Development of a Conceptual Site Model for Evaluating Seawater Intrusion under Sea Level Rise Scenarios Using Analytical Methods

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Abstract

This report presents work completed as partial fulfillment for the degree of Master of Science in Earth and Space Sciences: Applied Geoscience from the University of Washington. This program allows students to develop a project with an external mentor that incorporates elements of applied geoscience that align with their interests and career goals. Doug Kelly, Ms. Jefferson's external mentor, is the hydrogeologist for Island County, Washington, and worked with Ms. Jefferson to provide resources and expertise in the field of coastal hydrogeology. Island County is located in the Puget Sound of Washington State and includes several islands, the largest of which is Whidbey Island. Central Whidbey Island was chosen as the project site (Figure 1), as residents use groundwater for their water supply and seawater intrusion near the coast is known to contaminate this resource.

In 1989, Island County adopted a Saltwater Intrusion Policy and used chloride concentrations in existing wells in order to define and map "risk zones." In 2005, this method of defining vulnerability was updated with the use of water level elevations in conjunction with chloride concentrations. The result of this work was a revised map of seawater intrusion vulnerability that is currently in use by Island County. This groundwater management strategy is defined as trigger-level management and is largely a reactive tool. In order to evaluate trends in the hydrogeologic processes at the site, including seawater intrusion under sea level rise scenarios, this report presents a workflow where groundwater flow and discharge to the sea are quantified using a revised conceptual site model.

The revised conceptual site model used several simplifying assumptions that allow for first-order quantitative predictions of seawater intrusion using analytical methods. Data from water well reports included lithologic and well construction information, static water levels, and aquifer tests for specific capacity. Results from specific capacity tests define the relationship between discharge and drawdown and were input for a modified Theis equation to solve for transmissivity (Arihood, 2009). Components of the conceptual site model were created in ArcGIS and included interpolation of water level elevation, creation of groundwater basins, and the calculation of net recharge and groundwater discharge for each basin.

The revised conceptual site model was then used to hypothesize regarding hydrogeologic processes based on observed trends in groundwater flow. Hypotheses used to explain a reduction in aquifer thickness and hydraulic gradient were:

(1) A large increase in transmissivity occurring near the coast.
(2) The reduced aquifer thickness and hydraulic gradient were the result of seawater intrusion.
(3) Data used to create the conceptual site model were insufficient to resolve trends in groundwater flow.

For Hypothesis 2, analytical solutions for groundwater flow under Dupuit assumptions were applied in order to evaluate seawater intrusion under projected sea level rise scenarios. Results indicated that a rise in sea level has little impact on the position of a saltwater wedge; however, a reduction in recharge has significant consequences. Future work should evaluate groundwater flow using an expanded monitoring well network and aquifer recharge should be promoted by reducing surface water runoff.

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Introduction

This report presents work completed as partial fulfillment for the degree of Master of Science in Earth and Space Sciences: Applied Geoscience (MESSAGe) from the University of Washington. Masters of Science candidate Chelsea Jefferson completed this work on behalf of her Masters Supervisory Committee, which consists of include J. Michael Brown as Committee chair, Steven Walters as the second reader, Miao Zhang as subject matter expert, Doug Kelly as external mentor, and Kathy Troost as Project Coordinator. The MESSAGe program allows students to develop a project that incorporates elements of applied geoscience that align with their interests and career goals. Doug Kelly, Ms. Jefferson's external mentor, is the hydrogeologist for Island County, Washington and worked with Ms. Jefferson to provide resources and expertise in the field of coastal hydrogeology.

Island County, Washington includes Whidbey and Camano Island, as well as several smaller islands. Whidbey Island is located approximately 20 miles northwest of Seattle, Washington, and lies within the protected waters of the Puget Sound. Major population centers include Oak Harbor on the northern end of Whidbey Island and Coupeville, located in central Whidbey Island. North and central Whidbey Island are located within the rain shadow of the Olympic Mountains to the east and receive an average annual precipitation of 21 inches, compared to 37 inches for Seattle (usclimatedata.com). Figure 1 depicts the location of the project site (site) on central Whidbey Island. Residents at the site depend on groundwater for their water supply as there are no significant surface water resources; however, there is evidence of seawater intrusion into the groundwater supply near the site's coastline.

In 1989, the Island County Health Department and Washington State Department of Health adopted a Saltwater Intrusion Policy. This policy used chloride concentrations in existing wells in order to define and map "risk zones." In 2005, the Seawater Intrusion Topic Paper, an attachment to the Island County Water Resources Management Plan, was completed (Island County, 2005). This paper reviewed the County's Saltwater Intrusion Policy and addressed limitations. These limitations included false positives resulting from sources of chloride in groundwater not related to seawater intrusion. False negatives were also seen as a limitation of the policy. In order to provide a resource management tool that allowed for better prediction of seawater intrusion vulnerability, the paper introduced and tested the use of water level elevations in conjunction with chloride concentrations. The result of this work was a revised map of seawater intrusion vulnerability that is currently in use by Island County.

A conceptual site model (CSM) of the hydrogeologic processes at the site has been established for the purpose of evaluating seawater intrusion under various sea level rise scenarios. Data from water well reports were used to establish groundwater flow and its interaction with seawater. Next, analytical solutions were used to better understand the current extent of seawater intrusion and to predict how much seawater intrusion would occur under projected sea level rise scenarios. This method for evaluating seawater intrusion vulnerability is a first order look at the hydrogeologic processes at the site and how they influence the propensity for intrusion. This method is seen as complementary to the current method, by which seawater intrusion vulnerability is defined using trigger levels for chloride concentration and water level elevations.

Purpose and Scope

As there are no viable surface water resources at the site, residents of central Whidbey Island use groundwater for their water supply. Chloride concentrations are elevated across the site. Inland chloride concentrations are likely due to agricultural practices, septic system effluent, or dilution of groundwater by relict seawater (Island County, 2005). Elevated chloride concentrations near the coast are expected to be the result of seawater intrusion (Culhane, 1993). As a result of climate change, sea level in the Puget Sound is expected to rise by as much as 50 inches with an effective sea level rise (including the effect of storm surges) of 88 inches by 2100 (Melillo et al., 2014). A rise in sea level is expected to directly correspond to a rise in the freshwater/seawater interface position and inland extent of seawater intrusion. A potential consequence of seawater intrusion is the increased vulnerability of existing wells to the process of upconing. This process occurs when the freshwater/seawater interface rises in the shape of an inverted cone below a pumping well due to a lowering of the hydraulic head around the well.

The current CSM includes five unique aquifers: Aquifer A through Aquifer E (from oldest to youngest). These aquifers have common hydraulic properties and water quality, and are expected to be of more or less consistent thickness across the site. The younger aquifers, D and E, are not contiguous across the site, as ground surface elevation cuts them off. These aquifers do interact with one another—recharge infiltrates down in the lower conductivity aquifers and moves laterally in the higher conductivity aquifers (Jones, 1985). The only numerical model for the site was completed in 1988 and used this conceptualization in addition to five interspaced confining units in order to make quantitative predictions of groundwater flow and discharge as well as the freshwater/seawater interface position (Sapik et al., 1988).

In contrast to the current CSM, this report uses several simplifying assumptions regarding the site's hydrogeologic processes in order to create a revised CSM that allows for first-order quantitative predictions of seawater intrusion using analytical methods. Simplifying assumptions were:

1. A steady-state groundwater flux (recharge is equal to discharge).
2. A sharp freshwater/seawater interface where only freshwater is moving and the processes of diffusion and dispersion are negligible.
3. Thinking of the site as a single unconfined aquifer with constant head boundaries at the Puget Sound and no-flow boundaries to the east and west.

These simplifying assumptions were made due to limited time and data availability. The assumptions are reasonable because this report presents a conceptualization of the overall site hydrogeologic processes as opposed to a fine-scale treatment.

In order to create a revised CSM, available data from 201 water well reports were used. Data used consisted of lithologic information, well construction, static water level, and aquifer tests for specific capacity. Data from specific capacity tests define the relationship between discharge and drawdown in the well and were input for a modified Theis equation to solve for transmissivity (Arihood, 2009). Other relevant data were entered into Esri ArcGIS version 10.3 (GIS) for spatial analysis. Components of the

CSM included interpolation of water level elevation, the creation of groundwater basins, and the calculation of net recharge and groundwater discharge to the sea for each basin.

The revised CSM was then used to hypothesize regarding hydrogeologic processes. Where appropriate, analytical solutions for groundwater flow under Dupuit assumptions were applied in order to estimate the inland position of the saltwater wedge as a way to evaluate seawater intrusion vulnerability. This method is a first-order look at a flux-based approach to resource management of the central Whidbey Island aquifer, which can be used for planning purposes. A flux-based management approach has the capability of evaluating trends in the groundwater system and is seen as complementary to the trigger-level management paradigm currently in place.

Previous Investigations

In 1968, Washington Department of Water Resources published Water Supply Bulletin No. 25, which consisted of two parts: Part I: Pleistocene Stratigraphy of Island County by Don J. Easterbrook, and Part II: Groundwater Resources of Island County by Henry W. Anderson, Jr. Part I discusses the Pleistocene deposits from three glaciations and three interglaciations that form the stratigraphy of Island County. Work included the mapping of coastal bluff outcrops along most of western Whidbey Island.

Part II: Groundwater Resources of Island County (Anderson, 1968), a qualitatively reviews groundwater supply and quality in order to address the increasing population of Island County. Part II also includes a section entitled Chemical Quality of Groundwater by A.S. VanDenburgh. Based on water well reports available at the time, a productive groundwater source appears to be within the elevation range of 0 (corresponding to mean sea level [msl]) to 75 feet below msl. Change in head measurements was minimal and signals that there was no significant change in groundwater storage at the time. The water quality of Island County was also reviewed. Groundwater with dissolved solids content of 300 milligrams per liter (mg/l) was common on the northern portion of Whidbey Island, whereas a dissolved solids concentration of 300 to 1,000 mg/l with a hardness between 180 and more than 800 mg/l (as a result of calcium, magnesium, sodium, etc.) was observed on southern Whidbey Island.

The United States Geological Survey (USGS) prepared a preliminary survey of groundwater resources to address concerns over available groundwater and groundwater quality as demand continued to increase (Cline et al., 1982). The focus of the work was on groundwater withdrawals from the aquifer near or below sea level, which is likely the same groundwater source referred to in Part I: Pleistocene Stratigraphy of Island County by Anderson, discussed above. A water level elevation map was created and withdrawals from central Whidbey Island were estimated for the Cline report. Due to concerns regarding poor water quality, the Cline report identified central Whidbey Island as a problem area.

In 1985, the USGS, in cooperation with the Washington State Department of Ecology (Ecology) and Island County, prepared a report entitled Occurrence of groundwater and potential for seawater intrusion, Island County, Washington (Jones, 1985). This work presents a conceptual framework different from previous efforts made to characterize Island County's groundwater system. In this report, five unique aquifers were identified: Aquifers A through Aquifer E (from oldest to youngest). Aquifers A, B and C are thought to be continuous across Island County, whereas younger aquifers D and E are present where ground surface elevation was at least 150 feet above msl. Aquifers are not described in this report as confined, and appear to be used only for the benefit of consolidating common hydraulic properties and water quality with depth. This report identified aquifers C and D, occurring near and below sea level, as possibly being affected by seawater intrusion. This conclusion was based on chloride concentrations of 100 mg/l and greater.

The first and only numerical model simulating groundwater flow in Island County was prepared in 1988 (Sapiket al., 1988). This report continued using the conceptual model of five unique aquifers; however, unlike previous work, five confining units were identified. Conceptually, recharge to the aquifers flows down from the ground surface and passes through confining units; however, very little recharge was expected to infiltrate below Aquifer C.

There were not sufficient data to construct water table surface maps for each aquifer, so the authors relied on measurements of hydraulic head in Preliminary survey of groundwater resources for Island County, Washington (Cline et al., 1982). Maps of hydraulic head for each aquifer were then created using the groundwater flow model. The results of the model indicated a freshwater/seawater interface at a maximum depth of approximately 900 feet below msl and groundwater discharge to the sea, mainly from Aquifers C and D, from groundwater seeps below sea level.

