolved oxygen, total phosphorus, heavy metals, pesticides, and other volatile organic compounds.

Table 2.1 TMDL Priority List for SWAMP and Green WQA Study Areas

WRIA	Name of Water Body	Constituent
8	BEAR-EVANS CREEKS	Fecal Coliform, Mercury
8	CEDAR RIVER	Fecal Coliform
8	COAL CREEK	Fecal Coliform
8	COTTAGE LAKE	Total Phosphorus
8	EDEN (ETON) CREEK	Fecal Coliform
8	FAIRWEATHER BAY CREEK	Fecal Coliform
8	FORBES CREEK	Fecal Coliform
8	GREEN LAKE	Total Phosphorus
8	ISSAQUAH CREEK	Temperature, Fecal Coliform
8	JUANITA CREEK	Fecal Coliform
8	KELSEY CREEK	Fecal Coliform, Dieldrin, Heptachlor Epoxide, DDT
8	LAUGHING JACOB'S CREEK	Fecal Coliform
8	LEWIS CREEK	Fecal coliform
8	LITTLE BEAR CREEK	Fecal Coliform
8	LYON CREEK	Fecal Coliform
8	MARTHA LAKE	Total Phosphorus
8	MAY CREEK	Zinc, Lead, Fecal Coliform, Temperature
8	McALEER CREEK	Fecal Coliform
8	MERCER SLOUGH	Fecal Coliform, Dissolved Oxygen
8	MULLEN SLOUGH	Fecal Coliform, Temperature, Dissolved Oxygen
8	NORMA CREEK	Fecal Coliform
8	NORTH CREEK	Dissolved Oxygen, Fecal Coliform
8	PINE LAKE CREEK	Fecal Coliform
8	SAMMAMISH LAKE	Fecal Coliform, Temperature, pH
8	SCRIBER LAKE	Total Phosphorus
8	SILVER LAKE	Fecal Coliform

8	SWAMP CREEK	Dissolved Oxygen, Fecal Coliform
8	THORNTON CREEK	Fecal Coliform
8	TIBBETTS CREEK	Fecal Coliform
8	UNION LAKE / LAKE WASHINGTON SHIP CANAL	Dieldrin
8	WASHINGTON LAKE	Fecal Coliform
8	YARROW BAY CREEK	Fecal Coliform
9	COLD SPRINGS CREEK	Fecal Coliform
9	CRISP CREEK	Fecal Coliform
9	DES MOINES CREEK	Fecal Coliform
9	DUWAMISH WATERWAY AND RIVER	pH, Fecal Coliform, Benz(a)anthracene, PCB-1254, Total PCBs, Dissolved Oxygen, Fluoranthene, Acenaphthene, Dibenz(a,h)anthracene, Butylbenzyl phthalate, lead, copper, Chrysene, Anthracene, Phenanthrene, Benzo(ghi)perylene, Indeno(1,2,3-cd)pyrene, Dibenzofuran, Fluorene, Mercury, Phenol, Benzoic acid, Dimethl phthalate, Cadmium, Bis(2-ethylhesyl)phthalate, Zinc, Arsenic, Silver, Acenaphthene, 1,4-Dichlorobenzene, Copper, 2-Methylnaphthalene, Dibenz(a,h)anthracene, dibenxofuran, 1,2,4-Trichlorobenzene, PCB-1260
9	GALE CREEK	Temperature
9	GREEN RIVER	Temperature, Fecal Coliform, Mercury
9	HICKS (GARRETT) LAKE	Total Phosphorus, Fecal Coliform
9	HILL (MILL) CREEK	Fecal Coliform, Temperature, Dissolved Oxygen
9	JOE'S CREEK	Fecal Coliform
9	LAKOTA CREEK	Fecal Coliform
9	LONGFELLOW CREEK	Fecal Coliform
9	MERIDIAN LAKE	Total Phosphorus, Fecal Coliform
9	NEWAUKUM CREEK	Fecal Coliform, Dissolved Oxygen, Ammonia-N
9	SMAY CREEK	Temperature
9	SOOS CREEK SYSTEM	Fecal Coliform, Dissolved Oxygen, Temperature
9	SPRINGBROOK (MILL) CREEK	Fecal Coliform, Dissolved Oxygen, Chromium, Cadmium, Fecal Coliform, Mercury, Temperature, Zinc, Copper
9	UNNAMED CREEK WDF# 09.0046	Dissolved Oxygen

(Source: King County DNR SWAMP and Green WQA FTP.)

2.3.6 UPD Monitoring Program

The state Growth Management Act (GMA), passed in 1990, promotes smart growth by requiring cities and counties to adopt growth management plans and regulations. It also requires that communities contain urban-style development within designated urban growth areas (UGAs), protecting rural and resource lands from inappropriate sprawl development.

The construction of Urban Planned Development (UPD) projects will be ongoing for future years. Because of public concern, extensive data will be needed to document any ecological degradation that may occur. There is a monitoring plan currently in place for each UPD that covers a wide range of concerns including hydrology, water quality, habitat quality of the wetlands and streams, and potential geomorphic changes in the streams as a result of altered hydrology. A watershed model is often used as a cost-effective means to supplement the monitoring program to simulate ecological changes that result from urbanization, and also provides a tool to evaluate the effectiveness of current best management practices on a large scale.

2.3.7 Urban Water Supply Plan (Water Resources Planning)

Reclaimed water could provide a major new source of water for the SWAMP and Green WQA region. The amended Metropolitan King County Regional Wastewater Sewer Plan calls for developing a comprehensive water reuse program instead of a case-by-case approach, accelerates its implementation, and increases its flexibility to better meet the needs of the region. This will assist King County in surmounting three major challenges for water resource management:

- Providing sufficient, high quality water for people (Growth Management Act)
- Providing sufficient water of suitable quality for fish (Endangered Species Act)
- Responding to GMA and ESA in a way that results in the most efficient use of water.

Again, the watershed modeling program will be adopted in conjunction with the monitoring program to simulate the environmental impacts due to reclaimed water use.

2.3.8 Watershed Resource Inventory Area (WRIA) Planning

Two legislative acts are implemented on a WRIA watershed basis. HB 2512 (Watershed Management Act) was enacted to provide "a more thorough and cooperative" process for assessing the status of water resources in each WRIA. It is intended to enable local development of watershed plans for managing water resources and protecting existing water rights. In support of this legislation, watershed modeling can be used to assist local entities in water supply and potential instream flow decision making mainly from a water allocation perspective. HB 2496 (Salmon Recovery Act) was enacted in support of the Endangered Species Act (ESA) toward salmon habitat restoration and salmon recovery (see Section 2.3.4).

King County is currently involved in regional planning for salmon recovery in connection with other jurisdictions in WRIA 7, 8, and 9. Watershed modeling will be used to evaluate and prioritize proposed actions for salmon recovery.

2.3.9 Groundwater Management Program

Groundwater is threatened by several common human activities. As we develop our watersheds and increase paved surfaces, water that used to soak into the ground to replenish groundwater is instead diverted into storm drains. Besides being depleted, groundwater can be contaminated by landfills, septic systems, underground fuel tanks, and various land use activities (e.g. agriculture). Groundwater quality is also sensitive to the measures applied by the future water reuse program.

King County is developing a program to protect both the quality and quantity of the groundwater resources. The first step is a Comprehensive Groundwater Management Plan. The program is based on plans in five Groundwater Management Areas (GWMAs). Four of the five GWMAs are located in the SWAMP and Green WQA watersheds.

The GWMA Plans each include:

- Area Characterization: describe the geography, local jurisdictions, geology, and hydrogeology
- Management Strategies: outlines what can be done to protect the groundwater
- Implementation Process: describes how the program should work

The plans have been certified by WSDOE, and the program will be implemented on a county-wide basis. The watershed modeling tool will be used to establish the baseline and future flow and water quality conditions.

Specific modeling needs are addressed in the following sections. These include model types, time and spatial scales, and modeling parameters.

2.4 Watershed Modeling Needs

Watershed model applications generally are comprised of two integrated components:

1. Land activities and processes to produce water quality loadings (load modeling)
2. Routing transportation and transformation processes (instream water quality modeling)

The load modeling includes both point sources and nonpoint sources, which often occur as a result of human activities. Point source loading data have been compiled to meet federal Clean Water Act requirements. As a consequence, the nonpoint source loads are the main focus of the watershed modeling applications. Together the point and the nonpoint loads are the total loadings to the receiving water bodies. Watershed models generally include both components in order to represent the critical link between pollutant sources and instream water quality conditions.

These modeling applications can be further grouped by the modeling constituents as shown below:

- flow or hydrological modeling (storm-runoff and flow routing)
- physical parameters (temperature and sediment)
- chemical constituents (dissolved oxygen, nutrients, metals, and organics)
- biological parameters (bacteria and algae)

The data needs for modeling have been compared with the available database. Data gaps have been identified and determined whether or not they could be feasibly filled. Other important modeling needs include the selection of modeling time scales, land use representation (since the land use or land cover is an important component of watershed models) and internal and external coordination and cooperation for data transfers. The time scale needs include: the choice of steady state vs. dynamic model, and the necessary modeling time resolution in order to adequately represent watershed processes, and to capture water quality changes. The land use representation considers the spatial scale

(size of the watershed model components), and the issue of heterogeneous vs. homogeneous land use within the catchment.

The primary needs for developing a watershed modeling strategy for the SWAMP and Green WQA projects are:

- Selection of watershed models to meet the above modeling objectives
- Data assessment for model calibration and validation
- Land use simulation/representation strategy, and
- Coordination and cooperation for data transfer

A discussion of each of these needs is presented below.

2.4.1 Watershed Model Selection

In addition to meeting the various modeling objectives (see Section 2.5), other model selection considerations include:

- Model segmentation (catchment vs. grid-based)
- Input data set-up (explicit vs. implicit)
- Pre- and post-processor availability
- Run–time requirements
- Data management requirements
- Land use representation
- Conveyance system (open, existing, mitigation measures) representation

Water quality loading is commonly computed by one of three different methods:

1. multiplying measured flow data and measured water quality concentration data,
2. using a combination of modeling and observed data; using a hydrological model to simulate the flow (in lieu of gaged streamflows) and multiplying it by observed concentration data, or
3. using a model to simulate both flow and concentration after calibration to observed data.

King County is currently using method 2 to generate the nonpoint loads. King County uses HSPF to generate a time series of streamflow, with water quality concentration data obtained from past monitoring (for example, nutrient concentration data for SWAMP was obtained from a statistical analysis of measured nutrient data (Brett, 2001)). The same method is used to derive the sediment load in the Green River as the boundary condition for the Duwamish Model.

During the model selection process, it is important to address whether the watershed model or a receiving water model is used to simulate the pollutant transport and fate. Receiving water models have already been selected for Lake Washington, the Sammamish River, Duwamish Estuary and Elliott Bay. No decision has been made for Lake Sammamish, the Green River, and urban creeks such as Longfellow and Hamm.

2.4.2 Data for Model Calibration and Validation

In conjunction with the model selection, it is important to assess the data needs for model calibration and validation, and statistical model formulation purposes. It is essential to develop a strategy of matching the available data with the selected model or vice versa.

An accessible database of flow, land use related nutrient loading factors, suspended sediment, contaminant factors, etc., needs to be evaluated and data gaps identified for each of the modeling parameters. The data gap analysis leads to the development of suitable sampling schemes and schedule. For example, there is a potential data gap in modeling pollutant loads with respect to different land uses in urban watersheds such as Longfellow Creek, and water quality concentration in river reaches of the Green River (see Section 3.3.3).

2.4.3 Land Use Modeling Strategy

Pollutant loads correlate closely with land use and land cover. The costs to monitor pollutant changes resulting from land use changes are very high and often are not feasible. Therefore, it is useful to develop a land use modeling strategy so that pollutant loads can be accurately represented by watershed models under various land use scenarios. Models with sensitivity to land use changes (in a basin containing a wide range of land uses/land covers) is a critical need for the SWAMP and Green WQA.

UrbanSim, an existing urban simulation model developed for the Puget Sound metropolitan area by the University of Washington under the Puget Sound Regional Synthesis Model (PRISM) program, is being enhanced to include the ability to model the ecosystem effects evolving from land use changes in an urbanizing watershed. Evaluation of UrbanSim's role in this work is required prior to possibly using this land use model in the selection of future land use scenarios for the SWAMP and Green WQA projects.

2.4.4 Cooperation and Coordination

One of the goals of the SWAMP and Green WQA projects is to include the involvement of a broad range of expertise from land use to hydrology to water quality specialists. This will require the cooperation of many experts. The watershed modeling will need to take advantage of close coordination and cooperation of these experts from various institutions and consulting companies as well as King County staff.

2.5 <u>Specific Water Quality Modeling Objectives</u>

Specific water quality modeling objectives require water quality modeling of specific constituents including bacteria, metals, water temperature, dissolved oxygen, and sediment. Brief descriptions of each and its associated objectives follow.

Bacteria

Bacterial contamination results from agricultural operations such as large concentrations of animals and application of manure to cropland. It also occurs as the result of improper sewer connections, failing septic systems, failures of sanitary sewers, CSOs, and from wildlife such as birds and mammals.

One of the objectives is to estimate loads of bacteria that are occurring from specific subbasins in the watershed, particularly those subbasins that are listed under the 303(d) program. Since most bacterial sources are considered to be nonpoint, the bacterial loading will be parameterized by model land use. Therefore, once the model is calibrated, the model will also be able to provide estimates of loading for each land use type in the model. Furthermore, alternative scenario runs of the model can be designed to determine the impacts (i.e., the change in bacterial loadings) of the changed land use that occur as a result of development and growth.

Another objective is to evaluate the effectiveness of alternative abatement measures on bacterial loadings. In order to predict these impacts, the model must be adjusted to reflect the nature of the abatement measure and rerun. For some measures, this could be accomplished by reducing the loading rate from a land use in a subbasin by a simple factor, representing the fraction of animals removed, or the fraction of septic systems that have been repaired or converted to sanitary sewers, or the amount of CSO that has been eliminated.

Once a model is calibrated, and it is accurately predicting bacterial concentrations under baseline and storm conditions, it provides a tool for studying the duration and location of elevated bacterial concentrations. In this way, the model can serve as a replacement for resource-intensive monitoring programs that would require measurements at a high frequency over long time and spatial extents.

Metals

Metal contamination results primarily from nonpoint sources (residential development) and point sources (industrial). One of the main objectives of the model development is to provide estimates of peak and mean concentrations of key metals for comparison with acute and chronic levels, respectively, for various species of fish. A model calibrated to baseline and storm conditions can be used to make these estimates for specific locations, times, and conditions, and is much more cost effective than detailed monitoring.

Another objective is to determine the impacts of future growth, based on land use changes. As was described above for bacteria, a calibrated water quality model in which contaminant loading is based primarily on land use can be used to estimate the loading from various land uses. Furthermore land use changes can be implemented in the model to study the impacts of the changes that occur as a result of development. Similarly, abatement measures can be studied by changing the model parameters and loading factors to reflect the known effects of the measures.

Water Temperature

Since one of the principal concerns is to maintain/restore the viability of salmonids spawning, incubation and rearing, analysis of water temperature is a key objective for the model development. Water temperatures are negatively impacted by many activities, including development, which results in elevated temperature of runoff from impervious surfaces, removal of riparian vegetation, application of reuse water, and the operation of the dams for water supply and flood control.

The main objective of the modeling is to estimate peak temperatures at various locations under different climatic conditions, specifically average conditions and drought conditions. Once the model is calibrated to a time period that contains average and drought conditions, detailed analysis of the model output can be focused on the average and drought periods to provide peak temperatures. Similarly, since model results are in the form of long time series, the temperatures can be analyzed for frequency, duration and timing at any location, and for critical time periods or seasons (e.g., spawning).

The temperature model should be designed to be sensitive to estimates of streamside vegetation, which are implemented as shading factors and adjustments to the radiation inputs of heat. This would allow analysis of the impacts of changing the amount of vegetation. It should be possible to analyze the effectiveness of other abatement measures by changing model parameters to reflect the impact of the measure. For example, a reduction of impervious surface in the model should reduce the temperature and volume of runoff, and result in lower instream temperatures. The temperature model will also need to be designed to incorporate the effects of groundwater in order to address the issue of water reuse (with elevated temperature in the treated water).

<u>Dissolved Oxygen</u>

The objectives for dissolved oxygen are similar to those for temperature, since reduced dissolved oxygen levels are detrimental to the health of salmonid populations. However, dissolved oxygen is generally impacted by different processes than those that impact water temperature. DO levels are most heavily impacted where agriculture and failing septic systems result in runoff of nitrogen wastes that decay and consume oxygen. Nutrients also contribute to algal blooms, which result in lower DO levels from algal respiration and decay of algal material. The objectives of the modeling are: 1) to estimate DO levels at various locations under different climatic conditions, e.g., average conditions and drought conditions, 2) estimate frequency, duration and timing of lower DO levels, and 3) evaluate the effectiveness of abatement measures. As discussed for other constituents, these objectives can be met by development of a calibrated water quality model which is sensitive to the significant loadings of DO-affecting materials, and which is based on a continuous simulation structure and is driven by climatic variables.

<u>Altered Hydrology</u>

Altered hydrology includes all aspects of urbanization and water management (water extraction, irrigation/consumptive use, and export via sanitary sewers) plus dam operation of release flow patterns.

The main hydrological impact of urbanization is the change in runoff that produces higher peak flows and lower base flows. These impacts are analyzed by modifying the land use in the model and observing the altered hydrology (and water quality loadings) that result.

Water management (import and export of water within a subbasin) includes such activities as ground and surface water extraction for either irrigation or consumptive use on site, domestic and industrial water supply (import), and water export via sanitary sewers (infiltration into the sanitary pipe network). Water management affects water balance by either adding or subtracting water from a subbasin or transferring water from one subbasin to another. Such water management activities affect water quality (DO, temperature, etc.) and the availability of minimum flows to meet salmonids' needs.

Another component of altered hydrology is operation of dams in the headwaters of the Cedar and Green basins. One objective of the model is to evaluate the impacts of the Howard Hanson Dam on pollutants in downstream areas. Since the water released from the dam is relatively clean, the impacts are largely the result of the timing and amount of dilution in the main channel caused by the releases. There might also be a smaller impact caused by the erosion and deposition of pollutants and the effect of higher flow rates. Both of these impacts can be addressed by the use of a model that is accurate with respect to hydraulics, sediment transport, and pollutant transfers between the water column and sediment. Release rates and timing can be varied in a predetermined manner and the impacts analyzed at locations downstream.

<u>Sediment</u>
Suspended sediment and turbidity are primarily a problem during storm events when increased flows due to development cause erosion of stream banks. There are also problems with agricultural runoff from cropland in some tributaries, and sediments in some watersheds are contaminated with metals and organics. The objectives of sediment modeling are largely related to impacts on salmonids. The specific issues that have been identified are estimation of sediment concentrations and their durations, and the impact of contaminant transport with fine sediments.

2.5.1 SWAMP Study Area

King County's objectives for development of the SWAMP watershed and river water quality model can be briefly summarized as follows:

1. Model of the entire SWAMP basin (~ 40 subwatersheds that will have to be further subdivided)
2. Sensitivity to land use changes (in a basin containing a wide range of land uses/land covers)
3. Resolution sufficient to trace pollution to upstream sources and allow determination and evaluation of local water quality problems
4. Simulate the following constituents:
    - flow

- detailed nutrient forms and algae
- DO/BOD/TOC
- pH and alkalinity
- sediment
- metals
- temperature
- organic contaminants
- bacteria

General water quality objectives are discussed in Section 2.5 above.

The main priorities in terms of the short-term use of the models are: 1) development of boundary conditions for water quality models of the four primary mainstem water bodies (Lake Sammamish, Sammamish River, Lake Washington, Lake Union), 2) evaluation of water quantity and quality conditions for protection of salmonids throughout much of the basin, 3) evaluation of placement alternatives for the Brightwater WWTP, and 4) groundwater-surface water interactions in the Sammamish River basin.

The first two of these objectives require that the entire basin contributing to the water bodies be included in the model(s), and all of the water quality constituents listed above be simulated. The County has selected CE-QUAL-W2 and CH3D-ICM as the programs to be used to model the Sammamish River and the lakes. These programs model detailed water quality processes and constituents. The inputs that must be provided to CE-QUAL-W2 (whether from monitoring or modeling) are listed in Table 2.2. The inputs needed for CH3D-ICM are similar, but include a more detailed specification of the organic nitrogen and phosphorus into dissolved vs. particulate fractions and particulate labile vs. particulate refractory fractions. This detailed organic N and P fractionation will most likely be based upon laboratory analysis of multiple samples of organic matter in the region, i.e., the separate fractions will not be represented in the watershed model. Since CE-QUAL-W2 does not include these fractions, and the CE-QUAL-W2 model of the Sammamish River will provide a boundary condition for the CH3D-ICM model of Lake Washington, the same data will be needed to make this translation as will be the case for the watershed model to the CH3D-ICM lake models.

Since watershed modeling is required to provide the tools to satisfy requirements 2 and 3 above, the watershed model must also provide the boundary condition for the models of the primary mainstem water bodies (noted above). Furthermore, adequate simulation of the minimum set of the constituents required for the water quality model boundary condition is dependent on also modeling water quality processes (e.g., algal uptake and release of nutrients) in many of the tributary streams and rivers. Therefore, relatively complete (in terms of processes, constituents, and both spatial and temporal resolution) water quality models must be developed for the tributary watersheds. This includes land use-specific water quality response and instream process modeling.

Table 2.2. Monitoring and/or Model Constituents Required for CE-QUAL-W2 Boundary Condition

Minimum	**Additional useful [or required as a function of application]**
Inflow rate	Conductivity
Temperature	Dissolved oxygen (DO)
Total organic carbon (TOC)	PH
Soluble reactive phosphorus (SRP)	Total dissolved solids (TDS)
Total phosphorus (TP)	Dissolved and/or particulate organic carbon (DOC and POC)
Nitrate+nitrite nitrogen	Biochemical oxygen demand (BOD)
Ammonium nitrogen	Total dissolved phosphorus (TDP)
	Total inorganic phosphorus (TIP)
	Dissolved inorganic phosphorus (DIP)
	Total Kjeldahl nitrogen (TKN)
	Filtered TKN
	Total suspended solids (TSS)
	Inorganic and/or volatile suspended solids (ISS or VSS)
	Chlorophyll *a*
	Dissolved silica
	Alkalinity

It is our opinion that this is a very ambitious set of objectives. Few, if any, other organizations in the U.S. have undertaken a water quality modeling project that attempts to represent this diverse range of constituents in a basin the size of the SWAMP study area, with the resolution required to evaluate small-scale or local water quality conditions. For comparison, the Chesapeake Bay Watershed Model, which has been under continuous development since 1978 by EPA and three states, models a larger area than the King County basins, but at a significantly lower geographical resolution. The Chesapeake model represents nutrient loading from agricultural areas with detailed, data-intensive process algorithms, but the model's primary purpose is to provide estimates of loadings at the downstream water body (Chesapeake Bay), and therefore, it does not attempt to accurately represent local water quality conditions. Model calibration was limited to temperature, sediment, DO, nutrients, and algal concentrations at approximately twelve monitoring locations. It does not include metals, bacteria, organics, or detailed water temperature calibration. Based on this comparison, we believe that a commitment of significant resources to both model development and an ongoing comprehensive monitoring plan will be required to achieve the King County project goals. An estimate of the time and resources required should be made after a detailed simulation strategy is prepared, including phasing of model development and calibration.

Two of the primary short-term objectives of the SWAMP study include evaluation of the possible placement of the Brightwater WWTP in the Little Bear Creek watershed and determination of the groundwater-surface water interaction of the Sammamish River and tributaries in the Sammamish Valley.

The prospective Brightwater site is adjacent to Highway 9 in an industrial district adjacent to the City of Woodinville. The assessment of siting impacts can be used in the development of the EIS for the site and will require the modeling of all of the standard water quality constituents in addition to hydrology.

Waste reuse of partially treated wastewater for irrigation is under consideration in the Sammamish Valley. Understanding of the surface-groundwater interaction related to both quality and quantity requires modeling of the Sammamish River channel, the surrounding valley, tributaries to the river, and the valley aquifer system.

2.5.2 Green WQA Study Area

The needs of the Green WQA study are similar to the SWAMP, with one major exception. The water quality model that requires a boundary condition (EFDC) is being developed to model bacteria, metals, temperature, and sediment, and not detailed nutrient and algal dynamics. Since dissolved oxygen modeling is still required throughout the Green WQA area, we would generally recommend a complete nutrient and algal dynamics model; however, a simpler model of BOD/DO could be developed and calibrated that would satisfy the need for estimating dissolved oxygen without the data and calibration costs needed for a full algal model.

General water quality objectives are discussed in Section 2.5 above. King County's specific objectives for the Green WQA watershed and river water quality model are summarized below:

An objective of the Green WQA is to better understand and develop strategies to control bacterial contamination. Significant bacterial contamination occurs in Newaukum Creek, Big Soos Creek, and Mill Creek, primarily as a result of animal wastes from pastured animals; and in the lower portions of the Green River from the aforementioned tributary sources, and from septic system failure and CSOs in the older suburban and urban areas.

One of the objectives of the Green WQA is to estimate loads of bacteria that are occurring from specific subbasins in the watershed, particularly those Green WQA subbasins that are listed under the 303(d) program. Since most bacterial sources are considered to be nonpoint, the bacterial loading will be parameterized by model land use. Therefore, once the model is calibrated, the model will also be able to provide estimates of loading for each land use type in the model. Furthermore, alternative scenario runs of the model can be designed to determine the impacts (i.e., the change in bacterial loadings) of the changed land use that occurs as a result of development and growth.

Metals contamination is a particular problem in the Green-Duwamish basin, and results primarily from nonpoint sources (development) in the middle portions of the basin and both residential development and industrial sources in the lower portions of the basin. The tributary subbasins most affected by metal contamination are Mill Creek and

Springbrook Creek/Black River. The Soos Creek subbasin has also experienced elevated metals concentrations due primarily to development.

One of the main objectives of the model development is to focus on the Mill Creek and lower Green (Springbrook Creek) portions of the basin, and provide estimates of peak and mean concentrations of key metals for comparison with acute and chronic levels, respectively, for various species of fish. A model calibrated to baseline and storm conditions can be used to make these estimates for specific locations, times, and conditions, and is much more cost effective than detailed monitoring.

Water temperature is a concern in all subbasins and the mainstem, but is a particular problem in the middle and lower Green River and Mill Creek, with impacts from the Howard Hanson dam and urban/industrial development.

One of the specific objectives of the temperature modeling is to determine the impact of the Howard Hanson Dam and reservoir on temperatures. The model will make it possible to adjust the temperature and flow volume out of the reservoir in some predefined manner and observe the impacts downstream. However, in order to accurately estimate temperatures without the dam, it would be necessary to model the watershed above the dam. Under the current plan, the portion of the basin above the dam will not be modeled, i.e., the dam will provide an upper boundary point for the model. However, the selected models should be capable of representing the upper watersheds and reservoirs for use in assessing and evaluating future water management issues in these watersheds (discussed further in Section 3.1)

DO levels are most heavily impacted in the middle and lower Green and tributaries where agriculture and failing septic systems result in runoff of nitrogen wastes that decay and consume oxygen. In the lower basin, the nutrients also contribute to algal blooms, which result in lower DO levels from algal respiration and decay of algal material. As discussed in the general objectives above, the objectives of the modeling are: 1) to estimate DO levels at various locations in the basin under different climatic conditions, e.g., average conditions and drought conditions, 2) estimate frequency, duration and timing of lower DO levels, and 3) evaluate the effectiveness of abatement measures.

One objective of the Green model is to evaluate the impacts of the Howard Hanson Dam on pollutants in downstream areas. Since the water released from the dam is relatively clean, the impacts are largely the result of the timing and amount of dilution in the main channel caused by the releases. There might also be a smaller impact caused by the erosion and deposition of pollutants and the effect of higher flow rates. Both of these impacts can be addressed by the use of a model that is accurate with respect to hydraulics, sediment transport, and pollutant transfers between the water column and sediment. Release rates and timing can be varied in a predetermined manner and the impacts analyzed at locations downstream.

Suspended sediment and turbidity are primarily a problem in the Green during storm events when increased flows due to development cause erosion of stream banks. There

are also problems with agricultural runoff from cropland in some tributaries, and sediments in the lower Green and Springbrook Creek are contaminated with metals and organics. The objectives of sediment modeling are largely related to impacts on salmonids. The specific issues that have been identified are estimation of sediment concentrations and their durations, and the impact of contaminant transport with fine sediments.

2.6 Summary of Watershed Modeling Applications

To help put the watershed modeling work scope into perspective, the likely watershed modeling applications in King County SWAMP and Green WQA projects is summarized in Table 2.3. The table highlights the project clients, the modeling needs with respect to projects, modeling parameters, time and spatial resolutions, and specific modeling application notes.

Table 2.3 King County Watershed Modeling Needs

Client	Need	Modeling Parameters	Time Resolution Needed	Spatial Resolution Needed	Notes
Wastewater Treatment Division	Boundary conditions for receiving water body models	Water quantity, bacteria, nutrients, metals, conventionals	Various from less than one hour to daily	River basin to watershed (tens of sq. miles) scale	Parameters on a temporal and spatial scale are driven by the specific model needs for EFDC (Estuary Model), CEQUAL-ICM (Lake and Reservoir Quality Model), CH3D (Circulation Model). Extracting output data from sewershed model (both CSO and Infiltration & Inflow models) such as flow and pollutant loads.

Client	Need	Modeling Parameters	Time Resolution Needed	Spatial Resolution Needed	Notes
Wastewater Treatment Division	Water quality / quantity effects on ecology from current and future planned activities	Hydrologic regime, nutrients, temperature, DO, bacteria, metals	Various from hourly to annual	First order tributaries to river mainstem, lakes and impoundments	Model capabilities would need to respond to numerous levels of complexity addressing the needs of implementation of water re-use, addition/ subtraction of secondary discharges, CSOs, etc. These conditions may be in the form of changes from current conditions to future sitings and operations and how they meet Stormwater NPDES requirements, and TMDL and ESA criteria.

Client	Need	Modeling Parameters	Time Resolution Needed	Spatial Resolution Needed	Notes
Wastewater Treatment Division	Provide resultant water quality concentrations in the receiving water (both in the water column and sediment) for risk assessment	All parameters related to health, wildlife and ecological hazard characterization	Related to critical time period for exposure (most likely will be daily)	Downstream end of first order tributaries to river mainstem	Model capabilities would need to derive end of pipe water quality concentrations, achievable dilution in the receiving water body.
King County / WDOE	TMDL development	Temperature, DO, bacteria, metals, nutrients, conventionals	Various from daily to annual	First order tributaries to river mainstem	Modeling to determine load capacities and to allocate loads in meeting water quality objectives of those water bodies on the State's Water Cleanup List
King County	Assessment of BMPs and abatement measures	Flow, temperature, DO, bacteria, metals, nutrients, conventionals	Various from hourly to annual	First order tributaries to river mainstem, lakes and impoundments	Modeling functions include: a) simulate the performance of various BMPs (mostly dealing with non-point sources), and b) model the water quantity and quality effects of BMPs and abatement measures (similar to needs

Client	Need	Modeling Parameters	Time Resolution Needed	Spatial Resolution Needed	Notes
					identified for WTD).
King County	Assessment of altered hydrology impacts	Flow, temperature, DO, bacteria, metals, nutrients, conventionals	Various from hourly to annual	Small subbasins to first order tributaries to river mainstem	Modeling to determine flow regime changes (from instantaneous peaks to mean daily, monthly, and annual volumes) due to land use changes, water import/export, irrigation, and reservoir water release patterns.
King County	UPD monitoring (major development); water quality / quantity effects on ecology from current and future planned development activities	Flow, temperature, DO, bacteria, metals, nutrients, conventionals	Various from hourly to annual	First order tributaries to river mainstem, lakes and impoundments	Need to respond to major land use changes and addressing their effects on the environmental legislation such as TMDL and ESA.

Client	Need	Modeling Parameters	Time Resolution Needed	Spatial Resolution Needed	Notes
King County	Habitat Conservation Plan	Flow, temperature, DO, bacteria, metals, nutrients, sediment, conventionals	Various from daily to annual	First order tributaries to river mainstem	In addition to what is noted above as part of the WTD's need with regard to ESA, there is a need to furnish diagnostic data for the purpose of determining where water quantity and quality are factors of decline. The diagnostic functions include problems identification, data need assessment, and setup of the field monitoring program

Client	Need	Modeling Parameters	Time Resolution Needed	Spatial Resolution Needed	Notes
King County	Salmon Recovery Plan	Flow, temperature, DO, bacteria, metals, nutrients, sediment, conventionals	Various from daily to annual	First order tributaries to river mainstem	In addition to the above, there is a need to develop instream flow requirements in a catchment and evaluate flow regime changes (from instantaneous peaks to mean daily, monthly, and annual volumes)
King County	Groundwater Management	Flow, temperature, nutrients	Various from daily to annual	First order tributaries to river mainstem	Modeling functions include: a) to evaluate flow regime and catchment water balance as affected by land use change, water and wastewater management and operational scenarios, and b) develop management alternatives

Client	Need	Modeling Parameters	Time Resolution Needed	Spatial Resolution Needed	Notes
King County	Water Resources Planning	Flow	Various from daily to monthly	First and second order tributaries to river mainstem	To develop deregulated inflow traces, flow sequences at ungaged tributaries, and conduct integrated water resource system modeling under various existing and future operating conditions, (prescribed by various system demands and constraints).

