# 2.0 METHODS

The basic approach taken for this investigation was to design ground water flow and contaminant transport models for two locations on the Eastern Shore—one on the recharge spine and the other near the shore—to simulate the effects of various development scenarios on the availability and quality of ground water. The scenario results were then used to develop specific recommendations for protecting ground water from potential risks associated with new residential or commercial development. Two different numerical models were utilized—FEMWATER/LEWASTE to simulate the transport of contaminants from surface sources and SHARP was used to examine the potential for saltwater intrusion and excessive drawdown.

## 2.1 FEMWATER/LEWASTE

LEWASTE is a finite-element model that USEPA developed for delineating wellhead protection areas. The model simulates transient or steady-state three-dimensional transport of contaminants through unsaturated and saturated media, including adsorption and first-order decay. The hydrologic fluxes simulated by FEMWATER can be used as input to LEWASTE, which can consider multiple aquifers and confining units, spatially variable hydraulic properties, pumping wells, distributed sources/sinks, and various types of boundary conditions. LEWASTE is documented by Yeh and others (1992).

### 2.1.1 Model Grid

In order to simulate the effects of development on ground water on the Eastern Shore, a two-dimensional LEWASTE model grid was developed that was two elements long, one element wide, and ten elements deep, for a total of twenty elements (Figure 2-1). All elements were rectangular and had horizontal dimensions of about 740 feet (225 m) and a vertical dimension of about 14 feet (4.3 m). Therefore, each element had a top surface area of about 12.5 acres (50,625 $m^2$) and the entire grid had a thickness of about 140 feet (43 m). The uppermost five elements in each column represented the Columbia aquifer, giving this unit a modeled thickness of about 70 feet. The bottommost four elements in each column represented the upper Yorktown aquifer, with a modeled thickness of about 53 feet. The single element between these units represented the upper Yorktown confining unit with a thickness of about 14 feet. Hydrogeologic properties assigned to these units were selected to represent average conditions on the Eastern Shore. Based on a vertical hydraulic gradient of 0.001, a vertical hydraulic conductivity of 8 m/day, and a porosity of 30%, the vertical ground water flow velocity was calculated as 2.7 m/day.

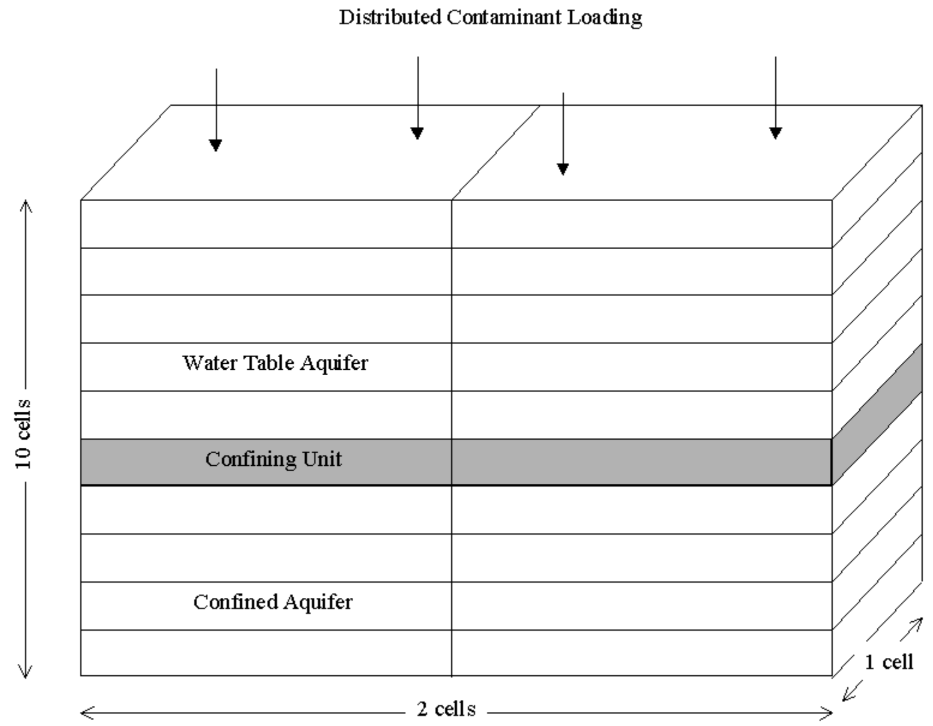

Figure 2-1: Schematic of LEWASTE grid.