In 1993, Ecology prepared a report detailing quantitative analyses used to investigate the source of elevated chloride concentrations from shallow groundwater sources on Whidbey Island (Culhane, 1993). Data from 20 groundwater wells completed above sea level were used. In order to distinguish groundwater impacted by seawater intrusion to that more closely resembling very hard water, methods including the Stiff Diagrams and chloride/hardness v. conductivity plots, etc. were used. These methods indicated no more than three of the 20 wells had groundwater chemistry resembling dilute seawater.

The USGS, in cooperation with Island County, estimated groundwater recharge to Island County using data from water years 1998 and 1999 (Sumioka and Bauer, 2003). This report uses a near-surface water balance method, the Deep Percolation Model (DPM), as well as a chloride mass balance method as a second, independent means of estimating recharge. Data required for the DPM included precipitation, land-surface elevation, shortwave solar radiation, air temperature, and properties of land cover (i.e. soils, vegetation type, impervious surfaces, etc.). Estimates of recharge from the DPM were seen as realistic values for recharge; whereas the values obtained by the chloride mass balance approach were seen as a possible lower limit.

In 2005, the Seawater Intrusion Topic Paper (Island County, 2005) attached to the Island County Water Resources Management Plan was completed. This paper reviews the County’s Saltwater Intrusion Policy, adopted in 1989, and provides an overview of limitations and potential for improvement. The main limitation identified was the possibility for false positives due to sources of chloride in groundwater not related to seawater intrusion. For Island County to better assess risk, this paper introduced and tested the use of water level elevations in conjunction with chloride concentrations. This approach resulted in a revised map of seawater intrusion vulnerability that is currently in use by Island County.

Background

Geologic Setting

Whidbey Island lies within the Puget Lowland, an elongated structural depression bounded by the Cascade Mountains to the east and the Olympic Mountains to the west. During the Quaternary Period, the Puget Lowland was at times overlain by 3,000 to 5,000 feet of ice as the Puget Lobe of the Cordilleran ice sheet cycled through phases of advancement and retreat. Consequently, the region is generally characterized by rolling topography and underlain by complex sequences of glacial and interglacial sediments. Whidbey Island consists mostly of Pleistocene glacial and interglacial deposits (Easterbrook, 1968). The northern portion of Whidbey Island consists of Tertiary-age (now the Paleocene to Neogene Period) and older volcanic and sedimentary bedrock (Jones, 1998).

According to Easterbrook (1968), there were at least three glaciations separated by interglacial periods. The stratigraphic sequence of these glacial and interglacial periods is presented in Table 1. The Double Bluff Glaciation is the oldest glacial deposit on Whidbey Island. The Double Bluff Glaciation is assumed to have been 185 to 125 kiloamperes (ka), based on marine oxygen isotope stage and stratigraphic position (Polenz et al., 2005). With exception of a possible till, the Double Bluff Glaciation is believed to be proglacial outwash. Deposits from the Double Bluff Glaciation are overlain by the Whidbey Formation, deposited during the Whidbey Interglaciation. The Whidbey Interglaciation is believed to have been between 125 to 80 ka, based on both the stratigraphic position and carbon dating performed (Polenz et al., 2005). The Whidbey Formation sediments appear to have been deposited in a floodplain with aggrading meandering streams surrounded by small lakes and swamps (Easterbrook, 1968).

Table 1: Stratigraphic Sequence of Glacial and Interglacial Periods

Adapted from Part I: Pleistocene Stratigraphy of Island County by Don J. Easterbrook (1968)

Quaternary	Pleistocene	Fraser Glaciation	Everson Interstade	Glaciomarine Drift
				Partridge Gravel
			Vashon Stade	Vashon Drift
		Olympia Interglaciation		Quadra Formation
		Possession Glaciation		Possession Drift
		Whidbey Interglaciation		Whidbey Formation
		Double Bluff Glaciation		Double Bluff Drift

The Possession Glaciation follows the Whidbey Interglaciation. The Possession Glaciation is believed to have been 80 to 60 ka (Polenz et al., 2005). Deposits from the Possession Glaciation consist of compact till, sand and gravel, and gravelly clay with shell fragments. These deposits are very discontinuous (Easterbrook, 1968). The Possession Glaciation is overlain by deposits from the Olympia Interglaciation, known as the Quadra Formation. This formation is believed to have been from 60 to 20 ka. According to

Easterbrook (1968), there is only one known outcrop representing this formation, located on north Whidbey Island. The Possession Glaciation is commonly overlain by deposits from the Fraser Glaciation (Easterbrook, 1968).

Members of the Fraser Glaciation represent deposits from the advance and retreat of the last Pleistocene Glaciation. It is believed that ice from the Fraser Glaciation covered Whidbey Island approximately 18 ka (Polenz et al., 2005). Fraser Glaciation Members that have been identified on Whidbey Island include (from oldest to youngest) Esperance Sand, Vashon Till, Partridge Gravel, and Everson Glaciomarine Drift (GMD). Esperance Sand is likely to date back 26 ka. The Everson GMD is believed to date back approximately 12 ka. The Esperance Sand consists of proglacial outwash deposits of cross-bedded sand and gravel. The Vashon Till typically consists of highly compacted deposits of poorly sorted silt, clay, sand, gravel, and cobbles. The Partridge Gravel and the Everson GMD represent a time of deglaciation (Easterbrook, 1968).

The surficial geology of the site consists mainly of GMD and Partridge Gravel. The low-lying, western portion of the site is known as Ebey's Prairie, which includes the town of Coupeville. Ebey's Prairie consists mainly of GMD and is at an elevation of approximately 100 feet above msl. This portion of the site is believed to represent paleo seafloor during the Everson Interstade of the Fraser Glaciation and is characterized by massive to rhythmic silt and clay with vertical desiccation cracks and marine shells (Polenz et al., 2005). Smith Prairie, to the east, is at an elevation of approximately 200 feet above msl, and has a surficial geology dominated by Partridge gravel, deposited as proglacial outwash into a marine environment, forming a kame delta. Smith Prairie is believed to represent a paleo sea level (Polenz et al., 2005). The generalized surficial geology and geologic cross section are presented in Figure 2.

According to Polenz and others (Polenz et al., 2009), the maximum seawater elevation, or the glaciomarine limit, was between 196 and 229 feet above msl at Smith Prairie. Outwash channels in the Partridge Gravel that depict flow toward Ebey's Prairie are visible on LiDAR above this elevation. An emergence (beach) facies is depicted below this elevation. This deposit has subtle benches that record a falling relative sea level. Another relic of a falling relative sea level is the fan deposits that are visible in the beach facies. These fan deposits are likely to have represented a time when paleo channels drained the Patridge Gravel. These channels would have likely continued to form fan deposits simultaneous with beach facies until sea level dropped such that groundwater levels in the Partridge Gravel could not support even ephemeral streams (Polenz et al., 2005).

Hydrogeologic Setting

Early reports identified a productive groundwater source from near to or below sea level (Easterbrook, 1968 and Cline et al., 1982). In 1985, The USGS presented a conceptual framework for Island County hydrogeology with five unique aquifers that were believed to have common hydraulic properties and water quality. This report identified Aquifers C and D, occurring near and below sea level, as possibly being affected by seawater intrusion (Jones, 1985). The first and only numerical model simulating groundwater flow in Island County was prepared in 1988. The conceptual model used the unique aquifers described in the Jones (1985) report; however, five interspaced confining units were also identified. The results of the model indicated a freshwater seawater interface at a maximum depth of approximately 900 feet below msl and subsea groundwater discharge from Aquifers C and D (Sapiket al., 1988). The Island County Seawater Intrusion Topic Paper (Island County, 2005) also references these aquifers.

According to the recent geologic map made for the site (Polenz et al., 2005), the site is underlain by a complex sequence of glacial and interglacial sediments. These sediments have been interpreted to reach a maximum thickness of approximately 3,300 feet at Smith Prairie. These deposits are highly variable in both thickness and extent, creating what can be interpreted as a single heterogeneous aquifer. Some of the deposits can move water very quickly in saturated conditions under a pressure gradient and other deposits behave as confining layers restricting groundwater flow. Recharge to the aquifer is from precipitation, as there are no significant surface water resources on central Whidbey Island.

Groundwater flow at the site is assumed to be in steady-state, meaning that recharge equals discharge. In a steady-state environment, the freshwater/seawater interface position is stationary, as groundwater discharges from the site to Puget Sound. In this environment, groundwater forms a lens above the dense seawater. The freshwater-saltwater interface can be estimated using the Ghyben-Herzberg relation, a one-dimensional solution representing the density differential of the two fluids. The Ghyben-Herzberg relation is given by the equation $z = 40 h$, where h is the height of the water column above sea level and z is the freshwater/seawater interface.

Seawater Intrusion Processes

Seawater intrusion is the movement of seawater into an aquifer. This the most common source of groundwater contamination in a coastal aquifer (Fetter, 2001). Seawater can intrude into an aquifer from the freshwater/seawater interface, or from a saltwater wedge at the coast intruding along the aquifer basement. A generalized depiction of these processes is shown in Figure 3. The extent of seawater intrusion is generally defined by either the position of the freshwater/seawater interface, or by the inland extent of a saltwater wedge. Both of these definitions of seawater intrusion are the result of hydrogeologic processes, including freshwater discharge to the sea.

Diversion of freshwater for water supply decreases the freshwater discharge to the sea and will result in seawater intrusion. Other causes of seawater intrusion are due to long-term changes in the environment that lead to a decrease in freshwater in storage. Examples of these include climate change and land-use change. Many causes of seawater intrusion are compounding. For example, a coastal aquifer once used seasonally by residents of a sleepy fishing village is now becoming heavily used as the village becomes a town with year-round residents. This change in population increases demand on the aquifer. In addition, the change in land use, specifically the increased area of impervious surface, reduce infiltration and recharge of the aquifer. Both increased withdrawal and reduced recharge will deplete the freshwater in storage and make the aquifer more vulnerable to seawater intrusion.

Water Quality

The first analysis of groundwater quality on central Whidbey Island was prepared by Ecology in 1993. This report used several quantitative methods to determine whether the source of elevated chloride concentrations from shallow groundwater were due to seawater intrusion or other sources of chloride contamination (Ecology, 1993). Data from 20 groundwater wells completed above msl, 10 of which were located at the site, were used. Methods included Stiff Diagrams and chloride/hardness v. conductivity plots. Results indicated that no more than three of the 20 wells had groundwater chemistry resembling dilute seawater.

One of these wells was located at the site and was constructed approximately 7 feet above msl. Groundwater collected from this well had a nitrate concentration greater than 2 mg/l, which may indicate chloride concentrations were caused by nutrient contamination of very hard groundwater (Ecology, 1993). According to Island County (2005), potential sources of elevated chloride concentrations not related to seawater intrusion include sea spray, irrigation with saline water, possible dilution by relic seawater, agricultural practices, septic system effluent, etc. When looking for potential seawater intrusion, any of these sources of chloride will result in a false positive, where an evaluation process identifies a source that in reality does not exist. The potential result of a false positive is the triggering of the Island County Saltwater Intrusion Policy.

Seawater Intrusion Policy

Island County Saltwater Intrusion Policy was adopted in 1989 by the Island County Health Department and Washington State Department of Health. This policy uses recorded chloride concentrations in existing wells in order to define “risk zones” and was intended to be used as a regulatory tool for requiring additional review of applications for new and expanding public water systems. Risk zones are drawn as a half-mile radius buffer around wells with chloride concentration less than 100 mg/l, between 100 and 200 mg/l, and over 200 mg/l, corresponding to low, medium, and high risk zones, respectively. This method of defining vulnerability produced what is known as the Circle Map.

In 2005, the Seawater Intrusion Topic Paper to the Island County Water Resources Management Plan (Island County, 2005) was completed. This paper reviewed the County’s Saltwater Intrusion Policy and discussed limitations of the Policy. These limitations include false positives resulting from sources of chloride in groundwater not related to seawater intrusion. False negatives were also seen as a limitation of the Policy. A false negative is where an evaluation process does not identify a problem where in fact there is one. False positives are a problem because they initiate additional regulatory review and often aquifer testing. False positives and false negatives are costly for both the County and the applicant. A false negative, however, has the potential for the applicant to move forward with groundwater development only to find later that there is not an adequate supply of freshwater.