3 ASSESSMENT OF MODELING DATA

An assessment of modeling data is provided to identify existing data available to support model application, and specific data gaps in the SWAMP and Green WQA study areas. This assessment relates to the watershed modeling needs described in Section 2 and the availability of water quantity modeling data and water quality modeling data for the two study areas.

3.1 Framework for Use of Modeling Data

The elements common to all the watershed modeling are primarily related to the data available for initial watershed characterization, input development, and hydrology calibration, although the level of detail needed may vary as a function of the strategy. Figure 1.1 showed the study areas for the SWAMP and Green WQA. Current GIS data available from King County, and other web sites, for vegetation/land cover, soils/surficial geology, topography (e.g., 10-meter DEM; see Figure 3.1), and land use appears to be adequate for watershed characterization for essentially all strategy levels. Precipitation and meteorologic data (discussed below) provide reasonable coverage for most of both watershed study areas, with some sparse coverages in the upper watersheds and selected regions in the lower areas (see Figure 3.13). The flow data available for hydrology calibration and validation (Figure 3.14) is also reasonable, based on past experience in watershed modeling both in King County and nationwide.

A potential problem with adding to the precipitation, meteorologic, and flow data collection effort is that long time periods of data are needed for modeling, so the new data would not be available for several years. As a result this effort is largely limited to historical data for input and streamflow calibration.

Boundary conditions for the watershed modeling would also apply to all modeling strategies. As noted earlier, the lower boundary conditions include the river inflows and direct drainage (both quantity and quality) to the Duwamish Estuary, Lake Washington Ship Canal, Sammamish River, and the lakes (Sammamish, Washington, and Union). The upper boundaries have traditionally been designated at or near Chester Morse and Howard Hansen reservoirs, for the SWAMP and Green WQA, respectively. Figure 3.2 shows the locations of these upper boundary conditions, and Table 3.1 shows the land use distributions for both the total watershed areas and the lower study areas below the upper boundary conditions. King County staff members have indicated some interest in extending the watershed modeling above the reservoirs, as a potential framework for watershed and reservoir management. If that direction is pursued, the modeling strategies (discussed in Section 5) would need to be revisited to address additional data needs together with the snow modeling and reservoir modeling capabilities required to properly represent the upper watershed regions.

In summary, the data for initial watershed characterization, model setup, and hydrology calibration appears to be quite adequate to support all of the potential modeling strategies presented in Section 5.

Figure 3.1 DEM of SWAMP and Green WQA Study Areas

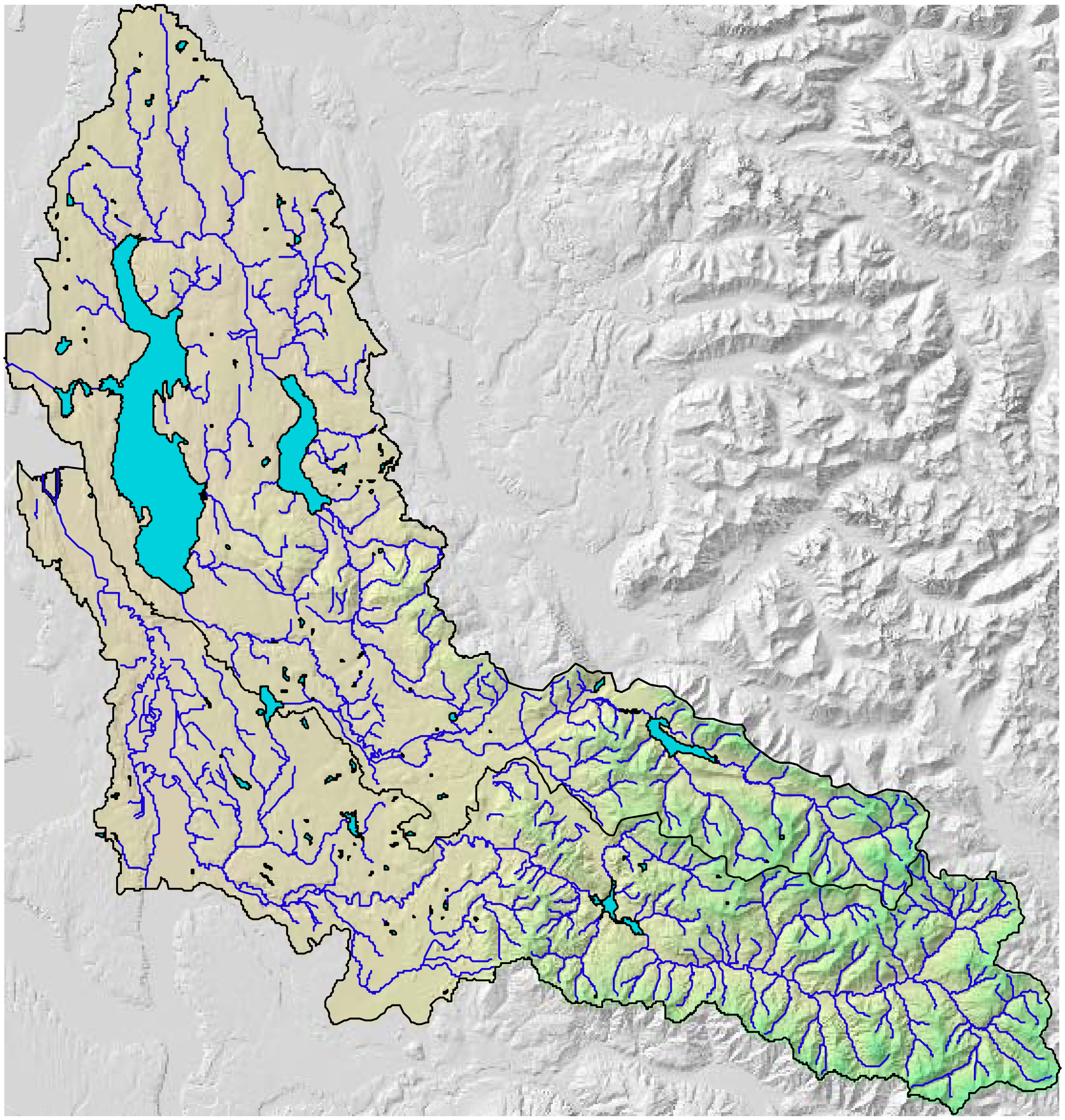


Figure 3.2 Boundary Conditions

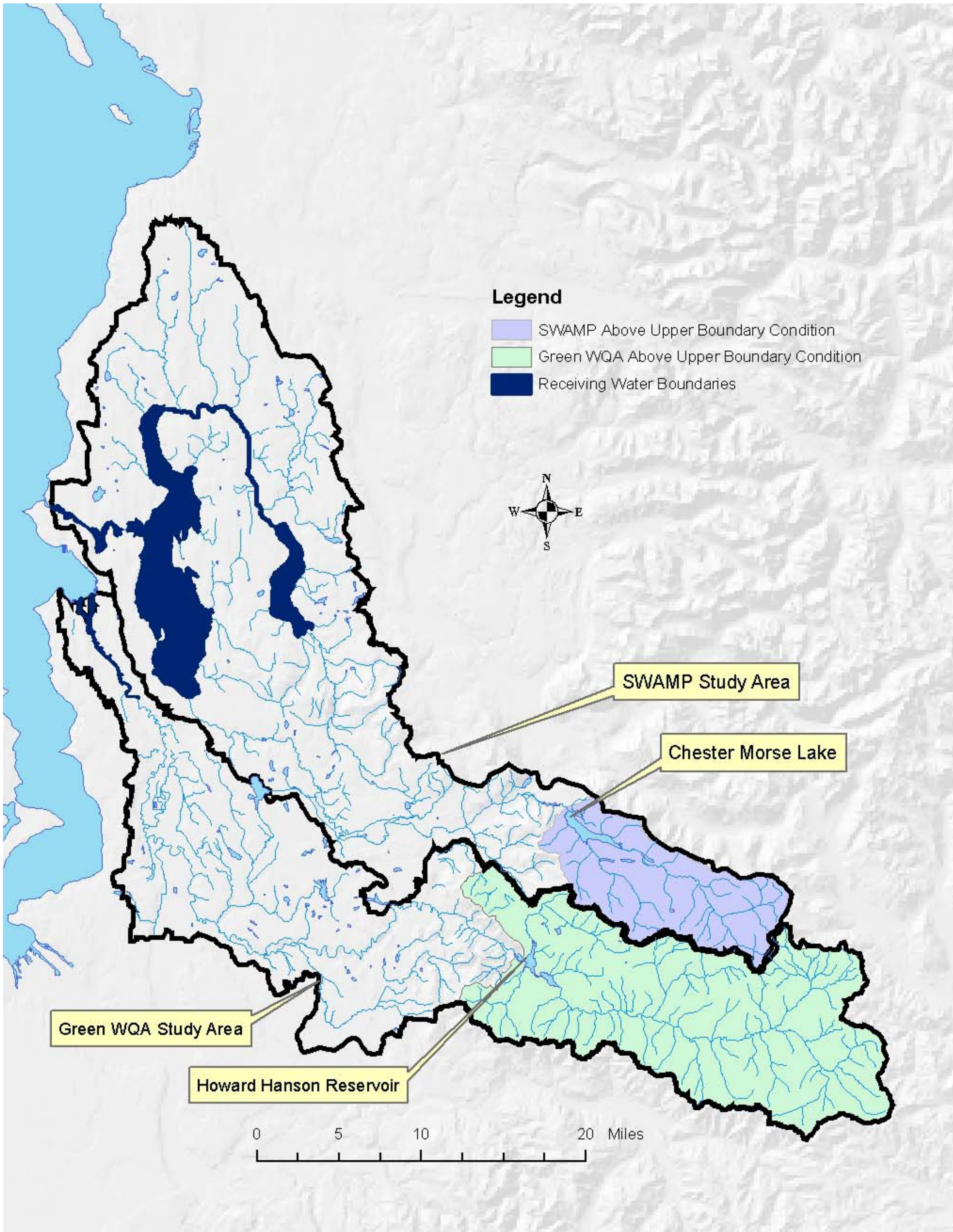


Table 3.1 Land Use Distribution for the SWAMP and Green WQA Study Areas

	SWAMP				Green WQA			
	TOTAL		LOWER		TOTAL		LOWER	
Description	Area (acres)	Percent of Total	Area (acres)	Percent of Total	Area (acres)	Percent of Total	Area (acres)	Percent of Total
Bare Ground/Asphalt	17,207	4.4%	17,122	5.2%	12,530	4.0%	12,269	7.2%
Bare Rock/Concrete	944	0.2%	913	0.3%	758	0.2%	725	0.4%
Conifer – Early	12,214	3.1%	5,240	1.6%	21,776	7.0%	5,346	3.2%
Conifer – Mature	10,030	2.6%	1,677	0.5%	20,435	6.5%	766	0.5%
Conifer – Middle	37,739	9.6%	13,417	4.1%	41,996	13.4%	4,546	2.7%
Deciduous	42,667	10.9%	40,947	12.4%	29,376	9.4%	24,107	14.2%
Developed High Intensity	8,813	2.3%	8,389	2.5%	7,472	2.4%	6,082	3.6%
Developed Low Intensity	85,527	21.9%	82,556	25.0%	45,900	14.7%	35,386	20.9%
Developed Med Intensity	52,558	13.4%	52,451	15.9%	21,891	7.0%	21,587	12.7%
Grass – Brown	10,488	2.7%	9,975	3.0%	11,500	3.7%	9,837	5.8%
Grass – Green	4,421	1.1%	4,278	1.3%	7,451	2.4%	6,977	4.1%
Mixed Forest	52,859	13.5%	48,969	14.8%	34,632	11.1%	20,963	12.4%
Open Water	29,087	7.4%	27,519	8.3%	2,621	0.8%	1,904	1.1%
Recently Cleared	2,333	0.6%	1,724	0.5%	5,734	1.8%	1,890	1.1%
Scrub/Shrub	24,236	6.2%	14,699	4.5%	48,845	15.6%	17,178	10.1%
Shadow	283	0.1%	38	0.0%	368	0.1%	73	0.0%
	391,406	100.0%	329,914	100.0%	313,286	100.0%	169,637	100.0%
	612 mi^2		515 mi^2		490 mi^2		265 mi^2	

3.2 Water Quantity Modeling Data

An assessment of water quantity data needed for watershed modeling purposes focuses on input data required by continuous simulation models and the procedures normally used to obtain these data.

3.2.1 Input Data

Model input data includes precipitation, evaporation, other meteorologic data, streamflow, land information, and conveyance system information. Each is described below for both the SWAMP and Green WQA study areas.

Precipitation
King County has long-term (40+ years) of hourly National Weather Service (NWS) precipitation data for SeaTac Airport and Landsburg that are representative of rainfall in the SWAMP study area. In addition, the County currently maintains 17 rain gage stations in the SWAMP area. These rain gages are listed in Table 3.2 below and shown in Figure 3.3.

Figure 3.3 Locations of Nearby Active King County Precipitation Gages

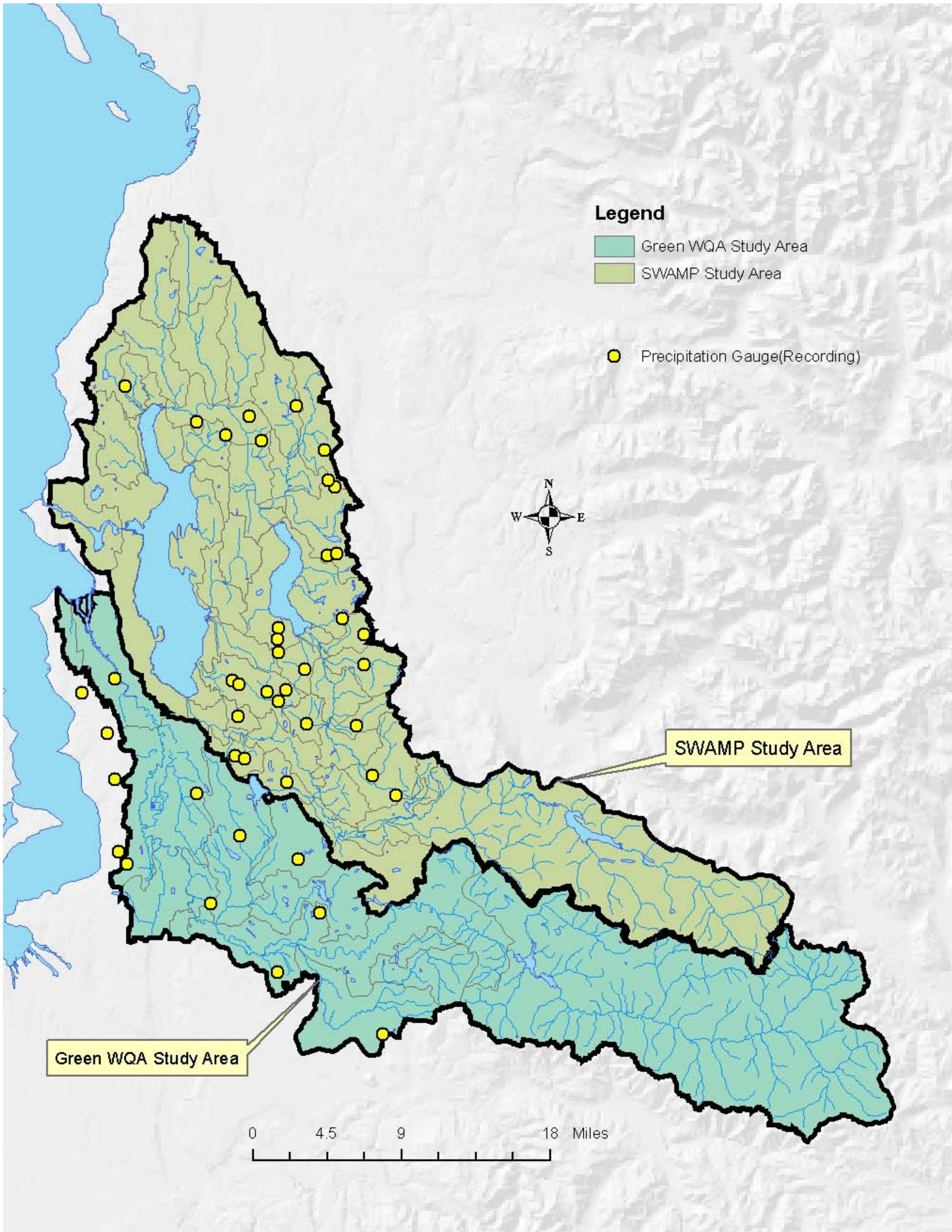


Table 3.2 King County Rain Gages in SWAMP Area

Gage No.	Location/Watershed	Period of Record
35U	Lyon Creek	10/91 – present
51U	Sammamish River	10/87 – present
27U	Juanita Creek	10/88 – present
02W	Bear Creek	10/94 – present
51W	Sammamish River	10/87 – present
02V	Bear Creek	10/94 – present
63Y	West Lake Sammamish	10/94 – present
67U	Tibbetts Creek	10/87 – present
37U	May Creek	10/90 – present
46U	Issaquah Creek	10/87 – 9/99
14U	Issaquah Creek	10/87 – present
25Y	Issaquah Creek	10/87 – 9/96
25V	Issaquah Creek	10/88 – present
37V	May Creek	10/88 – present
31U	Cedar River	10/87 – present
31Y	Cedar River	10/95 – present
31W	Cedar River	10/87 – present

Additional precipitation data are available for the Swamp Creek and North Creek watersheds that originate in Snohomish County. Everett NWS hourly precipitation is available starting October 1948 (same as for SeaTac Airport). Snohomish County also maintains two rain gages in the upper portions of the Swamp and North watersheds. These two gages have hourly data starting in 1988.

King County currently maintains eight rain gage stations in the Green WQA area. These rain gages are listed in Table 3.3 below.

Table 3.3 King County Rain Gages in Green WQA Area

Gage No.	Location/Watershed	Period of Record
26U	Jenkins Creek	10/91 – present
54U	Soos Creek	10/91 – present
03U	Black River	10/88 – present
41U	Lower Green River	10/88 – present
HCU	Duwamish River	10/95 – present
09U	Middle Green River	10/91 – present
40U	Middle Green River	10/91 – present
32U	Lower Green River	10/88 – present

Evaporation
Evaporation data are available from the station located in Puyallup at the Washington State University Experimental Field Station. Puyallup is outside of the SWAMP and Green WQA areas, but because evaporation does not vary greatly in the Puget Sound lowland watersheds the distance from the study areas is not significant.

The evaporation data must be adjusted to convert it to potential evapotranspiration data used in the models. A pan evaporation coefficient is used to convert the pan evaporation data to PET data. For the SWAMP and Green WQA study areas this coefficient should be set to about 0.74, based on the pan evaporation coefficient values shown on Map 4 of the NOAA Technical Report NWS 33, *Evaporation Atlas for the Contiguous 48 United States* (Farnsworth, et al, 1982). Some adjustment to this initial value may be required to adapt to local conditions during the model calibration efforts.

Other Meteorologic Data
Other meteorologic parameters includes air temperature, wind, solar radiation, dewpoint temperature, and cloud cover. Some or all of these data time series are required inputs for various water quality processes, and for snow simulation if the upper portions of the Cedar and Green watersheds are modeled.

Air temperature data are collected at SeaTac Airport and Stampede Pass by the National Weather Service. King County also monitors air temperature at some of its stream gaging stations. The University of Washington maintains a data collection site in support of the PRISM program. These locations should be sufficient for water quality and snow simulation, if required.

The other meteorologic data required for water quality and snow simulation are also collected at Sea-Tac Airport and by the University of Washington. These meteorologic data sources will be used in the watershed modeling with the knowledge that a long-term record of some meteorological data will have to be synthesized from other sources.

Water Quantity Data
Water quantity data includes both streamflow data collected at gaged sites in the SWAMP and Green WQA study areas and water extraction (pumping) and groundwater flow data.

Figure 3.4 shows the locations of the streamflow gaging sites in the two study areas. The discharge sites are where recording stream gages are located and provide locations at which the simulated water quantity results can be compared with measured streamflow.

The SWAMP area stream gages are listed in Table 3.4. Green WQA area gages are in Table 3.5. Depending on the length of record and corresponding water quality monitoring activities, these sites can be used in the calibration and validation process. Additional water quality monitoring sites have been included in the ongoing monitoring program (Burkey, 2001).

In addition, Snohomish County Surface Water Management maintains stream gages on North Creek and Swamp Creek in southern Snohomish County.

King County has a database of groundwater information including diversion point locations and wellhead data. This information is valuable in identifying subbasin channel losses and gains associated with groundwater outflows and inflows, respectively.

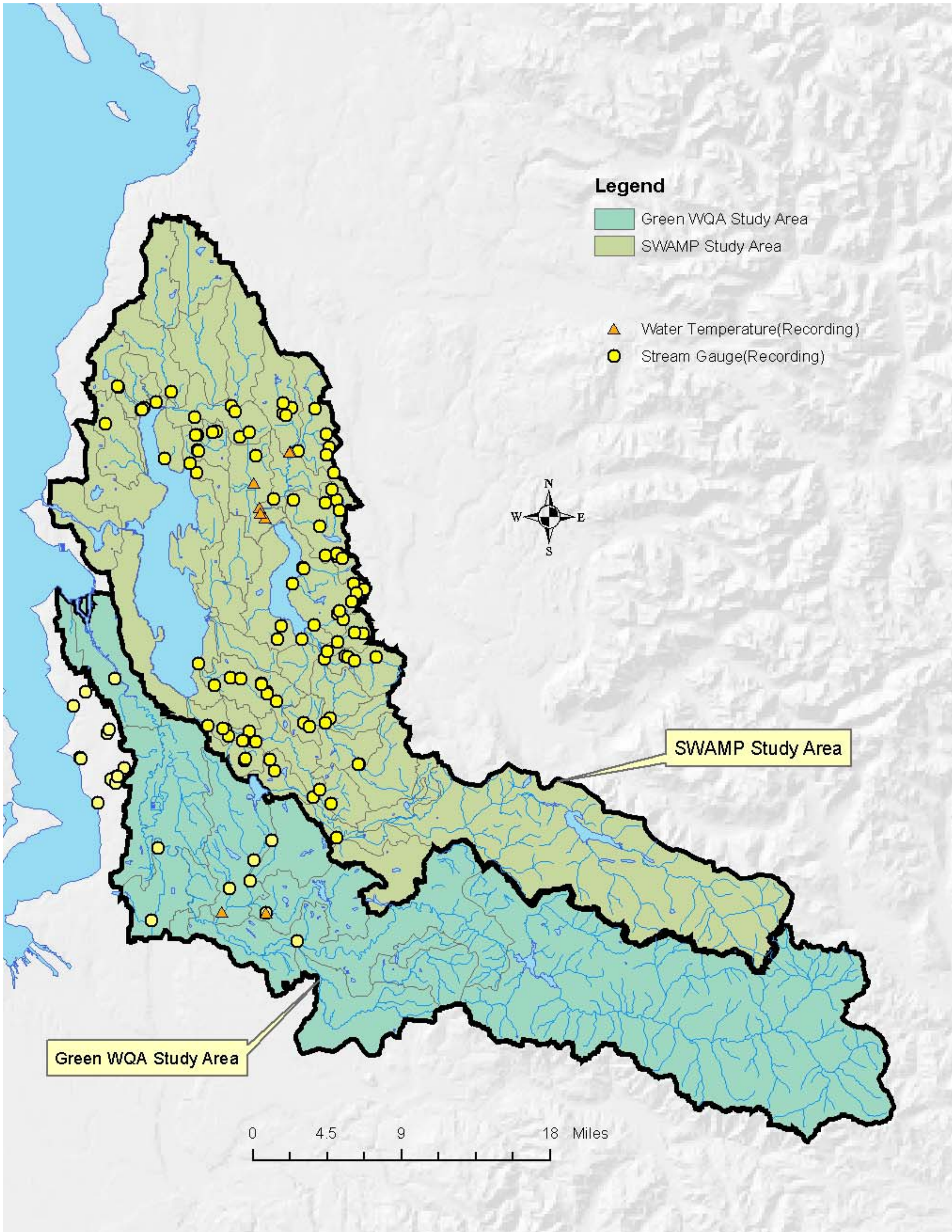
Table 3.4 King County Stream Gages in SWAMP Area

Gage No.	Location/Watershed	Period of Record
31L	Rock Creek near Maple Valley	10/94 – present
02E	Bear Creek at 133rd St NE	10/93 – present
30A	Little Bear Creek at Hwy 202	10/98 – present
02F	Bear Creek at Woodinville-Duvall Rd	10/94 – present
02A	Bear Creek at Union Hill Rd	10/87 – present
31B	Maplewood Creek	10/88 – present
31E	Lower Cedar Trib 0308 above Jones Rd	10/87 – present
31D	Madsen Creek at Maple Valley Rd	10/87 – present
37B	May Creek at Coal Creek Pkwy	10/91 – present
31G	Peterson Creek near mouth	10/87 – 9/91; 10/99 – present
31H	Taylor Creek at mouth	10/90 – present
31I	Upper Taylor Creek at 236th Ave SE	10/90 – present
27A	Juanita Creek at mouth	10/92 – present
34A	Lyon Creek near mouth	10/91 – present
35C	McAleer Creek above Bothell Way	10/91 – present
16A	North Lake Washington Trib 0056	10/92 – present
56B	Swamp Creek at 73rd Ave NE	10/98 – present
51D	Sammamish River Trib 0090 at NE 145th St	10/87 – 9/91
51E	Sammamish River Trib 0095B at NE 124th St	10/87 – present
18A	Evans Creek at Union Hill Rd	10/87 – present
14A	East Fork Issaquah Creek at Issaquah	10/87 – present
15C	Laughing Jacobs Creek at E L Sammamish Pkwy	10/91 – present
46A	North Fork Issaquah Creek at Issaquah	10/87 – present

Table 3.5 King County Stream Gages in Green WQA Area

Gage No.	Location/Watershed	Period of Record
09A	Covington Creek at 168th Way SE	10/88 – present
40B	Crisp Creek near Black Diamond	10/90 – present
40A	Green River at 218th Ave SE	10/91 – present
26A	Jenkins Creek near mouth	10/87 – present
40C	O'Grady Creek near Enumclaw	10/91 – present
41B	Mill Creek at 29th Ave NW	1989 – 1992
41C	Mill Creek at Peasley Canyon Rd	1989 – 1992
13A	Duwamish River Trib 0003	10/92 – present

Figure 3.4 Water Temperature and Discharge Gages



Land Information

Land information can be categorized into four major components: soil, vegetation, topography, and land use or human infrastructure data. In a watershed model the soil (or surficial geology), vegetation, and topographic information can be combined into different landscape types. Each landscape type has a different set of hydrologic characteristics that produces a unique runoff response to rainfall. Some land types produce a lot of runoff, others little.

The 1989 USGS modeling study (Dinicola, 1990) originally identified three main soil groups as appropriate categories to represent the surficial geology of the SWAMP and Green WQA study areas. These three soil groups were till, outwash, and saturated. They were selected based on their greatly differing responses to rainfall.

Till soils produce mostly interflow and groundwater, but also generate more surface runoff than outwash and saturated soil types. Outwash soils produce almost all groundwater and little or no surface runoff. Saturated soils (hydric soils) are found in wetland areas; when wet, they act like till, but when dry they act like outwash. A fourth surficial geology grouping can be designated as bedrock. These are areas of thin or no soil overlaying rock outcrops or similar geology and act much like impervious surfaces.

These four major soil groups can be used in the model to accurately simulate the runoff response to rainfall based on the amount of precipitation and evapotranspiration, and soil moisture and interception levels. These soil groupings have been used in HSPF models developed in King and Snohomish counties and are appropriate for other continuous simulation models. Figure 3.5 shows the spatial distribution of these four major soil groups across the study areas.

Vegetation (land cover) is another important land use/land cover information layer. Vegetation influences soil moisture and interception storage levels when computing runoff. The USGS study (Dinicola, 1990) also identified two major vegetation categories: forest and grass. For the purposes of the USGS study, forest represented land areas covered by tree canopy, with grass representing everything else.

Landsat and other satellite/aerial coverages can be used to identify a greater number of categories, based on reflective properties and photo interpretation. The 1995 Landsat land cover image has been used to identify the vegetation categories of mixed forest, deciduous, early conifer, middle conifer, matured conifer, recently cleared, scrub/shrub, brown grass, green grass, and bare earth (Figure 3.6).

Figure 3.5 Surficial Geology of Swamp Study Area & Green WQA

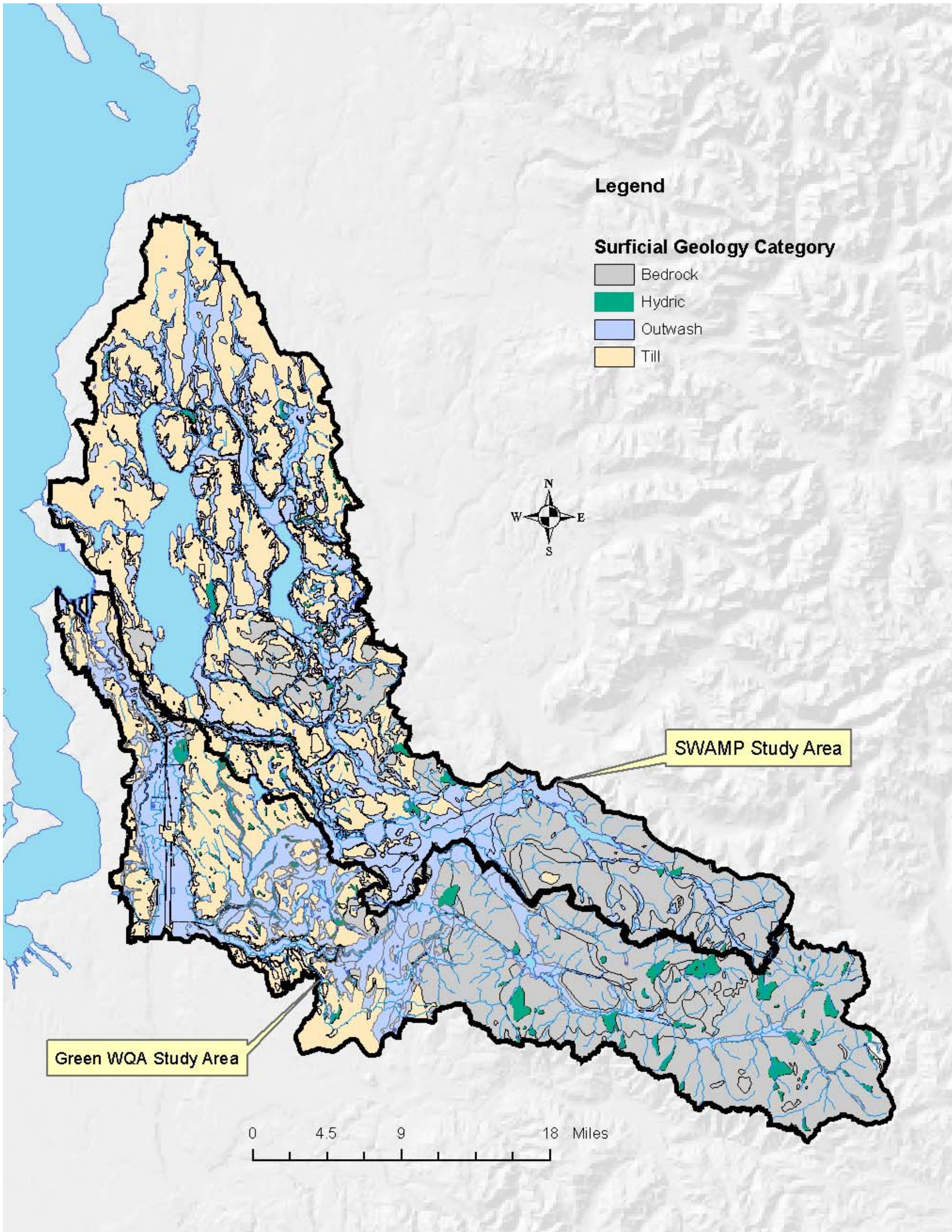
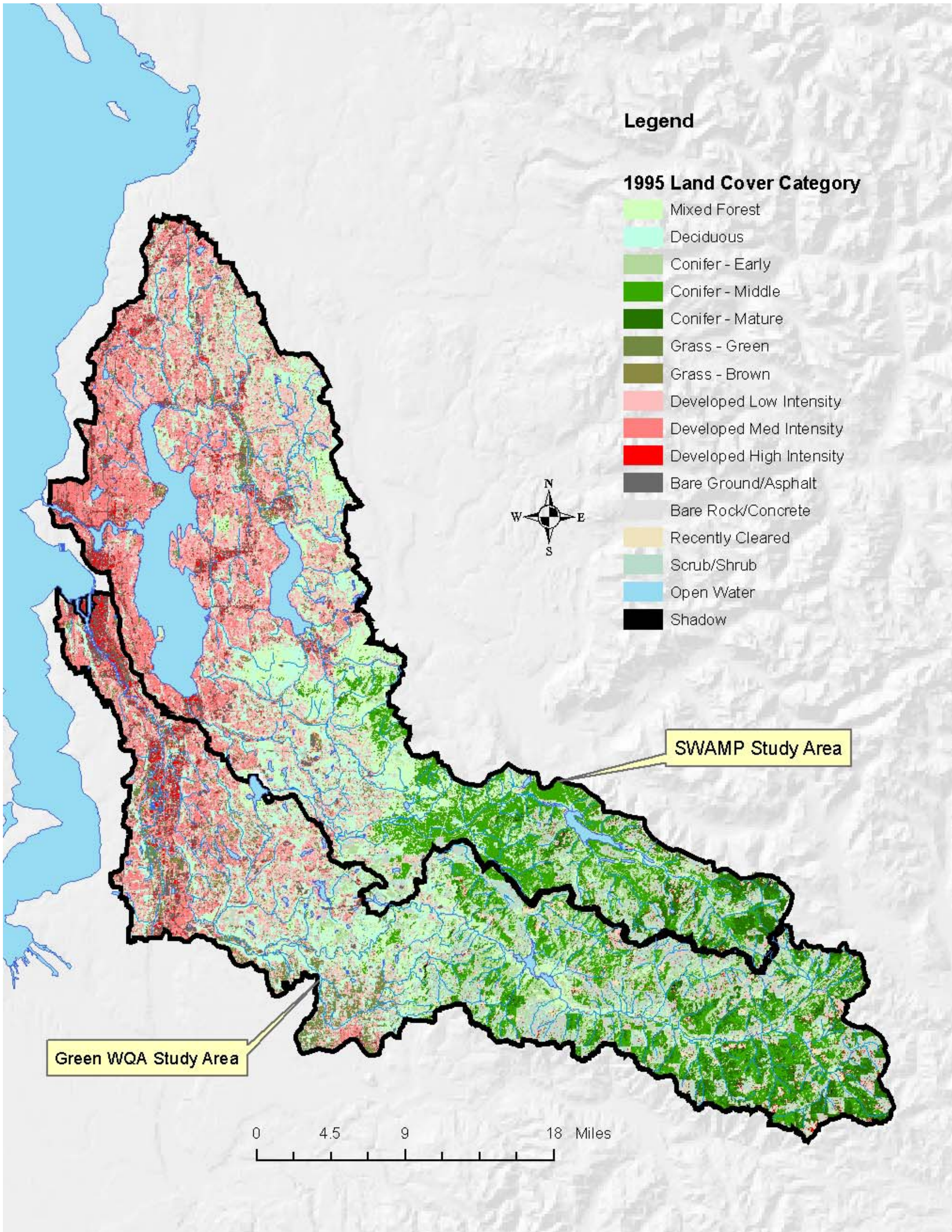


Figure 3.6 Land Cover from 1995 Landsat Image



Other land use information needed by the model is the human infrastructure that overlays the natural environment of the watershed. This includes buildings, roads, and open space (both developed and undeveloped). Land use influences runoff by decreasing or removing vegetation and increasing impervious land (roofs, roads, parking lots, etc.)