For the recharge spine setting, the simulated water tables lay about 20 feet (8.5 m) beneath the land surface. Soil properties were selected to represent a moderately well-drained sandy loam. The horizontal ground water velocities were selected to represent a low hydraulic gradient (0.001) and a porosity of about 30%. Identical ground water flow velocities were simulated for the near-shore setting, but in this scenario the water table was modeled as six feet beneath the land surface and soil properties were selected to represent a sandy soil.

### 2.1.2 Contaminant Transport

LEWASTE was used to simulate the infiltration and subsurface transport of *nitrogen* and a *herbicide* from developed areas. The two modeled sources of nitrogen were septic systems and fertilizer application. Moderately conservative assumptions regarding contaminant loading rates were made so that the scenarios would accurately represent developed conditions (Table 2-1). Where possible, assumptions were made consistent with those used in the *Ground Water Supply Protection and Management Plan for the Eastern Shore of Virginia* (HRH, Inc. 1992) for nitrogen under buildout conditions.

The herbicide 2,4-dichlorophenoxyacetic acid (abbreviated 2,4-D) was selected as the herbicide to model because it is the most commonly-used chemical herbicide for controlling broadleaf weeds on grass, is relatively water soluble (when applied as a dimethylamine salt, as is common), is relatively mobile in the subsurface, and has a Virginia water quality standard (0.1 mg/L). The soil adsorption and degradation rates used in the model for 2,4-D (Table 2-1) were selected from the lower range presented in the literature as tabulated by Balogh and Walker (1992). The modeled application rate was the maximum application rate specified by the major commercial formulation (Trimec®). It was further assumed that 20-percent of the herbicide applied was lost due to volatilization and aerosol drift. The remaining 80-percent would be available for downward leaching.

Contaminant loading to the ground water system was modeled by simulating the uppermost elements of the model grid as distributed source elements. The moisture flux from these source elements was calculated as the natural recharge (9 in/year on pervious surface, 2 in/year on impervious) plus septic system fluxes (about 165 gal/day per household). Average contaminant concentrations of the moisture entering the ground water system were calculated by dividing the estimated contaminant load by the moisture flux. The north and south vertical horizontal boundaries were defined as no-flow boundaries because the dominant regional ground water flow directions on the Eastern

## TABLE 2-1

## FACTORS USED TO COMPUTE GROUNDWATER DEMANDS, RECHARGE, AND CHEMICAL LOADINGS

| Factor | Units | Value |
|---|---|---|
| Potable water demand per lot | gal/day | 170 |
| Pavement area per lot | $ft^2$ | 500 |
| Roof area per lot | $ft^2$ | 1500 |
| Percentage of lot that is lawn | % | 50 |
| Road area per acre development | $ft^2$ | 1000 |
| Irrigation rate for lawns | in/year | 13 |
| Percentage of lot that is irrigated | % | 50 |
| Percentage of homeowners that irrigate | % | 50 |
| Recharge rate for pervious area | in/year | 9 |
| Recharge rate for impervious area | in/year | 2 |
| ***Septic system factors*** | | |
| Septic system effluent--flow per lot | gal/day | 165 |
| Septic system effluent--nitrogen concentration | mg/L | 40 |
| Percentage of septic system effluent recharged to Columbia aquifer | % | 100 |
| ***Fertilizer factors*** | | |
| Fertilizer nitrogen loading rate per unit area lawn | lbs/year/acre | 150 |
| Percentage of fertilizer nitrogen available for leaching | % | 80 |
| Percentage of homeowners that fertilize | % | 50 |
| ***Herbicide factors*** | | |
| Percentage of irrigation water recharged to Columbia aquifer | % | 20 |
| 2,4-D application rate to lawns | lbs/acre/year | 2 |
| Percentage of homeowners that apply 2,4-D | % | 50 |
| Percentage 2,4-D lost to volatilization/drift | % | 20 |
| 2,4-D degradation rate | $day^{-1}$ | 0.05 |
| 2,4-D soil adsorption coefficient | -- | 20 |