According to the Seawater Intrusion Topic Paper, the use of trigger-level chloride concentrations alone is unsuitable as a predictive tool and is seen as a reactive approach to resource management that has strong potential to result in error. To provide a more accurate resource management tool, the paper introduces and tests the use of water level elevations in conjunction with chloride concentrations. The water level elevation identified during this study was 8.4 feet above msl. This trigger-level elevation represents an empirical relationship to chloride concentrations believed to be the result of seawater intrusion. The result of this work was a revised map of seawater intrusion vulnerability that is currently in use by Island County.

Methods

Data Management and Processing

Data were provided by Island County Hydrogeologist, Doug Kelly, as GoogleEarth KMZ files and Microsoft Excel tables. These files contained well location, lithology, well construction, water level elevation, and groundwater chemistry data, when available. The type of water supply well was also available through the KMZ files. Much of these data were also provided by Island County in the form of Microsoft Excel tables. Additional data used for analysis and presentation purposes were GIS files publically available and LiDAR digital elevation model data for the site available through the Puget Sound LiDAR Consortium for the year of 2014 with a horizontal resolution of 3 feet (QSI Environmental, 2014).

Water Well Reports

The GoogleEarth KMZ files were imported into Esri ArcGIS 10.3. The water supply wells, as a point feature class, were placed in the correct location; however, no data were available in the attribute table. The first data entry step was to add each well’s ground surface elevation. This was achieved by simply moving between GIS and GoogleEarth for each of the 201 water supply wells at the site. Using the same method, depth to the well screen and well screen length were entered into the GIS attribute table. Well construction details were not always available, especially on older water well reports. When screen depth and length were not provided, a length of 5 feet was assumed at the bottom of the well. When a water well report did not have elevation, elevation from LiDAR was extracted at the point where the well was located. Finally, water level elevation was entered. This appears as static water level on water well reports and was reported by the driller.

These data were then exported from GIS to MS Excel where statistical analyses on trends in well construction were performed. Cumulative frequency and normal distribution analyses were performed. Results indicate that two-thirds of all wells at the site were completed below sea level and over half of all wells were constructed between sea level and 100 feet below msl.

USGS Recharge

Island County provided a GIS vector data layer for recharge rates at the site prepared by the USGS (Sumioka and Bauer, 2004). This dataset appeared to have been converted from a raster file, since each polygon was essentially a cell in a grid that represented a value for recharge in inches/year. The grid was continuous across the site with an individual polygon or cell having an area of approximately 160,000 square feet. Recharge rates ranged from 10.3 inches/year, corresponding to approximately half of annual precipitation, down to a rate of 0 inch/year, often corresponding to an impervious surface. Total recharge for the site was estimated at $1.97\text{x}10^8$ foot^3/year, or approximately 452,000 acre-feet/year.

Calculation of Hydraulic Conductivity

Several of the water well reports included data collected during specific capacity testing. Specific capacity is a simple aquifer test in which the well is pumped at a known discharge rate for a period of time and the resulting drawdown is recorded. Aquifer transmissivity can be estimated from specific capacity data using a modified form of the Theis equation (Arihood, 2009). This equation (shown below) requires the use of a dimensionless storage coefficient as well as the well radius. The well radius was often provided on water well reports. When no well radius was provided it was assumed to be four inches, or 0.33 foot. A storage coefficient of 0.1 was used for all specific capacity tests. This value corresponds to the low-end of an unconfined aquifer (Fetter, 2001).

$$T = 15.32 * \left(\frac{Q}{s}\right) * \left(-0.577 - log_e\left[\frac{r^2 S}{4Tt}\right]\right)$$

Where T = Transmissivity (foot^2/day)
Q = Well discharge (gallons/minute)
s = Drawdown (feet)
r = Well radius (feet)
S = Storage coefficient
t = Time (days)

Transmissivity (*T*) is on both sides of the equation, requiring that an iterative process be used in order to solve. This was accomplished using Matlab script in which an array of transmissivity values from 5 to 60,000 foot^2/day was tested in increments of 5 until both values of *T* converged to within a value of 5 foot^2/day. From the results of the transmissivity calculation, hydraulic conductivity (*k*) was calculated. Hydraulic conductivity describes the ease at which water flows through a porous media and was calculated using the well-known equation provided below.

$$T = kb$$

Where T = Transmissivity (foot^2/day)
k = Hydraulic conductivity (feet/day)
b = Aquifer thickness, in this case length of well screen

The results of the transmissivity calculation were divided by the length of the well screen at which the specific capacity test was performed. Values ranged from 0.2 foot/day to over 2,000 feet/day, with approximately 90 percent between 0 and 100 feet/day. The majority of conductivity values fall between 0 and 20 feet/day (approximately 60 percent). The geometric mean of the hydraulic conductivity values was calculated to be approximately 15 feet/day. The geometric mean of a dataset represents the central tendency of the values and is not strongly influenced by outliers.

Data Analysis

Further analysis was performed on only those wells with a well screen elevation between sea level and 100 feet below msl. These wells are expected to intercept groundwater that interacts with the freshwater/seawater interface. Water supply wells constructed above sea level were believed to be more likely to intercept groundwater that is perched above a confining layer and therefore not influenced by the freshwater/seawater interface. In addition, the few wells screened below 100 feet below msl were not considered, because a limited range of well screen elevations was desirable for this project, as this project focused on general hydrogeologic processes.

To create hydraulic boundaries at the site, “dummy points” were input along the north and south Puget Sound coastline as well as at the east and west site extent. The north and south site boundaries with the Puget Sound were assumed to represent a constant-head boundary of 0 foot msl water level elevation. The east and west site boundaries were assumed to be no-flow boundaries, where groundwater flows perpendicular to the boundary and does not cross it. The eastern no-flow boundary roughly follows a perennial stream that is expected to represent a groundwater divide at the maximum height of this boundary. The western no-flow boundary is also assumed to represent a groundwater divide. Water level elevations along these boundaries were both approximately 10 feet above msl; this value was input for the dummy points.

Water level Elevation Surface

To create the water level elevation surface, the water level elevations at the supply wells and dummy points were the input for simple kriging analysis in ArcGIS. The statistical interpolation process of kriging, also known as Gaussian process regression, is a well-known regression method in which surrounding values are weighted according to spatial covariance and as a function of the distance between respective sampling points. The resulting water level elevation surface is depicted in Figure 4.

Following this step, a line feature class of groundwater contours were created in ArcGIS using the interpolated groundwater surface raster. A contour interval of 15 feet was chosen. Groundwater contours represent a path of equal groundwater elevation or head and are important because groundwater flows perpendicular to the contours. Such contour data can therefore be used to look at groundwater flow pattern across an area. Groundwater contours for the site are presented in Figure 5.

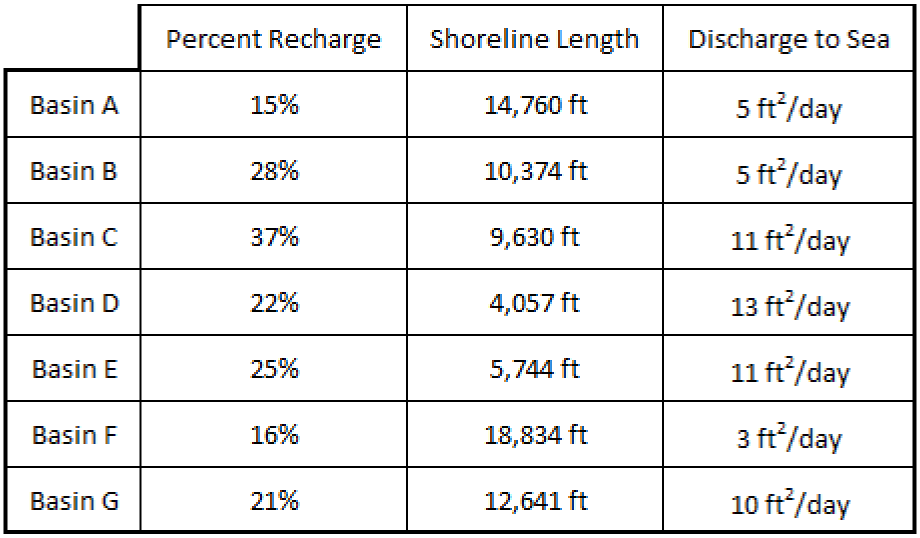
Groundwater Basins

Next, groundwater basins were created that represent areas of groundwater flow and discharge to the Puget Sound. Groundwater basins were created by using a hydrologic workflow in ArcGIS for estimating topographically determined flow patterns. The first step was to fill “sinks” or missing data within the groundwater surface raster. Next, a raster of cell-by-cell flow direction, estimated in the direction of steepest descent out of a cell, was calculated. From this layer, a raster for accumulated flow to each cell within the groundwater surface raster was calculated. Finally, a raster surface that delineates drainage basin areas was created. The groundwater basin raster was then converted into a polygon shapefile in order to analyze individual basin areas. A total of seven groundwater basins were created, named Basin A through G. Groundwater basins are depicted in Figure 6.

Calculation of Basin Recharge and Discharge to the Sea

The recharge polygon prepared by the USGS and provided by Island County was clipped to fit each groundwater basin. This process resulted in the recharge shapefile, representing total recharge area for each of the basins. In order to calculate recharge for the individual basins, the recharge rate was multiplied by the corresponding cell area. Then, these values were summed for every cell within the groundwater basin. This calculation gives the total recharge in volume/year for each groundwater basin. The total recharge for each basin as a percentage of precipitation is presented below in Table 2.

Table 2: Groundwater Basin Features and Calculated Values



	Percent Recharge	Shoreline Length	Discharge to Sea
Basin A	15%	14,760 ft	5 ft^2/day
Basin B	28%	10,374 ft	5 ft^2/day
Basin C	37%	9,630 ft	11 ft^2/day
Basin D	22%	4,057 ft	13 ft^2/day
Basin E	25%	5,744 ft	11 ft^2/day
Basin F	16%	18,834 ft	3 ft^2/day
Basin G	21%	12,641 ft	10 ft^2/day

Table 2 also provides calculated values for each basin’s shoreline and for groundwater discharge to the sea. As recharge is equal to discharge, discharge to the sea was calculated by simply dividing the total recharge to each basin by the shoreline length. This rate represents groundwater discharge per unit length of coastline.

Results

The results of the analysis described above were shown using basin flowlines that represent the average flow path for groundwater, from high water level elevation to the point of discharge at the Puget Sound (Figure 7). Profiles created along each basin flowline for ground surface and water level elevation are shown on Figures 8 through 10. Based on these profiles, it appears that for most of the basins, there is a noticeable reduction in aquifer thickness and hydraulic gradient as groundwater approaches the coast.

Based on this result, the following hypotheses were made:

- **Hypothesis 1:** There is an increase in transmissivity near the coast that allows for a greater volume of water to pass through a smaller cross-sectional area.
- **Hypothesis 2:** The reduction in aquifer thickness and hydraulic gradient near the coast represent the intrusion of a saltwater wedge.
- **Hypothesis 3:** Data are of insufficient quality and density to resolve a change in groundwater flow at the site. This represents the null hypothesis.

These hypotheses will be evaluated in this section. Because the only hypothesis that supports further analysis of seawater intrusion, including the scenario of sea level rise, is Hypothesis 2, a brief discussion will be included with the evaluation of this hypothesis. The Discussion section of this report will review the work completed in this report and take a close look at the assumptions made, and also will include recommendations for future work.

Hypothesis 1

In order to evaluate whether a significant change in transmissivity was reasonable, water well reports were used to create generalized geologic cross-sections along Basin A and Basin G flowlines (Figure 14). Basin A and G were chosen for this analysis because Basin A is has a reduced aquifer thickness and hydraulic gradient near the coast, whereas Basin G does not. The cross-sections appear somewhat similar. The sand and gravel associated with the Partridge Gravel deposits are depicted at the inland extent (Smith Prairie) for both cross-sections, and the fine deposits associated with GMD at the coast (Ebey's Prairie) are also shown. Sand and gravel deposits are both visible at the coast at an elevation of approximately 25 feet below msl and deeper.