Impervious land, as the name implies, allows no infiltration of water into the pervious soil. All runoff is surface runoff. Impervious land typically consists of paved roads, sidewalks, driveways, and parking lots. Building roofs are also usually impervious.

For modeling purposes a distinction is made between total impervious area and effective impervious area. Total impervious area includes all surfaces that do not infiltrate runoff. Roofs, paved streets, sidewalks, driveways, and parking lots are all part of the total impervious area.

Effective impervious area (EIA) is defined as the area where there is no opportunity for surface runoff from an impervious site to infiltrate into the soil before it reaches a conveyance system (pipe, ditch, stream, etc.)

Because it is extremely expensive and time consuming to look at every impervious surface in a watershed to determine whether or not it is an effective impervious area, average EIA values are used instead. Each average EIA value is based on the land use (forest, low density residential, high density residential, multi-family, commercial, etc.) and previous experience in other Puget Sound lowland watersheds. For example, the following EIA percentages in Table 3.6 are representative values that have been used in HSPF models to determine the number of impervious acres. Other continuous simulation models use similar schemes to separate out impervious areas from pervious. These land use categories in Table 3.6 can also be used to differentiate different land covers and pollutant sources.

Table 3.6 HSPF EIA Values

Land Use	**EIA (percent)**
Forest	0
Pasture	0
Lawn	0
Low Density Residential (<1 dwelling unit/acre)	4
Medium Density Residential (1-3 du/ac)	10
High Density Residential (3-7 du/ac)	26
Multifamily (> 7 du/ac)	48
School	48
Highways, State Roads, Major Arterials	86
Commercial and Industrial	86

<u>Conveyance System Information</u>

Conveyance system information (both natural and artificial drainage systems) is required to model the flow of water down to the receiving water body models. The speed at which water moves through a conveyance system depends on the size and shape of the storm sewer system, the natural stream channels and adjacent floodplain, the slope of the channels, the roughness of the channels and floodplain surfaces, and the size and location of obstructions in the channel network.

Conveyance systems include small roadside ditches and natural stream channels. Development near or in the drainage channel system often results in alterations to the natural channel system. Channels are constricted and wetlands filled in many locations. Natural vegetation is removed and replaced with riprap or ornamental shrubbery. Where roads cross the stream channels, culverts are installed to convey the flow under the road surface. Typically some of these culverts are undersized for large flood events and cause flood waters to backup behind them.

Culvert and associated roadway information are important in identifying flow constrictions that may cause flooding, bank erosion problems, and/or fish passage barriers. In extreme conditions floodwaters can also result in road overtopping and roadway or bridge washout. Culvert information should include the size and shape of the culvert, the slope and length of the culvert, culvert material, and entrance and exit conditions. If significant, culvert blockages should be noted. The same information should be collected for bridges that constrict flows with either a narrow opening or low bridge deck.

3.2.2 Calibration and Validation Data

Calibration and validation will include both water quantity and water quality. However, since many of the existing hydrologic models of the SWAMP and Green WQA watersheds have been calibrated for water quantity the emphasis of this discussion will be on the water quality calibration.

An assessment of the availability of water quality data for calibration and validation purposes and associated data gaps is the focus of Section 3.3, below.

3.3 Water Quality Modeling Data

An assessment of water quality data needed for watershed modeling purposes focuses on the existing water quality monitoring in the SWAMP and Green WQA study areas and its adequacy to support model calibration and validation.

3.3.1 SWAMP Study Area

Development of a watershed water quality model requires a large amount of monitoring data to allow calibration of tributary watersheds. The SWAMP basin consists of five primary water bodies and approximately 15 first-order tributary creeks that are likely to be modeled separately and are candidates for water quality calibration. The five primary

lakes and rivers are listed below (in order from downstream to upstream), and their contributing areas are described in terms of the major creeks and local drainage areas:

<u>Lake Union</u>
Lake Union drains to Puget Sound through the Lake Washington Ship Canal. Its contributing area consists of the urban areas immediately north of downtown Seattle. Lake Union receives most of its flow from Lake Washington by way of the Canal.

<u>Lake Washington</u>
Lake Washington receives most of its inputs from the Sammamish River at its northern end and the Cedar River at the southern end. There are a number of small urban creeks that contribute local drainage, as well the following larger creeks:

- Lyons Creek
- McAleer Creek
- Thornton Creek
- Juanita Creek
- Forbes Creek
- Mercer Slough and Kelsey Creek
- Coal Creek
- May Creek

<u>Cedar River</u>
The Cedar River originates in the Cascade Mountains and drains into the southern end of Lake Washington. The upper portions of the basin provide drinking water for Seattle and portions of suburban King County. An upstream boundary for the SWAMP watershed models will be located (effectively) at one of the dams on the upper river, either the Lower Dam or the Chester Morse Dam. There are two or three small tributary creeks to the Cedar that may be calibrated, depending on the location of the upper boundary point and their significance from a water quality viewpoint.

<u>Sammamish River</u>
The Sammamish River connects Lake Washington and Lake Sammamish. In addition to the outflow from Lake Sammamish, it receives local drainage plus contributions from the following tributary creeks:

- Swamp Creek
- North Creek
- Little Bear Creek
- Bear Creek (including Evans Creek)

<u>Lake Sammamish</u>
Lake Sammamish receives inputs from Issaquah Creek at the southern end, Tibbetts Creek, and some smaller local drainage areas.

One of the objectives of the SWAMP project is to provide loadings to separate water quality models of Lake Sammamish, the Sammamish River, and Lake Washington in order to predict the impacts of watershed changes on the water quality of these water

bodies. The requirements of these models, plus the planning needs of King County have determined the following list of water quality constituents that are to be represented in the models:

High Priority:

- Temperature
- Total suspended sediment
- Dissolved oxygen
- Total phosphorus
- Bacteria/pathogens (fecal coliforms)

Medium Priority:

- Organic phosphorus species
- Total nitrogen
- Inorganic nitrogen (NO_3, NH_3)
- Organic nitrogen species
- BOD and organic carbon species
- pH and alkalinity
- Metals

In order to adequately estimate the loads needed by the separate water quality models (CE-QUAL-W2 and CH3D-ICM), the nutrient (N, P, and C) species listed under the medium priority category would need to be modeled in the watershed model. At a minimum, the inorganic nitrogen species and total organic nitrogen, phosphorus, and carbon will be required. Therefore, we assume that these constituents are high priority. Furthermore, the need to provide these loads to the separate models implies that they be represented over the entire watershed model area, and be derived from a mixture of land uses.

In summary, the observed water quality data needed to develop calibrated tributary watershed models for the purpose of providing loadings of the SWAMP constituents to separate water quality models are listed below. Where possible, these tributary areas should have a predominate land use that produces a signature loading rate that can then be extrapolated to other tributary areas.

A minimum of two years of data is needed to provide an adequate basis for water quality calibration; three or more years of data are preferable. The data should be sufficient to characterize both storm and baseline conditions. In order to better characterize some of the larger tributary creeks, it would be preferable to have the following data at more than one location:

- Temperature (continuous preferred)
- Total suspended solids
- Dissolved oxygen
- Nutrients (NO_3, NH_3, PO_4)

- Total organic N, P (or Total N, P)
- Total organic C and/or BOD
- Chlorophyll a
- Bacteria
- Organics (dissolved and particulate preferred)
- Metals (dissolved and particulate preferred)
- pH & alkalinity

In addition, sufficient fractionation analyses of the organic material should be performed at representative locations with a single significant land use that is found throughout the watershed. The analysis can then be used to determine the typical makeup of organic N, P, and C with respect to labile vs. refractory fractions and dissolved vs. particulate fractions.

<u>Sammamish Basin</u>
The data review by DeGasperi (2001) provides details on this basin. Table 3.7 lists the primary tributary monitoring stations in the Sammamish and their periods of record for key constituents. Given the need for at least two to three years of data for calibration, the existing data provide a good basis for developing tributary models of temperature, oxygen, nutrients, metals, and bacteria. The primary deficiencies for these constituents are measurements of: (1) organic carbon (DOC, TOC) and BOD, (2) continuous temperature data on selected creeks, (3) chlorophyll *a* data to calibrate algal production, and (4) dissolved vs. particulate metals. A specific need for linking the tributary watershed models to the lake and river water quality models is the characterization of the organic nutrient species with respect to dissolved vs. particulate and labile vs. refractory fractions. It is apparent that there are very few data available for modeling toxic organics such as pesticides, herbicides, and petroleum products.

Table 3.7 Tributary Water Quality Monitoring Time Periods in the Sammamish River Basin

Location	Temperature	Dissolved Oxygen	Total Susp. Solids	Nutrients (NO_3, NH_3, TN, PO_4, TP)	Metals	Bacteria	Organics	pH & Alkalinity
Issaquah Creek (0631)	98-01	98-01	98-01	98-01	98-01 (dissolved)	98-01		98-01
Tibbetts Creek (A630)	93-96	93-96	93-96	93-96	93-96	93-96		93-96 (pH only)
Bear-Evans Creek (0484)	93-01	93-01	93-01	93-01	93-01	93-01		97-01
Little Bear Creek	93-01	93-01	93-01	93-01	93-01	93-01		98-01

(0478)								
North Creek (0474)	93-01	93-01	93-01	93-01	93-01	93-01		98-01
Swamp Creek (0470)	93-01	93-01	93-01	93-01	93-01	93-01		98-01

Lake Washington/Cedar River Basin

A review of the data available for the larger tributary creeks of Lake Washington (Table 3.8) suggests that the constituents, quantity, and geographical distribution of data are comparable to the Sammamish Basin. Therefore, we can make the same conclusions, i.e., there is likely sufficient existing data to develop preliminary water quality models of the tributary creeks, but additional data are needed as described above for the Sammamish. Also, a review of the Cedar River, which provides almost half of the total flow to Lake Washington, and which contains both developed and developing areas in its lower basin, suggests that the data available for the river above the mouth and its tributary creeks are limited. If needed, the monitoring station at the mouth provides data to verify the calibration of the entire basin. This is based on the concept of calibrating the loadings from the tributary watersheds that have a predominant single land use that provides most of the loadings. For the entire basin the mixture of these different land use loadings will be reflective of the monitoring data at the mouth. A check of the water quality results at this location will verify the accuracy of the upstream calibrations. The only limitation to this approach is that the data needed to characterize tributary creeks and the upper boundary condition at the Lower Dam or Chester Morse Dam may be limited.

Table 3.8 Selected Tributary Water Quality Monitoring Time Periods in the Lake Washington Basin

Location	Temperature	Dissolved Oxygen	Total Susp. Solids	Nutrients (NO_3, NH_3, TN, PO_4, TP)	Metals	Bacteria	Organics	pH & Alkalinity
Lyons Creek (0430)	95-01	95-01	95-01	95-01		95-01		97-01
McAleer Creek (A432)	95-01	95-01	95-01	95-01		95-01		97-01
Thornton Creek (0434)	95-01	95-01	95-01	95-01		95-01		97-01
Juanita Creek (0446)	95-01	95-01	95-01	95-01		95-01		97-01
Forbes Creek (0456)	95-01	95-01	95-01	95-01		95-01		97-01
Kelsey/Mercer Creek (0444)	95-01	95-01	95-01	95-01		95-01		97-01
Coal Creek (0442)	95-01	95-01	95-01	95-01		95-01		97-01
May Creek (0440)	95-01	95-01	95-01	95-01		95-01		97-01

Cedar River (X438)	96-99?	96-99?	96-99?	96-99?		96-99?		97-99?

3.3.2 Green WQA Study Area

A current water quality monitoring program is underway on the Green tributary watersheds (Burkey, 2001). The purpose of the program is to assess the effects of various types of land use and cover on water quality. Currently 10-12 auto samplers have been placed in the field.

The currently available water quality data for the Green-Duwamish basin is variable in its adequacy to support model calibration. The spatial availability of water quality data is highly variable. The mainstem of the Green and some of its tributaries have relatively little coverage, while other tributaries such as Newaukum Creek and Soos Creek, including Covington and Jenkins Creeks have a dense coverage of stations. The five mainstem stations extend from the Duwamish River to a station immediately upstream of Newaukum Creek; plus a new station has been added one-half mile downstream of the Howard Hanson Dam/Reservoir. The upper portion of this area is largely forested, and therefore has minimal water quality problems; however, the lower portion includes significant agricultural land use.

The adequacy of the constituents and monitoring frequency is also variable over the basin. In general, monthly measurements of water temperature are collected at most of the existing stations; however, few of these stations collect continuous temperature data that would be needed for a detailed hourly model of temperature that represented daily maximum and minimums. Also, the metals monitoring in the basin has been primarily focused on stormwater monitoring. Model development would require baseline, i.e., non-storm measurements. Most other constituents of interest for the Green WQA, such as dissolved oxygen, total suspended sediment, nutrients, and fecal coliform bacteria are monitored adequately.

Table 3.9 lists the water quality stations in the Green Basin by sub-watershed, and shows the constituents (by general classes) that are monitored at each station (excluding the Burkey 2001 sampling sites). These stations are shown in Figures 3.7 and 3.8, which are reproduced from the document *WRIA 9 Habitat-Limiting Factors & Reconnaissance Report* (King County and Washington Conservation Commission, 2000). Based on the King County records of these data, most of these stations have periods of record covering at least the most recent ten years for most constituents, and they continue to be actively operated. However, several of the stations in the Newaukum and Soos watersheds operated for limited periods between 1993 and 1998, while other stations in these two watersheds were installed in 1999 and have operated for only two years. Monitoring frequency for most constituents is monthly.

The Burkey 2001 monitoring program is designed to collect data from different types of land use and development. Runoff from low and medium density development is monitored at the Hamm Creek, Panther Creek, Soosette Creek, and Green River tributary

(Lea Hill) stations. Higher levels of development are found in the Newaukum tributary (in the city of Enumclaw) and the Mill Creek tributary in the Springbrook basin. Agriculture and pasture land use runoff is monitored at two stations on Newaukum Creek tributaries (one at 236th Ave SE; the second at the SE 424th Street ditch). Forest land use and forestry practices are monitored on a Newaukum tributary on Weyerhauser property, on Crisp Creek above the fish hatchery, and on a Green River tributary in the foothills near the TPU diversion. The monitoring program also includes stations located near the upstream and downstream boundaries of the Green River and its major tributaries. Table 3.10 lists the water quality data collected at each of these stations.

The Green River mainstem and each sub-watershed are briefly discussed below with respect to specific water quality problems, and data availability for model development.

Table 3.9 Water Quality Monitoring in the Green River Basin

Location	Temperature	Dissolved Oxygen	Total Suspended Sediment	Nutrients (NO3, NH3, TN, PO4, TP)	Metals	Bacteria	Organics
Mainstem RM 12 near I-405 (0311)	X	X	X	X	X	X	
Mainstem RM 12 near I-405 (3106)	X	X	X	X	X	X	few
Mainstem RM 34.5 (A319)	X	X	X	X		X	
Mainstem RM 41.5 (B319)	X	X	X	X	X	X	
Black R/ Springbrook Creek (0317)	X	X	X	X	X	X	
Mill Creek (A315)	X	X	X	X	X	X	
Big Soos Creek at mouth (A320)	X	X	X	X	X	X	
Soos Creek misc stations (-320)	varies	varies	varies	varies	varies	X	
Jenkins Creek (D320)	X	X	X	X		X	
Covington Creek (C320, R320, S320)	X	X	X	X		X	
Newaukum Creek mouth (0322)	X	X	X	X	X	X	few
Newaukum Creek misc stations (-322)	varies	varies	varies	varies	D322	varies	
Crisp Creek (0321, F321)	X	X	X	X	0321	X	few 0321

Figure 3.7 Water Quality Monitoring Stations in the Lower Green and Duwamish River Basins

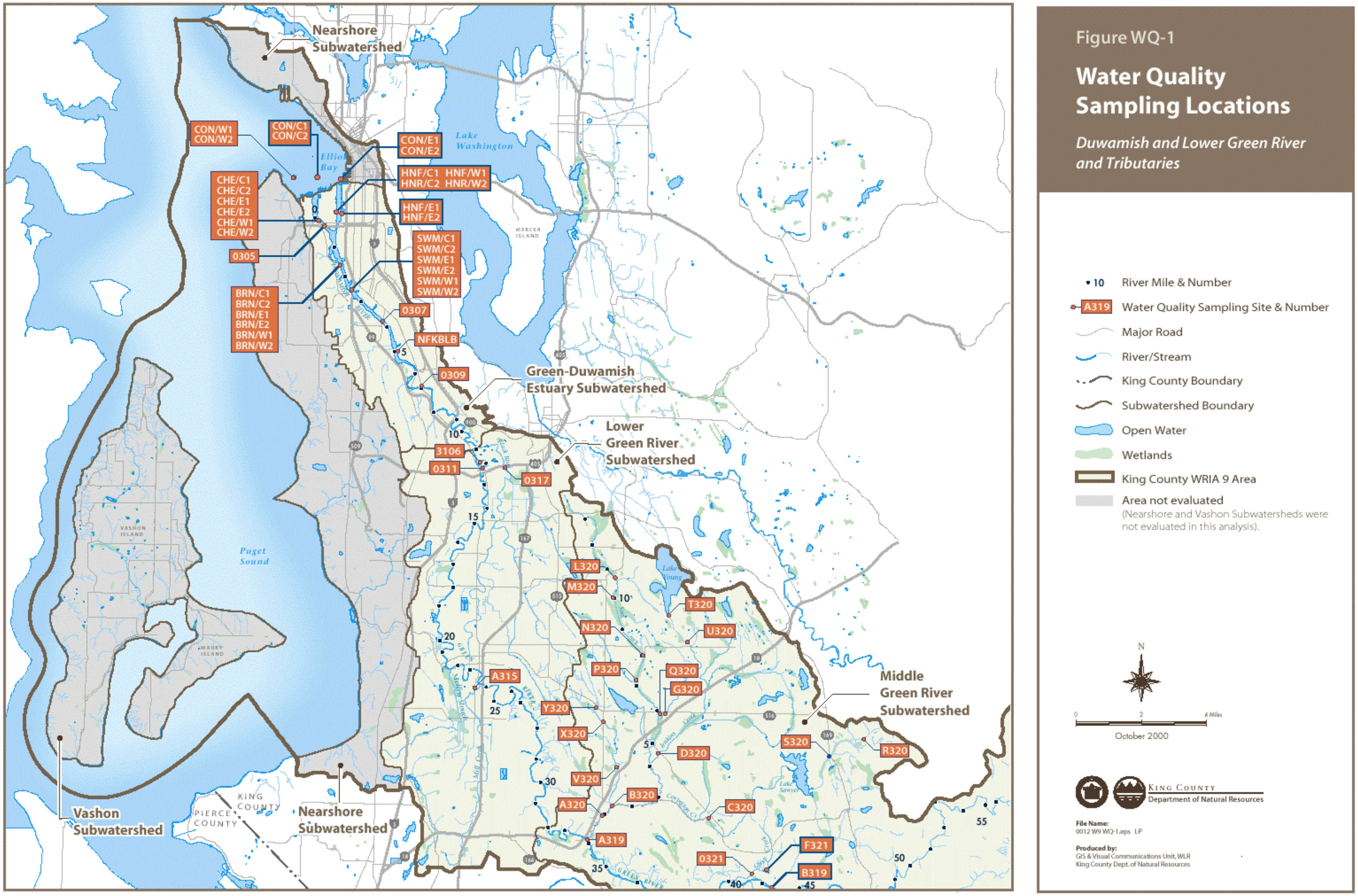


Figure 3.8 Water Quality Monitoring Stations in the Lower and Middle Green River Basins

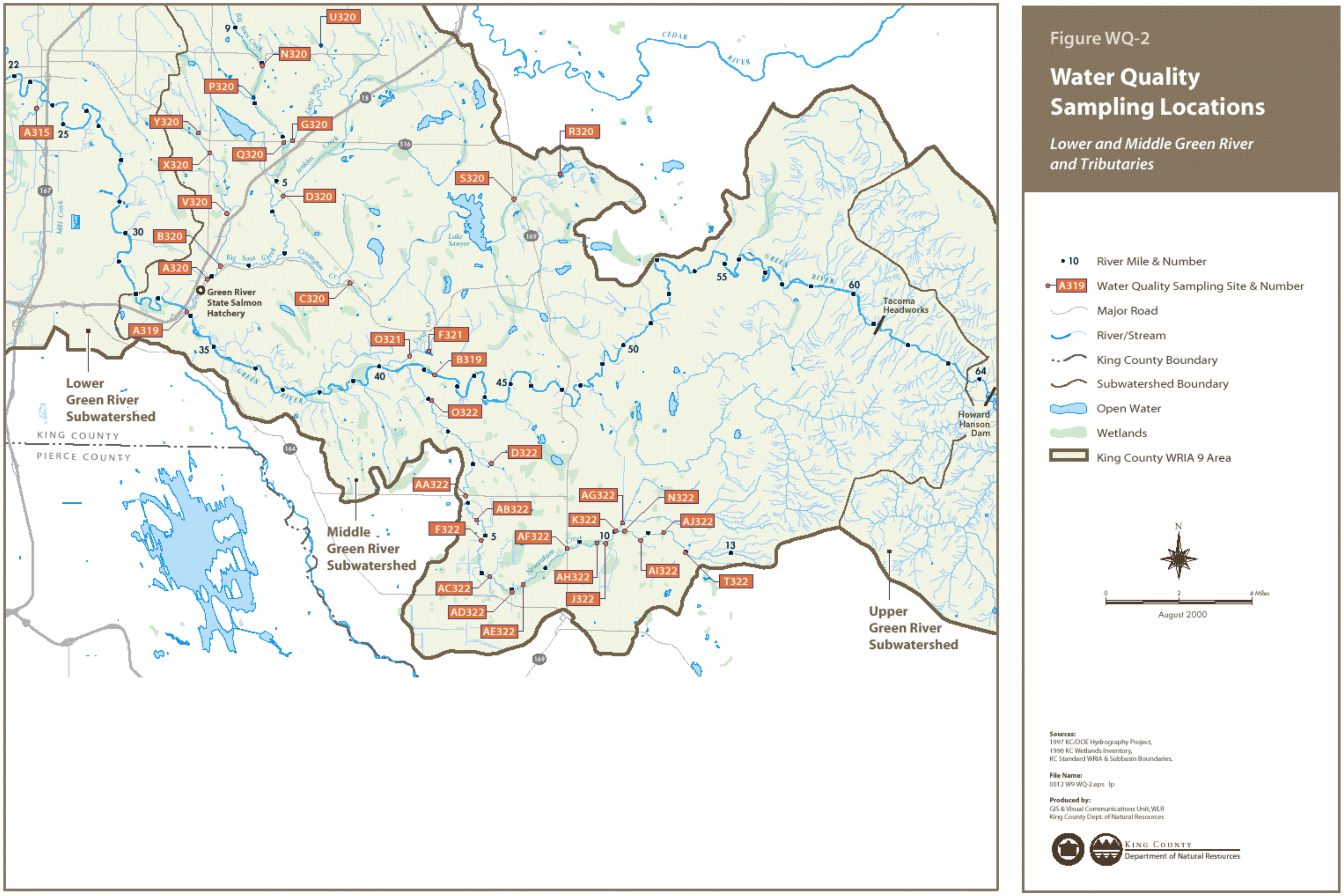


Table 3.10 Burkey 2001 Monitoring Stations

Description	Old Locator	New Locator	Sample Type	Micro	Conv	Nutrients	Metals	In-stream parameters	Organics
Hamm Creek	HAM205	A307	AS, MOG	S,B	S,B	S,B	S,B	S,B	--
Panther Creek	PAN121	A326	FG	S,B	S,B	S,B	S,B	S,B	--
Soosette Creek	Y320	Y320	AC, MOG	S,B	S,B	S,B	S,B	S,B	--
Green trib (Lea Hill)	LEA202	A330	FG	S,B	S,B	S,B	S,B	S,B	--
Newaukum trib (Enumclaw)	I322B	I322B	AC, MOG	S,B	S,B	S,B	S,B	S,B	--
Mill Creek trib (Springbrook basin)	SPR163	B317	FG	S,B	S,B	S,B	S,B	S,B	--
Newaukum trib (236th Ave SE)	D322	D322	AS, MOG	S,B	S,B	S,B	S,B	S,B	--
Newaukum trib (SE 424th St. – ditch)	NWK233	B322	FG	S,B	S,B	S,B	S,B	S,B	--
Newaukum trib (Weyerhauser)*	T322	T322	--	S,B	S,B	S,B	S,B	S,B	--
Crisp Creek above fish hatchery	F321	F321	FG	S,B	S,B	S,B	S,B	S,B	--
Green River trib in foothills near TPU diversion (Parker home)	MG209	A341	FG	S,B	S,B	S,B	S,B	S,B	--
Green River (Fort Dent Park)	DU1207	A310	AS, MOG	S,B	S,B	S,B	S,B	S,B	Q
Green River below HHD at USGS gaging station 12105900	TPU195	E319	AC, MOG	S,B	S,B	S,B	S,B	S,B	Q
Newaukum Creek near mouth	0322	0322	AC, MOG	S,B	S,B	S,B	S,B	S,B	Q
Springbrook Creek near mouth	SPR131	A317	AC	S,B	S,B	S,B	S,B	S,B	Q
Black River Pump Station	C317	C317	--	S,B	S,B	S,B	S,B	S,B	Q
Mill Creek near mouth	A315	A315	FG	S,B	S,B	S,B	S,B	S,B	Q
Soos Creek above fish hatchery	A320	A320	--	S,B	S,B	S,B	S,B	S,B	Q

A341 will be converted to AS, MOG after 2/5/2002

MOG = Metals Only Grab
S = Storm (8-10 per year)
B = Baseflow (bimonthly)
Q = Baseflow (quarterly)
AC = Auto-composite (no MOG)
AS = Auto-sequential (no MOG)
AC, MOG = Auto-composite+metals only grab
FG = Full grab

*not operational

Mainstem of Green River

As listed above in Table 3.10, part of the Green WQA Sampling & Analysis Plan (Burkey 2001) includes added stations defining boundary conditions for the mainstem of the Green. The downstream site is located very near the lower of the two current sites near I-405 (Station ID A310, at Fort Dent Park). The upstream sampling location is located approximately 0.5 mile downstream of Howard Hanson Dam (ID: E319).

There are five water quality monitoring stations located on the mainstem of the Green River. Two are located close to each other (upstream/downstream of Renton Treatment Plant) near I-405 in the Lower Green River. In this area of the basin, much of the land use is urban or agricultural. A third location has been started (December 2001) just downstream of Mullen Slough. The river is heavily impacted, including problems with temperature, bacteria, metals (chromium and mercury), DO, and sediment. The major gaps in monitoring are the lack of spatial variability, lack of continuous temperature, minimal metals data, and nonexistent organics monitoring.

In the Middle Green River, development is much lower, and there is substantial open space and agriculture. Temperature is the main impairment in this part of the mainstem Green. There are two water quality monitoring stations in the Middle Green, one located above the confluence of Big Soos Creek (RM 34.5), and the other above the confluence of Newaukum Creek (RM 41.5). The monitoring at these two stations would support modeling of Green WQA constituents with the exception of temperature, metals, and organics. Since temperature is monitored monthly, it would not be adequate to develop a model that represented daily maximum and minimum conditions. Also the metals data are minimal, and toxic organics are not monitored.

The Upper Green basin is largely forest, and there are few impairments. The watershed boundary for modeling is the City of Tacoma's water supply diversion dam at river mile 61 and/or the Howard Hanson Dam located approximately three miles upstream. The new water quality monitoring station one-half mile downstream of the dam will provide data for the upstream definition of the boundary condition for the modeling.

Black River/Springbrook Creek

The Black River/Springbrook Creek basin is entirely urban (residential, industrial, and commercial). Water quality is poor, and the primary concerns are DO, sediment, temperature, ammonia, bacteria, and metals. There are currently two active water quality monitoring stations in the basin, including the new station downstream of I-405. At the new station near the mouth the temperature data are continuous and the existing metals data include both baseflow and storm periods. Toxic organics are monitored quarterly.

Mill Creek

Mill Creek is a heavily impacted watershed, containing large amounts of residential, urban, commercial, industrial, and agricultural land uses. As a result, Mill Creek has poor water quality, including severe DO problems, high water temperatures, high suspended sediment, and high ammonia levels. The main constituents of concern are DO,

temperature, sediment, ammonia, and bacteria. There is only one monitoring station in Mill Creek, and it is not likely to be representative of a significant portion of the basin; therefore, one or more additional stations are recommended. However, the current monitoring is sufficient to develop a loading model for most Green WQA constituents for downstream areas.

Soos Creek/Big Soos Creek
The Soos Creek basin includes the Little Soos Creek, Big Soos Creek, Jenkins Creek, and Covington Creek. The basin has areas of high density residential and commercial development. Portions of Jenkins and Covington Creeks contain pasture and farms, and there is some mining of sand, gravel, clay, and coal. The Soos Creek basin is characterized by many wetlands and lakes. The primary constituents of concern are temperature, dissolved oxygen, nutrients (TP), and bacteria. There are extensive water quality monitoring stations in the Soos basin. There are sufficient data stations to support model development for Green WQA constituents with the addition of the new water quality monitoring stations (part of the Burkey 2001 monitoring program).

Newaukum Creek
Newaukum Creek water quality is impaired due to agriculture and residential development. The main areas of concern are dissolved oxygen, ammonia, temperature, bacteria, and toxic organics (due to agriculture). There are extensive water quality monitoring stations in the watershed, and there are sufficient monitoring stations to support calibration of a model of the basin for all constituents of concern in the Green WQA with the exception of toxic organics. All of the stations monitor temperature, but only the new Burkey 2001 stations are continuous. There are no data for any organics, such as pesticides or herbicides.

Crisp Creek
Crisp Creek is a small, relatively unimpaired watershed. It is of concern because of development pressures and the presence of a fish hatchery. There are two monitoring stations, which collect sufficient data to support modeling of Green WQA constituents with the exception of toxic organics.

3.4 Data Gap Analysis

The data gap analysis focuses on the water quality data needed to meet the modeling needs described above. Data gaps have been identified in the assessment of water quality data (Section 3.3) and are summarized below.

3.4.1 SWAMP Study Area

In the SWAMP study area, several data gaps should be filled to allow model calibration to support the SWAMP requirements. Additional stations may be needed on the larger tributaries such as North Creek and the Cedar River to better calibrate smaller subbasins and provide more resolution to the estimation of local water quality problems and to track

the sources of pollutants. A good quality station is needed at the selected upper boundary point for the Cedar River, e.g., the Lower Dam.