Shore are east-west rather than north-south. Similarly, the bottom boundary was defined as a no-flow boundary.

## 2.2 SHARP MODEL

The SHARP model (Essaid 1990) is a quasi-three-dimensional, finite-difference model that simulates freshwater and saltwater flow separated by a sharp interface in layered coastal aquifer-confining unit systems. SHARP can consider multiple aquifers and confining units, spatially variable hydraulic properties, pumping wells, distributed sources/sinks, and various types of boundary conditions. The USGS developed a ground water model of the Eastern Shore of Virginia using the SHARP model to simulate flow and predict the position of the saltwater/freshwater interface for the Yorktown aquifers (Richardson 1991).

Malcolm Pirnie used the USGS model as the basis for the SHARP model used on this project, although several significant modifications to the original model were made. The following sections describe the setup and calibration of the Eastern Shore SHARP model, followed by a description of local modifications used to examine the effects of development on the recharge spine and near-shore settings.

### 2.2.1 USGS Eastern Shore SHARP Model

The USGS Eastern Shore model area, developed by Richardson (1991), included all of the Eastern Shore peninsula and portions of the surrounding Chesapeake Bay and Atlantic Ocean. The northern limit of the model area extended only a very short distance north of the Virginia-Maryland State line. The model grid used to represent aerial distribution of aquifer characteristics and ground water elevations consisted of 106 rows and 59 columns, ranging in area from a minimum of 0.24 $mi^2$ to a maximum of 10.82 $mi^2$.

The USGS Eastern Shore model simulated flow in the Yorktown aquifer system (upper, middle, and lower Yorktown aquifers). The overlying Columbia aquifer (water table aquifer) is represented as a constant head boundary and the underlying St. Mary's confining unit as a no-flow boundary. The confining units separating the Yorktown aquifers were represented by leakance values, allowing vertical flow between the aquifers.

The western and southern boundaries for the Eastern Shore peninsula is the Chesapeake Bay and the eastern boundary is the Atlantic Ocean. The edges of these boundaries were represented as no-flow boundaries in the model. Near shore saltwater-flow characteristics were handled by extending the offshore boundaries well away from the coastline. The northern boundary of the model was an artificial boundary located immediately north of the Virginia-Maryland State line and was simulated as both a no-flow boundary and a constant head boundary in the model simulations.

Pre-pumping heads were estimated in the model based on surface topography and previous ground water level estimates by Bal (1977). Ground water elevations prior to 1940 were assumed to represent pre-pumping conditions. The first ground water withdrawal in the model began in 1940 and continued through 1988. Changes in the ground water withdrawal rates were simulated as 12 pumping periods over this time. The Eastern Shore model was calibrated to 1988 ground water levels and verified against 12 ground water observation wells with historical water level information.

The saltwater-freshwater interface was represented in the model as a sharp interface. There are no offshore data for the Eastern Shore; therefore, the actual position of the saltwater-freshwater interface and the width of the transition zone are unknown. Initial position of the saltwater interface was simulated by the model based on the Ghyben-Herzberg approximation (incorporated in the SHARP model).