There is no clear change in transmissivity near the coast based on the generalized geologic cross-sections presented in Figure 14. One explanation could be that there is no, or very limited, seawater intrusion in Basin G. One reason for this could be the estimated discharge to the sea of 10 foot^2/day, as compared to 5 foot^2/day at Basin A. This increased discharge would push back an intruding saltwater wedge. Another explanation is that the data quality and density were insufficient to resolve changes in aquifer thickness and gradient (see Hypothesis 3). Because static water level reported at the time of well installation was used, data can be misleading as water level changes seasonally and over longer periods of time due to change in land use and stress to the aquifer.

Hypothesis 2

Hypothesis 2 is that the reduced aquifer thickness and hydraulic gradient may be due to an intruding saltwater wedge. This hypothesis was evaluated by comparing the water level elevation profiles to the Glover solution for freshwater head above an intruding saltwater wedge. The Glover solution is a modified version of the Dupuit solution in that it accounts for the change in thickness of the freshwater/seawater interface, thereby resulting in a greater effective gradient. This correction has been discussed previously and is approximated using the Ghyben-Herzberg relation. In the Ghyben-Herzberg relation, the hydraulic head is proportional to the depth to the interface below sea level. Therefore, as the depth to the interface decreases, so will the hydraulic head by a factor of 0.025 foot. The Glover solution can therefore be thought of as the Dupuit-Ghyben-Herzberg solution and is shown below (Fetter, 2001).

$$h = \sqrt{\frac{2q'x}{GK}}$$

Where h = Hydraulic head (feet)
q' = Basin discharge (foot^2/day)
x = Length inland from the coast (feet)
G = Density correction, assumed to be 40 (unitless)
K = Hydraulic Conductivity (feet/day)

The Glover solution was compared to the lower gradient slope for each basin (Figure 11 through 13). Conductivity is the same for each basin because it is the geometric mean for all values calculated at the site. Basin discharge is unique for each basin and was calculated by dividing the total recharge for the individual basin by the length of the basin's shoreline. With the possible exception of Basin G, all other basins appear to have a geometry at the coast that appears to be a close match to the Glover solution.

Based on this analysis, the reduced aquifer thickness and hydraulic gradient would represent the presence of a saltwater wedge, the inland extent of which is variable across the site. A relatively consistent trend is that these changes appear to occur at an approximate water level elevation of 8 feet for many of the basins. This could be caused by a geologic control, creating an effective aquifer thickness. Using the Ghyben-Herzberg relation, this thickness would be approximately 320 feet below msl. As there are few data recorded at this depth, the possibility of a geologic control could not be evaluated here.

Because vulnerability is defined as the inland extent of the saltwater wedge, the vulnerability proposed by Hypothesis 2 closely matches Island County's vulnerability map, as the water level elevation used as a trigger value is 8.4 feet. This water level elevation was determined using an empirical relationship to elevated chloride concentrations expected to be the result of seawater intrusion. Hypothesis 2 therefore provides a possible theoretical basis for this value.

To calculate the change in saltwater wedge position as a result of sea level rise and other climate change scenarios, the Glover solution (presented above) was applied. In the case of an effective aquifer thickness of 320 feet, the resulting saltwater wedge intrusion due to a sea level rise of 4 and 6 feet would be minimal; however, a reduction in discharge to the sea results in a much greater change in the inland position of the saltwater wedge. For example, if Basin A discharge per unit length of coastline were to be reduced by 10 percent, this would potentially cause a 500-foot inland advance of the saltwater wedge.

Hypothesis 3

Hypothesis 3 is the null hypothesis where data are of insufficient quality and density to resolve changes in hydraulic gradient and aquifer thickness. This could be due to the difference in time the data were reported, or the accuracy of the data reported on the water well reports. Data collected regularly from a monitoring well network would be more accurate; however, it is unknown whether this level of accuracy is needed for evaluating trends in groundwater flow and vulnerability to seawater intrusion like that presented in this report.

Discussion

The method presented in this report is a first-order look at how a flux-based approach to resource management can be used to evaluate vulnerability to seawater intrusion as a result of climate change. This is important for the site, as residents depend on groundwater for their water supply and seawater intrusion has been identified as a contaminant near the coast. A flux-based management approach has the capability of evaluating trends in the groundwater flow and is seen as complementary to the trigger-level management paradigm currently in place. In order to look at flux-based vulnerability, a revised CSM was needed that simplifies the hydraulic conditions at the site.

In contrast to the previous CSM that identified five aquifers with unique hydraulic properties, the updated CSM is simplified by assuming a single heterogeneous unconfined aquifer. This assumption is reasonable because the glacial and interglacial periods during the Pleistocene deposited sediments that were highly variable in both extent and thickness. Other simplifying assumptions allowed for the quantitative prediction of seawater intrusion using analytical methods. These assumptions were: steady-state groundwater flux; a sharp freshwater/seawater interface where only freshwater is moving and the processes of diffusion and dispersion are negligible; and constant head boundaries at the coast and no-flow boundaries to the east and west.

A steady-state groundwater flux means that groundwater withdrawals were not accounted for. This assumption was made because of time limitations and limitations in the data (many individual and group water supply wells are not metered). A sharp freshwater/seawater interface is a reasonable assumption as overall groundwater flow was of interest and fine-scale processes are not believed to effect the overall hydrologic processes. Hydraulic boundaries were necessary for this project and the only assumption that has a potential impact is the no-flow boundaries to the west and east. This assumption is not believed to significantly affect the flux of groundwater at the site.

Based on the results of this project, it appears that the site is most vulnerable to a reduction in recharge as a possible result of climate change and change in land use. Sea level rise appears to have a minimal impact on the inland movement of the saltwater wedge. Therefore, change in storage should be monitored by increasing the groundwater monitoring network at the site and using the methods described in this report to create a water level elevation surface that can be compared to future results in order to evaluate trends. Recharge to the aquifer should also be promoted. Surface water runoff should be limited by construction of swales and infiltration basins where impervious surface area is limiting natural recharge.

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Figure 1: Location of Project Site