In addition to these possible additional stations, the following changes are recommended:

- Temperature monitoring should be continuous at all stations.
- All constituents/parameters should be monitored during both baseflow and storm periods.
- Metals data should be added to the constituents monitored (the information provided didn't include metals, but they may already be monitored); dissolved and particulate metals fractions are preferable.
- Any toxic organic constituents of interest should be included in the monitoring.
- Organic carbon (DOC, TOC, BOD) and chlorophyll should be monitored to support algae calibration.
- The organic nutrient species should be characterized with respect to dissolved vs. particulate and labile vs. refractory fractions. This will support linking the tributary watershed models to the Lake Sammamish, Lake Washington, and Sammamish River water quality models.

3.4.2 Green WQA Study Area

In summary, to address the data gaps identified in Section 3.3.2, at least two additional Green River mainstem stations plus one station in Mill Creek were needed prior to the implementation of the current water quality monitoring program. Current efforts address these data gaps (Burkey, 2001).

A monitoring station should be installed in or near the Mill Creek watershed, for example the Mullen Slough area.

In addition to the new station described above, the following changes are recommended:

- Temperature monitoring should be continuous at all stations
- TSS monitoring should include two or more size fractions of sediment (e.g. < 10 microgram, 10 – 62 microgram, > 62 microgram).
- All constituents/parameters should be monitored during both baseflow and storm periods.
- Any toxic organic constituents of interest should be included in the monitoring.
- If algae modeling is needed to accurately represent nutrients and DO, total organic carbon (TOC) and chlorophyll should be monitored.

4 STRATEGIC REVIEW OF MODELING APPROACHES

The strategic review of modeling approaches is based on a series of steps. These steps begin with a discussion of the watershed model applications required for SWAMP and Green WQA. This is followed by a discussion of appropriate model processes (both quantity and quality), a review of available watershed models, appropriate model selection criteria, and the model selection process. These steps produced a short list of candidate models that most closely match the needs for the SWAMP and Green WQA efforts. Following these discussions, the selected candidate models are described in more detail.

4.1 Watershed Model Applications

The SWAMP and Green WQA study areas require watershed models that produce water quantity and quality information for use in the applications required to meet the needs of the watershed modeling clients described in Section 2.

The applications can be divided into two categories: water quantity (flow) and water quality (temperature, nutrients, bacteria, metals, etc). Water quality can be further divided into modeling to determine the loadings for the receiving water models' boundary conditions and modeling of instream water quality.

As identified in Section 2, the Wastewater Treatment Division needs a model (or models) that can provide input to the receiving water body models representing Lake Sammamish, Lake Washington, and Lake Union for the SWAMP project and the Green-Duwamish estuary for the Green WQA program. These models need to be able to provide water quality information at the receiving water model boundaries at time intervals ranging from an hour or less to daily. The water quality constituents of interest include water temperature, DO, bacteria, nutrients, and metals.

Additional water quality and quantity information is needed to evaluate the impact of current and future planned activities on the environment to meet NPDES and ESA requirements. The proposed Brightwater WWTP is an example. The models need to simulate changes in hydrologic regime and water quality in the tributaries where the changes occur down to the rivers and lakes at the downstream end of the system. Information is needed at time intervals ranging from an hour to annual variations.

State and federal TMDL requirements will drive some modeling needs. Modeling will be required to determine load allocations for first order tributaries and larger water bodies. The primary water quality problems in the two study areas are fecal coliform and water temperature. Other cited problem water quality parameters are pH, dissolved oxygen, total phosphorus, heavy metals, pesticides, and other volatile organic compounds. Information on loading rates is needed at time intervals ranging from daily to annual.

King County has a number of other programs that require information that can best be obtained from water quantity and quality modeling results. The assessment of BMPs and proposed abatement measures is enhanced with data produced by the modeling of these activities. Information can be in the form of changes in hydrologic regime, water temperature, DO, bacteria, nutrients, and metals with a time resolution ranging from hourly to annual. In a similar fashion, UPD monitoring can be supplemented with both water quantity and quality modeling results on an hourly to annual time scale.

Habitat conservation plans and specific work in the development and implementation of a salmon recovery plan benefit from water quantity and quality data provided by the modeling work. In addition to the ESA requirements noted above, model results are needed to provide diagnostic data for the purpose of determining where water quantity and quality are factors of habitat and species decline. The data can be used to identify problem areas, assess additional data needs, and provide input to the implementation of a field monitoring program. The salmon recovery plan will also need to develop instream flow requirements for water courses ranging from small tributaries up to the mainstems of the major rivers (Green, Cedar, and Sammamish). The time interval of interest varies from a day to a year.

Groundwater management has its own set of modeling needs. Here the models need to provide groundwater stage and discharge, surface flow, water temperature, and nutrient information on a daily to annual time step to evaluate flow regime, drawdown and water balance changes produced by changes in land use, water supply, and wastewater management. The information can then be used to develop and evaluate management alternatives. One identified site for detailed groundwater management is the Sammamish Valley and potential reuse of partially treated wastewater for irrigation.

Water resources planning encompasses many of the previously discussed model applications as they relate to the determination of flow rates and volumes. The time frame ranges from daily to monthly for various first and second-order ungaged tributaries where flow values are needed to establish deregulated flows as part of an integrated water resource modeling program linked to many of the above described applications.

In summary, the watershed model applications are varied and comprehensive. They encompass a broad range of both water quantity and water quality constituents over spatial resolutions starting with small tributary areas and then expanding to the entire study areas of both the SWAMP and Green projects. The time resolution needs are equally broad, ranging from hourly or less to daily, monthly, and annual values. The selected model(s) must have the appropriate range of water quantity and quality algorithms to represent all of the constituents of interest, and they must be applicable over the range of time and spatial scales described above.

4.2 Model Processes

The selection of a model (or models) to meet the needs of the model applications depends on the ability of the model processes to accurately produce the information needed in a

timely manner within the resources and budget of King County. Therefore, it is important to identify the critical water quantity and quality modeling processes of interest and their usefulness in meeting King County's needs.

4.2.1 Water Quantity Modeling

The purpose of water quantity (hydrologic) modeling is to quantify the change in streamflow related to land use and other changes in the study areas. It also transports water quality constituents and is used in the calculation of pollutant loadings. Therefore it is important that the hydrology is accurately modeled and that the assumptions built into a hydrologic model are appropriate for the area(s) modeled.

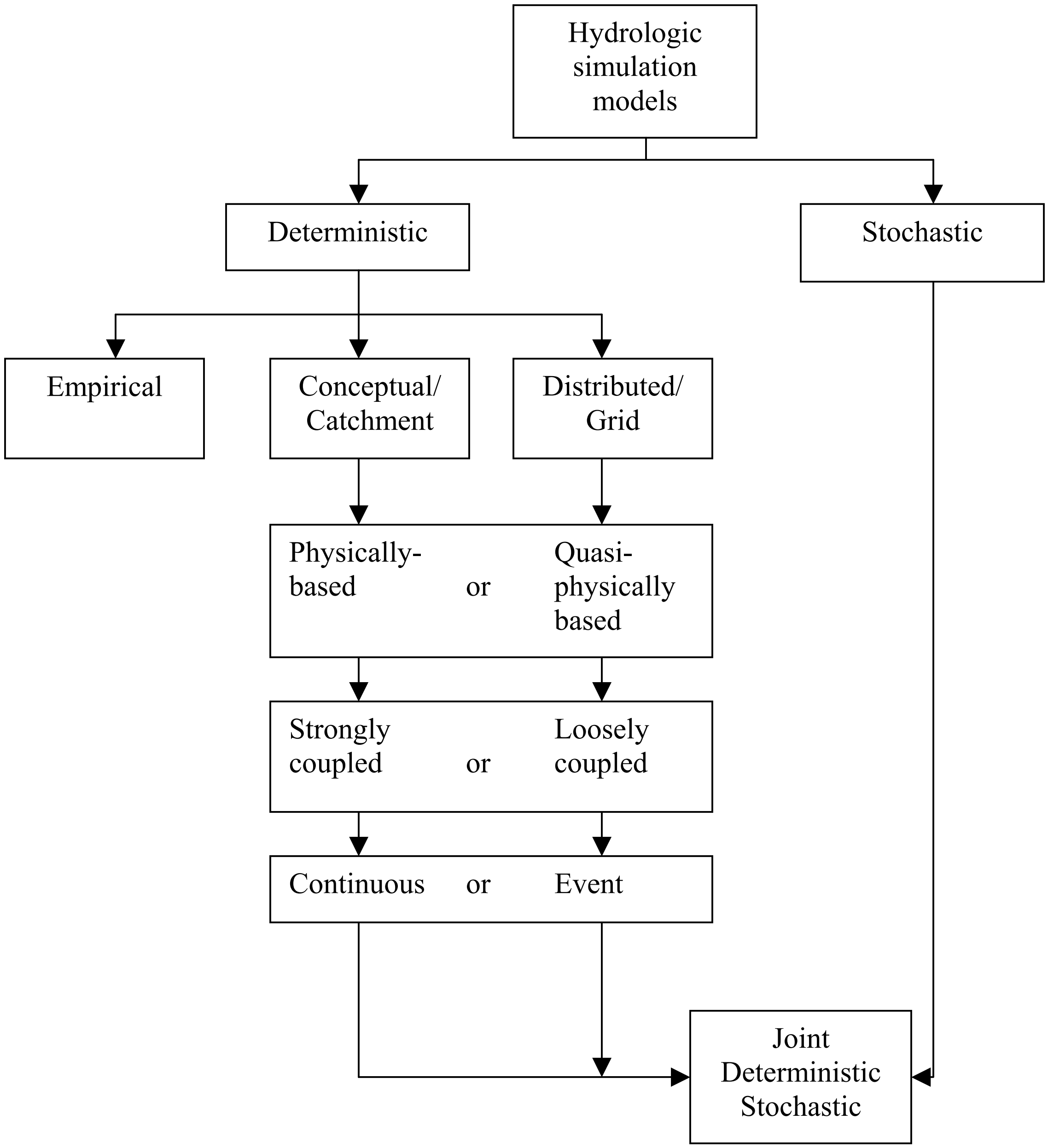
Water quantity modeling can be divided into stochastic modeling and deterministic modeling and then subdivided into smaller, more specific model approaches (see Figure 4.1).

Stochastic modeling approaches in hydrology are generally used to extend limited records of time series data such as precipitation by preserving both systematic temporal patterns and the probability of random fluctuations indicated by the available data. Stochastic models use Monte Carlo modeling to add degrees of uncertainty to the model's parameter values. This is useful in models with only a few key parameters or variables that have limited uncertainty. Otherwise, the number of computations becomes quite onerous due to the near infinite number of combinations of possible parameter values. Using a low, medium, high range of values the number of simulations becomes 3 to the N power, where N is the number of parameter value combinations. Such analysis is not feasible when using a complex watershed model with multiple parameters.

The SWAMP and Green WQA watersheds have long meteorological records that are needed for deterministic modeling. In addition, in these study areas the key model questions to be answered are most focused on the deterministic relationship between land use and water management actions and receiving water flow and quality. As a result, this report focuses on deterministic models that relate land and water management activities to receiving water quality.

Deterministic modeling uses physical processes observed in the watershed to reproduce the rainfall-runoff relationship. Simple deterministic models relate rainfall and runoff to a single event (a 100-year storm, for example) and are called empirical models. The Rational Method is an empirical model. More complex deterministic models simulate the continuous interaction between rainfall and runoff using soil moisture and evapotranspiration calculations to determine how much rainfall becomes runoff. The two major forms of these models are conceptual/catchment models, such as HSPF, and distributed/grid models, such as MIKE SHE.

Figure 4.1 Model Approaches



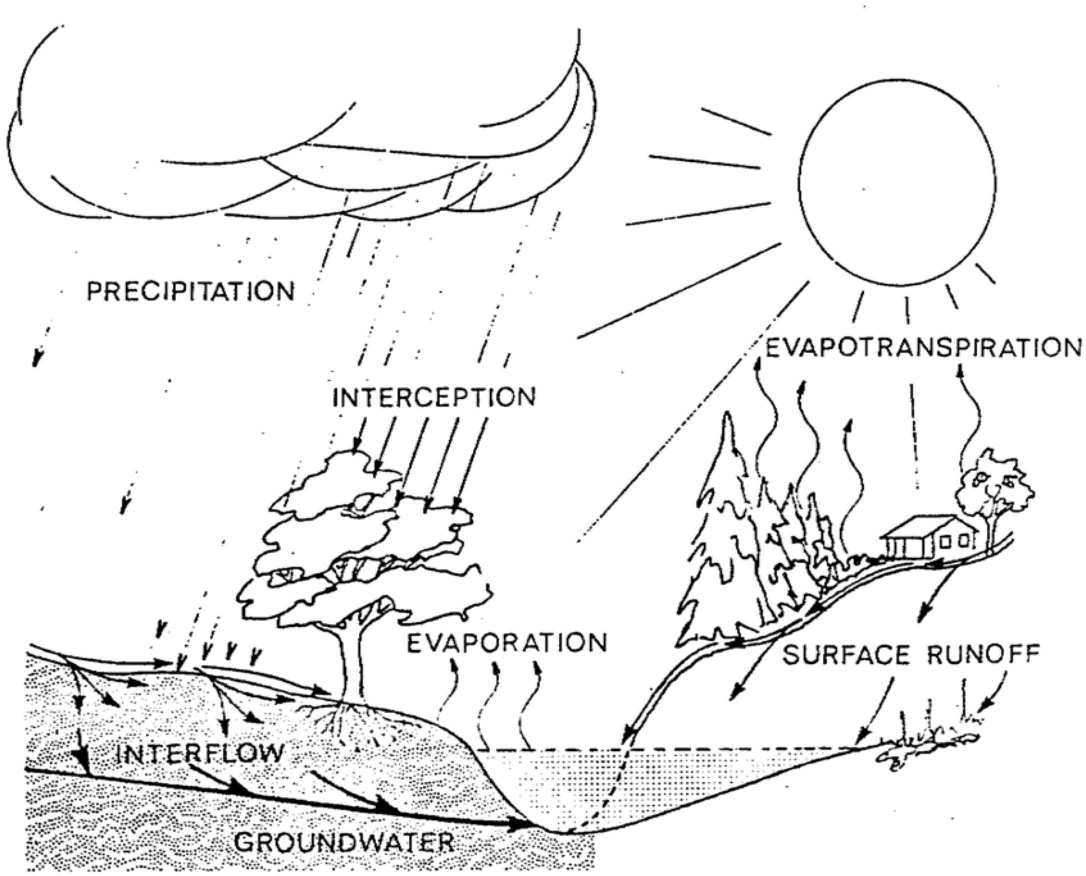
Catchment and grid continuous simulation models offer the greatest accuracy and flexibility to model the hydrologic processes of interest in the SWAMP and Green WQA study areas. This is because of their ability to represent a wide range of land use conditions, vegetation, soils, and human activities that affect both water quantity and quality. These models include HSPF, MIKE SHE, and DHSVM. These models are complex, require time series databases for model input and output, and work best on fast desktop computers. A brief description of their modeling processes follows.

4.2.1.1 Hydrologic Modeling of Watershed Processes

Hydrologic modeling processes are critical to water quality modeling because runoff and flow routing are the basic transport mechanisms for most pollutants. Some pollutants, such as sediment and total phosphorus, are transported primarily by overland flow or surface runoff. Others such as nitrogen and soluble phosphorus and pesticides are transported in the unsaturated soil zone and groundwater. Therefore, it is important that the hydrologic modeling processes adequately represent flow conditions and pathways.

Watershed hydrologic modeling is performed by computing the division of precipitation into interception, infiltration, soil moisture, evapotranspiration, and runoff. This describes the terrestrial phase of the hydrologic cycle (Figure 4.2). Runoff is then routed through the watershed's conveyance system to a downstream point of interest, such as the mouth of a river. These different processes must be represented to produce a model that is accurate and sensitive to parameters that reflect changes in land use/cover as well as routing pathways. This section presents a general discussion of these processes and the data requirements for modeling the hydrology of the SWAMP or Green WQA study areas.

Figure 4.2 Hydrologic Cycle



Interception

Interception of rainfall is the first process that occurs each time it rains. Interception acts like an umbrella in sheltering the soil from the initial rainfall. The amount of interception storage depends on the type of land cover or vegetation. A large tree provides more interception than a grass lawn, but both store some amount of water before any water reaches the soil surface and has an opportunity to either infiltrate into the ground or run off to the stream. Water is removed from interception storage through evaporation.

Infiltration

Infiltration is the movement of water through the soil column. The rate of infiltration (inches per hour) depends on the soil and its characteristics (particle size, pore space, etc.). Clay soils have lower infiltration rates than sandy soils. For a specific soil the actual infiltration rate varies according to the precipitation rate and the existing soil moisture level. If a sandy soil is already saturated and the rainfall intensity is high then the actual amount of water that infiltrates may be very low. Water that does not infiltrate tends to run off instead.

Some models, like HSPF, use a user-supplied index to the infiltration capacity of the soil. The actual infiltration of water into the soil varies each time step with the change in soil

moisture. As the soil gets wetter the actual infiltration rate decreases. The infiltration index is a calibration parameter because of the spatial variability in effective infiltration rates; even for a homogeneous soil the actual infiltration rate will vary with soil density, moisture, and surface conditions across the landscape. Rather than try to use or modify a literature value or field measurement, the infiltration index parameter value is calibrated by comparing simulated and recorded annual flow volumes and individual peak events.

Other models, like MIKE SHE, determine infiltration rates for each grid cell by using a finite difference scheme to solve a 1-D, partial differential equation for vertical, unsaturated flow known as Richard's Equation. Theoretically, the parameters for this equation are soil-physical properties that can be measured with sufficient accuracy to avoid calibration. However, this rarely turns out to be the case outside of rigorously controlled laboratory conditions. Three-dimensional spatial variability that occurs often at the sub-grid modeling scale in the field virtually guarantees the need to perform calibration based on field data, and as with other modeling approaches, there is some risk of scale-dependent parameter values resulting from the calibration process.

Soil Moisture

Soil moisture is the amount of water stored in the vadose or unsaturated soil column. The number of soil layers or zones represented in a model depends on the complexity of the soil column and the detail required by the modeler. Soil moisture is computed for each layer or zone, generally with interactions between each layer.

The amount of water in each soil layer varies based on the inflow to the layer and the flow out of the layer. Inflow is usually in the form of the water that infiltrates from the surface or the next layer above. Flow out of the layer can be via runoff (interflow), percolation down to the next layer (groundwater), and/or evapotranspiration through the roots of the overlying vegetation. This influx and outflux is simulated every time step.

Evapotranspiration

Evapotranspiration is the combined process of evaporation and transpiration. Evaporation occurs from land surfaces; transpiration is moisture removed from the soil by plants. Next to precipitation, evapotranspiration is the largest single factor in influencing the hydrologic cycle and the amount of runoff from a watershed. A typical watershed in the Puget Sound lowlands receives 40 inches of precipitation a year. Of this 40 inches approximately half (or 20 inches) returns to the atmosphere as evapotranspiration. The other half becomes runoff.

Actual evapotranspiration is computed based on the evapotranspiration demand, also known as the potential evapotranspiration (PET). PET is input to the models as a pan evaporation data time series multiplied by a coefficient. The coefficient (usually between 0.7 and 0.8) converts pan evaporation data to PET data.

Actual evapotranspiration (AET) is less than or equal to the PET. In hydrologic models AET is generally computed based on the amount of water available in interception storage and from the different soil layers or zones including groundwater.

Runoff

Rainfall that is not evaporated or transpired back to the atmosphere or is not stored in the soil becomes runoff. There are two major types of runoff: surface runoff and subsurface runoff. Surface runoff (also known as overland flow) occurs where either soils have become temporarily saturated or the land surface is impervious. Runoff on the surface is relatively fast in reaching a stream channel or conveyance system. In urban areas, where a large fraction of the land surface is impervious, surface runoff is the primary runoff component and is the major source of flooding problems.

Subsurface runoff, as the name implies, travels underground most or all of its way to reach a stream channel. Consequentially it is slower and more dispersed in adding water to the stream compared to surface runoff. Subsurface flow can be divided into interflow (flow through the unsaturated soil zone(s)) and groundwater (flow from a saturated soil zone). In undeveloped watersheds with little or no impervious area, interflow can be the major flow component. However, in urban watersheds interflow is usually smaller than surface runoff.

Groundwater is an important runoff component as it supplies streams and rivers with a continuous source of water. The calculation of groundwater discharge to rivers, lakes, and streams is done in one of two ways. The simplest way is to relate groundwater discharge to the groundwater storage and a discharge variable (also known as a recession constant). HSPF uses this approach. A more complex approach is to connect a 3-D groundwater model (like MODFLOW) to the channel system. Discharge from groundwater to the river is based on the relative head of each. MIKE SHE uses this method.

Groundwater transfer from one subbasin to the next can occur naturally through interconnection aquifers or can result from groundwater pumping that changes the slope and direction of the groundwater table. These groundwater changes will need to be explicitly included the watershed models.

Table 4.1 provides a summary of the data requirements.

Table 4.1 Typical Data Required for Water Quantity Modeling in SWAMP and Green WQA Study Areas

Process	Land Use/ Land Cover	External Environmental Data	Model Calibration

Interception	Vegetation	Precipitation PET	No
Infiltration	Surficial Geology/ Soil		Yes
Soil Moisture	Soil Vegetation	PET	Yes
Evapotranspiration	Vegetation	PET	Yes, annual water balance
Runoff	Soil Vegetation Land Use Topography	Precipitation PET	Yes

4.2.1.2 Key Factors for Hydrologic Modeling

All of the continuous simulation water quantity models of interest include algorithms that represent the hydrologic processes described above. However, there are some key factors that differ from model to model. These key factors include how the watershed is segmented in the models, routing mechanisms, and computational speed.

<u>Watershed Segmentation</u>

Watershed segmentation is a model's conceptualization of basin characteristics such as topography, land cover, soils/surficial geology, and flow patterns. In general there are two distinct segmentation concepts applied by watershed models, depending on whether they are catchment-based or grid-based. In catchment-type models such as HSPF, maps and/or GIS are used to sub-divided watersheds into topographically defined drainage areas or catchments. Each catchment is then identified as an input to a specific hydraulic routing reach of the channel network. This channel routing connection is the fundamental association of the land in the catchment to a geographic position within the watershed. While diverse slopes, soils, and land cover combinations or hydrologic response units (HRUs) may be represented within a catchment, the geographic position of these HRUs within the catchment is not represented by the model. This has the following consequences:

1. All areas within a catchment classified as belonging to an HRU behave hydrologically the same regardless of how areas associated with the HRU may be positioned within the catchment.

2. Hydrologic responses of different HRUs are assumed to be independent of one another and essentially contribute to a channel reach "in parallel".

3. Effects of sub-catchment-scale topography such as concentration of water and transported material from up-gradient areas is not represented at the sub-catchment scale.

Catchment-based models are not well-suited to determining topographically-driven hydrologic response at the sub-catchment scale. However, catchment areas can be subdivided to a level of spatial detail equivalent to that needed to represent a

topographically-driven response, if need. In addition, catchment-based models generally have a large computational efficiency advantage over grid-based models in that the number of HRUs needed to represent a watershed is generally two to three orders of magnitude less than the number of computational units needed by a grid-based model.

In grid-based water quantity models such as MIKE SHE and DHSVM topographic data such as a DEM (Digital Elevation Model) is linked to a grid system overlaying the watershed. The direction of the slope is used to determine the movement of runoff from one grid cell to an adjacent cell prior to reaching a conveyance system (stream or river). Slope steepness and direction are computed from the elevation data.

Each grid cell of a grid-based distributed water quantity model is assigned a specific land cover from aerial or satellite photography. In some models, such as MIKE SHE, this land cover can be either pervious or impervious, but it cannot be partially pervious and partially impervious. This is because these models have been developed and used primarily in large basins where the percentage of impervious area in the entire study area has been insignificant. In these basins there has been little or no need to explicitly model impervious area and impervious area is not an issue.

Other grid-based models, like DHSVM, were also originally developed for non-urban watersheds, but have recently been adapted for urban watersheds that contain large amounts of impervious area. These models allow for the user to assign a specific land cover to each grid cell. Land covers can include a value for impervious area that ranges from 0 to 1.0. The value is the fraction of the grid area that is impervious. In this adaptation, the impervious fraction is not spatially registered but treated similar to an impervious HRU in a catchment-based model.

The primary advantage of grid-based models is the potential to simulate the spatial distribution of water and transported materials at the scale of the individual grid. This detail is potentially accurate and useful to the extent that grid cells are small enough to be treated as homogeneous and that suitable parameters for each grid can be identified.

Routing Mechanisms

Conveyance system information (both natural and artificial drainage systems) is required to route the flow of water down to the receiving water body models. The speed at which water moves through a conveyance system depends on the size and shape of the storm sewer system, the natural stream channels and adjacent floodplain, the slope of the channels, the roughness of the channels and floodplain surfaces, and the size and location of obstructions in the channel network.

Routing of flows through a conveyance system can be done with different levels of sophistication. The simplest methods use nomographs and/or empirical equations based on drainage area or hydraulic length.

A more accurate method is reservoir (level pool) routing. This method is based on the continuity equation and a stage-discharge relationship. Typically stream channel cross

section information is used with Manning's equation to compute a stage-discharge relationship for each stream reach. A stage-volume relationship can also be established based on channel cross section information and the length of the stream reach. The combined stage-volume-discharge information can then be used together with the continuity equation to route flows through a drainage channel system.

This approach is adequate for estimating flow based on hydraulic properties that are averaged over the stream reach. However, this method generally requires use of rating curves that do not vary with time. Therefore transient backwater conditions in which a downstream reach temporarily alters the hydraulics of an upstream reach (in other words, the discharge is controlled by varying tailwater conditions) cannot be represented.

The most accurate method to route stream flows uses both the continuity equation and the momentum equation in the form of the St. Venant equations. The advantage of this full equations routing methodology is that backwater effects are explicitly modeled, unlike the level pool routing method.

If the timing and magnitude of flows from the tributary streams to the receiving water body models is important, then accurate representation of the major stream channel systems is important. Accurate representation includes good cross section data, appropriate Manning's roughness values, and constriction/culvert information. Good cross section data can be obtained in the field using standard surveying techniques or from advanced aerial photography using LIDAR (laser-based bald earth contour mapping).

The selection of appropriate Manning's roughness values requires a trained eye and modeling experience. Such publications as *Roughness Characteristics of Natural Channels,* USGS Water Supply Paper 1849 (Barnes, 1967), provide good guidance on the selection of Manning's roughness values, but ultimately selection of a roughness value is a judgment call by the modeler.

<u>Computational Speed</u>
With today's faster computers computational speed is less of an issue than in the past. However, as computer speed has increased so has the complexity of models. This is particularly true for grid-based models like MIKE SHE that track watershed moisture and flow by numerically solving partial differential governing equations for infiltration, groundwater movement, and streamflow. Table 4.2 provides a comparison of HSPF, DHSVM and MIKE SHE approximate run time to calculate streamflow in a 16 square mile watershed subdivided into 1036 grid cells with 60 channel reaches for a 5-year simulation period and a 1-hour time step. For this comparison, the catchment-based model, HSPF, was assumed to include 1036 different HRUs, an extremely large number and an unlikely application of a catchment-type model. However, the purpose of this comparison is to obtain a first approximation of run time for the same number of unique hydrologic units for each of the example models.

Table 4.2 Run Time Comparison

MODEL	NUMBER OF HYDROLOGIC SIMULATION UNITS	NORMALIZED RUN TIME (min)	TIME/ UNIT/ SIMULATION YEAR (sec)	SOURCE OF ESTIMATE
MIKE SHE	1036 grid cells, 60 channel segments	100	1.09	Personal Communication, David Hartley, 3/14/01.
DHSVM	1036 grid cells, 60 channel segments	25	0.27	Personal Communication, Mark Wigmosta, PNNL, 11/6/01
HSPF	1036 HRUs (PERLNDs), 60 channel segments	4	0.04	Personal Communication, David Hartley, 11/20/01.

The comparison is approximate and includes only water quantity calculations. No quality algorithms were operational. Run times on different hardware platforms were normalized to a 600-megahertz Pentium computer using clock speed as the normalizing factor. It is recognized that many other hardware and other factors may affect run times. However, the results are considered to be approximately valid and certainly provide a relative comparison of the different models. Thus, from column 4 in Table 4.2, HSPF is about 25 times faster than MIKE SHE and 6 times faster than DHSVM.

To simulate runoff over an entire watershed similar in size to the Cedar-Lake Washington or the Green-Duwamish with the same 200-meter resolution in the example above would require perhaps 35 times as much computation time. To increase the resolution to 30-meter grids consistent with LANDSAT data resolution would increase computation time by another factor of about 38.

The results shown in Table 4.2 reflect the complexity of the mathematical algorithms applied by each model. MIKE SHE is by far the most computationally intensive because it uses finite difference schemes to solve partial differential equations (PDEs) for 2-D overland flow, 1-D unsaturated flow, 3-D groundwater flow, and 1-D channel flow. In contrast, HSPF treats all of these flow processes as uni-dimensional and represents them mathematically with linear and non-linear reservoirs that are comparatively efficient from a computational perspective. However, while parameters of HSPF equations have some physical meaning, most cannot be field-measured. One exception is the channel and reservoir level-pool routing that is based on geometric and roughness properties of the drainage system. DHSVM's mathematical treatment of flow equations lies somewhere between those of MIKE SHE and HSPF. DHSVM does not route surface runoff but merely delivers it to a user-defined outlet in a single computational time step. Unsaturated flow calculations are based on a series of algebraic equations using

theoretically measurable, soil-physical, parameters such as saturated hydraulic conductivity and bubbling pressure. DHSVM applies a simplified, kinematic, approach to 3-D groundwater flow that is designed to represent topographic effects on the concentration and dispersion of groundwater and hence on the generation of surface runoff through variable saturation over the landscape. DHSVM's channel routing methodology is approximately equivalent to the one employed in HSPF.

As a practical matter, a catchment-based model like HSPF would rarely, if ever, be operated with 1036 distinct HRUs. A primary strategy of the catchment-based, HRU concept is to achieve computational efficiency by applying a hydrologic mapping unit approach. Consequently, hydrologic and transport effects associated with the spatial arrangement of HRU areas within a catchment are neglected in favor of two types of information:

1. Prediction of aggregate surface, interflow, and groundwater flow and transport at the catchment and multiple catchment scales, and

2. Unit area flow and transport for each HRU.

A highly detailed application of a catchment-based model to the 16-square mile watershed discussed above might include 50 HRUs and 50, 200-acre catchments with associated channel segments. In this region, such a model would resolve all first order perennial streams into 3-4 separate units. There would also be sufficient HRUs to characterize a wide range of soil, topographic, cover, land use/management, and elevation-dependent, climate variation. With a total of approximately 100 computational units, run time would be one-tenth of the amount shown in Table 4.2 for the 5-year, hourly simulation.

4.2.2 Water Quality Modeling

Water quality modeling has developed in parallel with water quantity modeling. Initially, simple procedures were developed to provide general water quality information. These are screening models. They are relatively simple and do not usually calculate actual pollutant concentrations, but yield rankings and risk potentials. Screening models are often used to prioritize water quality problems over a large geographic area so that a more complex simulation model can be focused on the areas of highest risk and provide more detailed and reliable assessments.

Screening models, also referred to as 'simple methods', are often defined as compilations of expert judgment and empirical relationships between physiographic characteristics of watersheds and pollutant export or loadings (EPA, 1992). They are usually implemented in a spreadsheet program, do not require site-specific information, and usually provide only mean annual loading estimates. Sometimes these mean annual loads are combined with mean annual flow to produce generalized concentration estimates for relative ranking and risk assessment purposes. Examples include EPA Screening Procedures (Mills et al., 1985), the Simple Method (Scheuler et al., 1987), USGS Regression Method

(Tasker and Driver, 1988), FHWA Method (Driscoll et al., 1990), and others identified in EPA's Compendium of Watershed-Scale Models for RMDl Development (1992).

For King County's watershed modeling needs, screening models do not provide specific detailed information that can be used to evaluate and analyze water quality problems, and provide boundary condition inputs to the receiving water models at the needed time and space resolution.

Simulation models (like those described in Section 3.1.1) represent specific water quality processes and calculate specific pollutant concentrations and loadings. These models include water quality land, soil, routing, and transport algorithms and can represent a wide range of water quality constituents including temperature, sediment, dissolved oxygen, nutrients, algae, bacteria, toxic organics and pesticides, and metals. The processes related to each are described below.