Leakage between the saltwater and the freshwater zone was restricted by the model. Saltwater was not allowed to leak into the freshwater zone. The leakage of freshwater was distributed between the saltwater and the freshwater zones based on the amounts of each type of water in the node receiving the leakage. The approach was designed to reproduce the general response of the interface and did not provide information concerning the nature of the transition zone between saltwater and freshwater.

Vertical leakage of saltwater into freshwater was not directly simulated; evidence of vertical saltwater intrusion from overlying saline surface-water bodies was provided by examination of the water level gradients and areas of reversed ground-water flow.

The model was not able to simulate upconing of saltwater through a confining unit as a result of pumpage. Because of the density gradient between fresh and brackish ground water and the restricted flow through the confining unit, upconing through a confining unit would generally occur only when there was a very large gradient between the two aquifers or the confining unit was effectively absent. Within an aquifer, upconing was represented by a change in the interface position for mixed cell areas.

### 2.2.2 Modified Eastern Shore SHARP Model

In recreating the USGS Eastern Shore SHARP model, Malcolm Pirnie made two principal changes. First, the northern boundary of the original model extended only a short distance beyond the Virginia-Maryland border. The northern model boundary was extended to include the Maryland counties of Somerset, Wicomico, and Worcester, and this boundary was set as a no-flow boundary. Secondly, the uppermost aquifer (Columbia aquifer) was defined in the USGS model as a constant head boundary. This was changed to an unconfined aquifer to predict drawdown in the Columbia aquifer as a result of regional ground water withdrawals in the Yorktown aquifer.

Because the upper model layer was defined as the water table aquifer, two additional conditions were incorporated into the model. Recharge, representing the amount of precipitation reaching the saturated zone minus loss through evapotranspiration, was added as a constant rate. The initial value for recharge was 12 inches/year and the final recharge value after calibration was 9 inches/year. The second addition was a leaky head-dependent boundary to simulate recharge/discharge of ground water to surface water. This head-dependent boundary was defined only for model cells with major rivers or creeks. The head for these cells was set equal to pre-pumping ground water levels presented in Richardson (1991) and ground water levels presented in Cushing et al (1973). Leakance through this boundary was set to a constant $1 \times 10^{-3}$ day$^{-1}$. The leakance represented streambed leakance. Because no streambed leakance values were available for this area, a constant vertical hydraulic conductivity of $1 \times 10^{-6}$ cm/sec and a uniform streambed thickness of 3 feet was assumed.

For the modified SHARP model, the pre-pumping interface was assumed to be roughly equal to the interface predicted by the USGS Eastern Shore model. The initial interface position was calculated based on the Ghyben-Herzberg solution. Some minor modifications to the model during calibration were necessary to provide an interface position closely matching the USGS Eastern Shore model.

*Setup and Calibration*: Model setup involved assigning initial aquifer characteristics, boundary conditions, and ground water elevations to the model. Information on the aquifer distribution used in developing the model was obtained principally from published data for the USGS Eastern Shore model (Richardson 1991) and the USGS Water Resources of the Delmarva Peninsula (Cushing et al 1973). The top of the aquifers and confining layers, ground water elevations, and aquifer and confining layer thicknesses were obtained from these sources.

To "discretize" the information presented on the maps for the model, a grid 3 $mi^2$ (1.75 mile on a side) was overlain on the Eastern Shore model maps and Delmarva Peninsula maps and representative values were assigned to each grid location. The discretized data was then smoothed using an inverse distance algorithm, and individual values assigned to each model cell location using the nearest neighbor approach. Hydraulic conductivity values were initially set at the values presented in the USGS model and adjusted to closely match measured transmissivities. Leakance was initially set as an assumed vertical hydraulic conductivity of $1\text{x}10^{-6}$ cm/sec for the upper Yorktown confining unit and $5\text{x}10^{-5}$ cm/sec for the middle and lower Yorktown confining units divided by the calculated thickness of the confining unit.