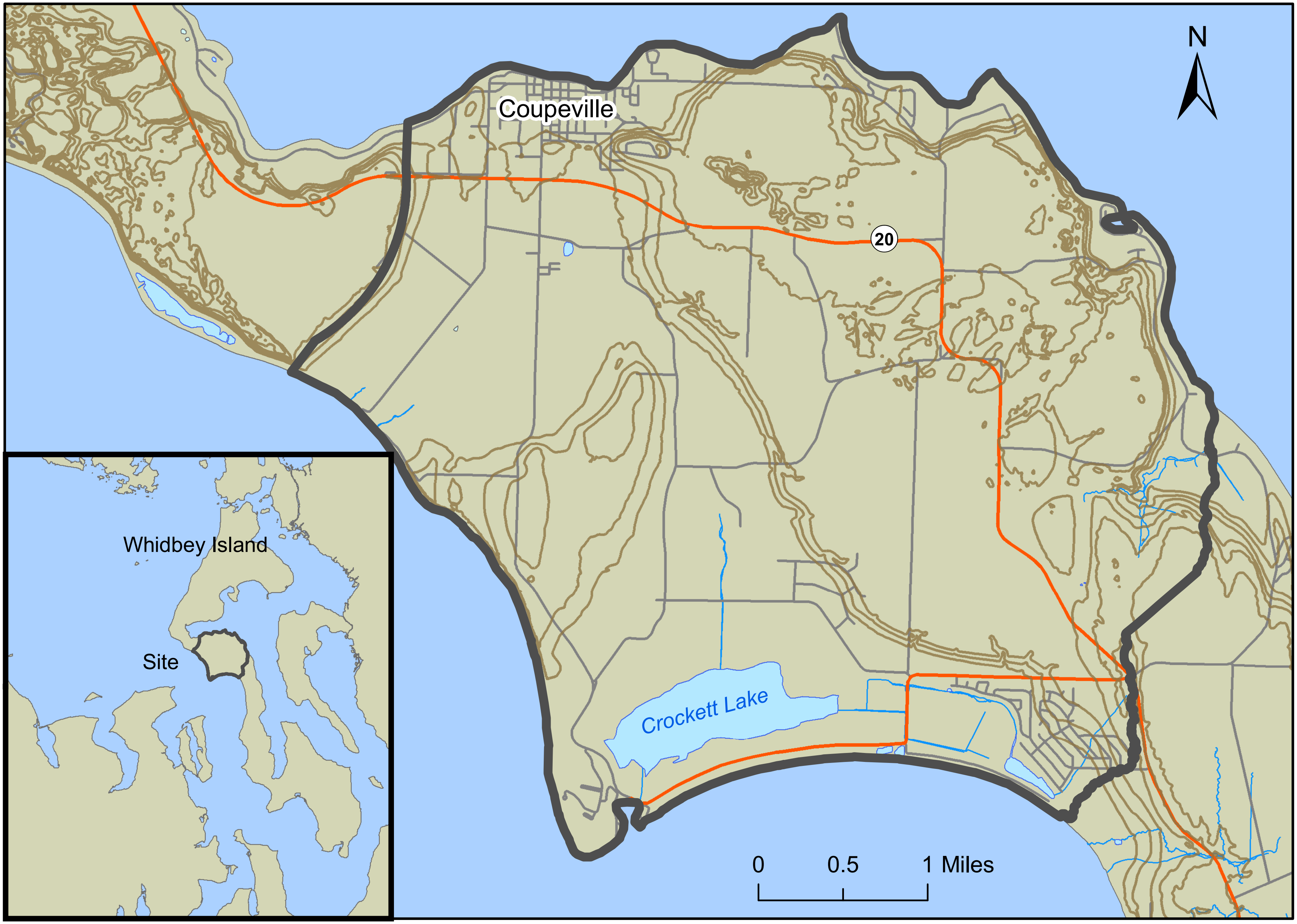


Figure 2: Generalized Surficial Geology

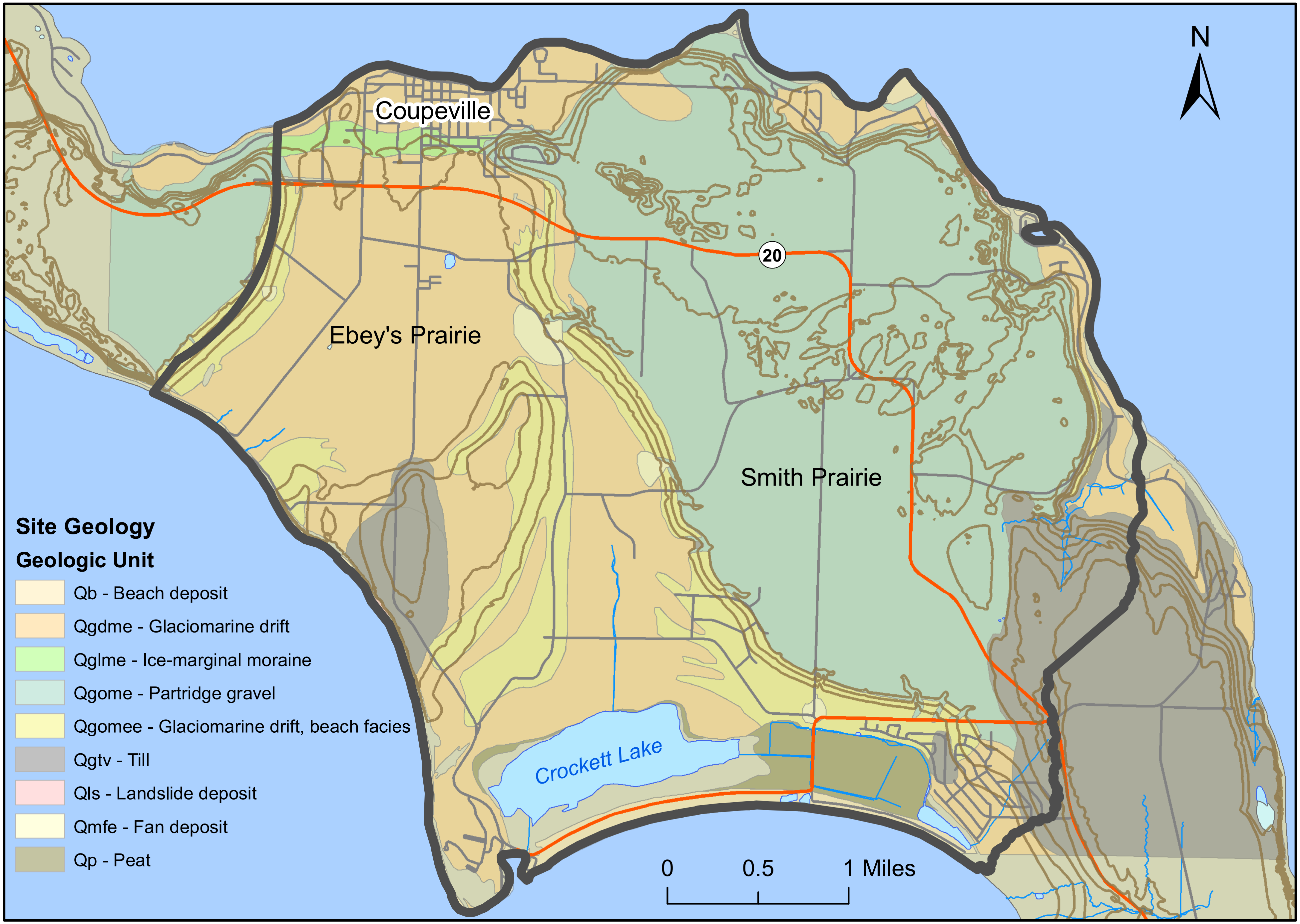
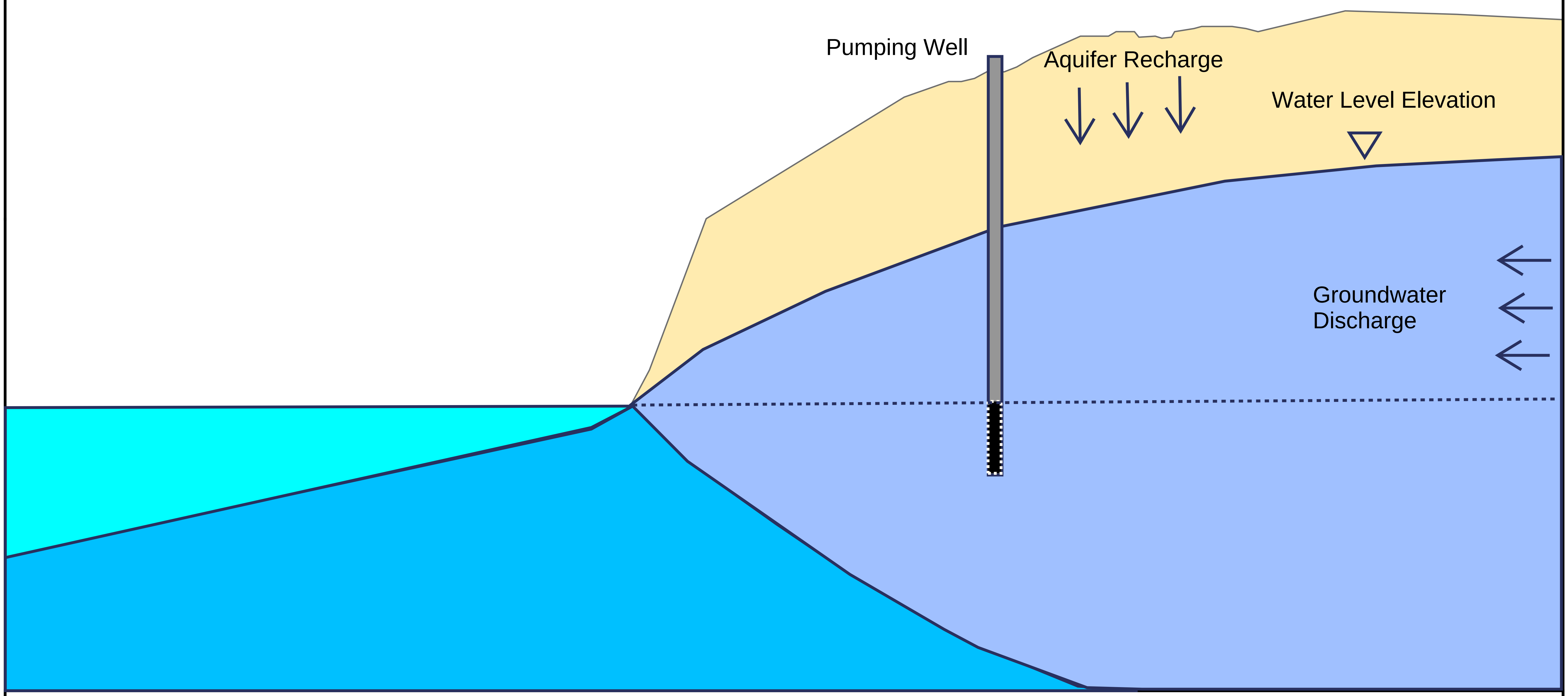


Figure 3: Generalized Seawater Intrusion Processes

Unconfined Aquifer with Freshwater-Seawater Interface:



Unconfined Aquifer with Intruding Saltwater Wedge:

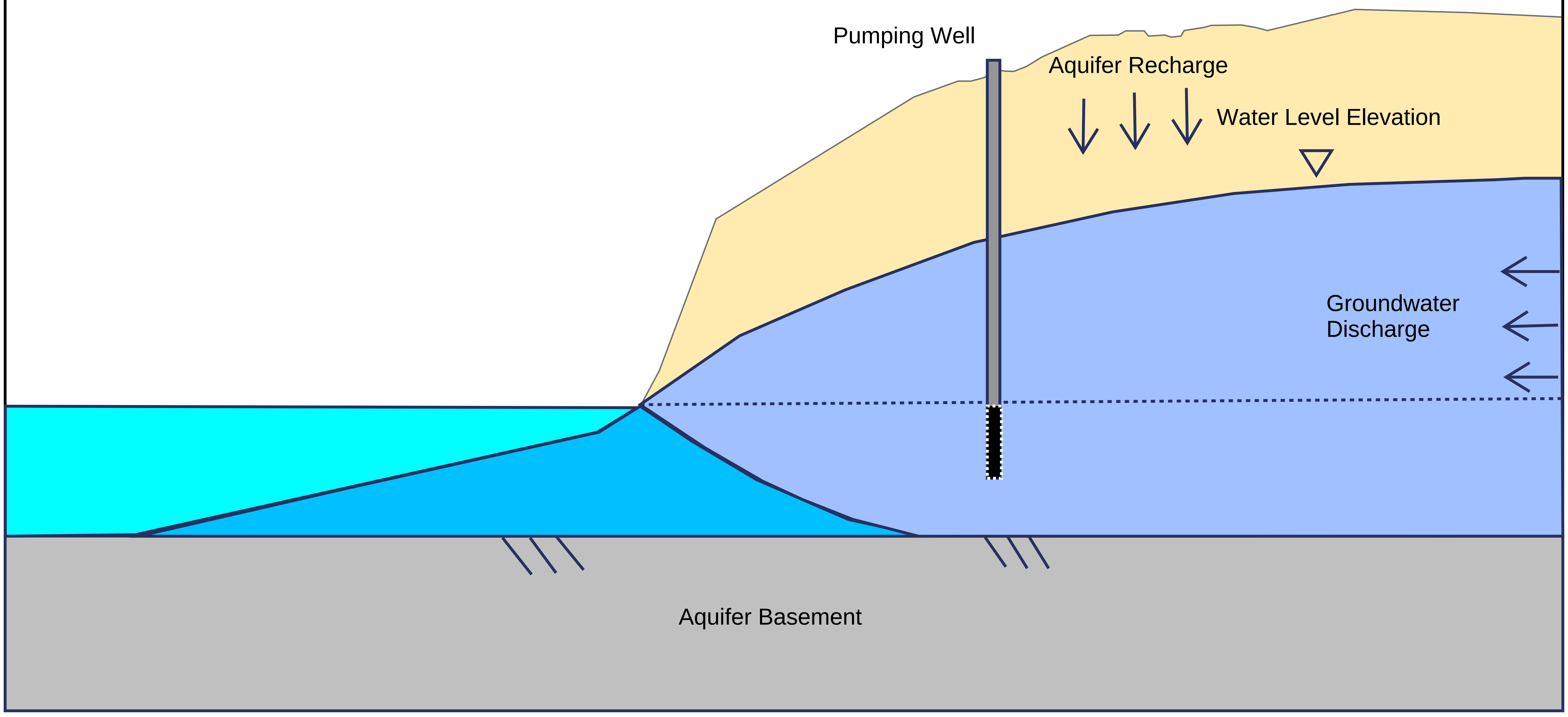


Figure 4: Water Level Elevation Surface

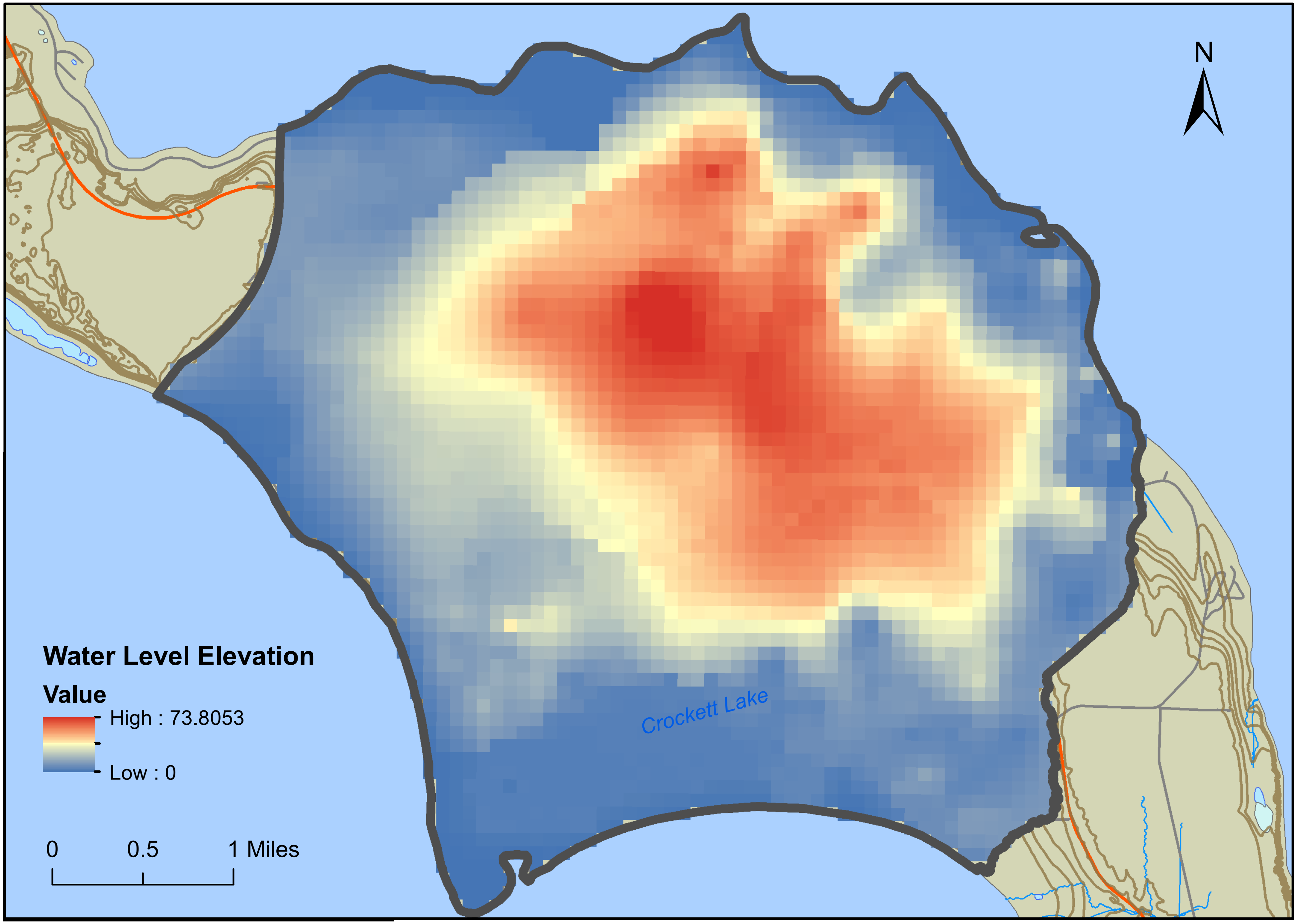


Figure 5: Groundwater Contours

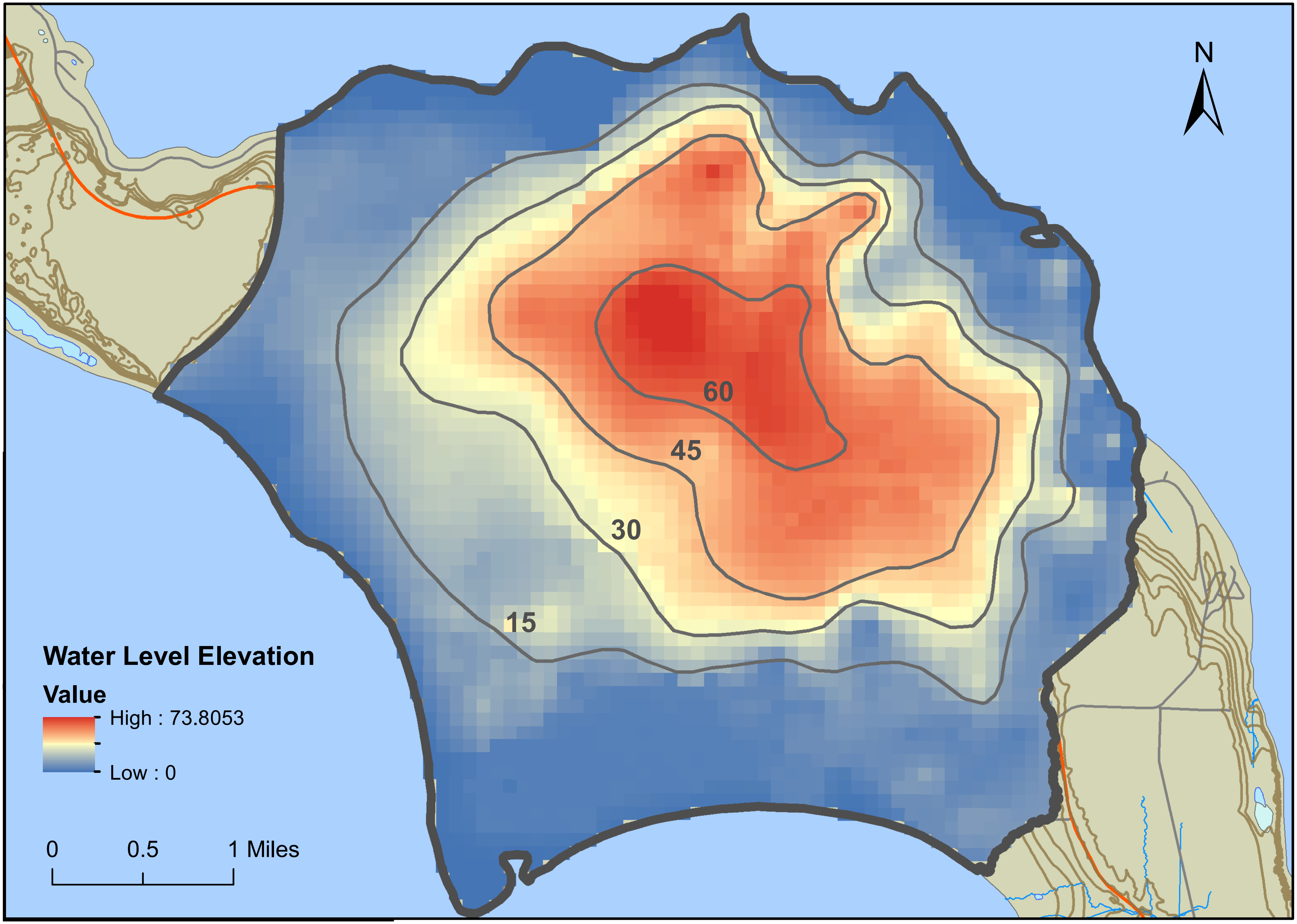


Figure 6: Groundwater Basins

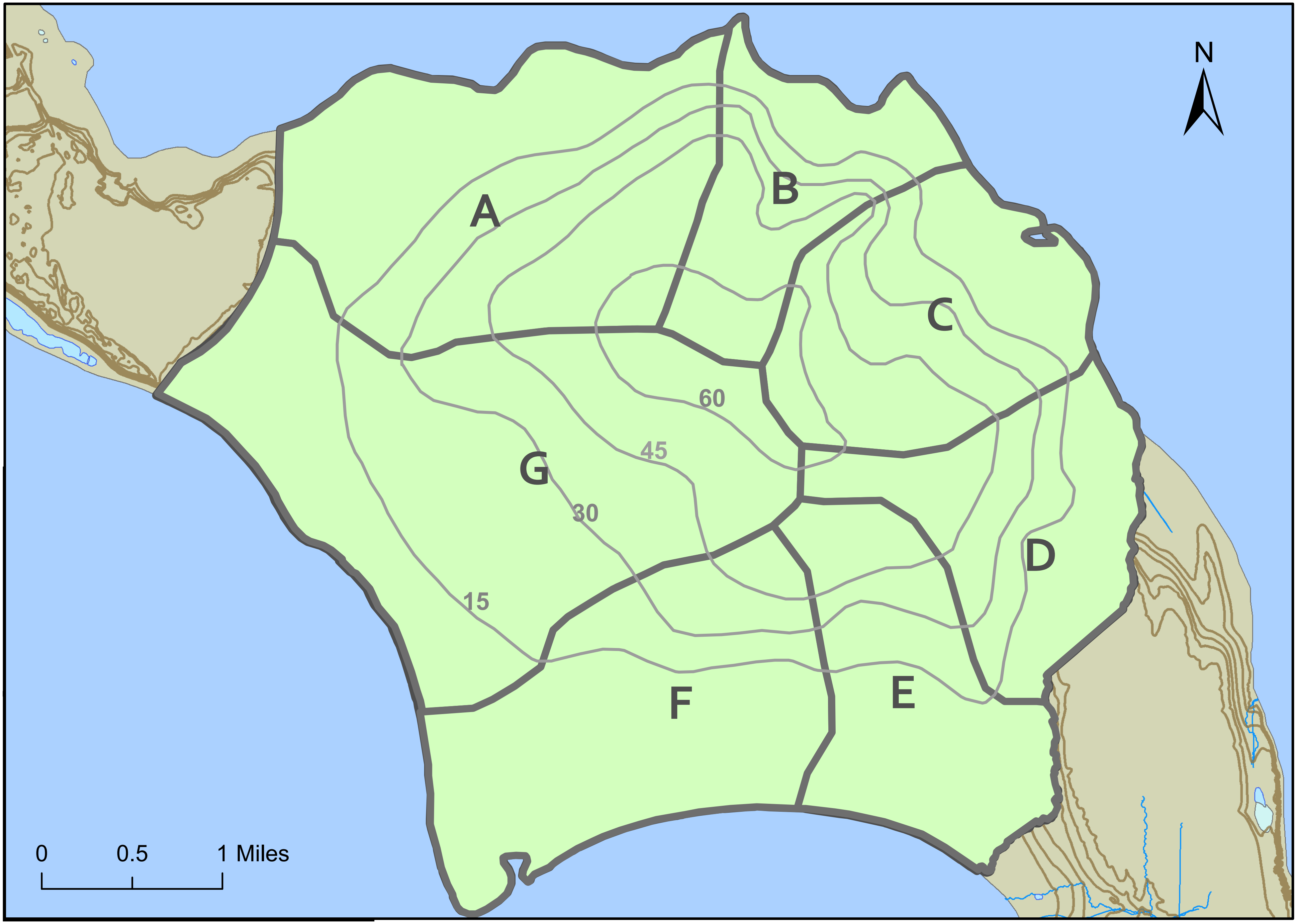


Figure 7: Basin Flowlines

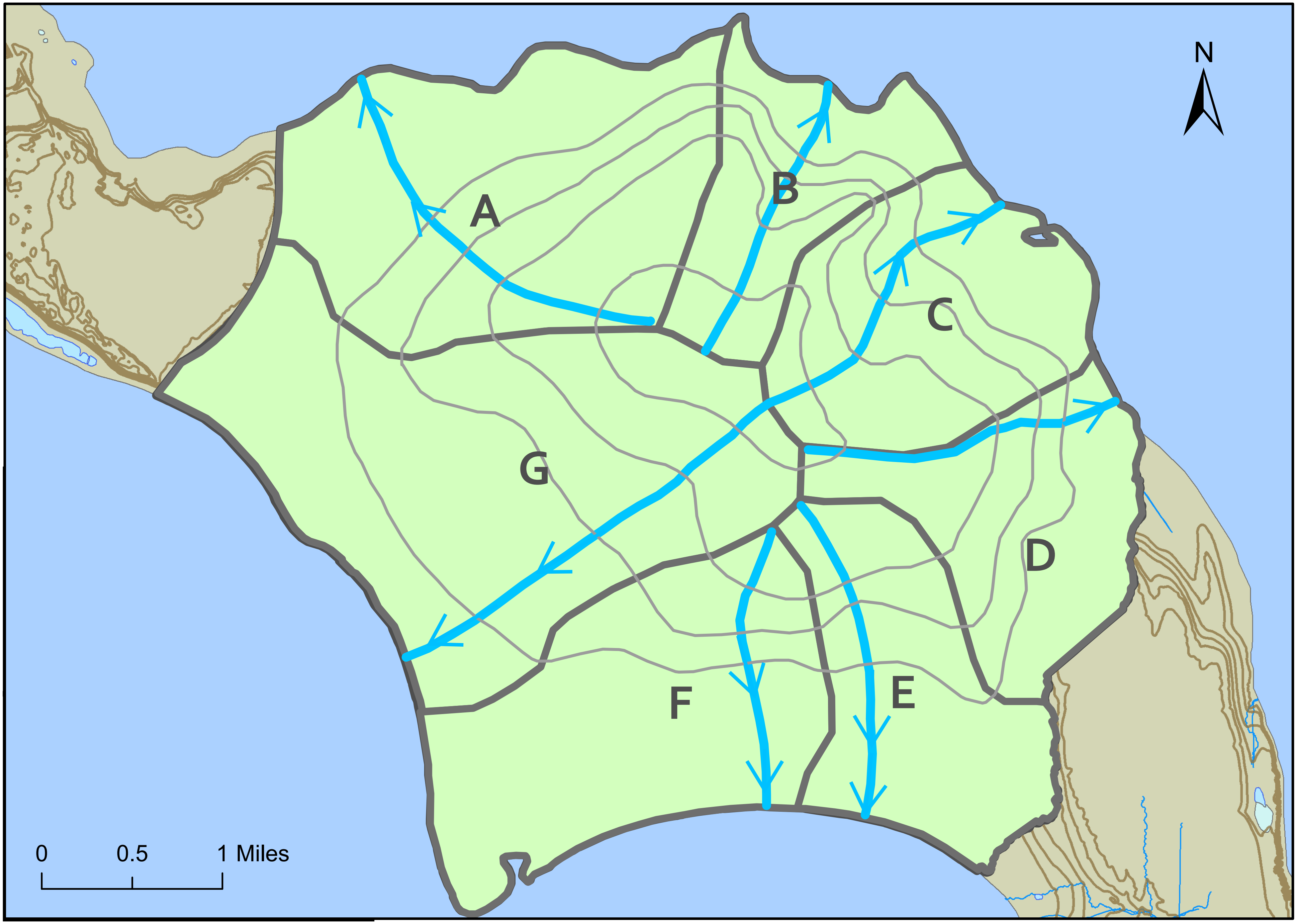


Figure 8: Basin A - C Flowline Profiles for Ground Surface and Water Level Elevation