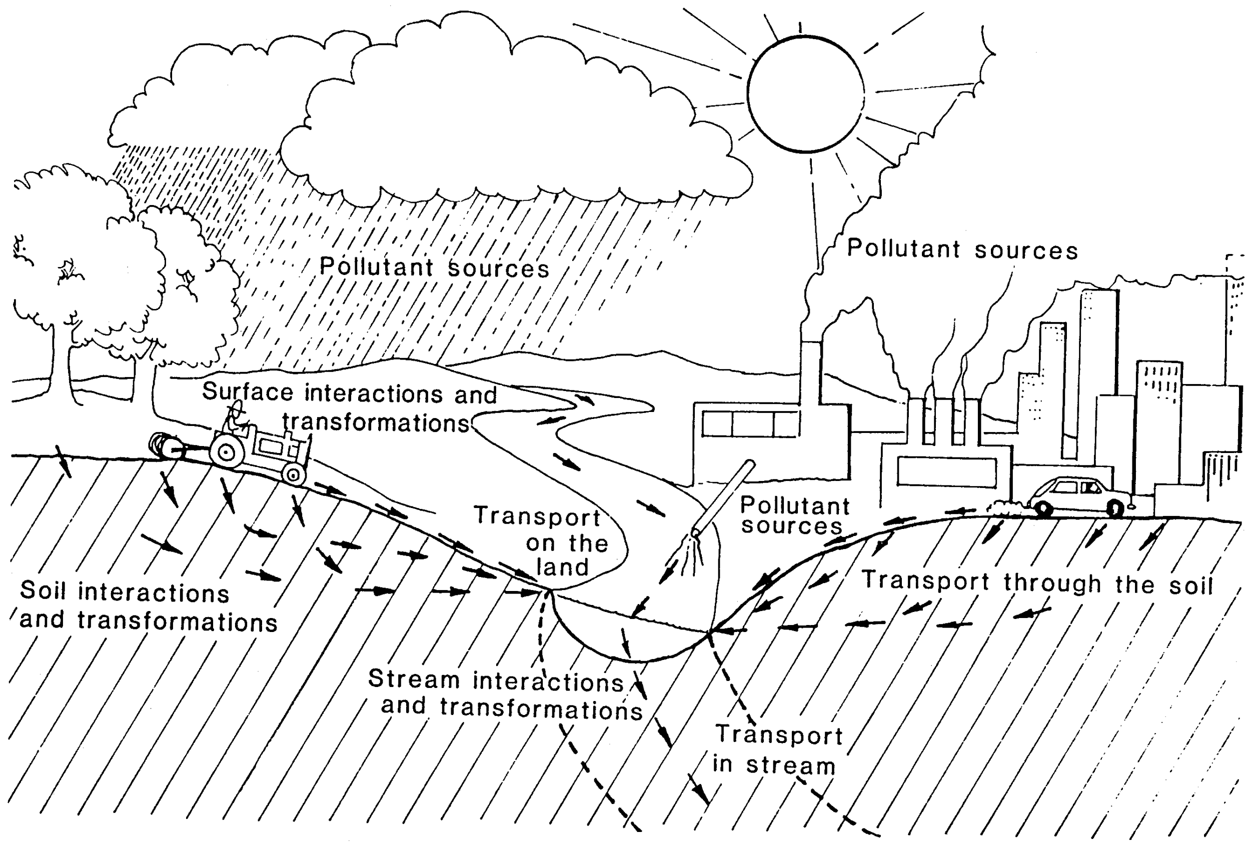
4.2.2.1 Water Quality Modeling Processes

Watershed water quality modeling is performed by estimating the loads of pollutants generated from land areas and point sources to surface waters, and then transporting and transforming the pollutants in the water until they exit the watershed. This process is illustrated in Figure 4.3. A wide variety of processes must be represented to produce a model that is accurate and sensitive to parameters that reflect changes in land use/cover as well as waste treatment processes. This section presents a general discussion of these processes and the data requirements for modeling the water quality constituents that are needed in either the SWAMP or Green WQA study areas or both. Table 4.3, at the end of the discussion, provides a summary of the data requirements.

<u>Temperature</u>

Modeling of temperature is necessary primarily because of the impacts of increased temperatures on desirable species of fish, specifically salmonids. Also, temperature is required for accurate representation of most other water quality processes and constituents. Increased water temperatures result from urbanization and forest removal, which produces large quantities of warm water from impervious surfaces, and removes riparian vegetation that shade and cool the water in streams. Some streams are also impacted by point source loadings of heat such as power production, industrial facilities, lumber production, and municipal wastewater treatment.

Figure 4.3 Overview of Watershed Water Quality Sources and Mechanisms



Temperature modeling is generally performed using a heat balance approach in which heat transfers across the air-water interface are the most important processes. These include conduction/convection, warming due to direct and indirect sunlight, radiational (longwave) heating and cooling, and evaporation. The types of data required to carry out temperature modeling are detailed meteorological measurements at a short time interval (e.g., solar radiation, wind, air temperature, humidity, dewpoint temperature, and cloud cover), accurate estimates of water surface area and shading due to terrestrial features and streamside vegetation, instream water temperatures at a number of locations, and estimates of the quantity and temperature of point sources, groundwater inflow, and runoff from land areas as well as un-modeled tributary streams.

Water temperature models that are based on the processes described above have been developed for use in QUAL2E, HSPF, CE-QUAL-W2, and others. The temperature modeling package Heat Source (Boyd, 1996), developed for Oregon DEQ, is also being used to develop TMDLs for a number of basins in the Pacific Northwest. Heat Source is a one-dimensional temperature model with steady-state flow that was designed for simulating temperature dynamics in streams and evaluating impacts of vegetative and terrestrial shading. Its detailed temperature and shade computation algorithms make it useful in analyzing specific tributaries under critical flow conditions where elevated temperatures are impacting salmon habitat. However, its use of steady flow would limit its applicability for watershed temperature modeling where variable flow conditions are

needed to provide dynamic boundary conditions for downstream water quality models. For full watershed simulations where dynamic flow is required, HSPF or CE-QUAL-W2 could be used. These dynamic temperature models offer less detail than Heat Source with respect to shading impacts, but include similar fundamental heat transfer algorithms which can be adapted (by adjusting the input solar radiation) to provide similar results for shading alternatives. For situations where depth-dependant temperature and more accurate hydrodynamics are needed, such as lakes or deep, slower-moving rivers, the two-dimensional CE-QUAL-W2 would offer more validity at the expense of significantly more detailed hydraulic inputs (i.e., cross-section data).

Sediment

Suspended sediments are of particular concern to King County because of negative impacts on salmonids and their association with and potential for transporting adsorbed pollutants such as metals, nutrients, and toxic organics from land areas into water streams and lakes. Increased sediment loads to surface waters result from urbanization (land development), forest removal, erosional impacts of higher flows in streams, and agricultural practices such as cultivation, removal of land cover, and bank erosion from grazing near streams.

In order to model suspended sediment, two primary processes must be represented. First is estimating the amount and nature of sediment that is eroded from the land and delivered to streams. This process is a function of the amount of soil exposed directly to rainfall and surface runoff, which in turn is affected by rainfall, land cover, land slope, soil disturbance, and transport properties of the soil. The second main process is transport in the streams and lakes, including advection, deposition, and scour. These instream processes are affected by the quantity and timing of flow, hydraulic properties of the water body (cross-section, etc.) and transport properties of the sediment. Therefore, sediment modeling requires detailed rainfall intensity data, estimates of land cover and slope, analysis of local soil and sediment properties, extent and timing of soil disturbance, stream and lake hydraulics (flow rates and geometry), and measurements of instream suspended sediment concentration over time and during a range of flow levels.

Dissolved Oxygen

Dissolved oxygen (DO) is a primary indicator of the health of an aquatic system. It is impaired by decay of carbon and/or nitrogen wastes resulting from point and nonpoint discharges, and is also affected secondarily by growth/respiration/death of algae which grow in response to nutrient inputs to the system. Lowered levels of DO caused by these processes are the main causes of fish and other species decline in natural waters. The main sources of low DO levels are point and nonpoint discharge of carbon and nitrogen-containing materials from waste treatment plants and agricultural operations, and discharges of nitrogen and phosphorus from waste treatment and urbanized areas which promote growth of algae.

In some cases where the effects of waste disposal are primary, and production of algae are minimal, modeling of DO can be limited to consideration of point and nonpoint discharges of carbon (CBOD) and nitrogen (NBOD) wastes, which degrade according to

relatively straightforward mechanisms. In this case, the types of data required are estimates of runoff of the wastes from various land uses, points source loads, laboratory analysis of carbon and nitrogen waste degradation rates, water temperature, and measurements of DO for model calibration. Ambient measurements of the CBOD and NBOD material are also useful for model calibration. For highly impacted water bodies, estimates will also be required of the impacts of bottom sediments on the anoxia. Some models include these benthic processes in the form of simple benthal release of BOD and/or benthal uptake of DO from the water column. More detailed models include complex sediment diagenesis processes.

Most water quality models include process algorithms that consider CBOD and NBOD inputs and standard decay processes that deplete DO. They also include detailed equations for estimating reaeration, which is the primary DO restoration process. Reaeration is strongly affected by flow (turbulence), water temperature, and wind speed; therefore, accurate data or information for estimating these effects is necessary.

Nutrients and Algae

When nutrient (inorganic nitrogen and phosphorus) enrichment occurs in natural waters, it promotes growth of free floating and attached algae, which results in anoxia and unpleasant water conditions. DO levels are reduced by respiration of the algae and decay of the resulting organic material following algal death. The main sources of nutrient enrichment in a watershed are a direct result of development and agriculture; they are both nonpoint and point, and include erosion of disturbed soils during construction activities, erosion due to agriculture, discharge of wastewater treatment effluent, and atmospheric deposition from transportation and fossil fuel-based power generation.

Modeling of nutrients and the resulting algal processes in watershed is commonly accomplished by estimating the loadings of nutrients from various land uses and point sources, transporting the nutrients in streams, and consideration of uptake by various species of algae in the streams and lakes. The algal growth processes are modeled such that the entire cycle of uptake, growth, respiration, death, and recycling of the nutrients is represented, and mass balances are computed for all key components. These include the various inorganic nutrient forms (NO_3, NH_3, PO_4), organic N, P, C, and algae. In addition, the effects of the various nutrient species and processes on DO are generally computed. Some models consider more complex systems such as complex growth dynamics, multiple species of algae, and more detailed fractionation of organic N, P, and C into dissolved vs. particulate and labile vs. refractory forms.

The data necessary to model nutrients and production of algae include loading of the individual nutrient forms (inorganic N and P) to the water, continuous solar radiation and water temperature, effects of shading on the available light, chemical information on the species of algae dominant in the waters (and seasonal changes), estimates of algal growth rates, and ambient measurements of the nutrient forms and algae (commonly in the form of chlorophyll) for model calibration.

Bacteria

Bacteria (e.g., fecal coliforms) are problems primarily because of their human and animal health effects. The main sources of bacteria result from: 1) development, which results in mixing of untreated human wastes with storm runoff, such as combined sewer overflows (CSO) or releases from septic tanks; 2) agriculture, which includes runoff of waste from animal feeding/grazing activities and runoff of manure applied as fertilizers; and 3) wildlife, such as large concentrations of birds and mammals (e.g., raccoons, skunks, and domestic pets).

Modeling of bacteria is typically accomplished by estimating loads from land areas and point sources (if significant), and using relatively simple instream processes such as first-order decay and possibly adsorption to suspended solids. Since bacteria may live for longer periods in the sediments, consideration of the bed sediment as a source/sink of bacteria may be necessary for some watersheds. The types of data necessary for modeling bacteria are estimates of loading from land areas and point sources, decay rates, water temperature, association with sediment, estimates of releases from the contaminated sediments, and measurements of ambient concentrations in receiving waters. Since bacteria are so highly correlated with storm runoff, monitoring of storm flow concentrations are required.

Most models contain mechanisms capable of modeling bacteria at the level of sophistication indicated in the above discussion, i.e., loading from the land and a simple decay mechanism. The main area of complexity may be the ability to model the effects of benthal sources and association with sediment.

Toxic Organics and Pesticides

Toxic organic compounds are of interest because of their effects on human health and animal species, including fish. The primary sources of these pollutants include washoff of pesticides and herbicides from developed and agricultural areas, and industrial process wastes. Therefore, specific urban and agricultural land uses and industrial point source discharges must be represented in the model, and loading rates from these sources must be estimated.

In order to model complex organic chemicals, models generally account for a wide range of processes, primarily transport in soil and water, adsorption to sediment and organic carbon, biological and physical degradation, and volatilization. Because these processes are inter-related, collection of site-specific data to parameterize the important processes for a chemical is ideal. These include adsorption coefficients, decay rates, and volatilization parameters. In addition, observations of dissolved and particulate forms in the water column and sediments at various times of the year must be available to calibrate the model. Water temperature is needed for instream modeling since degradation processes are temperature-dependent. Some models also incorporate bioaccumulation processes to directly assess health effects, but this is likely unnecessary for the current effort.

Metals

The processes and sources that are important for metals modeling are similar to those for organic pollutants with a couple of differences. Metals are of interest because of their toxicity to humans and animals, and their primary sources are nonpoint (generally transportation) and industrial waste discharges. Many of the processes associated with metals are similar to organics, specifically transport and adsorption. While metals do not degrade or volatilize to any significant extent, they do undergo complex speciation reactions in the environment, which results in highly site- and region-specific properties and process parameters. As a result, metals modeling in large scale systems such as a watershed or river generally is performed with simplified processes (i.e., adsorption) and approximate parameters that attempt to characterize the gross behavior of the total metal. The types of data required for such a model are estimates of metal runoff from various land uses, focused primarily on urban and industrial areas, estimates of point sources, region-specific adsorption parameters derived from laboratory analysis with local waters and sediments, and measured concentrations of dissolved and particulate fractions in rivers, lakes, and sediments (for model calibration).

Table 4.3 Typical Data Required for Watershed Water Quality Modeling of Constituents Needed in Swamp and Green WQA Study Areas

Constituent	Loading (Nonpoint & Point)	Instream Transport/ Transformation	External Environmental Data	Instream Measurements for Model Calibration
Water Temperature	Heat in runoff and point sources	Flow rate Shading Heat transfer coefficients	Meteorological data (solar radiation, air temperature, wind speed, humidity, cloud cover, etc.)	Continuous or daily temperature
Sediment	Sediment mass by size fraction	Flow rate and velocity Bed composition by size fraction Settling rates of particles Deposition/scour parameters		Base flow and storm concentrations and/or loads (by size fraction)
Dissolved Oxygen, Nutrients, and Algae	Oxygen Oxygen-consuming matter (CBOD, NBOD) Nutrients (NO_3, NH_3, PO_4)	Flow (rate and velocity) Water temperature Shading and bathymetry Organic matter decay rates Reaeration rates Algal growth, etc. parameters Benthal effects (release rates) Sediment transport Adsorption properties of nutrients	Solar radiation Wind speed	Dissolved oxygen Oxygen consuming organics Nutrients (NO_3, NH_3, PO_4) Chlorophyll
Bacteria	Mass of bacteria organisms	Flow Sediment Water temperature Bacteria decay rates		Base flow and storm measurements
Toxic Organics and Pesticides	Total mass of pollutant	Flow rate Sediment Adsorption parameters Decay rate Water temperature		Dissolved and adsorbed concentrations Base flow and storm measurements
Metals	Total metal	Flow rate Sediment Adsorption parameters		Dissolved and adsorbed concentrations Base flow and storm measurements

4.3 Watershed Model Selection

A strategic review of modeling approaches was conducted through a customized literature search of water quantity and water quality models that meet SWAMP and Green WQA project needs, goals, and objectives. The following strategy was used in conducting this review.

This strategy was based on the use of a recent compilation and review of a total of 150 water quality models for a range of water quantity and quality features and options, covering the range of hydrodynamic, rural and urban watershed, receiving water, chemical fate/transport, and groundwater models (Fitzpatrick et al., 2001). Of these 150 water quality models, 46 are watershed models that have modules and algorithms that represent the water quantity and quality processes described above.

The model selection process made use of extensive Internet research and evaluations of prior model compendiums. Table 4.4 lists the 46 watershed models evaluated as part of the selection process. This information was used in the consideration of alternative models for King County's use.

Table 4.4 Watershed Models (adapted from Fitzpatrick et al., 2001)

Model Acronym	Model Name	Sponsor/Developer
AGNPS – 98	Agricultural Non-Point Source Pollution Modeling System - continuous version	USDA ARS
ANSWERS	Areal Nonpoint Source Watershed Environmental Response Simulation	Beasley, N.C. State
APEX		Texas A&M, USDA ARS
BASINS	Better Assessment Science Integrating Point and Nonpoint Sources	EPA OST
CREAMS	Chemicals, Runoff, and Erosion from Agricultural Management Systems	USDA ARS
DHSVM	Distributed Hydrology Soil Vegetation Model	University of Washington
DR3M-QUAL	Distributed Routing Rainfall Runoff Model – Quality	USGS
EPIC	Erosion/Productivity Impact Calculator	USDA ARS
ETD	Enhanced Trickle-Down Model	Nikolaidis and Schnoor
FHWA	Pollutant Loading Model From Highway Stormwater	Federal Highway Administration
GISPLM	Lake Champlain Phosphorus Loading Model	VT Dept. of Conservation
GLEAMS	Groundwater Loadings Effects of Agricultural Management Systems	USDA ARS
GWLF	Generalized Watershed Loading Functions	Cornell U.
HSPF	Hydrological Simulation Program - Fortran	U.S. EPA, USGS, AQUA TERRA
HUMUS	Hydrologic Unit Model GRASS/SWAT Interface	USDA ARS
HUWQ	Hydrologic Unit Water Quality GIS Interface to AGNPS, SWRRBWQ, EPIC and GLEAMS	USDA NRCS
ILWAS	Integrated Lake-Watershed Acidification Study	EPRI, Tetra Tech
KINEROS	Kinematic Runoff and Erosion Model	Smith

Model Acronym	Model Name	Sponsor/Developer
LWWM	Linked Watershed/Water body Model	SWFWMD/Dames and Moore
MAGIC	Model of Acidification of Groundwater in Catchment	U.S. EPA Corvallis
MIKE SHE	Distributed and Physically-Based Modeling System for Flow, Water Quality and Sediment	Danish Hydraulic Institute
NAPRA	National Agricultural Pesticide Risk Analysis Screening Using GLEAMS	USDA
NLEAP	Nitrate Leaching and Economic Analysis Package	USDA
Opus	Simulation Model for Agricultural Management Practices	USDA ARS
OWLS	Object Watershed Link Simulation	Chen, Oregon State
PRMS	Precipitation-Runoff Modeling System	USGS
PRZM-3	Pesticide Root Zone Model	U.S. EPA CEAM
RZWQM	Root Zone Water Quality Model	USDA ARS
SHE/SHESED	Basin Scale Water Flow and Sediment Transport Modeling System	Univ. of Newcastle, UK Institute of Hydrology, Danish Hydraulic Institute
SITEMAP	Stormwater Intercept and Treatment Evaluation Model for Analysis and Planning	Omicron Associates
SLOSS-PHOSPH	Simplified Pollutant Yield Approach	VPI
SLURP	Simple Catchment Reservoir Parametric Model	Kite
SPUR-91	Simulation of Production and Utilization of Rangelands	USDA ARS
SSARR	Streamflow Synthesis and Reservoir Regulation Model	U.S. ACOE
STORM	Storage, Treatment, Overflow, Runoff Model	U.S. ACOE HEC
SWAT	Soil and Water Assessment Tool	Texas A&M, USDA ARS
SWMM	Storm Water Management Model	University of Florida, U.S. EPA CEAM, Oregon State
SWRRBWQ	Simulator for Water Resources in Rural Basins	USDA ARS
USGSREGR	Pollutant Loading Regression Method	USGS
UTM-TOX-WHTM	Unified Transport Model for Toxics	Oak Ridge National Lab
WARMF	Decision Support System for Watershed Management	EPRI, Systech
WATERSHED	Phosphorus Loading Spreadsheet Model	U. of Wisconsin
WEPP	Water Erosion Prediction Project	USDA ARS
WMM	Watershed Management Model	FL DEP/CDM
WMS	Watershed Modeling System	Brigham Young, U.S. ACOE WES
WSTT	Watershed Screening/Targeting Tool	EPA OWOW

Additional detail on each of these watershed models is included in the model matrix shown in Table 4.5. The matrix provides information on space-scale, time-scale, pollutants, processes, input/output aids, BMP evaluation, level of effort, data requirements, modeler expertise, and model availability.

4.3.1 Model Selection Criteria

Model selection criteria were established to reflect King County's needs, as related to the watershed model application discussion above. This allowed us to develop a specific list of decision criteria for evaluation of the watershed models. The criteria included the type of model, time scale, pollutants simulated, processes, input and output aids, resource requirements, model support, and model availability (Fitzpatrick et al., 2001). Each is briefly described below.

4.3.1.1 Type of Model
Three major types of models are included in the watershed model decision criteria: rural, urban, and sewershed. Rural models represent forest and agricultural land with little or no significant impervious area and open channel conveyance systems. Urban models include the complexities of the urban landscape, drainage features, and pollutants. Sewershed models are specifically designed to simulate sanitary sewer systems and their associated infiltration and inflow problems.

4.3.1.2 Time Scale
The time scale of the models is an important criterion. The time scale can be either event based, continuous, or annual. Event based models simulate a single occurrence, often hypothetical like a 100-year flood. Continuous models simulate actual hydrologic and water quality conditions over a wide range of historical meteorological events. Continuous models have the ability to simulate results on all time scales and aggregate results on a daily, monthly, and annual basis. By comparison, an annual model is often used as a screening tool to quickly summarize total water quality loadings without considering seasonal or shorter time variations.

4.3.1.3 Pollutants
For the purposes of this criterion pollutants have been grouped into three major categories: sediment, nutrients, and other chemicals. Sediment is related to erosive processes both on the land surface and in the stream channel system. Nutrients include both nitrogen and phosphorus in their many forms. The other chemicals category is for any other pollutant, like pesticides, metals, bacteria, etc.

4.3.1.4 Processes
Processes are divided into two major categories: transport of pollutants and transformations. Transport is the movement of pollutants in soil, from the land to the channel system, and through the channel system. The transformation process allows chemical and biological interactions that change a pollutant either on the land surface, in the soil profile, and/or during routing through the channel system.

Table 4.5. Watershed Model Matrix (adapted from Fitzpatrick et al., 2001)

	Space-scale					Time-scale		Pollutants			Processes		I/O Aids		BMP Evaluation		Level of Effort			Data Requirements			Modeler Expertise			Model Availability	
	Field	Small Watershed	Large Watershed	Catch-ment	Distributed	Event	Con-tinuous	Sediment	Nutrients	Chem-icals	Trans-port	Trans-formations	GUIs	Linkage to GIS	Simple	Detailed	Low	Medium	High	Low	Medium	High	Low	Medium	High	Public Domain	Proprietary
AGNPS-98	X	X	X		X	X	X	X	X	X	X	X	X	X	X	X		X	X		X	X		X	X	X	
ANSWERS	X	X	X		X	X	X	X	X		X				X	X		X	X		X	X		X	X	X	
APEX	X	X		X		X	X	X	X	X	X	X	X	X	X	X		X			X			X		X	
BASINS (HSPF)	X	X	X	X		X	X	X	X	X	X	X	X	X	X	X		X	X		X	X		X	X	X	
BASINS (SWAT)	X	X	X	X		X	X	X	X	X	X	X	X	X	X	X		X			X			X		X	
CREAMS	X			X		X	X	X	X	X	X	X			X	X		X	X		X	X		X	X	X	
DHSVM		X	X		X	X	X							X					X		X	X		X	X	X	
DR3M-QUAL	X	X		X		X	X	X	X	X	X							X			X			X		X	
EPIC	X			X		X	X	X	X	X	X	X	X	X	X	X		X			X			X		X	
ETD	X	X		X		X	X			X	X	X			X		X	X		X			X	X		X	
FHWA	X	X		X		X			X	X							X			X			X			X	
GISPLM	X	X	X	X		X	X		X		X		X	X	X	X		X			X			X		X	
GLEAMS	X			X		X	X	X	X	X	X	X		X	X	X		X	X		X	X		X	X	X	
GWLF	X	X	X	X		X	X	X	X		X				X		X			X				X		X	
HSPF	X	X	X	X		X	X	X	X	X	X	X	X		X	X		X	X		X	X		X	X	X	
HUMUS	X	X	X		X	X	X	X	X	X	X	X	X	X	X	X		X			X			X		X	
ILWAS	X	X	X	X		X	X		X	X	X	X			X	X			X			X			X		X
KINEROS	X	X			X	X	X	X			X				X	X		X	X		X	X		X	X	X	
LWWM	X	X	X		X	X	X	X	X	X	X	X	X	X	X	X			X			X			X	X	
MAGIC	X	X		X			X			X	X	X			X		X	X		X	X		X	X		X	
MIKE SHE	X	X	X		X	X	X	X	X	X	X	X	X	X	X	X		X	X		X	X		X	X		X
NAPRA	X			X		X	X	X	X	X	X	X	X	X	X	X		X	X		X	X		X	X	X	
NLEAP	X			X		X	X		X		X	X	X	X	X	X	X	X		X	X		X	X		X	
Opus	X	X		X		X	X	X	X	X	X	X	X	X	X	X			X			X			X	X	
OWLS	X	X			X	X	X						X	X	X			X			X			X			X
PRMS	X	X	X	X		X	X	X			X		X	X	X	X		X	X		X	X		X		X	
PRZM-3	X	X		X		X	X	X	X	X	X	X			X	X		X			X			X		X	
SHE/SHESED	X	X	X		X	X	X	X			X			X	X	X			X		X	X		X	X		X
SITEMAP		X		X		X	X		X		X		X		X			X			X			X			X
SLAMM	X	X		X		X	X	X	X	X	X			X	X	X		X			X			X		X	
SLOSS-PHOSPH	X	X		X		X		X	X		X						X			X				X		X	
SLURP	X	X	X		X	X	X						X	X				X			X			X		X	
SPUR-91	X	X		X		X	X	X	X		X	X		X	X	X		X	X		X	X		X	X	X	
SSARR	X	X	X	X		X	X						X		X	X		X			X			X		X	
STORM	X	X	X	X		X	X	X	X	X					X			X	X		X	X		X	X	X	
SWAT	X	X	X	X		X	X	X	X	X	X	X	X	X	X	X		X			X			X		X	
SWMM	X	X	X	X		X	X	X	X	X	X		X	X	X	X			X			X			X	X	X
SWRRBWQ	X	X	X	X		X	X	X	X	X	X		X		X	X		X	X		X	X		X	X	X	
USGSREGR	X	X	X	X		X		X	X	X							X			X			X			X	
UTM-TOX-WHTM	X	X	X	X		X	X	X	X	X	X								X			X			X	X	
WARMF	X	X	X	X		X	X	X	X	X	X	X	X	X	X			X				X		X			X
WATERSHED	X	X		X		X		X	X		X				X			X			X			X		X	
WEPP	X	X		X		X	X	X			X		X	X	X	X		X				X		X		X	
WMM	X	X	X	X					X	X	X	X			X		X			X				X			X
WMS (HSPF)	X	X	X	X		X	X	X	X	X	X	X	X	X	X	X		X	X		X	X		X	X		X
WSTT	X	X	X	X		X	X	X	X	X	X		X	X	X		X			X			X			X	

4.3.1.5 Input and Output Aids

Input and output aids to watershed models consist of GUIs (graphical user interfaces) and linkages to GIS. GUIs have been added to models written in Fortran to improve user input of model data and specify model outputs through a graphical interface. Newer models have been developed using software tools and languages that automatically include a graphical interface. Linkages to GIS simplify the connection of model to land use and land cover information, DEMs (digital elevation models), and GIS databases. The most common GIS link is to Arc-View.

4.3.1.6 Resource Requirements

Resource requirements relate to three different types of resources needed to apply a watershed model: level of effort, data, and modeling expertise. These requirements relate to the type of model, time scale, level of analysis, processes, and input and output aids described above. For each one of these resource requirements a value of low, medium, or high can be assigned. For example, a simple screening model may only require a low level of effort, low amount of data, and low modeling expertise. In exchange a screening model produces a low amount of results with low accuracy.

4.3.1.7 Model Support

Model support is judged in terms of documentation, the amount of sponsor support, and the availability of training and other workshops. Documentation is important in understanding the theory and application of a model and can be either weak or strong. Sponsor support of a model is a good indication of its usefulness and value. A strongly supported model will have more resources dedicated to its use and future development. The availability of workshops is another gauge of model support and use. Workshops help to train new users and provide new ideas and uses to more experienced users.

4.3.1.8 Model Availability

Models are either made available through the public domain or are proprietary. Public domain models can usually be obtained free of charge directly from the Internet or the supporting government agency. Their computer source code can be read and analyzed to better understand model algorithms and operations. Proprietary models are the property of the developing company or agency and are sold for a fee ranging from a few hundred dollars to many thousand dollars. The source code is usually not available for inspection or modification.

4.3.2 Model Selection Process

This set of criteria was used to narrow the list of watershed models for consideration for King County watershed model applications. The software selection criteria were applied to both urban and rural watersheds to reflect the variety of watershed conditions found within the SWAMP and Green WQA study areas.

4.3.2.1 Type of Model

The water quantity and quality information provided by the selected model(s) needs to include both urban and rural watershed areas. Significant pollutants include those from urban streets (metals and oils) and suburban and urban landscaping (nutrients and bacteria) and rural sources (agricultural pollutants, such as fertilizers and livestock wastes). Runoff quantity and quality from both urban and rural lands contributes to the boundary condition information required for the receiving water body models for both SWAMP and Green WQA study areas. In addition, both small and large watershed areas need to be modeled to include both small tributary areas and the combined runoff as input to lakes and the mainstem of rivers which are either the downstream terminus or boundaries for the receiving water body models.

Of the 46 watershed models listed in Table 4.5, 26 meet this criterion, although some are primarily rural watershed models with limited capability to represent the complexities of urban drainage.

4.3.2.2 Time Scale

As previously discussed, the time scale of the model applications varies from hourly to annual. Only a continuous simulation model can provide information over this range of time scales.

This criterion reduced the number of potential candidate models by two more to 24. These 24 include: BASINS, DHSVM, HSPF, MIKE SHE, SWMM, and others.

4.3.2.3 Pollutants

The pollutants required for modeling for the receiving water body models, TMDL studies, and other water quality requirements (NPDES, ESA, etc.) include water temperature, DO, nutrients, bacteria, and metals. This also requires the ability to model sediment transport of these pollutants.

This criterion further reduces the available field of models to AGNPS-98, BASINS, DHSVM (see below for additional details), HSPF, HUMUS, LWWM, MIKE SHE, STORM, SWMM, SWRRBWQ, UTM-TOX-WHTM, WARMF, WMS, and WSTT.

DHSVM does not currently include water quality algorithms and could have been eliminated from the selection process for not meeting this criterion. However, it was decided to keep DHSVM as a viable model option due to the work at the University of Washington and Battelle Pacific Northwest Laboratory to add water quality to DHSVM, and the direct applicability of DHSVM to the King County region.

4.3.2.4 Processes

The water quality processes to be included in the modeling applications require both the ability to model the transport of pollutants from the land surfaces to and through the

stream channel system and the transformation of pollutants through chemical and biological processes enroute. These processes are required for the receiving water body model boundary conditions and the evaluation of water quality changes for TMDL studies, assessment of BMPs, UPD monitoring, habitat conservation plans, and ESA requirements.

This criterion reduces the field to AGNPS-98, BASINS, DHSVM, HSPF, HUMUS, LWWM, MIKE SHE, WARMF, and WMS.

4.3.2.5 Input and Output Aids

This criterion does not further reduce the potential list of models as all of the remaining models have some form of graphical user interface available and a link to GIS either directly or indirectly.

4.3.2.6 Resource Requirements

Resource requirements relate to the resources required by the model compared to the resources available to the modeler. These resources requirements are difficult to quantify. All of the remaining models fall into the medium to high range in terms of the resources required to set up and run the models. This is expected for the range of sophisticated application needs of the King County programs, as described in Section 2.

This criterion does not reduce the list of potential models.

4.3.2.7 Model Support

Model support is another criterion that is difficult to quantify, as each model has some level of support associated with it. Newer models tend to have less model support available due to the limited use and experience. For example, DHSVM, a new model undergoing testing and refinement at the University of Washington, does not yet have a users manual available. Obviously, this makes model support more limited. Proprietary models (listed below in Section 4.2.2.8) rely upon the software developers to be the sole source of model support. This does not necessarily result in less model support, but does decrease the user's options when seeking support and/or assistance in use of the model.

No models were eliminated from the list based on this criterion.

4.3.2.8 Model Availability

The model availability criterion is important if there is a need to limit the model selection process to either public domain (free) software or proprietary (pay) software. King County has not expressed a specific preference for public domain software and recognizes that even with public domain software there are inherent costs associated with learning and applying the software. Of the remaining nine models, five are public domain software (AGNPS-98, BASINS, DHSVM, HSPF, and HUMUS) and four are proprietary (LWWM, MIKE SHE, WARMF, and WMS).

4.3.2.9 Model Selection Finalists

Forty-six models were initially considered for selection to meet King County's model application needs. Through the model selection criteria presented above, the list was narrowed down to a potential list of nine models: AGNPS-98, BASINS, DHSVM, HSPF, HUMUS, LWWM, MIKE SHE, WARMF, and WMS.

Rather than continue to consider all nine models, a brief summary of each is presented below, so as to provide additional information by which the field can be further reduced.

AGNPS-98 and HUMUS are agricultural water quality models developed and supported by the USDA ARS. They are not designed for urban watersheds and do not have algorithms specifically related to the modeling of impervious surfaces. While they may be useful for some limited water quality applications in the agricultural upland areas of the Green WQA study area, they are not appropriate to provide water quality boundary condition information in the urban and suburban portions of the SWAMP and Green study areas. As a consequence, these two models are removed from further consideration.