The calibration step included optimizing the matrix solution parameters (SIP parameters), adjusting aquifer characteristics to match pre-pumping and existing ground water elevations, and the initial saltwater interface position (based on the USGS Eastern Shore model). A total of 146 model runs were used to calibrate the model. The initial model runs were used to select the most efficient SIP parameters. The following SIP and related parameters were used in the final model:

- Number of Iteration Parameters (NITP) = 10
- Convergence Closure Criteria (ERR) = $1\text{x}10^{-3}$
- Steady State Criteria (STST) = $1\text{x}10^{-3}$
- Relaxation Factor (RFAC) = 0.4

- Weighting Factor (WFAC) = 0.5
- Factor Used in Calculating Iteration Parameters (WITER) = 10000

Once the iteration parameters were set, the next step in calibration was to reproduce pre-pumping ground water elevations predicted by the USGS Eastern Shore model and current ground water elevations as measured at 77 ground water observation wells. Ground water elevations were first matched against pre-pumping levels. To obtain pre-pumping levels, the model was run with the initial parameters until steady state conditions were achieved (as defined by the steady state criteria). To accelerate convergence to steady state, pre-pumping storage was set to zero. Concurrent with the pre-pumping ground water elevation calibration, position and distribution of the saltwater interface was checked against the USGS predicted positions and adjustments were made to correct for major discrepancies.

Parameter Estimation: Local transmissivities were calculated for each model grid block using a method similar to the procedure Richardson (1991) used in calibrating the USGS Eastern Shore model and were not varied during calibration. The vertical leakance for each confining unit was calculated based on well logs describing the physical characteristics of the section. Leakance values were set constant across each confining unit. Initial values were set at $1x10^{-6}$ cm/sec for the upper Yorktown confining unit and $5x10^{-5}$ cm/sec for the middle and lower Yorktown confining units. During calibration runs these values were adjusted by as much as five times the initial value in order to obtain adequate matching between predicted and observed water levels. The storage coefficient for each model grid location was set at a constant value: 0.05 for the Columbia aquifer, and $1 \times 10^{-4}$ for the confined aquifers. Porosity of all aquifers was set at 0.25, which is the value used in the USGS Eastern Shore Model.

### 2.2.3 Recharge Spine Setting

The SHARP model described above was developed for the entire Eastern Shore of Virginia. In order to examine the more localized effects of development, it was necessary to modify the grid to provide greater resolution in localized areas. For the recharge spine setting, the model cell size was reduced from the minimum USGS cell size of 0.24 $mi^2$ to

30 acres in the vicinity of a hypothetical development in central Accomack County (Figure 2-2).