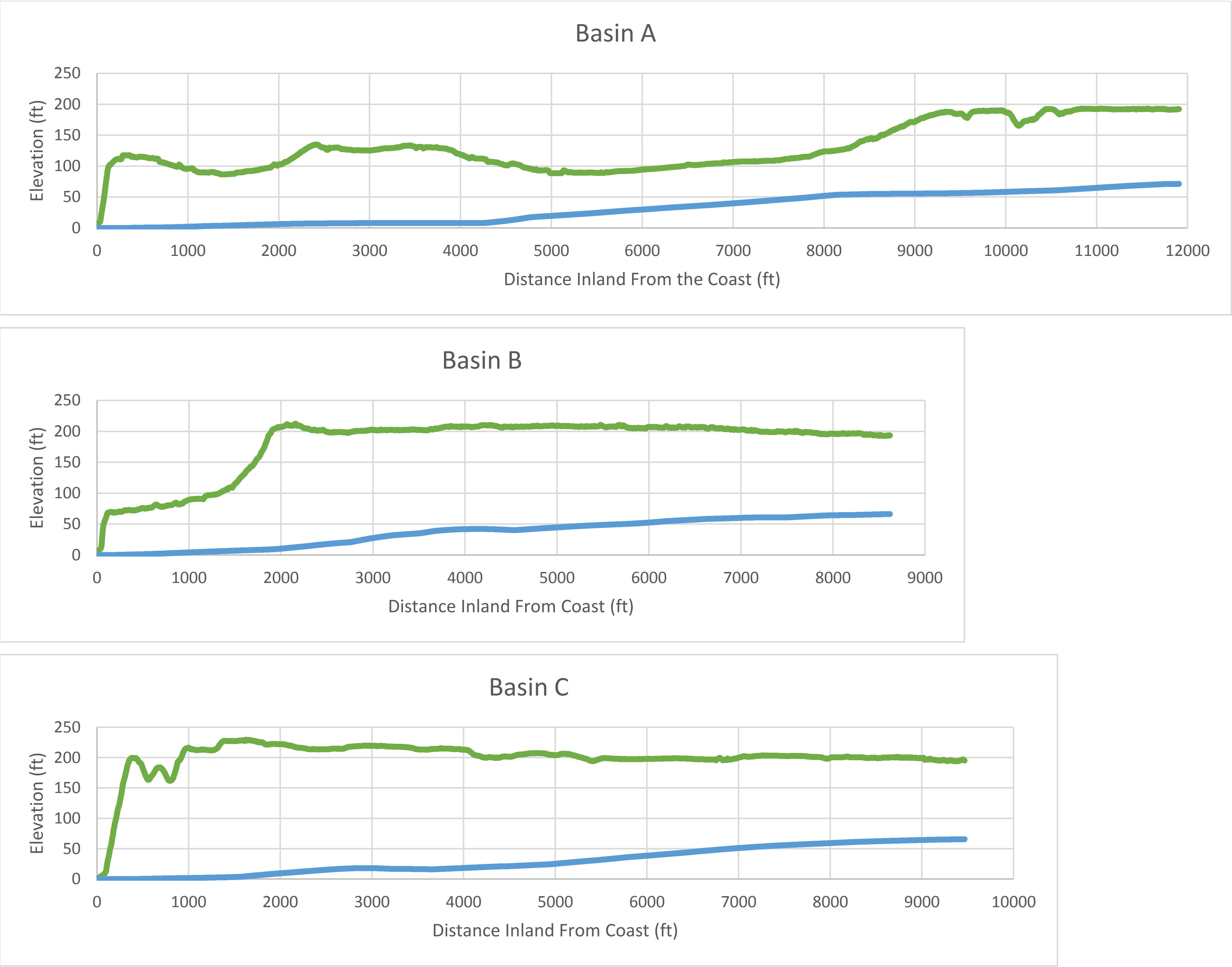
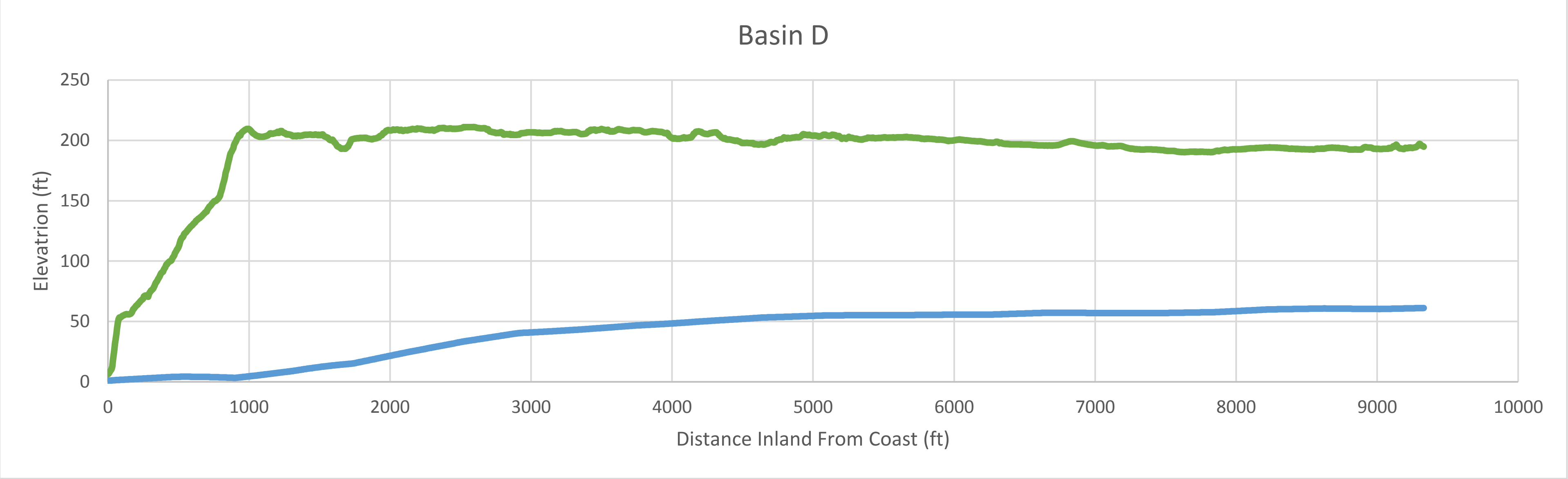


Figure 9: Basin D and E Flowline Profiles for Ground Surface and Water Level Elevation



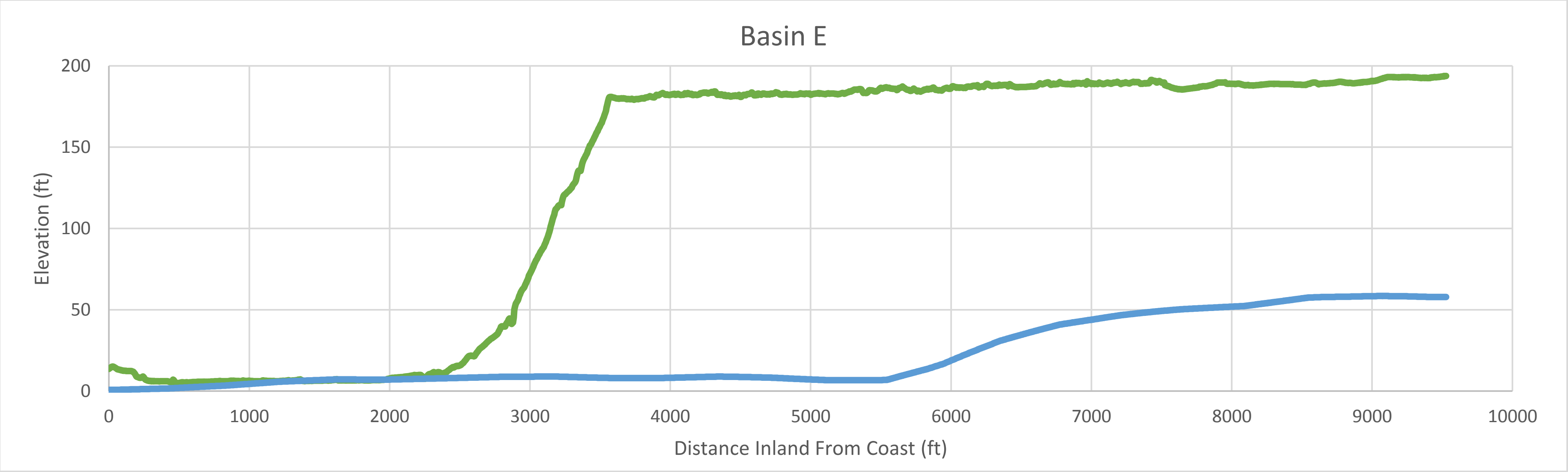
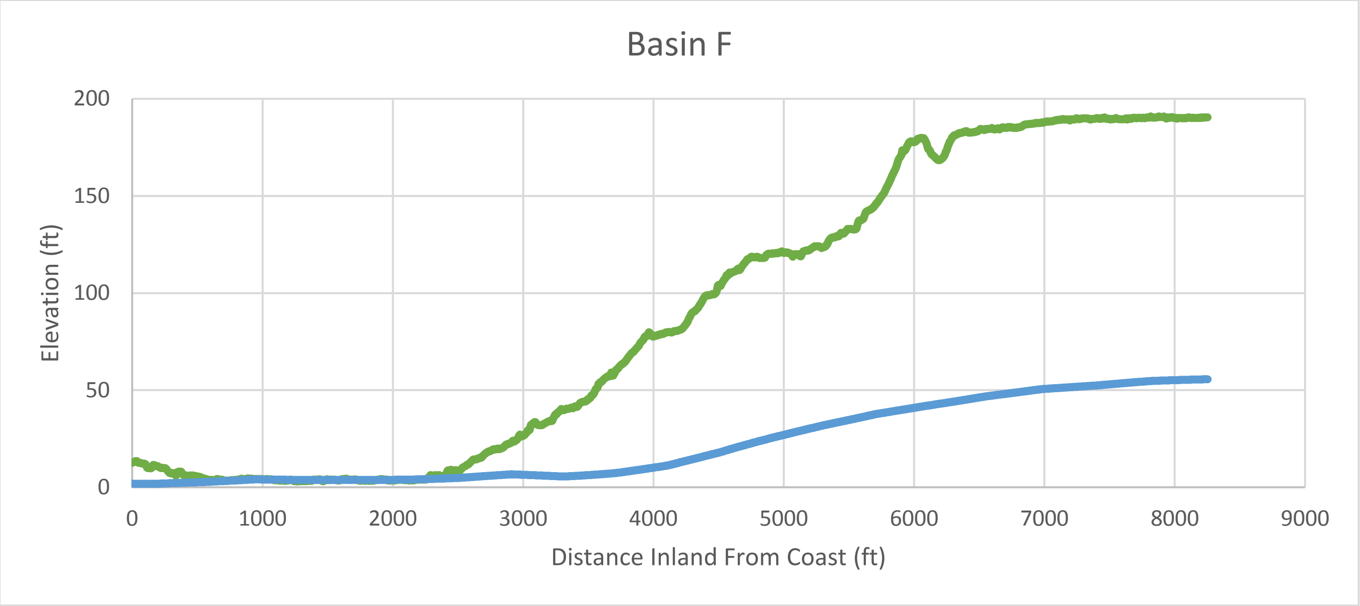


Figure 10: Basin F and G Flowline Profiles for Ground Surface and Water Level Elevation