LWWM is a linked watershed/waterbody model (hence the name) that uses the SWMM Runoff block to generate runoff and associated water quality loadings. It is a proprietary model developed jointly by ASCI Corporation and Dames & Moore for the Southwest Florida Water Management District. The simplified hydrology of LWWM, combined with its limited application to the water quality processes and pollutants that are predominately found in Florida's tropical climate, made LWWM less useful for King County's needs than the alternative models available.

WARMF (Watershed Analysis Risk Management Framework) is a proprietary decision support system for TMDLs developed by Systech Engineering, Inc., under the sponsorship of Electric Power Research Institute. WARMF is a useful tool to help establish consensus about TMDLs among various stakeholders and might be appropriate for the future King County/Department of Ecology TMDL work. However, it does not have the capability to model detailed urban and suburban drainage systems nor to specifically separate and distinguish different land uses and their individual contributions to water quantity and quality. Therefore WARMF does not have the flexibility to provide sufficient information to King County's internal clients and programs. As a result, this model is removed from consideration.

MIKE SHE is a proprietary model developed by the Danish Hydrology Institute (DHI). It is a complex watershed model with many components and modules that can be used to model hydrology, hydraulics, groundwater, and water quality. As previously noted, MIKE SHE is a grid-based model that uses finite difference schemes to solve partial differential equations (PDEs) for 2-D overland flow, 1-D unsaturated flow, 3-D groundwater flow, and 1-D channel flow. It is very computationally intensive. MIKE SHE has seen only limited use in the United States. MIKE SHE remains under consideration and will be discussed more in Section 4.3.

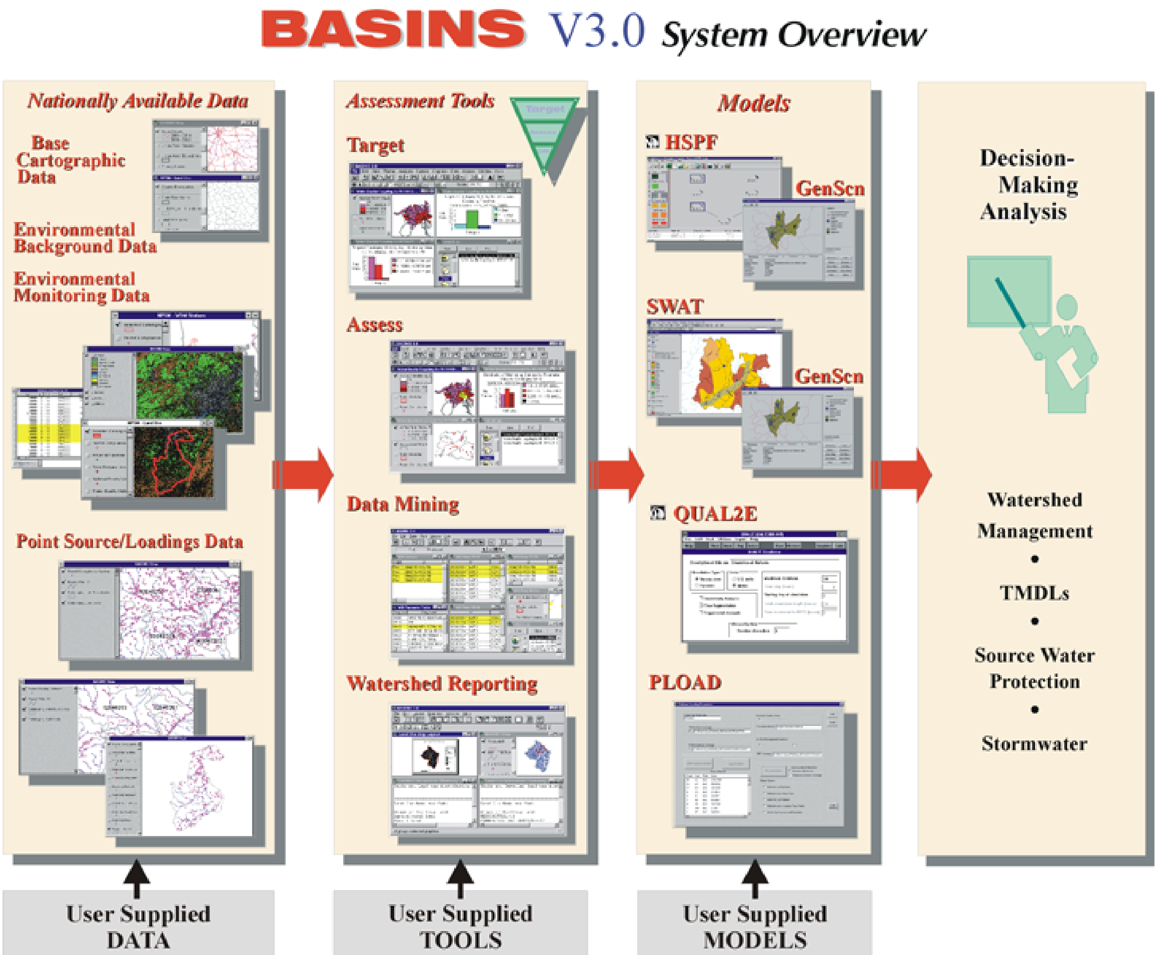
DHSVM (Distributed Hydrology Soil Vegetation Model) is a grid-based model has been developed as the water quantity component of the University of Washington PRISM

program. It was originally developed to model large forested watersheds and has been recently enhanced to include urban areas and impervious surfaces. DHSVM does not currently include water quality algorithms. This inability to model water quality is a major drawback to the use of DHSVM to provide water quality information for receiving water body models or input to the computation of TMDLs. However, it was decided to keep DHSVM as a viable model option due to proposed work at the University of Washington and Battelle Pacific Northwest Laboratory to add water quality to DHSVM.

Three of these nine models (BASINS, HSPF, and WMS) use HSPF for the detailed water quantity and water quality simulations.

BASINS, developed and supported by EPA, is a regional watershed water quality assessment tool designed specifically for TMDL development. Unlike all the other models reviewed, BASINS includes national-scale databases, data assessment and evaluation capabilities, and models, as shown in Figure 4.4; thus it is a packaged system of data, tools and models to facilitate watershed assessments. HSPF has been the primary watershed model in BASINS since its initial release in 1996. In BASINS 3.0 released in 2001, the agricultural model SWAT and an annual load screening model (PLOAD) have been added to supplement HSPF and QUAL2E. Since BASINS 3 includes HSPF and its auxiliary programs (i.e. WinHSPF, WDMUtil, GenScn), its primary distinction and added features are its databases. These national databases of land use, vegetation, soil, point sources, hydrography, and meteorologic data do not provide sufficient resolution and detail for the needed watershed modeling of the SWAMP and Green WQA study areas. If no local data were available for the SWAMP and Green WQA study areas (as described in Section 3), then BASINS would be a strong candidate for selection; however, BASINS, currently offers no significant advantage over the direct use of HSPF and its supporting programs, in conjunction with the local data for these watersheds. Moreover, linkage with the receiving water models (i.e. EFDC and CE-QUAL-W2) will be easier to implement directly with HSPF (with WinHSPF and GenScn) than within the BASINS framework. Thus, direct use of HSPF is the preferred approach.

Figure 4.4 BASINS Overview Chart



WMS contains a number of water quantity models including HSPF, but the only integrated watershed quantity and water quality option in WMS is HSPF. WMS has a proprietary Windows interface developed at Brigham Young University (BYU) for the U.S. Army Corps of Engineers. WMS does not offer any advantage over directly using HSPF with its own Windows interfaces (WinHSPF and GenScn), and has the disadvantage that WMS is proprietary and must be bought from BYU. For these reasons WMS was removed from the selection process.

HSPF, which is supported by both EPA and the USGS, has been used to model water quantity and quality throughout the United States. In the Puget Sound region it has been used extensively to assess hydrologic impacts of land use changes. HSPF was written prior to the introduction of personal computers and executes from an ASCII text file. However, today it is available with auxiliary Windows-based programs, WDMUtil and WinHSPF, to shelter the user from the older environment. WDMUtil is a Windows-based program for maintaining the time series database used by HSPF; it includes the ability to add new stations, edit or fill-in missing data, estimate or disaggregate

meteorological data, and format data. WDMUtil also includes capabilities to display time series data graphically and textually. WinHSPF allows the user to create an initial HSPF input file, and then modify model parameters for calibration and evaluation of watershed management strategies. WinHSPF includes a reach editor, a simulation time and meteorological data specifier, a land use editor, a HSPF option editor, a pollutant selector, a point source editor, an initial parameter defaulter, an input data editor, and an output manager. If needed, WinHSPF can link to GIS file, using ARC-View. This linkage is entered through the BASINS interface. The main window of WinHSPF contains a schematic diagram of the watershed. Displayed within this watershed schematic are graphical representations of the amount of each land use contributing to each reach. Point sources and meteorologic segments are also visible through this schematic. A direct manipulation capability allows the user to select any HSPF operation and edit the tables associated with that operation. HSPF operating logic is included in the interface, so that when a user turns on a new operating module, graphic displays indicate prerequisite tables and timeseries.

4.3.2.10 Model Selection Summary

Three models have been selected for further evaluation: MIKE SHE, DHSVM, and HSPF. Each is discussed in more detail in Section 4.4. A fourth option, using HSPF together with CE-QUAL-W2's enhanced routing through the mainstem rivers and major tributaries is also included for comparison purposes.

4.4 Comparison of Selected Models

A literature search via the Internet and associated sources provided information on the University of Washington PRISM program and its water quantity component, DHSVM. Information on MIKE SHE was obtained from a three-day DHI workshop held in Port Orchard, Washington, in March 2001, plus supplementary material provided by DHI. Information on HSPF and its associated interface programs, WinHSPF and GenScn were obtained from literature sources and AQUA TERRA Consultants directly.

The key factors described in Section 4.2.1.2 relate to some of the differences between HSPF, MIKE SHE, DHSVM, and HSPF with CE-QUAL-W2. These factors and others are summarized below in Table 4.6.

Table 4.6 Model Selection Factors

Key Factor	HSPF	MIKE SHE	DHSVM*/WQ	HSPF/ CE-QUAL-W2
Watershed Segmentation	Catchment (HRUs)	Grid-based	Grid-based	Catchment (HRUs)
Water Quality Routines	Temperature Sediment Conservatives Nonconservatives DO/BOD Inorg Nutrients Simple Organics Phytoplankton (1) Zooplankton (1) Benthic algae (5)	Temperature Sediment Conservatives Nonconservatives DO/BOD Inorg. Nutrients Complex Organics Phytoplankton Zooplankton Benthic algae	None*	Temperature Sediment Conservatives Nonconservatives DO/BOD Inorg. Nutrients Complex Organics Phytoplankton (3) Coliform bacteria
Routing	Hydrologic (level pool, multiple exits)	Hydraulic (full equations)	Hydrologic (level pool, single exit)	Hydraulic (full equations)
Calibration	Yes (unless using regional parameter values)	Yes (see discussion below)	Yes (see discussion below)	Yes (routing)
Computational Requirements	Low	High	Medium	Medium
Preprocessor	Yes	Yes	Yes	Yes
Postprocessor	Yes	Yes	Yes	Yes
Data Management	WDM file (binary data library)	ASCII files	ASCII files	ASCII files
Availability	Public domain	Proprietary	Public domain	Public domain
Institutional Support	EPA, USGS, Aqua Terra	DHI	UW, Battelle	USACOE, Portland State

* DHSVM currently has no water quality module; it must be either linked to a water quality model or have water quality loading and instream algorithms added if it is to be used by King County.

4.4.1 Advantages and Disadvantages

Each of these four models has advantages and disadvantages, some of which have been previously described. A brief summary is provided below.

4.4.1.1 Watershed Segmentation

Watershed segmentation differs between HSPF, MIKE SHE, and DHSVM. HSPF uses the catchment or hydrologic response unit (HRU) approach. MIKE SHE and DHSVM

use a grid system of cells to represent the watershed area. HSPF with CE-QUAL-W2 will use HSPF's HRU approach.

A grid-based model has the advantage of the land use/land cover information in the model being linked directly to a DEM and/or GIS. More importantly, a grid-based model has the potential to simulate the spatial distribution of water and transported materials at the scale of the individual grid. The disadvantages of this approach are (1) a large cell size is usually selected to maintain reasonable computational requirements, and (2) the difficulty in accurately representing impervious surfaces with large grid cells. Smaller grid cells provide more accuracy but increase model computational needs.

A catchment model is computationally faster because of the aggregation of areas that all have the same hydrologic and water quality characteristics. This difference in computational requirements (see Table 4.2) becomes significant when modeling both water quantity and quality for multiple subbasins within a large watershed. HSPF is approximately an order of magnitude faster than DHSVM, which in turn is approximately an order of magnitude faster than MIKE SHE.

One disadvantage is the additional work required to convert the land use/land cover information from a GIS to the format required by a catchment model such as HSPF. Recent work by jurisdictions like King County and Snohomish County to develop tools to automate this conversion process has made this less of a disadvantage.

As grid cells get larger and the hydrologic response unit (HRU) size for catchment models get smaller, the two methodologies represent similar conditions in a similar amount of detail. This blending of the two methodologies is the expected long-term direction of watershed modeling.

4.4.1.2 Water Quality Routines

HSPF includes a range of methods for generating pollutant loadings from the land areas including sediment erosion/transport, simple concentrations of subsurface flows, concentrations on sediment (potency factors), accumulation-washoff methods, and detailed soil nutrient and pesticide dynamics. The instream water quality routines are comprehensive and include temperature, sediment transport (deposition and scour), conservatives, nonconservatives, DO/BOD dynamics, inorganic nutrients, simple organics, and algae. The algae submodel includes one phytoplankton species, one zooplankton species, and up to five benthic algae species.

The terrestrial model (MIKE SHE) includes a series of "add-on modules" which allow the user to add various water quality capabilities to the system. The basic (simpler) modules include soil erosion, advection/dispersion, and sorption/degradation. Other, extremely complex and data intensive modules include geochemistry, biological degradation, and a soil plant simulation model. The river/stream model (MIKE 11/12) is constructed in a similar manner; water quality is added to the basic hydrodynamic model using "add-on modules." The water quality capabilities are comprehensive, including temperature, cohesive and noncohesive sediment transport, conservatives,

nonconservatives, DO/BOD, nutrients, complex organics, phytoplankton, zooplankton, benthic algae, and metals.

DHSVM currently has no water quality capabilities. University of Washington and Battelle PNNL have tentative plans to add water quality to the system.

The combination of HSPF for land simulation and CE-QUAL-W2 for instream water quality has the advantage of using comprehensive, and more spatially explicit (i.e. 2D), instream water quality routines with a more accurate hydrodynamic model, than what's available in HSPF. This linked system would also minimize the state variable discrepancies in the linkage between the watershed model and the receiving water models such as CE-QUAL-W2, EFDC, and CH3D-ICM. CE-QUAL-W2 includes temperature, suspended sediment, conservatives, nonconservatives, DO/BOD dynamics, inorganic nutrients, complex organics, three phytoplankton species, and coliform bacteria. It does not include zooplankton.

4.4.1.3 Routing

HSPF and DHSVM compute the movement of water in the stream channels and lakes using hydrologic routing. MIKE SHE and CE-QUAL-W2 use hydraulic routing.

Hydrologic (or level pool routing) is relatively simple and fast to compute. It requires a stationary stage-discharge rating curve or table to compute the outflow from a stream reach. As a result, it is accurate for flow conditions that do not involve backwater effects. Backwater effects can be implicitly included in hydrologic routing by the user providing the stage-discharge relationship. However, fluctuating head and tailwater relationships cannot be accurately represented.

DHSVM is limited to a single exit for each stream reach. This single exit is the connection to the next downstream reach. HSPF allows up to four exits per stream reach. The additional exits can be used to represent flow diversions, multiple lake outlets, or dam spillway gates and/or discharge valves.

Hydraulic (full equations routing) is more complex than hydrologic routing and explicitly computes backwater effects. This can be important where there are constrictions in the channel system (narrow bridges or undersized culverts) that affect flood flows or areas of tidal influence. Hydraulic routing is computationally more intensive than hydrologic routing.

4.4.1.4 Calibration

Calibration is the process by which the model output is compared with recorded streamflow and/or water quality data to determine whether or not the model is producing accurate results. HSPF requires calibration to establish certain input parameter values unless regional water quantity parameter values are used. HSPF regional values have been developed by the USGS (Dinicola, 1990; Dinicola, 2001) for use in King and Snohomish counties and by AQUA TERRA Consultants for the Washington Department of Ecology's Western Washington Hydrology Model (WWHM).

The advantage of the calibration process is that the model can be checked and adjusted to accurately reproduce recorded streamflow and water quality data. This calibration process produces a visual and numerical confirmation that the model correctly represents the full range of hydrologic and water quality conditions (high flows, low flows, seasonal and annual totals, etc.) observed in the watershed under study. The disadvantage of the calibration process is that the user needs a minimum of 3-5 years of continuous recorded streamflow data together with storm and non-storm event water quality data with which to compare the simulated results to perform calibration and evaluate the model results.

MIKE SHE and DHSVM do not have an explicit calibration process, nonetheless some form of calibration or checking of the model results with real-world data is required.

For both MIKE SHE and DHSVM all of the input parameter values are selected from databases, either national or local. MIKE SHE determines infiltration rates for each grid cell by using a finite difference scheme to solve a 1-D, partial differential equation for vertical, unsaturated flow known as Richard's Equation. Theoretically, the parameters for this equation are soil-physical properties that can be measured with sufficient accuracy to avoid calibration. However, this rarely turns out to be the case outside of rigorously controlled laboratory conditions. Three-dimensional spatial variability that occurs often at the sub-grid modeling scale in the field virtually guarantees the need to perform calibration based on field data. Therefore, while some might prefer to call needed adjustments to the soil information something other than calibration, this is in fact the procedure being used to determine the validity of the user-supplied information.

CE-QUAL-W2 is calibrated by adjusting the stream channel friction factors to change the flow velocities and depth. The calibration is done in comparison with measured stream flows (cfs) and flow depths.

4.4.1.5 Computational Requirements

As noted earlier in Section 4.3, with today's faster computers, computational requirements are less of an issue than in the past. However, as computer speed has increased so has model complexity. This is particularly true for grid-based models.

Table 4.2 presented information on the standardized run times (hydrology only) for a 5-year simulation at an hourly time step for HSPF, MIKE SHE, and DHSVM. However, for scenario evaluation and analysis, the length of a simulation run can be 50-years or more. The simulation of water quality increases computer run time by a factor of 2-10 depending on the water quality constituents simulated and the algorithms used. Scaling the clock speed normalized run times by these factors, a 50-year HSPF water quality model simulation will take on the order of 1-5 hours to complete. DHSVM (assuming water quality is added) will take 6 to 30 hours. MIKE SHE's run time for the same scenario will be in the 25-100 hour range. All of these estimates are based on a 600 MHz PC.

Faster computers will decrease all of these projected run times. However, both MIKE SHE and DHSVM will tax even the fastest personal computers and may result in run times that may be considered unacceptable when simulating a 50-year time period.

HSPF with CE-QUAL-W2 combines HSPF relatively fast runoff and routing routines with CE-QUAL-W2's more computationally intensive routing for the mainstem rivers and major tributaries. This will lead to an increase in computational times. The increase will vary in relationship to the number of HSPF HRUs and stream reaches compared to the number of CE-QUAL-W2 reaches.

4.4.1.6 Preprocessor

All of the models have their own preprocessor to assist in model set up. MIKE SHE and DHSVM are both designed for the Windows environment and offer multiple windows of information and data input.

HSPF was written prior to the introduction of personal computers and executes from an ASCII text file. Auxiliary Windows-based programs, WDMUtil and WinHSPF, have been written to shelter the user from this environment. WDMUtil is a Windows-based program with the ability to maintain the time series database used by HSPF; it includes the ability to add new stations, edit or fill-in missing data, estimate or disaggregate meteorological data, and format data. WDMUtil also includes capabilities to display time series data graphically and textually.

WinHSPF allows the user to create an initial HSPF input sequence, and then modify model parameters for calibration and evaluation of watershed management strategies. WinHSPF includes a reach editor, a simulation time and meteorological data specifier, a land user editor, a HSPF option editor, a pollutant selector, a point source editor, an initial parameter defaulter, an input data editor, and an output manager. The main window of WinHSPF contains a schematic diagram of the watershed. Displayed within this watershed schematic are graphical representations of the amount of each land use contributing to each reach. Point sources and meteorologic segments are also visible through this schematic. A direct manipulation capability allows the user to select any HSPF operation and edit the tables associated with that operation. HSPF operating logic is included in the interface, so that when a user turns on a new operating module, graphic displays indicate prerequisite tables and timeseries.

CE-QUAL-W2 has its own graphical user interface (GUI) preprocessor to assist the user in the set up of input files.

4.4.1.7 Postprocessor

Postprocessors assist in analysis of the model results. Once again, all three models have Windows-based postprocessors to present, graph, and analyze model output.

MIKE SHE contains a statistics module for the processing, analysis, and presentation of model results in addition to a graphics package for plotting of animated, time-variable results.

DHSVM uses Excel spreadsheets to process, analyze, and present model results.

HSPF also has the ability to output data to spreadsheet programs (Excel and others) to process, analyze, and present model results. In addition, HSPF has postprocessors that provide additional features for analysis and presentation of results.

WinHSPF summarizes model output by creating seven standard reports from the new HSPF REPORT module (land surface total loads, land surface percent loads, land surface unit load, reach total loads, reach total change, point loads, and BMP removals) along with watershed characteristics (drainage area land use, reach network) and produce both a watershed summary and summary by reach. Once these reports are produced they can be accessed by the user without running HSPF.

GenScn is another interactive HSPF postprocessor. GenScn was developed by AQUA TERRA Consultants for the USGS (Kittle, et al, 1998) to analyze and manage high volumes of input and output of complex river basin models, primarily those based on HSPF. It was designed specifically to support analysis of water quantity and quality for numerous scenarios of changes in land use, land-use management practices, and water management systems.

GenScn has a Windows interface and allows the user to request information from a specific location by clicking on the appropriate spot on the watershed map. Individual water quantity and water quality constituents for a single or multiple scenarios can be specified, analyzed, and viewed. Graphs of values versus time can be requested in terms of either standard hydrographs, bar charts, scatter plots, and percent of time exceeded. Time series data can be animated, either spatially for model segments or for a stream profile, to provide a visual representation of model behavior, such as when a critical value set by the user has been exceeded. Exceedance can result from flood levels overtopping a structure, a pollutant concentration exceeding lethal limits, or a stream running dry.

CE-QUAL-W2 has a GUI postprocessor for use in analyzing the model's output. Output is written to ASCII files.

4.4.1.8 Data Management

Data management is an important component of watershed modeling. When a model computes streamflow and water quality constituents at numerous locations for multiple years a lot of numbers are generated. For a 50-year simulation period this means almost a half million hourly flow values per output location. If one multiplies this value by 100 model output locations (there are probably more than 100 in the SWAMP area), and by the number of output constituents of interest, and finally by the number of scenarios to be modeled, then even a large computer hard drive can be filled to capacity by one

simulation. Data management systems are designed to efficiently store all of this output and then analyze it to provide the user with specific information.

MIKE SHE, DHSVM, and CE-QUAL-W2 use individual ASCII-format files to store each output time series. This is a simple, but relatively inefficient method for storing large amount of data.

HSPF uses a Watershed Data Management (WDM) file. The WDM compresses and stores the time series data in a binary format. All of the time series data (both input and output) can be stored in a single WDM file, although multiple WDM files may be accessed simultaneously. The data in the WDM may be accessed with one of the HSPF built-in utilities or the pre/postprocessor interfaces WDMUtil, WinHSPF, and GenScn.

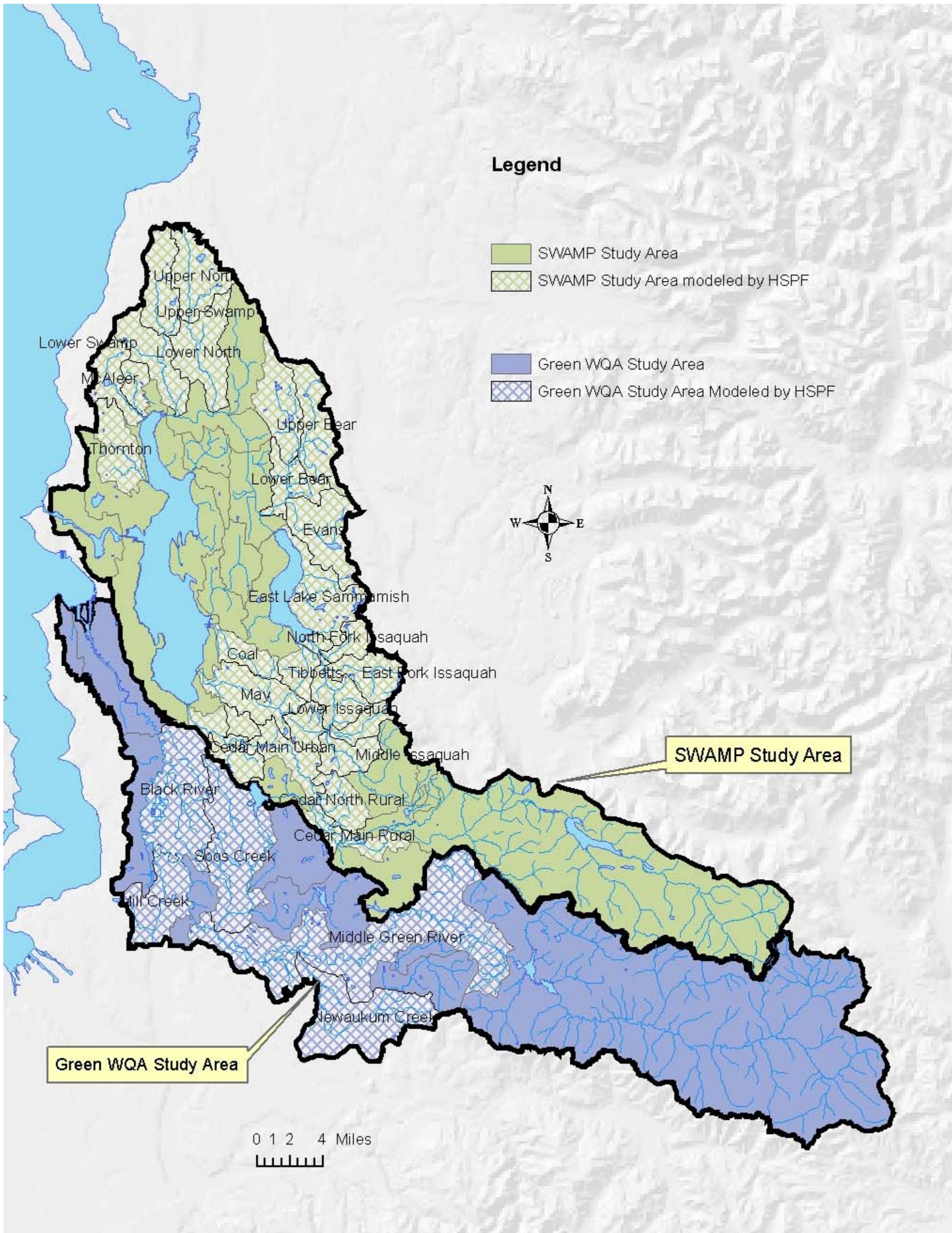
4.4.1.9 Availability

HSPF, and its supporting programs, are all public domain software, available free of charge from the USGS and EPA web sites. MIKE SHE is proprietary software sold by DHI (Danish Hydrologic Institute). It costs about $10,000 for a one-computer site license. An annual maintenance fee of $1,000 per site is an additional cost. DHSVM is available free from the University of Washington. CE-QUAL-W2 is available from the U.S. Army Corps of Engineer Waterways Experiment Station via their ftp site.

4.4.1.10 Institutional Support

HSPF is supported at the federal level by the U.S. Environmental Protection Agency and the U.S. Geological Survey. AQUA TERRA Consultants provides technical support to the federal agencies and state and local jurisdictions. Watershed quality modeling applications similar to the proposed SWAMP and Green WQA projects have been conducted for the Chesapeake Bay watershed, Connecticut River watershed, and in Minnesota. In the Puget Sound region, local counties, such as King, Snohomish, and Thurston, have used HSPF extensively to do watershed modeling. As shown in Figure 4.5, HSPF models have been developed for a majority of the watersheds in both the SWAMP and Green WQA study areas. The data and knowledge gained from these existing HSPF models is a benefit of using HSPF.

Figure 4.5 Basins within SWAMP & Green WQA Study Areas where HSPF has been applied



MIKE SHE is a product of and is supported by the Danish Hydrological Institute (DHI). MIKE SHE has not been used in King County; however, a recent water quantity application has been finished for the Chico watershed in Kitsap County. Water quality applications using MIKE SHE have been limited both in the United States and elsewhere. There have been no water quality applications of MIKE SHE equivalent to the planned water quality modeling for the SWAMP and Green WQA study areas in terms of size of area, number of constituents, or types of processes. This information was confirmed from multiple sources, including an Internet literature search, the DHI (MIKE SHE developers) web site, and direct contact with DHI representatives.

DHSVM was developed at the University of Washington and receives support from Battelle Pacific Northwest National Laboratory in Seattle. DHSVM has been used locally as a research tool by researchers at the University of Washington. Its primary focus has been on simulating the hydrology of large rural, forested basins, such as the Snohomish River Basin and the Skagit River Basin. A local urban application has been done on a tributary of the Cedar River. A water quality module is planned by University of Washington researchers, but work on it has not yet begun as of the autumn of 2001.

CE-QUAL-W2 was developed at the U.S. Army Corps of Engineer Waterways Experiment Station in Vicksburg, MS. It is supported by the U.S. Army Corps of Engineer Waterways Experiment Station, and also currently receives support by researchers at Portland State University.

5 WATERSHED MODELING APPROACH AND STRATEGIES

The model approach must incorporate the needs presented in Section 2 together with the data described in Section 3. A large number of watershed models were evaluated in Section 4 based on the needs and data presented in the two previously mentioned sections. This section recommends a modeling approach and an associated monitoring package that are consistent with prioritized watershed modeling needs in each watershed.

Once a model has been selected, the development of alternative watershed water quantity and quality modeling strategies must assess the relationship between and among the modeling needs and existing model capabilities, and the data available to support model application. A modeling strategy based on data that are not available will simply not work; likewise, a strategy that demands more detail and accuracy than available in current models may require many years of model development and testing efforts, along with additional data collection. This section specifically responds to the Work Order requirement to develop three (3) modeling strategy packages that reflect low, moderate, and high levels of monitoring data support. Below we discuss the overall framework for the proposed modeling efforts on the SWAMP and Green WQA in terms of elements common to all strategies, followed by descriptions of each strategy, comparative evaluations, phasing and piloting options, summary of data gaps, and a specific recommendation for implementation.

5.1 Modeling Approach Recommendation

In Section 4, this report reviewed available models in relation to the water quality and quantity modeling needs of the SWAMP and the GD-WQA projects. In this section, that review is used as the basis for the development of a watershed modeling strategy. Given the prominence of these two projects, their links to other King County projects, and the likelihood of application of SWAMP and GD-WQA adopted methods to other King County watersheds in the future, it is important to choose a strategy wisely.

The Section 4 review provided a screening level assessment of dozens of existing models and a somewhat more detailed assessment of three models- HSPF, MIKE SHE, and DHSVM. Based on that assessment, a combination approach appears to be prudent in which HSPF applications are extended to include remaining un-modeled watershed areas and water quality to both watershed projects over the next two to four years. During that time parallel cooperative and pilot studies can be pursued to test, compare, and gain experience with grid models such as DHSVM and MIKE SHE. This work will allow better-informed decisions to be made in future years as to whether a transition to one of these grid models should be made for generalized, water quality, watershed modeling, or whether they should be applied in special applications on a more site-specific basis.

5.1.2 Near-Term Modeling Needs

The four primary reasons in support of using HSPF to meet near-term modeling needs are as follows:

1. Integration of watershed runoff processes with extensive water quality algorithms for both the land surface and instream that have been tested and used throughout the United States. Watershed applications on a comparable scale and level of complexity as the proposed SWAMP and Green WQA studies include Chesapeake Bay (Donigian et al., 1994), Connecticut (AQUA TERRA Consultants and HydroQual, Inc, 2001), and Minnesota (Donigian et al., 1996; Donigian and Duda, 1997; Patwardhan et al., 1996). Additional there are a number of options of representing land use changes or evolution over time. These options range from using multiple input files, to land use time series, to connection to an Access database.

2. Packaging with a sophisticated Windows-based preprocessor (WinHSPF), postprocessor (GenScn), and a file management system (WDM) that assists the user in creating, analyzing, and storing model time series results.

3. Quantity model components that have been used extensively in King County with much of the SWAMP and Green WQA study areas already modeled. King and Snohomish County currently has several staff who are trained in the operation of the model and have access to several local and national consultants who are available to provide additional support. The model is in the public domain, and has support from EPA and USGS. Very detailed written documentation describes both model algorithms and the mechanics of model use.

4. Application and execution on the large SWAMP and Green WQA watershed areas with reasonable computer run times that are orders of magnitude smaller than the other models.

5.1.3 Current Status of DHSVM

At this time, only a very small number of knowledgeable users have applied DHSVM. There is no published users' manual and the model currently includes no water quality modeling routines. Limited support for the model may be available from the UW and Battelle PNNL. The model requires at least 10 times as much computer time as a catchment based, response unit type model like HSPF. The model's primary use has been in a research mode in forested watersheds. It has had minimal application in heterogeneous, urban watersheds to date.