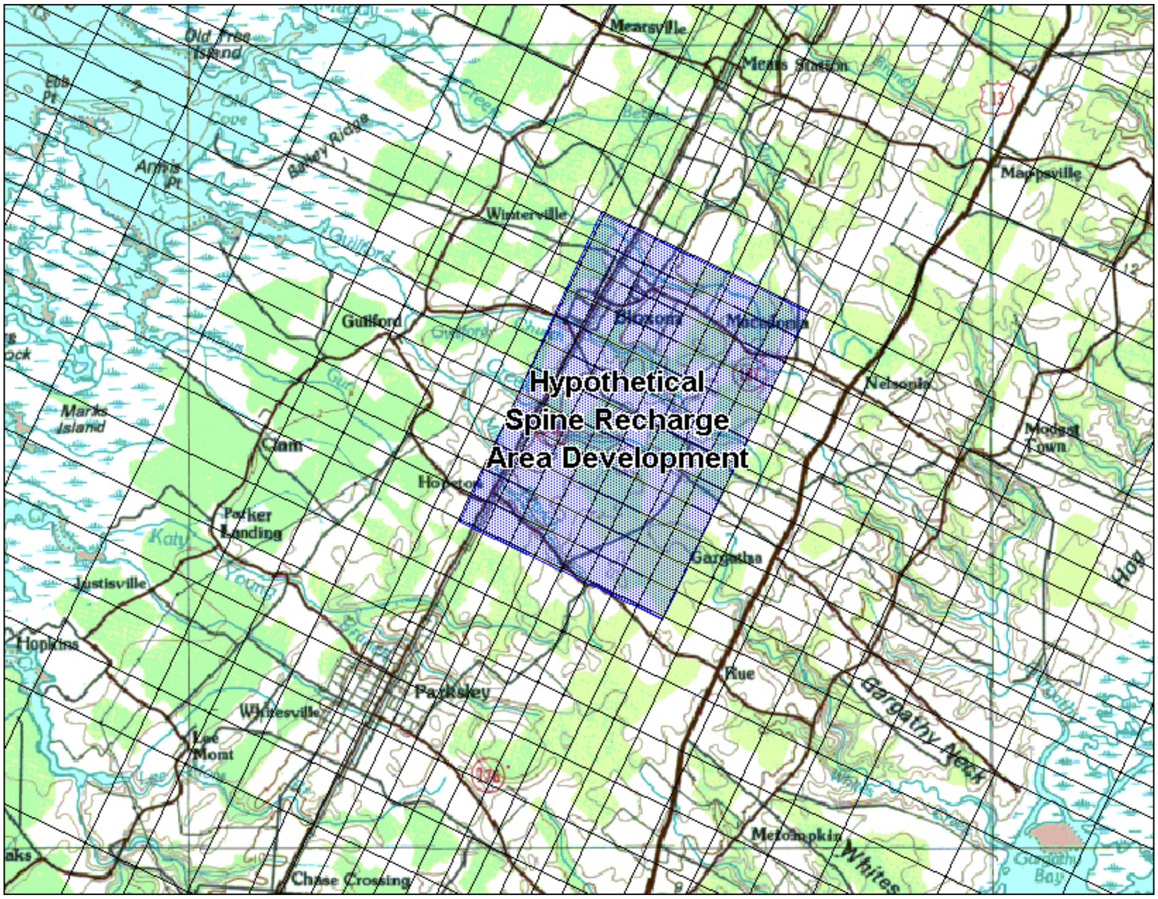

Figure 2-2 Spine Recharge Model Area

The cell size increased to a maximum of 12.25 $mi^2$ with distance from the developed area. To accommodate the smaller cell size and increased area to the north, 81 rows and 61 columns were used to cover the entire model area.

### 2.2.4 Near-Shore Setting

As for the recharge spine setting, the grid spacing of the Eastern Shore SHARP model was modified to provide adequate resolution of a hypothetical development on the Chesapeake Bay side of Accomack County (Figure 2-3).