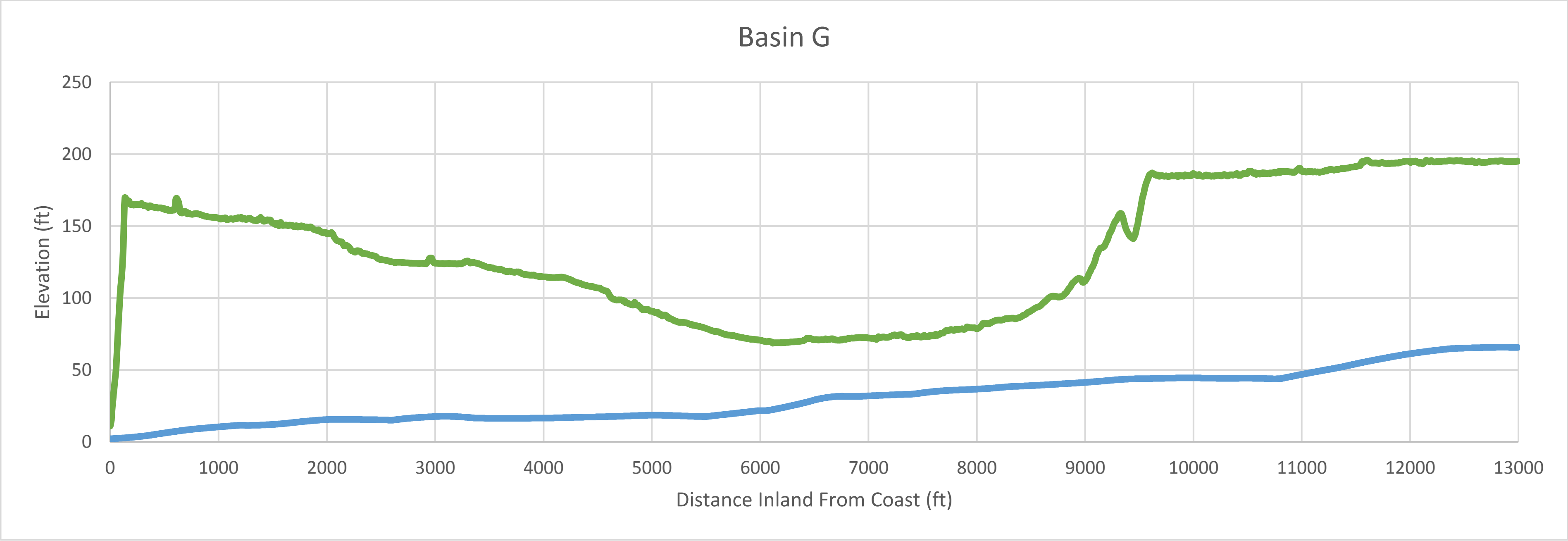
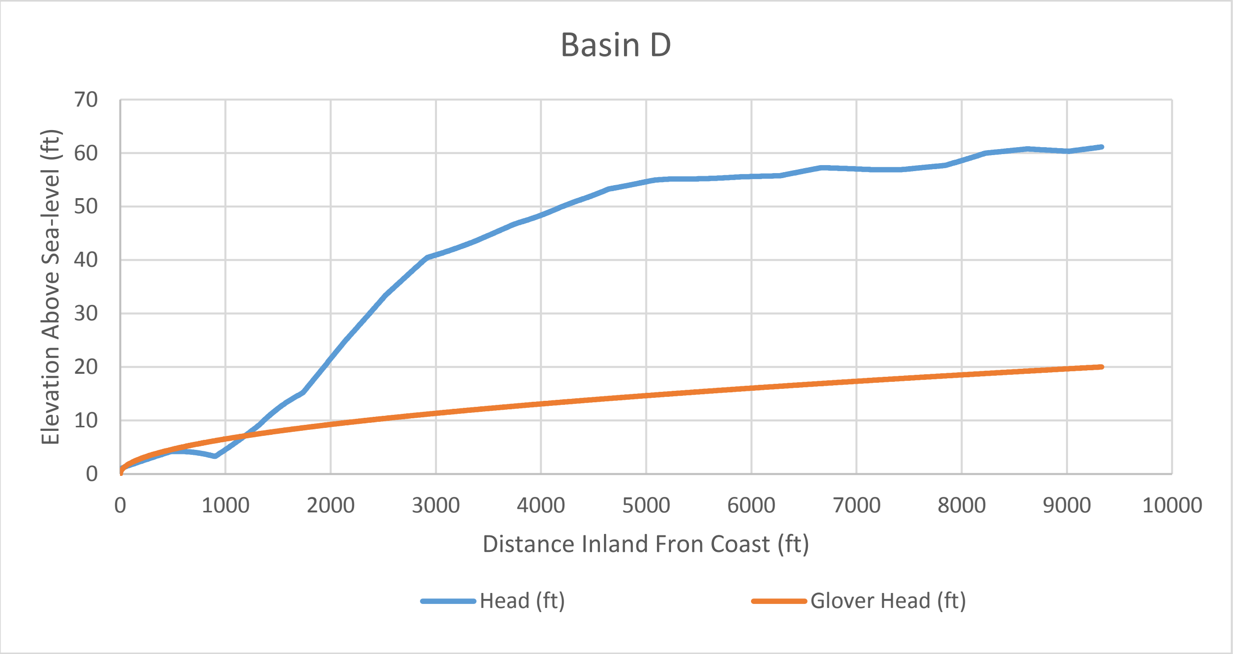


Figure 11: Basin A - C Flowlines with Glover Solution

Figure 12: Basin D and E Flowlines with Glover Solution



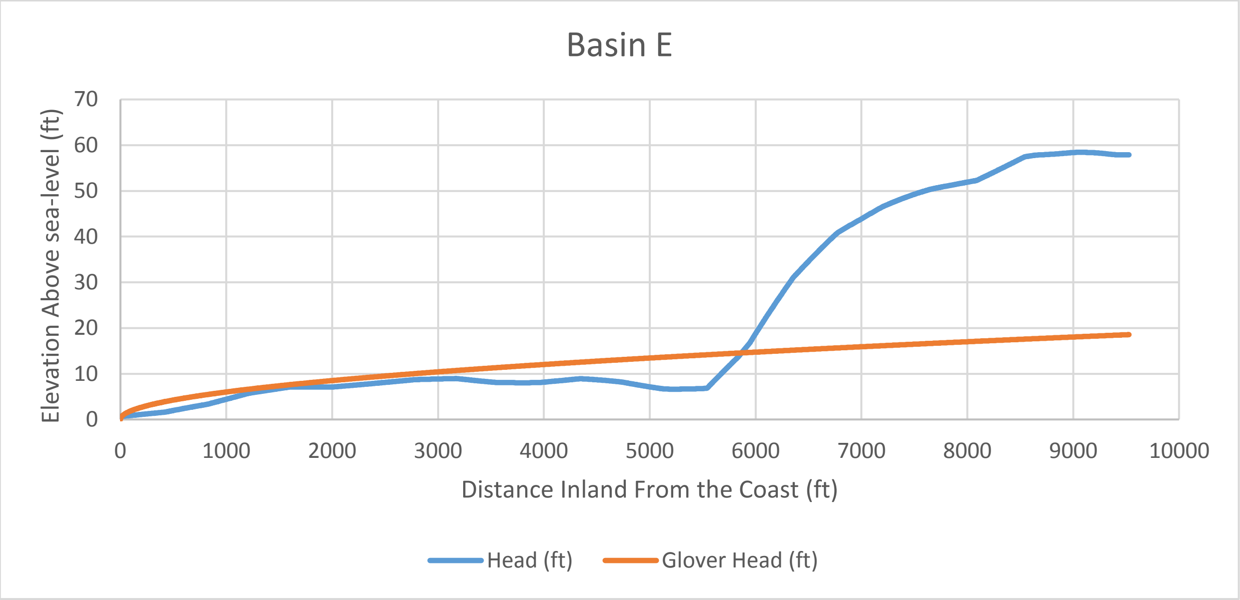
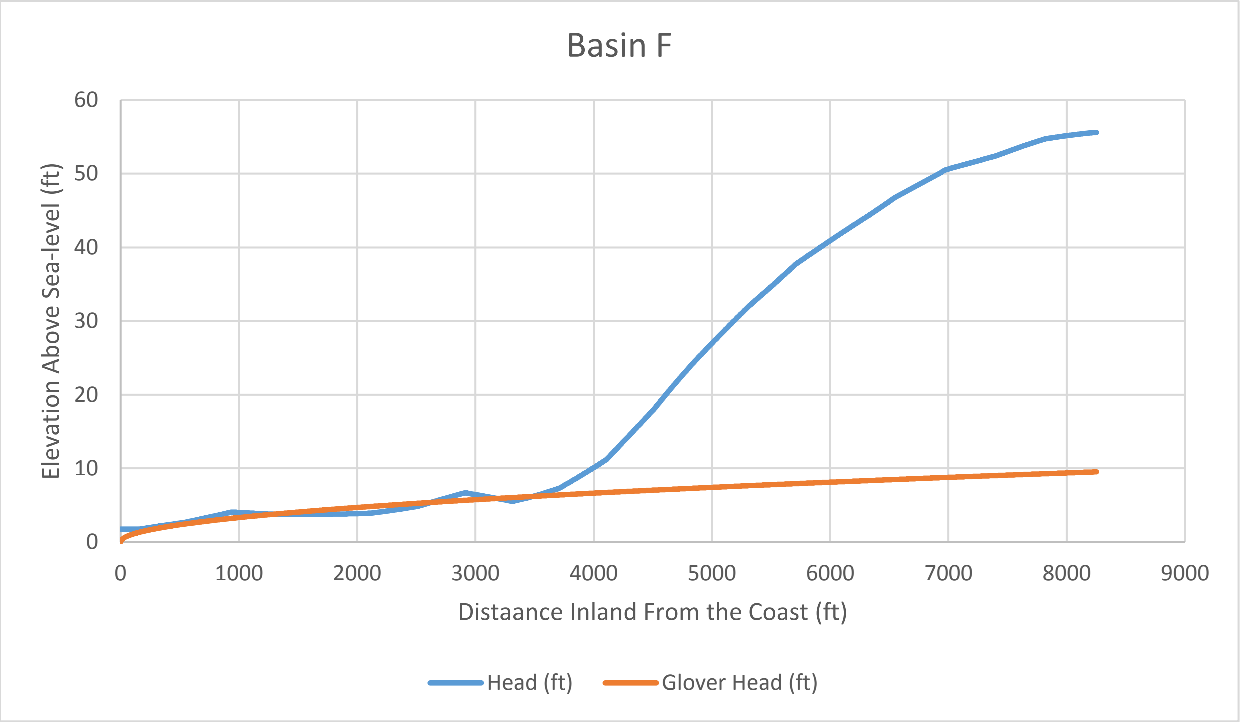


Figure 13: Basin F and G Flowlines with Glover and Dupuit Solutions



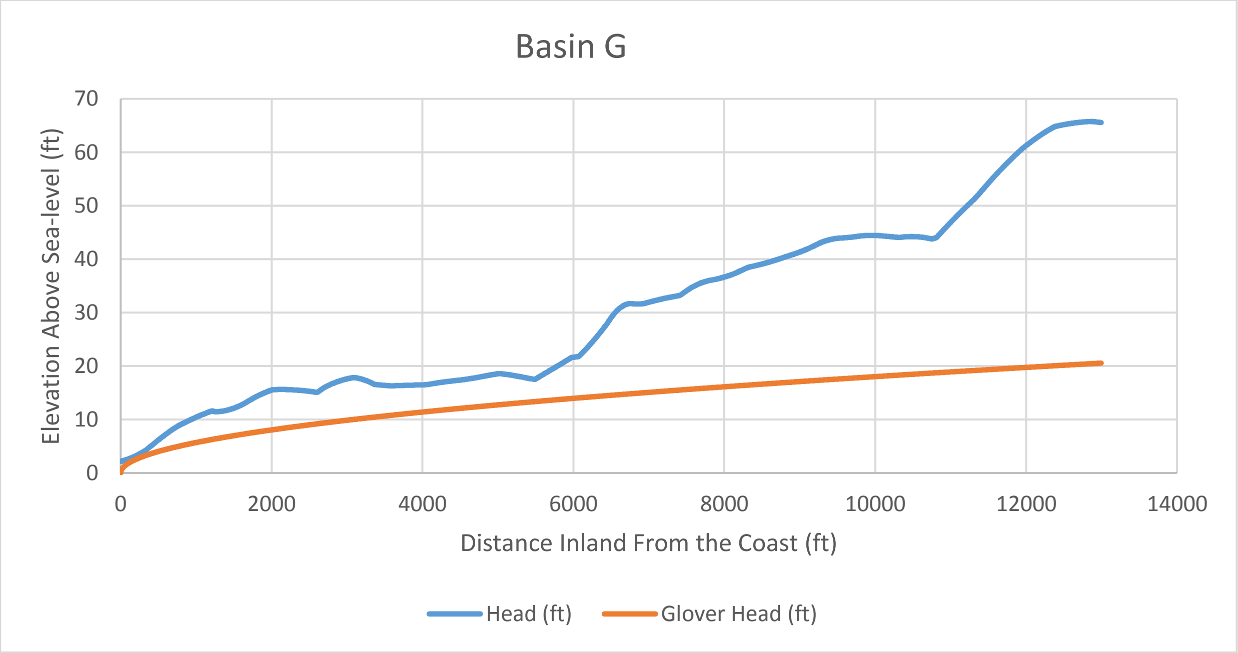


Figure 14: Basin A and Basin G Geologic Cross Sections