In the future DHSVM may be augmented with water quality. Additionally, documentation may be developed (Wigmosta, 2001). Cooperation between the UW-PRISM Program and PNNL is under discussion regarding support and assistance to a graduate student to work on development of water quality routines for DHSVM (Rattanaviwatpong, 2001). However, the details of the cooperation and of what water quality routines will be developed are speculative as of this time. In spite of this, if DHSVM becomes more of an operational model that includes water quality routines in

the future, it could be an attractive approach to spatially distributed watershed modeling because of its simplification of the governing equations and resultant reduced computational effort compared with the more rigorous MIKE SHE. In order to stay abreast of and assist in these developments, King County should cooperate with the UW and PNNL effort by providing data and assisting in the testing and comparison of the accuracy and detail of simulated flows with a catchment-based model like HSPF with both models given access to equivalent input data sets.

5.1.4 Piloting of MIKE SHE/MIKE 11

MIKE SHE/MIKE 11 is proprietary software that is well supported and documented by DHI. It includes several highly detailed, computationally intensive, water quality modules. Run times are expected to be at least 100 times as long as catchment-based models for quantity and perhaps much more for quality. The MIKE SHE software package includes good links to GIS data and a user-friendly GUI. Initial costs of software and annual support are relatively high. Indications are that the learning curve and spin-up time to make MIKE SHE operational is likely to be steep and extended in time (Camp Dresser & McKee Inc., 2001; Nelson, 2002). At this time, the model is not practical as a general tool for a large-scale, urbanizing, watershed with heterogeneous land cover.

In spite of these limitations, the MIKE SHE/MIKE 11 software has many attractive features. The model is very well-supported and documented by DHI and is under continuous development including features which may make it more efficient representing heterogeneous, urbanizing watersheds in the future. (Storm, 2001). It does detailed, mechanistic, unsaturated zone, saturated zone, and stream hydraulic calculations and includes some powerful water quality transport and fate routines for groundwater and channels. MIKE SHE appears to have some unique capabilities with respect to simulation of surface and groundwater interactions (Camp Dresser & McKee Inc., 2001) that could be especially relevant in flatter terrain such as low-gradient river valleys. On this basis, it is recommended that a cooperative program of piloting and testing MIKE SHE be considered.

5.2 Watershed Modeling Strategy Packages – Overview and Modeling Assessment

In support of selecting HSPF for near-term modeling needs, three watershed modeling strategy packages are described below. The three packages reflect a range of monitoring data efforts from low to high to support the watershed model application. A strategy with low data requirements (Package 1) is implementable with currently existing data. A medium data requirement strategy (Package 2) requires a moderate amount of modification and augmentation of the current monitoring program. At the upper end is a high data requirement strategy (Package 3) that is based on significant modification and enhancement of the monitoring program to meet the needs of the associated level of modeling. In addition, some model code development and testing efforts may be needed at this level of model complexity and spatial detail.

Data requirements for the individual strategies described below impose time restrictions and phasing requirements on the associated modeling packages. The time needed for data sampling, analysis, and tabulation must precede the water quality modeling to make the most effective use of the data. Although database development, model setup, and hydrology calibration can proceed while water quality sampling is being performed, the final water quality calibration must await the completion (or near completion) of the sampling. Thus, while Strategy Package One can be initiated immediately, Package Two strategy must await a time period (approximately 1 or 2 years), of sampling, and Package Three strategy would likely need a longer time (approximately 3 or 4 years) before final water quality calibration could proceed.

Both the data and the timing constraints impose specific requirements on the modeling packages appropriate for each strategy level. The modeling strategy for Package One must be suitable for immediate application, while Packages Two and Three strategies would need some additional time to refine current capabilities to be consistent with, and appropriate for, the water quality modeling needs and collected data for this effort.

How do these requirements relate to the three modeling packages selected in the model review discussed in Section 4 – HSPF, MIKE SHE, DHSVM/WQ? As discussed earlier, HSPF is the modeling package most suitable for near to mid-term application schedules associated with the low and medium data strategies. The high data strategy which would require 3-4 more years of additional water quality data collection could be implemented with a more spatially refined HSPF model or optionally with one of the grid-based models depending on the county's piloting evaluations and future developments of those models. With this background on the comparative assessments of the three models, the proposed modeling strategies and data requirements are discussed below.

5.2.1 Modeling Strategy Package One – Low Data Requirement

The low data requirement strategy makes use of currently existing data and models, but may require a few additional data collection/samples and analyses to fill in critical data gaps. The water quality approach in this strategy would be to develop expected loading rates for sediment, nutrient, bacteria, and metals for specific land uses within the study areas. These expected values would be developed from the work by Brett, other local data, and national values to compare with model predictions; calibration to available data would be performed to ensure that the model land use loading rates are consistent with the expected ranges, while the instream concentrations are a reasonable match with the observations. Both of these comparisons are needed as part of the water quality calibration effort for watershed models.

Table 3.1 shows the land use distributions for both the SWAMP and Green WQA study areas, respectively, for both the total and the lower area below the reservoirs. Although land use coverages often include up to 15 or 20 different land use/cover types, watershed models typically cannot effectively represent, and differentiate (i.e., parameterize), more than five to 10 different categories for both quantity and quality. In addition, there is real

concern with the accuracy of the coverages, i.e., whether the slight differences can be distinguished from the raw data often derived from remotely-sensed information.

Under this option strategy, the land uses would be grouped into the five major categories of forest, urban (pervious and impervious), agriculture, grass/open, and wetlands.

Although agriculture is not a major activity in terms of spatial coverage, it can be a significant nonpoint source of pollutants; it is usually included in the general grass vegetation GIS coverage but will need to be separated out for watershed modeling. Agriculture tends to be somewhat more extensive in the Green WQA than in the SWAMP study area, but the subdivision of each into subbasins will allow the representation of agricultural contributions in each watershed. Wetlands are important because of their impacts on both water quantity and quality; a separate wetlands coverage available from King County will be used to identify the spatial locations within the study areas.

For water quality contributions from land areas, the water quality modeling will need to rely on either runoff coefficients, EMCs (event mean concentrations), or the simplest water quality methods in HSPF (constant concentration of pollutants associated with water or sediment or both), due to the paucity of land use-specific data. These methods are essentially the same as runoff coefficients/EMCs. The use of HSPF will result in a more efficient and flexible system in terms of application and operation. In order to provide the basic boundary condition requirements to the mainstem water quality models (CE-QUAL-W2, etc.), an instream water quality model would be necessary, but can be limited to temperature, bacteria, metals, dissolved oxygen, and transport/transformation of nutrients (nitrate, ammonium, and phosphate) without consideration of algal growth. Some minimal level of water quality sampling and analyses will be needed to help characterize the nonpoint organic loadings and fractionate them into appropriate components (i.e., labile, refractory, dissolved, particulate) for linkage with the downstream receiving water models.

Thus, the characteristics of the Low Data Modeling Strategy are:

- Use current HSPF models, and extend them to unmodeled areas
- Integrate existing HSPF models with newly modeled areas within a consistent user-friendly framework based on WinHSPF and GenScn
- Use runoff coefficients/EMCs for land water quality or HSPF simplest PQUAL/IQUAL options (essentially the same as runoff coefficients/EMCs)
- Use HSPF instream water quality (HTRCH, GQUAL, RQUAL) without modeling detailed algal dynamics

This low data requirement strategy can be initiated immediately, along with performance of the minimal additional data sampling and analyses (discussed above), and can be entirely completed within a 2 to 3 year time frame. No new software development is required, and much of the data is in readily available form for use with HSPF/GenScn.

The accuracy to be expected from this strategy, and from any modeling effort, is difficult to define in absolute terms even when the modeling has been completed. To state beforehand what level of accuracy and reliability can be provided by this strategy can best be described as an educated guess based on accumulated years of experience in watershed modeling. Moreover, different levels of accuracy are likely to result for different portions of the study area, for the quantity and quality components, and for each of the modeled constituents. Table 5.1 shows the expected calibration/validation targets and tolerances that have been presented in HSPF Training Workshops over the past 15 years; they are presented as reasonable goals for model accuracy/performance, not absolute thresholds for model acceptance, subject to the caveats listed in the table.

Table 5.1 General Calibration/Validation Targets or Tolerances for HSPF Applications (Donigian, 2000)

	Percent Difference Between Simulated and Recorded Values	Percent Difference Between Simulated and Recorded Values	Percent Difference Between Simulated and Recorded Values
Constituent	VERY GOOD	GOOD	FAIR
Hydrology/Flow	< 10	10-15	15-25
Sediment	<20	20-30	30-45
Water Temperature	<7	8-12	13-18
Water Quality/Nutrients	<15	15-25	25-35
Pesticides/Toxics	<20	20-30	30-40

Caveats: Relevant to monthly and annual values; peak events may differ more.
Depends on the quality and detail of the input and calibration data.
Varies according to purpose of model application.
Depends on the availability of alternative assessment procedures.
Depends on resource availability (time, money, personnel)

Using the classifications in Table 5.1, for this low data requirement strategy, we would expect a flow/quantity simulation with good to very good results, and a water quality simulation with no more than fair results and worse than fair for some difficult constituents, like metals and bacteria. As an overall relative assessment of accuracy, based on a scale of 0 to 10 (where 0 is unacceptable, 5 is adequate, and 10 is exceptional agreement) this Low Data Requirement Strategy produces a ranking in the range of 2 to 4.

5.2.2 Modeling Strategy Package Two – Medium Data Requirement

The medium data requirement strategy addresses the need to obtain stormwater data for characterizing the land contributions of the various land use categories in the study area. A storm sampling program as described by Burkey (2001) is required to provide the site

specific data to calibrate the nonpoint source contributions by land use category throughout the basins. This sampling program should be modified to correct the apparent gaps as described in Section 3.3. This includes the addition of three stations, two on the Green River and one in the Mill Creek watershed, plus the following improvements in monitoring of specific constituents for both baseflow and storm event conditions: (1) temperature, (2) TSS, (3) toxic organics, and (4) TOC and chlorophyll a.

Storm sampling over a two-year period is recommended to obtain sufficient reliable data for a thorough nonpoint source water quality calibration; if water quality validation is required ongoing sampling for an additional 2 years would be needed.

Calibration procedures will extend beyond the ones used in the Low Data Strategy with the additional calibration to the subbasin sites selected for monitoring. The same consistency checks will be performed (as described above) to ensure the loading rates are consistent with expected value ranges, the instream concentrations are a reasonable match with observations, and the match with the newly collected storm data is acceptable.

Land use categories represented in the model can be extended, if supported by the additional data, to include multiple categories for urban (e.g., low, medium, high density residential; commercial, industrial), forest (e.g., mature vs new-growth, rural residential), and agriculture (e.g., pasture, crops, hay). Clearly not all these categories are justified by the data and the extent of coverage in the study areas.

The modeling package strategy for this option is essentially an extension of the low data strategy by using the slightly more complex and accurate empirical methods for the land response of water quality. This involves the use of the accumulation/washoff methods in the HSPF PQUAL/IQUAL modules. The instream water quality model will be extended to include the consideration of algal growth to more accurately predict nutrient delivery for the boundary condition, and provide water quality predictions at a local level. An option under this case is to extend the CE-QUAL-W2 model to more of the mainstem rivers and the tributary streams (Mill Creek and Springbrook Creek), in order to take advantage of its more spatially detailed methods and improve the linkage/interface at the boundary locations.

The characteristics of the Medium Data Requirement Strategy are:

- Use current HSPF models, and extend them to unmodeled areas (same as the low data strategy)
- Integrate existing HSPF models with newly modeled areas within a consistent user-friendly framework based on WinHSPF and GenScn (same as above)
- Use HSPF water quality for land areas (PQUAL/IQUAL with more detailed methods (accumulation/washoff) calibrated to site/land specific data
- Allow additional categories of land use as sources
- Use HSPF or CE-QUAL-W2 water quality in streams, with algal dynamics represented

This medium data strategy can also be initiated immediately, but nonpoint source and water quality calibration will need to extend out to 3 or 4 years, with the 2-year sampling program starting in the first year. If water quality sampling for validation is performed, the validation will need to wait until after an additional 2 years of validation data are available.

Regarding accuracy for this medium data strategy, we expect a flow/quantity simulation with good to very good results, and a water quality simulation with overall good results. The flow simulation will likely improve somewhat over the low data strategy (with additional storm flow data at sampling sites), but the water quality should show considerable improvement with the land use specific water quality data to support the calibration. On the 0 to 10 scale, the Medium Data Requirement Strategy would correspond to a ranking of 4 to 6.

5.2.3 Modeling Strategy Package Three – High Data Requirement

The high data requirement strategy focuses on implementing a much finer, spatially-explicit model of the study areas, and thereby demands an extensive water quality sampling program. This strategy also focuses on stormwater data for characterizing the land contributions, but requires two to three times the sampling intensity as planned by Burkey (2001). The current sampling program is consistent with the Medium Data Strategy.

The current data layers for watershed characterization appear to be generally adequate even for this level of spatial detail, with some coverages providing resolution down to 10 meters. For distributed models that require this level of resolution (i.e., cell sizes of 100 to 200 feet), some additional ground-truthing and refinement of the selected data layers may be needed. In addition, additional precipitation gages may be needed to accurately model at this spatial scale for assessment of both local water quality conditions, and for providing downstream loading conditions for the receiving water models.

If appropriate, the high strategy can also configure the model water quality input and output so as to be coordinated with the needs of the UEM (Urban Ecosystem Model) development work. Additional process model development may be required if this strategy is pursued.

The high strategy modeling package assumes a distributed type model, or a catchment (HSPF-type) model with many more individual subbasins, either providing finer spatial detail. The advantages of a more scientifically valid (with respect to process algorithms) distributed model are fairly clear; the additional spatial detail, and assumed increased physical representation of processes, should lead to more accurate results.
The available options for a High Data Requirement strategy are:

- MIKE SHE, DHSVM/WQ, or other distributed model, or
- HSPF with finer segmentation and detailed AGCHEM module for selected land uses

Although this high data requirement strategy can be initiated immediately, it requires extensive additional data collection (beyond that currently envisioned by Burkey (2001), and part of the medium strategy), and possibly significant model/code development. The data collection should extend for a minimum of 3 to 4 years, with some continuing data collection for model validation. In turn, the water quality modeling will extend 5 to 6 years, or longer, to take advantage of the additional extensive data for calibration.

The accuracy expectations for this High Data Strategy are very good for flow/quantity and good to very good for water quality. On the 0 to 10 scale, that corresponds to a ranking of 7 to 9.

5.2.4 Modeling Strategy Summary

Tables 5.2 through 5.4 summarize the three modeling strategies and how they relate to the needs described in Section 2.

Each modeling strategy was evaluated in terms of how it meets the needs for TMDL support, ecological planning, BMP evaluation, groundwater, water resources planning, receiving waterbody modeling, and UPD monitoring and assessment. The ability to meet these needs was summarized into categories of Very Low, Low, Medium, and High to reflect in general terms the appropriateness of the strategy to meeting a particular need.

For each strategy the strengths and weaknesses of that particular strategy are briefly described in the last column of the three tables. Further amplification of each modeling strategy's limitations or benefits is presented in the general critique of the model package, following each table. These relate to the modeling package discussion above.

Table 5.2 Summary of Modeling Strategy Package 1 (Data & Model Capabilities to Meet Projects' Needs)

Modeling Strategy	TMDL Support	Ecological Planning	BMPs	Groundwater	Strengths/Weaknesses
Package 1 (GIS/HSPF): EMC pollutant generation with hydrological driven loadings. Limited land use categories. Level pool hydraulics with simplistic fate & transport mechanisms.	Low	Low	Low	Low	➢ Simulations of bacteria should be restricted to 3rd or 4th order drainage areas. Support to TMDL development also limited to systemic/chronic evaluations on higher order streams. Evaluations of acute concentrations would have relatively low confidence. UPD monitoring requires much higher level of spatial discretization. ➢ EMC approach derived from limited observations –most appropriate for annual loads, and least accurate for individual events. Also limits temporal accuracy for boundary condition loads to lake/estuary models ➢ Limited observed data for metals and bacteria would be problematic for TMDLs. ➢ Lack of algal simulation would compromise nutrient processes and diurnal patterns. ➢ Multiple input files will be required to represent dynamic land use change. ➢ Use of HSPF for all boundary conditions would ignore backwater and tidal effects in lower tributaries.
	Water Resource Planning	**Receiving Waterbody Boundary Conditions**	**UPD Monitoring & Assessment**		
	Low	Medium	Very Low		

General Critiques of Modeling Packages

Package 1: Accuracy of simulated hourly or daily concentrations in streams and at receiving water boundaries is compromised by use of EMCs, or seasonal or annual loading coefficients. Simplicity of pollutant generation and in-stream processes inhibits the assessment of water quality conditions in headwaters streams. Acceptable predictive power likely limited to 3rd and higher order stream concentrations on seasonal to annual time scales. Watershed-wide water quality trends associated with land use change could be estimated.

Table 5.3 Summary of Modeling Strategy Package 2 (Data & Model Capabilities to Meet Projects' Needs)

Modeling Strategy	TMDL Support	Ecological Planning	BMPs	Groundwater	Strengths/Weaknesses
Package 2 (GIS/HSPF/CE-QUAL): Build-up & wash-off pollutant generation, greater number of land use categories, added algae dynamics to nutrient algorithms, diffuse wave computations for some stream/river reaches.	High	Medium	Medium	Low	➢ Buildup and washoff algorithms provide improved individual storm simulations. ➢ Refined land use categories allow for improved spatial detail within subbasins. ➢ Improved spatial detail provided by extending CE-QUAL-W2 through portions of mainstem and tidal tributaries. ➢ Algal simulation within HSPF and CE-QUAL-W2 provides improved nutrient process representation and linkage to estuary/lake models. ➢ Time series of dynamic land use changes to model land use evolution. ➢ Additional monitoring to support improved metals and bacteria modeling, but with increased costs and extended time schedule.
	Water Resource Planning	Receiving Waterbody Boundary Conditions	UPD Monitoring & Assessment		
	Medium	High	Medium		

General Critiques of Modeling Packages

Package 2: Monitoring data support calibration/validation of a model capable of simulating diurnal fluctuations in loads at receiving water boundaries. More specific characterization of land use and pollutant processes enables analysis of water quality conditions in small tributary streams, and impacts of land use on pollutant loading. Higher levels of sophistication should be phased in on a project-by-project basis.

Table 5.4 Summary of Modeling Strategy Package 3 (Data & Model Capabilities to Meet Projects' Needs)

Modeling Strategy	TMDL Support	Ecological Planning	BMPs	Groundwater	Strengths/Weaknesses
Package 3 (GIS/HSPF/CE-QUAL/Other): High degree of spatial resolution, upgraded water temperature algorithms.	High	High	High	Medium[1]	➢ Provides highest level of both spatial detail and process representation. ➢ Nonpoint modeling could consider pollutant mass balance and soil processes. ➢ Refined water temperature algorithms would represent riparian and buffer shading impacts. ➢ Added detail would allow more accurate representation of BMPs and remediation alternatives, both spatially and temporally. ➢ Linkage to Access database to allow for dynamic land use change. ➢ Additional observed data would allow complete calibration/validation effort, but would extend time schedule.
	Water Resource Planning	Receiving Waterbody Boundary Conditions	UPD Monitoring & Assessment		
	High	High	High		

[1] The change from "Low" to "Medium" for Groundwater from Package 2 to Package 3 is due to more detailed spatial representation (both surface, and by extension, subsurface), better process representation (quantity and quality), and more data. This could include the option of linking HSPF with MODFLOW.

General Critiques of Modeling Packages

Package 3: Benefits of higher level of spatial detail likely to be limited for simulation of perennial streams over medium strategy, yet level of additional effort to implement this package would be significant for monitoring data, model development, and operation. Conversely, the higher level of spatial resolution provides the ability to evaluate headwater catchments down to the non-perennial reach scale, and potentially improve representation of surface/groundwater interactions. Water temperature algorithms would be enhanced to account for spatially explicit riparian vegetation, and topography such as slope and aspect either through pre-processing or code modification.

5.3 Phasing and Piloting Options

In this section, phasing and piloting options are explored as a basis for accomplishing the SWAMP and Green WQA studies in a manner that addresses local information and decision-making needs, modeling requirements, data collection activities, and other ongoing efforts within the region.

Phasing refers to the need to schedule the component tasks of the study efforts to provide information to meet near-term (1-year), mid-term (3-year) and long term (> 5 years) project needs associated with specific geographic areas. For example, a near-term need is a tool to assess the impacts of a potential North Treatment Plant Facility siting in the Little Bear Creek watershed on Sammamish River tributary basins.

Piloting refers to selection of specific subbasin sites within the SWAMP and Green WQA watersheds for initial modeling efforts, which serve the following purposes:

- As initial templates for each watershed to fully test and define model application procedures before extension to all other subbasins within the study areas. This is a common procedure when modeling large, complex watersheds, most recently demonstrated in the Connecticut Watershed Modeling effort using HSPF and GenScn (AQUA TERRA Consultants and HydroQual, Inc., 2001).

- To address local site-specific information needs for subbasins where significant water resource and/or water quality management decisions are needed (e.g., North Treatment Plant siting).

- As testing sites for alternative future and emerging technologies to fully assess the costs and benefits of such alternatives before widespread application is undertaken. This would be especially fruitful for evaluating the feasibility of applying MIKE SHE and/or a hybrid approach like DHSVM/WQ, and could be extended to include additional modeling tools discussed in Section 3.2.4.

Clearly, phasing and piloting efforts will need to be coordinated so that the site selection and timing of subbasin modeling work is designed to meet the identified information needs throughout the study areas. Details of a phasing schedule must await the selection of the modeling strategy – low, medium, high – by King County, and subsequent development of a detailed simulation plan for each study watershed (see Section 5.5, below).

5.3.1 Potential Sites for Phasing and Piloting

Potential sites for both phasing and piloting are discussed below for both the SWAMP and Green WQA study areas. These sites can be used to meet one or more of the piloting purposes listed above, and can be coordinated to meet specific phasing needs for local water resource and/or water quality issues.

Pilot studies and initial calibration should be performed to explore issues with specific constituents and the simulation strategy, and to verify the adequacy of the data and the selected strategy. Initial calibration should be performed in subbasins where the water quality data are adequate, and where prior modeling has occurred in order to take advantage of previous data collection and model parameter selection. Another reason for selecting subbasins for initial studies is to explore the range of land use conditions, such as degree of urbanization, extent of agricultural land, and concentration of industrial areas specific to the modeling strategy and its purpose.

Based on these criteria, we have identified six subbasins for possible initial model application. It should be noted that after a more detailed simulation plan is developed for each basin (SWAMP and Green), these recommendations may change.

5.3.1.1 SWAMP Study Area

In the SWAMP study area, we recommend initial calibration for temperature, DO, nutrients, sediment, and algae on the Issaquah, Swamp, Thornton, and Little Bear creeks. These subbasins are well-monitored, three of the four have existing HSPF-based models, and they reflect a range in land use conditions. Issaquah is more forested, less urbanized, and contains agricultural areas, while Thornton Creek is highly urbanized. Swamp Creek is typical of the overall basin land use. Detailed stream temperature models should be developed and compared for a subbasin, using alternative water temperature models, for example Heat Source, HSPF, and CE-QUAL-W2. A possible location for this is Swamp Creek or a creek where there are at least two continuous temperature stations available.

The possible Brightwater wastewater treatment plant in the Little Bear Creek watershed, in the northern part of the SWAMP study area, is another potential opportunity for a pilot study. This pilot study would use the water quality data monitored in the watershed (see Table 3.9). Water temperature, dissolved oxygen, TSS, nutrients (N, P), metals, and bacteria data have been collected since 1993; pH and alkalinity data since 1998. A HSPF model of the Little Bear watershed can be constructed and calibrated for both water quantity and quality. The calibrated model represents baseline conditions. Discharges from the Brightwater facility (both quantity and quality) can be added to the model to evaluate their impacts to the Little Bear watershed, the Sammamish River, and Lake Washington. If appropriate, this modeling work can be done in support of the development of an EIS for this site.

5.3.1.2 Green WQA Study Area

In the Green WQA study area, Soos Creek or Newaukum Creek are good candidates for initial calibration because of the density of monitoring sites in these subbasins. Both basins have had previous HSPF applications. Soos Creek (or one or two Soos subbasins) may be preferable because of the good network of continuous temperature monitoring; and, since DO levels are degraded in much of this subbasin, it would be a good location to study the issues with these two important constituents (temperature and DO). While Mill Creek has only one existing monitoring station, its degraded water quality conditions make it a good site for exploring the issues with all constituents of interest in the basin, including sediment, metals, and bacteria. Since there is only one monitoring station, an

initial model application will help to determine whether this data gap needs to be filled, and whether it will cause difficulties in other locations.

5.3.2 Resource Needs for Piloting of Grid-Based Models

Pilot studies of MIKE SHE and DHSVM should be undertaken with due consideration to labor and software and other piloting costs and the scopes of these efforts should be adjusted to match available resources. What follows is a first approximation of the level of effort required for a pilot program that includes the following elements:

- Cooperation (planning and coordination) of model applications and/or development to pilot basins including data and model exchanges
- Design, installation, and operation of augmented monitoring to support comparison testing
- Acquisition of software as needed
- Calibration, comparison runs, and reporting
- Training and consultant support of King County staff on new model(s)

5.3.2.1 Staff Allocation

A watershed model piloting program involving both of the grid-based models with sites in both watersheds could easily require a full FTE at the senior-level engineer's level. This person should have skills and experience in both hydrology and watershed water quality modeling. This can be accomplished using a 3-year TLT (term-limited temporary) employee; however, it would be essential that model application skills and experience be transferred to permanent staff prior to TLT termination. Another option is to add an FTE to support both pilot studies, technology transfer, expanding needs for model applications associated with stormwater regulation, watershed management, ESA-response, infrastructure development, and surface-groundwater interaction and management.

5.3.2.2 Software Costs for Piloting of Grid-Based Models

DHSVM is currently a public domain model, and for purposes of this discussion, it is assumed that it will remain in the public domain and become an integrated watershed water quantity and quality model. MIKE SHE/MIKE 11 is a proprietary system. There are approximately 12 modules relevant to the SWAMP and GD-WQA projects (quantity, quality, and utilities) that have a one-time total cost of approximately $40,000 and a recurring annual cost of $5000 for a license on a single computer (Kjelds, 2002). Except for water temperature, the available set of modules appears to comprehensive for groundwater and channel processes, but is less complete for dynamic load simulation from different land uses.

5.3.3 Phasing

With a modeling application of this geographical extent and resolution and its consideration of a wide range of constituents, the issue of phasing is important. Some phasing is generally useful with regard to constituents, so that the modelers can focus on a subset of the constituents which are not impacted by other uncalibrated constituents.

For example, it is generally advantageous to calibrate temperature first, and then sediment. Then oxygen and nutrients (and algae) can be done together as a group; and bacteria, metals, and organics can be done as another group. However, some tasks related to time series data management and GIS data development are more efficient when the entire area, the ultimate areal resolution (segmentation), and the entire range of input data are handled at one time. This also improves the consistency and documentation of these tasks, which facilitates any changes that become necessary.

As the project proceeds and a detailed simulation plan is developed, the phasing of various subbasins and different groups of constituents (as dictated by data availability and the current needs of the County) will become easier to determine.

5.4 Summarization of Data and Monitoring Gaps

5.4.1 SWAMP Study Area

Additional stations may be needed on the larger tributaries such as North Creek and the Cedar River. In addition, a water quality station is needed at the model's upper boundary on the Cedar River.

Other major SWAMP monitoring gaps:

- Continuous temperature data at all stations.
- Baseflow and storm periods monitoring of all constituents.
- Metals data; preferably dissolved and particulate metals fractions.
- Toxic organics of interest.
- Organic carbon (DOC, TOC, BOD) and chlorophyll.
- Characterization of organic nutrient species with respect to dissolved vs. particulate and labile vs. refractory fractions.

5.4.2 Green WQA Study Area

At least one additional station should be installed in or near the Mill Creek watershed, for example in the Mullen Slough area.

Other major Green WQA monitoring gaps:

- Continuous temperature data at all stations.
- TSS data including two or more sediment size fractions.
- Baseflow and storm periods monitoring of all constituents.

- Toxic organics of interest.
- Total organic carbon (TOC) and chlorophyll, if algae modeling is needed.

5.5 Modeling Strategy Recommendations

For the SWAMP and Green WQA study areas, we recommend the Medium Data Requirement/Modeling strategy. This strategy provides appropriately complex and accurate empirical methods for the land response of water quality. This strategy includes the use of the accumulation/washoff methods in the HSPF PQUAL/IQUAL modules. The instream water quality model can include algal growth to more accurately predict nutrient delivery for the boundary conditions and provide water quality predictions at a local level. This can be done by either using HSPF or extending the CE-QUAL-W2 model to more of the mainstem rivers and the tributary streams to take advantage of its more detailed methods and to improve the linkage at the boundary locations. The strategy will:

- Use current HSPF models, and extend them to unmodeled areas (same as above)
- Integrate existing HSPF models with newly modeled areas within a consistent user-friendly framework based on GenScn (same as above)
- Use HSPF water quality for land areas (PQUAL/IQUAL with more detailed methods (accumulation/washoff) calibrated to site/land specific data
- Allow additional categories of land use as sources (e.g., multiple urban categories)
- Use HSPF or CE-QUAL-W2 water quality in streams, with algal dynamics represented

The medium data requirements include storm sampling over at least a two-year period, following the initial design of Burkey (2001) to obtain sufficient reliable data for a thorough nonpoint source water quality calibration and accurate land use impact representation; if water quality validation is required, ongoing sampling for an additional two years would be needed.

The selection of the Medium Data Requirement Strategy/Medium Strategy Modeling Package (Package 2) provides medium to high modeling ability to meet the needs of each of the potential users of the modeling results, with the single exception of groundwater. It is realized that groundwater has unique needs that may only be fully met by using a more sophisticated groundwater modeling program than is found in Package 2. For specific groundwater study areas of interest this can best be addressed through the use of phasing and piloting options described above.

The initial step in proceeding with this strategy should be the development of a detailed Simulation Plan that describes the modeling framework, data, schedule, and procedures to be applied in each study area. This is a standard approach for large, complex and comprehensive watershed modeling efforts, such as the Connecticut HSPF effort (noted above) and an ongoing Superfund effort for PCB fate/transport/bioaccumulation on the Housatonic River (Beach et al., 2000). The Simulation Plan should include:

- Data available for watershed characterization and segmentation
- Expected watershed segmentation showing subbasin and land use delineation
- Land uses to be explicitly modeled
- Stations/sites for pilot studies and watershed calibration/validation
- Specific constituents to be modeled, and model options/algorithms to be used
- Coordination of data sampling, collection, and analysis efforts with the modeling
- Calibration/validation time periods and procedures
- Model performance targets for all constituents
- Alternative watershed scenarios to be evaluated

In addition, the plan will need to address and develop a strategy for integrating existing HSPF models within each of the SWAMP and Green WQA watersheds which have been developed for different purposes, by different groups, and different time periods. A review of these existing models will be one of the first activities in the development of the Simulation Plan. This review will include checking land use information, meteorologic data, and channel routing information in each model for consistency and completeness. In particular, land use information and subbasin segmentation will probably have to be updated to be used for the water quality simulation and otherwise meet the needs of the SWAMP and Green WQA objectives.

Coordination with Snohomish County and their current modeling work on the North Creek and Swamp Creek watersheds should also be included in the Simulation Plan so as to take advantage of recent HSPF modeling work done in those two SWAMP tributary areas.

These activities are a key aspect of obtaining the greatest benefit from these prior HSPF studies in the region.

6 COORDINATION/COOPERATION STRATEGY

The watershed modeling program for the SWAMP and Green WQA projects will need to exchange information with other modeling related programs and personnel. Many of these programs are internal to King County while others are external. Coordination and cooperation among these programs and individuals is necessary and will become a critical factor to the successful implementation of the watershed modeling program.

The purpose of this section is to identify and evaluate the likely scope, feasibility, protocol, and schedule for coordination and cooperation (C/C) among watershed project components, consultants, and cooperators.

The C/C refers to the process/act of organizations and/or individuals, with related interests and activities, communicating and sharing ideas and information (models, data, etc.) to attain the greater good for the study and for all in the community. For the SWAMP and Green WQA projects the greater good can be defined as the most effective maintenance and management of water quantity and quality while ensuring environmental protection.

The C/C strategy consists of the following three components:

1. Organizations – related programs and interests and people
2. Structure – a framework for communication and information exchange
3. Mechanisms – processes and activities to make the C/C strategy successful

Each component of the coordination and cooperation strategy is discussed in the subsequent sections.

6.1 <u>Organizations</u>

The watershed modeling strategy has six C/C elements:

1. Land Use Scenarios and Modeling
2. Receiving Water Modeling
3. KC-WTD Sewer Modeling
4. Human and Ecosystem Impact Assessment
5. Additional Modeling Tools
6. King County Model Integration Project

The King County Watershed Modeling Team (members are David Hartley, Jeff Burkey, and AQUA TERRA Consultants, King County's watershed modeling consultant) will be at the core of the C/C program and will interact directly with each of the elements (Figure 6.1). The essence of the C/C is for information sharing and transferring. Table 6.1 lists the primary information that would be shared and transferred between the Watershed Modeling Team and each subject element.