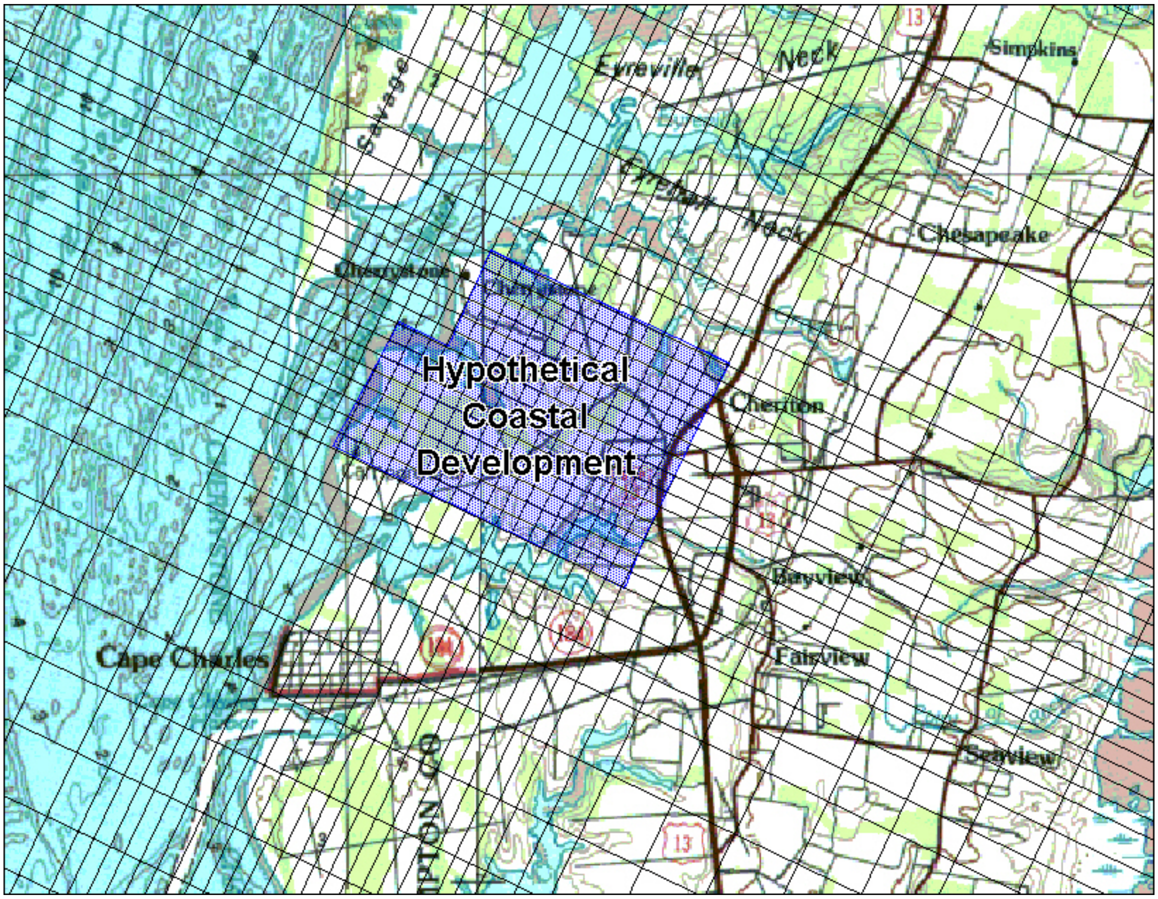

Figure 2-3 Coastal Development Model Area

The model cell size was reduced to 7.6 acres in the area of simulated development and increased to a maximum cell size of 12.25 $mi^2$ with distance from the well field. To accommodate the smaller cell size and increased area to the north, 76 rows and 75 columns were used to cover the model area.

## 2.3 MODEL SCENARIOS

Virginia's zoning law was amended in 1988 to allow localities to adopt zoning ordinances that "include reasonable provisions…to protect surface water and ground water." In the publication *Wellhead Protection: A Handbook for Local Governments in Virginia* (VGPSC, 1991), the Virginia Ground water Protection Steering Committee endorses the following regulatory methods for protecting ground water:

- Prohibition of certain uses
- Reduced densities
- Limits on impervious surface
- Special requirements for septic systems
- Strict control of hazardous and toxic materials storage and management
- Special stormwater and waste disposal restrictions

For the purposes of this modeling investigation, the most important of these potential ordinance restrictions are reduced densities and limits on impervious surface. High lot density (and associated high impervious area) has the potential to impact ground water in several ways. Ground water pumping rates, septic system loads, fertilizer application rates, and pesticide application rates increase with lot density, whereas ground water recharge rates decrease. Lot density is a function of the individual lot size and the total number of lots on a developed parcel. On the Eastern Shore of Virginia, the vertical placement of well screens may be as important as the aerial density in protection of the aquifers. For example, wells that are screened too deep might cause upconing of saltwater. Similarly, overpumpage of the confined aquifers might cause saltwater intrusion or unacceptable amounts of drawdown.

### 2.3.1 Contaminant Transport

LEWASTE model scenarios were developed to examine the effects of lot density on ground water quality. Modeled lot densities were 4, 2, 1, 0.5, and 0.33 lots/acre, corresponding to individual lot sizes of 0.25, 0.5, 1, 2, and 3 acres. Scenarios were run to predict the ground water nitrogen concentrations from septic systems alone, fertilizer application alone, and both septic systems and fertilizer application. The model result of interest was the maximum concentration of nitrogen/herbicide in the Columbia aquifer, which occurred directly beneath and immediately downgradient of the development.

### 2.3.2 Saltwater Intrusion and Drawdown

SHARP model scenarios were developed to examine the effect of lot number, lot size, and ground water development pattern on the position of the saltwater interface and the potentiometric surface (Table 2-2). The model was used to simulate development sizes of 50, 250, and 500 lots and lot sizes of 0.25, 1, and 3 acres. For a particular lot number and size, three ground water development scenarios were simulated: (1) all wells pumping from the upper Yorktown-Eastover aquifer; (2) all wells pumping from the deepest fresh water aquifer; and (3) potable water wells pumping from the deepest fresh water aquifer and irrigation wells pumping from the water table (Columbia) aquifer. For the spine scenarios, the deepest fresh water aquifer was the lower Yorktown-Eastover aquifer. For the coastal area, the middle Yorktown-Eastover was assumed to be the deepest fresh water aquifer. The potable water demand was assumed to be 170 gpd per household, and the irrigation demand was estimated by assuming a 13 in/year irrigation rate for 50% of the lawn area (Table 2-1). It was further assumed that 20-percent of this irrigation water would recharge the Columbia aquifer.

## TABLE 2-2

## SHARP MODEL SCENARIOS

| Model Scenario[1] | Lot Size (acres) | Number of Lots | Screened Aquifer:[2] Primary Wells | Screened Aquifer: Separate Wells for Non-Potable Uses |
|---|---|---|---|---|
| 1 | NA | 0 | NA | NA |
| 2 | 0.25 | 50 | Upper Yorktown | NA |
| 3 | 0.25 | 50 | Lowest Confined | NA |
| 4 | 0.25 | 50 | Lowest Confined | Columbia |
| 5 | 0.25 | 250 | Upper Yorktown | NA |
| 6 | 0.25 | 250 | Lowest Confined | NA |
| 7 | 0.25 | 250 | Lowest Confined | Columbia |
| 8 | 0.25 | 500 | Upper Yorktown | NA |
| 9 | 0.25 | 500 | Lowest Confined | NA |
| 10 | 0.25 | 500 | Lowest Confined | Columbia |
| 11 | 1 | 50 | Upper Yorktown | NA |
| 12 | 1 | 50 | Lowest Confined | NA |
| 13 | 1 | 50 | Lowest Confined | Columbia |
| 14 | 1 | 250 | Upper Yorktown | NA |
| 15 | 1 | 250 | Lowest Confined | NA |
| 16 | 1 | 250 | Lowest Confined | Columbia |
| 17 | 1 | 500 | Upper Yorktown | NA |
| 18 | 1 | 500 | Lowest Confined | NA |
| 19 | 1 | 500 | Lowest Confined | Columbia |
| 20 | 3 | 50 | Upper Yorktown | NA |
| 21 | 3 | 50 | Lowest Confined | NA |
| 22 | 3 | 50 | Lowest Confined | Columbia |
| 23 | 3 | 250 | Upper Yorktown | NA |
| 24 | 3 | 250 | Lowest Confined | NA |
| 25 | 3 | 250 | Lowest Confined | Columbia |
| 26 | 3 | 500 | Upper Yorktown | NA |
| 27 | 3 | 500 | Lowest Confined | NA |
| 28 | 3 | 500 | Lowest Confined | Columbia |

[1] Model scenarios for the recharge spine and near shore settings are deisgnated with the letters RS and NS, respectively; e.g scenarios 8-RS and 8-NS.

[2] The lowest confined aquifers for the recharge spine and near shore scenarios are the lower Yorktown and middle Yorktown aquifers, respectively.