Figure 6.1 Coordination and Cooperation Organization for Watershed Modeling

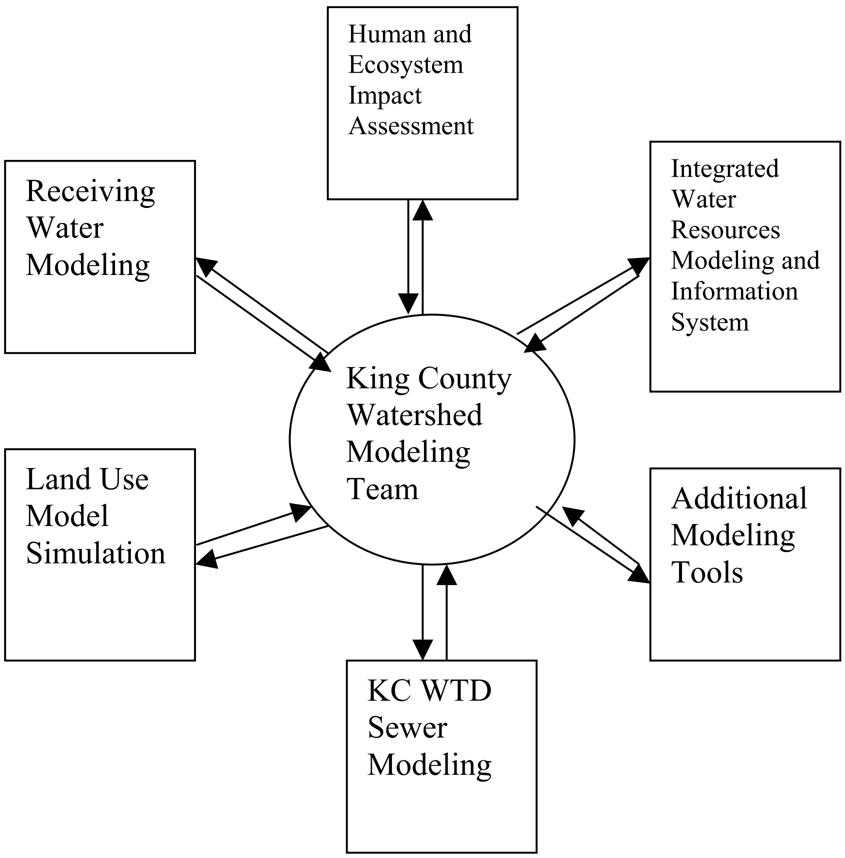


Table 6.1 Primary Information Flow between the Watershed Modeling Project and Related Modeling Elements

Watershed Modeling Elements	**Information Transfer and Directions: to (⇒), from (⇐) Watershed Modeling Project, or both directions (⇔)**
Land Use Scenarios and Modeling: *HSPF and UrbanSim*	⇒ future land use scenarios ⇐ water quality contributions by land use
Receiving Water Modeling: *SWAMP – Sammamish River, Lakes Washington, Sammamish, and Union* *Green WQA – Main Stem of Green, Duwamish Estuary, and Elliott Bay*	⇐ boundary conditions ⇒ receiving water model needs
KC WTD Sewer Modeling: *CSO and I & I Studies*	⇒ water diverted by sewerage for watershed water balance ⇐ water quality contributions from urban land uses
Human and Ecosystem Impact Assessment: *Risk Assessment and UEM*	⇐ instream water quality concentrations ⇐ non-point source pollutant loads ⇒ local and contaminant needs locations
Additional Modeling Tools: *UW's PRISM, DHSVM and UrbanSim, UEM*	⇒ technology transfer and ⇔ regional database
Model Integration Project: *IWRMS and Integrated Watershed Model for SWAMP and Green WQA*	⇐ information system specifications ⇔ watershed data management

Information flows either in one direction or in both directions. For example, the land use scenario is the primary information transfer between the element of land use scenarios and modeling and the watershed modeling. Specifically:

- The future land use scenarios provide information for watershed modeling
- The modeled water quality loads/contributions from the given land use scenarios, in turn, are shared with the interested parties in the same element

The scope and the organizations of each C/C element are further discussed in the following sections.

6.1.1 Land Use Scenarios and Modeling

Table 6.2 shows the organizations of C/C for the land use scenarios and modeling element. The organizations include affiliated parties (both internal groups within King County and the external organizations or individuals) and the respective information of interest.

Table 6.2 Organization of C/C for Land Use Scenarios and Modeling

Affiliation (key person)	**Information of Interest**
King County	
Land Use Scenarios (Larry Jones)	Future Land Use Scenarios
GIS Information Center (Ken Rauscher)	Land Use Related GIS Information
Watershed Modeling Team (David Hartley, Jeff Burkey and ATC)	Watershed Model, Modeling Applications and Database, Update model parameters (see above), Develop Interface between watershed model and UrbanSim
External Parties	
USGS /Tacoma (Rick Dinicola)	HSPF data base and regional parameters
Puget Sound Regional Council	Land Use Projections
U of W (Marina Alberti and Paul Waddell)	UrbanSim core model development applied to four Puget Sound counties, which must be completed first before it can be applied to SWAMP and Green WQA study areas.

The main C/C is the specification of future land use scenarios for the watershed modeling.

The main objective of the watershed modeling project is to simulate the water quantity and quality contributions from different land uses. It is of paramount importance to select a watershed model that meets this objective and the model must be driven by land use. A watershed model selection process has been conducted and is documented in Section 4 of this report.

The selected watershed model requires land use data as inputs. Future land use scenarios will be needed by the watershed model to project the future water quality contributions from the SWAMP and Green WQA study areas.

The future land use scenarios could be prescribed from UrbanSim. UrbanSim, a grid-based regional transportation and land use simulation model, is being configured for the Puget Sound region. The purpose of the model is to help policy agencies make decisions on modifying land uses. UrbanSim has the capability of generating land use scenarios that will be input to the watershed modeling process.

In order for UrbanSim to simulate future land use scenarios for the SWAMP and Green WQA study areas, the core UrbanSim model must be calibrated for the four Puget Sound counties. If UrbanSim is to be applied to two counties now (without a calibrated core model), it must be operated under certain assumptions which would severely limit the model's function. Puget Sound Regional Council (PSRC) is currently evaluating the UrbanSim for future land use simulations.

Future land use scenarios for SWAMP and Green WQA will be provided by King County, following coordination with the PSRC.

For information sharing purposes, the UrbanSim program continues to be supported by the University of Washington and National Science Foundation. The model could be supported by PSRC in the near future. Through the coordination and cooperation strategy, King County Watershed Modeling Program could leverage the on-going land use simulation modeling research at the University of Washington.

As part of the PRISM program an integrated urban development and ecological simulation model (UEM) is being developed. UrbanSim provides the framework for UEM. UrbanSim researchers have an interest in expanding the model to include water quality features. Through the C/C of this element, the UrbanSim researchers at University of Washington should also benefit through the sharing of information generated by the King County Watershed Modeling Team.

Another interested party is the King County GIS Information Center, which will be the party to receive land use information data from UrbanSim or PSRC for the future land use scenarios, as well as the water quality contribution data from the watershed modeling team for mapping purposes.

Current watershed modeling strategy is based on five major land use categories. It is anticipated that the number of land use categories will be expanded should the water quality monitoring of future land use changes indicate such a need. This aspect of C/C will continue, based on results from the water quality sampling program.

Future water management issues such as water import and export, extraction, irrigation, reuse, and consumptive use will have to be included with the future land use changes in

the models. The magnitude of these water balance changes will be dependent on the assumptions made as part of the future analysis.

Dinicola (1990, 2001) has developed regional parameter values for the study areas based on the watersheds previously modeled. As the watershed modeling work continues to expand to include previously unmodeled watersheds, the new modeling results will provide additional information to update or validate the regional parameter values.

Through the C/C, King County can act as a catalyst by joining with Puget Sound Regional Council to support the UrbanSim model development effort. 2004 is the target year for the UrbanSim program to complete the calibration of the core Puget Sound Model. This completion date of 2004 is after the expected completion of the model calibration work, based on the medium water quality strategy described in Section 5.2.2. However, there may be future modeling applications that will be able to take advantage of the UrbanSim information.

6.1.2 Receiving Water Model Project Component

The main C/C issue here is to provide the boundary condition (B/C) data specified by the King County Receiving Water Modeling Team.

Table 6.3 shows the organizations of C/C for the receiving water modeling. The receiving water modeling priority in SWAMP is Sammamish River and Lake Washington. The data for these receiving water models need to be available in early 2002. The watershed modeling data will not be available by 2002 to provide boundary condition data to the receiving water models. Therefore, it is important to coordinate data needs and adjust schedules accordingly. Prior to the completion of the watershed modeling, there may be opportunities to provide the receiving water models with preliminary data.

Table 6.3 C/C Organizations For Receiving Water Modeling	
Affiliation (key person)	**Information of Interest**
King County	
Receiving Water Modeling Team (Kevin Schock and Curtis DeGasperi)	Boundary conditions to Lake Washington and Sammamish River models
Watershed Modeling Team (David Hartley, Jeff Burkey, and Aqua Terra Consultants)	Watershed Model, Modeling Applications and Database
Temperature Analysis Team (Tim Hyatt)	Temperature Modeling and Data Collection/Analysis.
Water Quantity and Quality Database (Jon Frodge and LIMS)	Water Quantity and Quality Monitoring and Sampling Analysis
External Parties	
U.S. Army COE WES (Tom Cole)	Lake Washington model development: CH3D-ICM and Sammamish River model development: CE-QUAL-W2
U of W (Professor Michael Brett)	Water quality data analysis with respect to land use changes

The C/C between the watershed and receiving modeling teams needs to be on going and frequent enough to resolve the modeling approach to critical model interface issues such as data frequency, data storage and transfer method.

Continued C/C will be needed for the modeling of Lake Sammamish and Lake Union in the SWAMP study area as the receiving water model has not been selected and the bulk of the receiving water modeling work is presently targeted to be completed in 2004.

The Watershed Modeling Team, working in cooperation with Dr. Brett, has already computed the EMCs and used them as boundary conditions (e.g., nutrient loads, or nutrient concentrations and flows) for the Lake Washington Model (Schock, 2001). The current C/C effort with the University of Washington should be continued. As part of the on-going C/C effort, the EMCs work for the Green WQA study area should also be undertaken if it has not been started.

For the Green WQA study, the C/C issues for the receiving modeling involve:

- selection of receiving water model for the main stem of the Green River
- the receiving water model boundary condition requirements for the Green study area are likely to be the same as for SWAMP, including temperature, nutrients load, and partitioning of organics
- selection of a watershed model for temperature and water quality simulations for the two urban creeks, Longfellow Creek and Hamm Creek, which drain directly into the Duwamish River

As mentioned in Section 3.3.2, the Green WQA team has begun a basinwide water quality sampling program. The purpose of the monitoring program is to acquire site-specific storm runoff information and use it to characterize nonpoint loads from various land use categories. The data obtained from this program will augment the existing ambient water quality database by providing more detailed information about concentration and load variations during storms. This water quality sampling program is targeted for completion in 2003. The C/C effort will be heavily relied upon for the selection of the receiving water and the watershed models for the Green WQA study area.

6.1.3 King County WTD Sewer Modeling

There are two primary C/C issues:

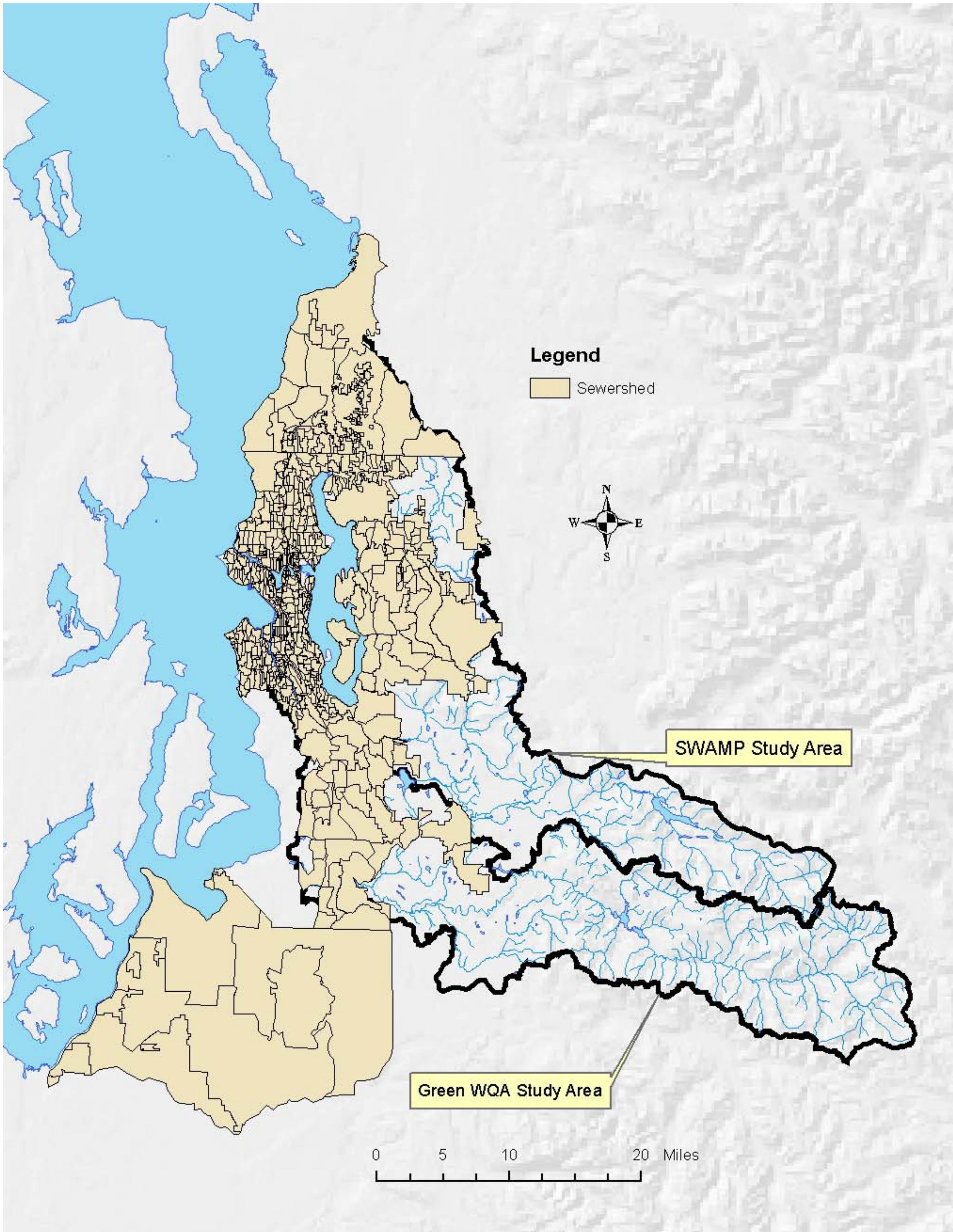
- The quantity of sewage in King County/Metro sewerage system has been modeled in detail through the past CSO and infiltration and inflow (I & I) studies. The amount of water that infiltrates into the sewerage system from the subsurface flow is equivalent to the amount that is diverted from the watershed. This information would be useful for the watershed modeling team in performing the water balance analysis for the watershed.

- Past sewer modeling study has been focused on water quantity. The Watershed Modeling team could apply the quality runoff coefficients to the sewershed modeling database to derive the water quality contributions from urban land uses.

Table 6.4 shows the C/C organizations of the King County WTD Sewer Modeling element. Figure 6.2 shows the modeled sewershed area. It should be noted that the modeled sewershed areas cross hydrologic boundaries. The cross-boundary issue needs to be addressed in the water quantity modeling work so as to correctly represent the service areas and the impacts on overall water balance. Other keys to accurately modeling the water balance include water import and export, groundwater extraction and transfer, irrigation, consumptive use, and reuse.

Table 6.4 C/C Organizations For KC WTD Sewer Modeling	
Affiliation (key person)	**Information of Interest**
King County	
Sewershed Modeling Team (Bob Swarner, Mark Lampard, Bruce Crawford, and Zhong Ji)	Water quality contributions from urban land use
Watershed Modeling Team (David Hartley, Jeff Burkey, and Aqua Terra Consultants)	Water diverted by sewerage for watershed water balance; water supply (import and export); water reuse and consumption
Receiving Water Modeling Team (Kevin Schock and Curtis DeGasperi)	Interface with receiving water model
External Parties	
DHI (Vendor of MIKE SHE and MOUSE software)	?
EarthTech (Consultants for I & I Study)	?

Figure 6.2 Sewershed Modeled Areas



As part of the CSO modeling program, an in-house runoff model has been used to model the King County/Metro sewerage service area. The model simulated the hydrologic events and performed unsteady hydraulic analysis. The modeling results give a profile of the combined sewer overflow (CSO) events at selected CSO locations. The modeling exercise has been conducted on King County's VAX computer, which is available only to the King County staff.

King County has embarked on an infiltration and inflow modeling study. This is a three-year program. DHI's sewer model, MOUSE, is the selected sewershed model. It runs on Windows-based computers and could be accessed by external groups such as personnel from other sewer agencies. DHI has recently customized the model so it will simulate the subsurface components in line with the in-house runoff model.

This I & I study is focused on modeling the sewerage flows in the separated sewer areas (a total of 150 subbasins). The objective of this modeling program is to simulate I & I flows for the project subbasins (the same areas that are currently being modeled by the in-house model) and to identify areas where an abatement program can be used to significantly reduce I & I flows. Currently the MOUSE model is being calibrated on two subbasins. The lack of large storm events in the past year has hampered the progress of the model calibration work. The study is targeted to be completed by 2004. The C/C should focus on coordinating with the water quantity and quality modeling work.

6.1.4 Human and Ecosystem Impact Assessment

The purpose of the human and ecosystem impact assessment is to support a number of on-going efforts in SWAMP and Green WQA, including:

- An evaluation of using reclaimed wastewater in the study area
- Development of a Habitat Conservation Plan (HCP)
- Siting and design of the Brightwater wastewater treatment plant
- Salmon Recovery Planning

The scope of the risk assessment (RA) study recently signed for the SWAMP sheds light on the information needs for the above efforts. In summary, the information needs are:

1. Characterize existing conditions in the major water bodies in the study area and identify any associated risks to aquatic life (including threatened and endangered species), wildlife, and people.
2. Same as item 1, but for conditions predicted to occur under future conditions as defined by the King County Comprehensive Plan and Growth Management Act.
3. Evaluate the potential effects of using reclaimed wastewater in the study area for existing and future conditions and any potential risks to aquatic life, wildlife, and people.

In the short term, the data needs for the risk assessment study are primarily focused on Lake Washington, by conducting a screening level risk assessment (SLRA) at the mouth

of tributary streams (e.g., Sammamish River). Unless there is a particular problem found at the mouth, then the assessment will be shifted further upstream. By that time the watershed model results will be available for use.

The RA work will follow the same timeline as the modeling work of the receiving water models (see Section 6.1). A SLRA will be conducted for the three lakes (Washington, Sammamish, and Union) and at the tributary mouth to assess human cancer risk and ecological health risk.

Before the modeling work is fully deployed, the RA work is supported by a comprehensive water quality sampling program. The sampling program will cover a large number of water quality constituents. A subset of these water quality constituents (e.g., fecal coliform) will most likely be selected for the modeling work. The model results also could be used to address specific questions on temporal and spatial resolution for the sampling data.

The scope of risk assessment study for the Green WQA area will be different from the SWAMP study, but the details of the scope are less well defined as of August 2001 (Simmonds, 2001). TMDLs, best management practices, and runoff controls are likely issues for health and ecological impact assessment in the Green WQA study area.

In summary, the corresponding C/C needs should include:

- Characterization of the existing and future water quality conditions; they are normally specified in terms of water quality concentrations in the water column and sediment and of their distributions (both temporal and spatial).
- Water quality changes resulting from the application of pollution abatement measures.

Table 6.5 shows the C/C organizations of the human and ecosystem impact assessment component.

Table 6.5 C/C Organizations For Human and Ecosystem Impact Assessment	
Affiliation (key person)	**Area of Interest**
King County	
Risk Assessment Team (Jim Simmonds, Lorin Reinelt)	Instream water quality concentrations and non-point source pollutant loads
Water Quality Sampling Team (Jon Frodge)	Water quality monitoring and sampling analysis
Watershed Modeling (David Hartley, Jeff Burkey and Aqua Terra Consultants)	Modeling instream water quality concentrations
Water Reuse Team (Karen Huber, John Lombard) WTD HCP Team (Steve Gilbert) WRIA 8 Team (Scott Brewer)	ESA and HCP
WTD Brightwater Treatment Facility Team (Steve Gilbert)	EIS and Risk Assessment
Receiving Water Modeling Team (Kevin Schock and Curtis DeGasperi)	Modeling chemical and toxic concentrations in receiving waters
External Parties	
National Marine Fisheries Service Federal and State Fish and Wildlife Service Seattle Public Utility Washington Conservation Commission	ESA and HCP
U of W (Marina Alberti and Derek Booth)	Leverage on the UW studies supported by other agencies)
WDOE	On-going study of the Ecological Impact (on habitats) due to land use changes
Parametrix (Consultant for the SWAMP Risk Assessment Study)	Risk Assessment

The instream water quality concentrations can be modeled by the instream module of the watershed model or by the receiving water models. The former would be using simplified process models in combination with assumptions that treat certain model

variables as constant. The latter would provide more accurate results, but it must be extended upstream from mainstem to tributaries. The modeling strategy will be a key issue for C/C. The other related C/C issue is the definitions of the existing and the future conditions for the watershed modeling team.

The UrbanSim researchers (Section 6.1.1) have expressed interest in extending the model for assessing the ecological impacts due to land use changes. The model is currently being applied to study the impact of land use changes on habitat and ecological conditions in the lowland Puget Sound area (below 100m elevation). The study is part of the State level watershed planning effort steered by the Puget Sound Action Team of Washington Department of Ecology (WDOE). Continued C/C with the UrbanSim program and WDOE would be beneficial to all affiliated parties.

6.1.5 Additional Modeling Tools

Puget Sound Regional Synthesis Model (PRISM) is a potential watershed modeling package worth future consideration. Table 6.6 shows the C/C organizations of this element. Section 6.1.2 has already addressed the C/C with UrbanSim, one of the models in PRISM. The main C/C effort will be on transferring technology and sharing the regional database.

Table 6.6 C/C Organizations For Additional Modeling Tools

Affiliation (key person)	Information of Interest
King County	
Land Use Scenarios (Larry Jones)	Future land use scenarios and impact evaluation
SWAMP and Green WQA (Jon Frodge and Lorin Reinelt)	Water quality assessment methods and tools and regional watershed related database
Watershed Modeling (David Hartley, Jeff Burkey, and Aqua Terra Consultants)	Model development, technology transfer, watershed database
External Parties	
UW PRISM (Jeff Richey) UW DHSVM (Pascal Storck) UW UrbanSim (Marina Alberti and Paul Wadell)	Model research and development, demonstration study, technology transfer and regional database

When the models in the PRISM program are fully integrated for the whole Puget Sound region (no date has been scheduled), then there may be value for the SWAMP and Green WQA teams to make use of all or part of it. For example, the future watershed models in SWAMP and Green WQA could become subregional models of PRISM and used to model local land use and boundary conditions. In return, the ongoing development of the watershed modeling program and the collected monitoring and sampling data could be shared with PRISM for use in its model development, calibration, and validation activities.

6.1.6 Model Integration Project

There are two aspects of model integration effort in the SWAMP and Green WQA:

1. With respect to the Integrated Water Resources Modeling and Information System (IWRMS) project, and
2. With respect to the integration of all watershed modeling results for the respective study area

The second aspect can be integrated into the first.

C/C with IWRMS can include the operational aspect of the watershed modeling, namely: functional and system requirements, model utility interfaces (such as GUI), database management, County resource management (e.g., data, computational, personnel, etc.), automation of the transfer of data between models and database, utilization of in-house visualization software, program documentation, and management of model input and outputs, etc.

Pacific Northwest National Laboratory (PNNL) is the contractor for the King County's IWRMS. PNNL has identified the follow objectives for IWRMS:

- Building on the County's existing hardware and software infrastructure
- Preferentially use commercial-off-the-shelf software and non-proprietary protocols (planned scientific treatment)
- Emphasize flexibility and utility of the design to allow for future expansion of project models and the ability to address facility siting, environmental, and risk assessment issues
- Providing a means for documenting and tracking model runs and associated input variables
- Enabling project models to be run in isolation or together in combination as appropriate.

The Watershed Modeling team will need to C/C with the IWRMS team to achieve these objectives. The scheduled completion of the IWRMS work is in 2004 and should be coordinated to make use of the watershed modeling information available at that time.

Other C/C activities with IWRMS include providing information about the watershed modeling program; for example, information related to the following types of questions:

- What watershed modeling tools does King County currently have ready access to?
- For what purposes are analytical models used?

Table 6.7 shows the C/C organizations of the model integration project component.

Table 6.7 C/C Organizations For Model Integration Project

Affiliation (key person)	Information of Interest
King County	
Watershed Modeling Team (David Hartley, Jeff Burkey, and Aqua Terra Consultants)	Data process (e.g., statistical analysis) and watershed modeling database management (e.g., WDMUtil and GenScn), simulation results, etc.
Receiving Water Modeling Team (Kevin Schock and Curtis DeGasperi)	Model boundary conditions (related watershed data management)
Water Quality Sampling Team (Jon Frodge)	Information Management (watershed quantity and quality data)
External Parties	
Battelle PNNL	Information system specifications Models need to be integrated with water resources modeling and information systems.

Important data process features of the HSPF model, such as WDMUtil and GenScn (presented in Section 5.1), which provide database management and statistical analysis for the watershed model simulation results are also items to be incorporated in the integration project.

6.2 C/C Structure

A technical advisory committee (TAC) composed of the identified interests in Table 6.1 can assist in determining the C/C structure. An example of one structure is outlined below in the form of a Project Integration Committee and associated subcommittees.

Since the level of coordination and cooperation effort required for the watershed modeling study is extensive, it may be desirable to establish a Project Integration

Committee (PIC) to act as the central focus of the C/C process. Based on the nature of the C/C components, the PIC can be divided into three subcommittees as follows:

1. Model Development Subcommittee for the C/C of Land Use Simulation Modeling and Additional Modeling Tools

2. Current Project Subcommittee for Receiving Water, WTD Sewer Modeling, and Human and Ecosystem Impact Assessment

3. Model Integration Subcommittee

The parties identified in Tables 6.1 to 6.5 should be considered as members of the appropriate subcommittees. The SWAMP and Green WQA project managers could share the duty of chairperson and take turns chairing the subcommittees. A member of the Watershed Modeling Team will act as the subcommittee secretary who has the day-to-day responsibility for the C/C affairs. Depending on the C/C needs, the subcommittee should meet at least twice to four times a year. For the Current Project Sub-Committee, the frequency of meeting should be more than four times a year. The PIC (Project Integration Committee) should meet together annually for a progress/status meeting.

6.3 C/C Mechanism

Other than the routine Project Integration Committee and subcommittee meetings, the other C/C mechanisms, such as ones described below, should be considered to enhance communications among identified C/C parties as well as provide a mechanism to exchange information among additional relevant parties:

- Website for disseminating information, meeting announcements, agendas, notices, etc.
- Newsletter (to be sent out as an email)
- Joint studies and publications
- Incentive program for the most valuable, most improved, and most creative information transfers
- Demonstration or pilot studies for certain model development or data collection program
- Workshops on specific topics, perhaps join sponsor with organization such as University of Washington, on the subject of watershed model development

6.4 Conclusions

The C/C subject is complex and comprehensive, and the difficulty is compounded with the involvement of multiple interested parties. It will take a concerted effort of all of the identified internal parties of King County and the external parties to accomplish the C/C work. The C/C strategy, as outlined above, will face potential time and/or budget constraints. But the most important single factor for the success or the lack of success of implementing the C/C strategy is finding the key person in the management to

consistently champion this cause and provide the vision and leadership to the C/C organizations.

The other important success factor is to continue to identify common interests and chart common goals for all parties. Focus should be on the common goals and interests. Persistence and hard work in communication will bring out the accomplishment that in turn will cultivate further cooperation, trust, and fulfillment. The C/C strategy described above is feasible and could be initiated within a few months.

7 SUMMARY

This section summarizes information described in detail in sections 2, 3, 4, 5, and 6. Only the highlights of these sections and their conclusions are presented below.

7.1 Review of Modeling Needs

The purpose of the watershed modeling needs assessment is to provide review, refinement, clarification, and summarization of modeling needs with regard to what, when, where, how, and why water quality and quantity parameters need to be modeled in each watershed. The result of the needs assessment will be used to assess feasibility of achieving modeling goals, objectives, and schedule and to recommend adjustments to project team.

Ten programs and plans have been identified as potential clients for use of the information obtained from the watershed modeling work. These programs and plans include the Wastewater Program, NPDES Permit Program, Habitat Conservation Plans, Salmon Recovery and Conservation Plans, Total Maximum Daily Load Program, UPD Monitoring Program, Urban Water Supply Plan, Watershed Resource Inventory Area (WRIA) Planning, and Groundwater Management Program.

Specific water quality needs are focused on providing water quality constituent input to the receiving water models, EFDC, CE-QUAL-W2, and CH3D-ICM. The water quality inputs that must be provided to these models are substantial and must also provide the boundary condition for these models. Furthermore, adequate simulation of the minimum set of the constituents required for the water quality model boundary condition is dependent on also modeling water quality processes (e.g., algal uptake and release of nutrients) in many of the tributary streams and rivers. Therefore, relatively complete (in terms of processes, constituents, and both spatial and temporal resolution) water quality models must be developed for the tributary watersheds. This includes land use-specific water quality response and instream process modeling.

7.2 Strategic Review of Modeling Approaches

A strategic review of modeling approaches was conducted through a customized literature search of water quantity and water quality models that meet SWAMP and Green WQA project needs, goals, and objectives. Two strategies were pursued in conducting this review.

A model selection process for the assessment of availability and use of water quality models was used to evaluate watershed models with a defined set of criteria. A total of 46 watershed models were evaluated and analyzed for a range of water quality features and options. This model selection process made use of extensive research by the Water Environment Research Foundation to review the availability and use of water quality models.

Other model information sources were also investigated. A literature search via the Internet and associated sources provided information on DHSVM at the University of Washington. Information on MIKE SHE was obtained from a three-day DHI workshop held in Port Orchard, Washington, in March 2001, plus supplementary materials provided by DHI and other sources.

Three different watershed models have been reviewed in detail. These models are HSPF, MIKE SHE, and DHSVM (with a water quality module or algorithms to be added).

7.3 Development and Detailing of Modeling Alternatives

The development of a water quantity and quality modeling strategy is based on the relationship of the modeling needs to the data available. Specific recommendations are made based on a functional assessment together with project schedule and budget.

Three watershed modeling strategy packages are described in Section 5. The three packages reflect a range of monitoring data support from low to high. A strategy with low data requirements is implementable with existing data. A medium data requirement strategy requires a moderate amount of modification and augmentation of the monitoring program. At the upper end is a high data requirement strategy that is based on significant modification and enhancement of the monitoring program.

The medium data requirement strategy provides appropriately complex and accurate empirical methods for the land response of water quality. This strategy includes the use of the accumulation/washoff methods in the HSPF PQUAL/IQUAL modules. The instream water quality model can include algal growth to more accurately predict nutrient delivery for the boundary condition and provide water quality predictions at a local level. This can be done by extending the CE-QUAL-W2 model to more of the mainstem rivers and the tributary streams to take advantage of its more detailed methods and to improve the linkage at the boundary locations. The strategy will:

- Use current HSPF models, and extend them to unmodeled areas
- Integrate groundwater and water extraction and use information into the models
- Combine existing HSPF models with newly modeled areas within a consistent user-friendly framework based on WinHSPF and GenScn
- Use HSPF water quality for land areas (PQUAL/IQUAL with more detailed methods (accumulation/washoff) calibrated to site/land specific data
- Allow additional categories of land use as sources
- Use CE-QUAL-W2 water quality in streams, with algal dynamics represented

7.4 Coordination/Cooperation Strategy

The water quantity and quality modeling strategy for SWAMP and Green WQA projects included the involvement of numerous internal and external programs and personnel. To implement this watershed modeling strategy will necessitate the coordination and cooperation of these programs and personnel in the affiliated organizations.

The watershed modeling strategy for SWAMP and Green WQA projects has identified six coordination and cooperation (C/C) elements:

1. Land Use Scenarios and Modeling
2. Receiving Water Modeling
3. KC-WTD Sewer Modeling
4. Human and Ecosystem Impact Assessment
5. Additional Modeling Tools
6. King County Model Integration Project

The C/C refers to the process/act of organizations and /or individuals, with related interests and activities, communicating and sharing ideas and information (e.g. models, data, etc) to attain the greater good for the study and for all in the community. The focus of the C/C is on the transfer of modeling information.

A Project Integration Committee (PIC) to provide the structure for the C/C process is recommended. The C/C effort will be conducted using three subcommittees, namely: Model Development Sub-Committee for the elements 1 & 5, Current Project Sub-Committee for the elements 2, 3, and 4, and Model Integration Sub-Committee for element 6.

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