GIS-BASED APPROACHES FOR ESTIMATING MEAN ANNUAL SURFACE RUNOFF

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ABSTRACT: Sinclair Inlet and Dyes Inlet are two inter-connected sub-estuaries of the Puget Sound estuarine system, located in the region of (-122^0 43’, 47^0 39’) and (-122^0 37’, 47^0 32’), north of Bremerton, WA. In support of a Total Maximum Daily Load (TMDL) study in Sinclair Inlet and Dyes Inlet, estimates of mean annual surface runoff were required from the various gaged and ungaged systems draining into the two inlets, not only to support the development of a Water Quality Analysis Simulation Program (WASP) model for the two inlets, but also a watershed monitoring plan and a water quality sampling design. Three GIS-based approaches have been developed by separate groups involved in the TMDL study to estimate mean annual surface runoff for the large number of systems that drain into Sinclair Inlet and Dyes Inlet. They include

1. a simple loss function approach based on a raster data product of percent impervious cover,
2. the curve number approach developed by the Soil Conservation Service (SCS) of the U.S. Department of Agriculture, and
3. a distributed application of the ‘surface runoff function’ originally derived by Eagleson (1978).

Runoff volume may subsequently be multiplied by mean runoff concentrations for constituents of interest to obtain the estimated load of each constituent from each watershed.
KEY TERMS: mean annual surface runoff, geographic information systems.

INTRODUCTION

The Puget Sound Naval Shipyard (PSNS) Environmental Investment (ENVVEST) project was initiated, under a final project agreement among PSNS, the U.S. Environmental Protection Agency, and the Washington State Department of Ecology on 25 September 2000 (Navy, Ecology, and USEPA, 2000), to develop better ways to protect and improve environmental quality than can be accomplished under the current regulatory framework. PSNS is located on the shore of Sinclair Inlet and it is homeport to several of the U.S. Navy’s active fleet. PSNS is a large industrial facility that provides support for ships and service craft, performing construction, conversion, overhaul, repair, alteration, dry docking, decommissioning, and outfitting of ships. These operations produce wastes, such as metals and organics, which may access waterbodies via runoff, seepage, and fugitive losses. The modeling effort for the PSNS ENVVEST project is a joint effort among Concurrent Technologies Corporation (*CTC*), the U.S. Navy’s Space and Naval Warfare Systems Center, San Diego (SSCSD), and the U.S. Army Corps of Engineers Engineer Research and Development Center (ERDC). The goal of this effort is to develop an integrated watershed modeling system for Sinclair and Dyes Inlets in Puget Sound, near PSNS in Bremerton, WA (Figure 1). Selected watershed and receiving water models will be capable of simulating water quantity and water quality for both existing and future conditions. These model simulations will be used to address system-wide issues related to ecological risk assessment and environmental resource management for the Sinclair and Dyes Inlet watershed. The watershed model is an application of the Hydrological Simulation Program – FORTRAN (HSPF) model. Hydrology and nonpoint source contaminant loads, computed using a number of HSPF models, will serve as input to the Curvilinear Hydrodynamics in 3 Dimensions (CH3D) and WASP models.

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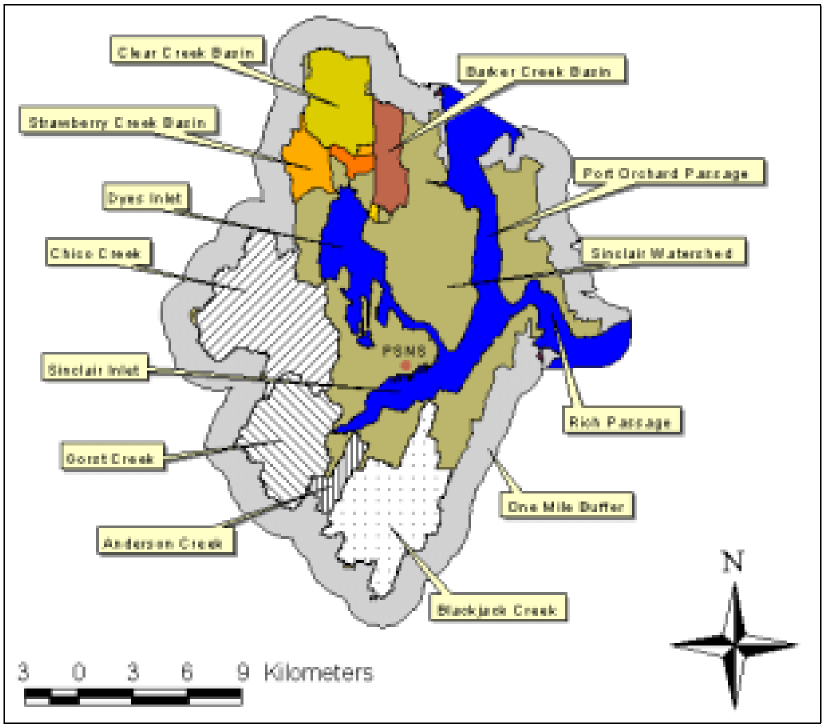

Figure 1. PSNS and significant watersheds and marine water bodies located within the project study area.

HSPF, CH3D, and WASP are data intensive models. For example, both HSPF and WASP require extensive streamflow discharge records for model calibration. While streamflow data were available for a few gaged watersheds within Sinclair and Dyes Inlet prior to the initiation of the ENVVEST project, insufficient records were available to support either HSPF or WASP model calibration. In contrast, data relevant to runoff generation and surface flow; such as, elevation, soils, land use and land cover (LULC), and vegetative cover, are readily available today at multiple scales in raster or grid cell Geographic Information Systems (GIS) format, and GIS technology provides a means for data storage, handling, mapping, and evaluation. The purpose of this article is to describe and compare three GIS-based approaches that have been developed by separate groups involved in the TMDL study to estimate mean annual surface runoff for the large number of systems that drain into Sinclair Inlet and Dyes Inlet. Results from the GIS analyses may be symbolized to show mean annual surface runoff and the relative contribution of each landuse class within a given watershed. Runoff volume may be subsequently multiplied by mean runoff concentrations for constituents of interest to obtain the estimated load of each constituent from each watershed.

DATA DEVELOPMENT

The Sinclair and Dyes Inlet watershed covers an area of approximately 62,348 acres. It is entirely within Kitsap County and includes all or portions of the cities of Bremerton, Port Orchard, and Bainbridge Island as well as land under the jurisdiction of the Washington State Department of Natural Resources and the U.S. Navy. Physical watershed-specific data relevant to the partition of precipitation at the land surface, in a GIS format, were obtained from a map of the project study area, United States Geologic Survey (USGS) ten meter Digital Elevation Models (DEMs), LULC and percent impervious data, for 1999, that were derived from Landsat 7 Thematic Mapper satellite imagery using standard image processing techniques, the Soil Survey Geographic (SSURGO) database for the Kitsap County Area, Washington, and mean annual precipitation data in a raster GIS format that was obtained from the Oregon Climate Service at Oregon State University (Figure 2).

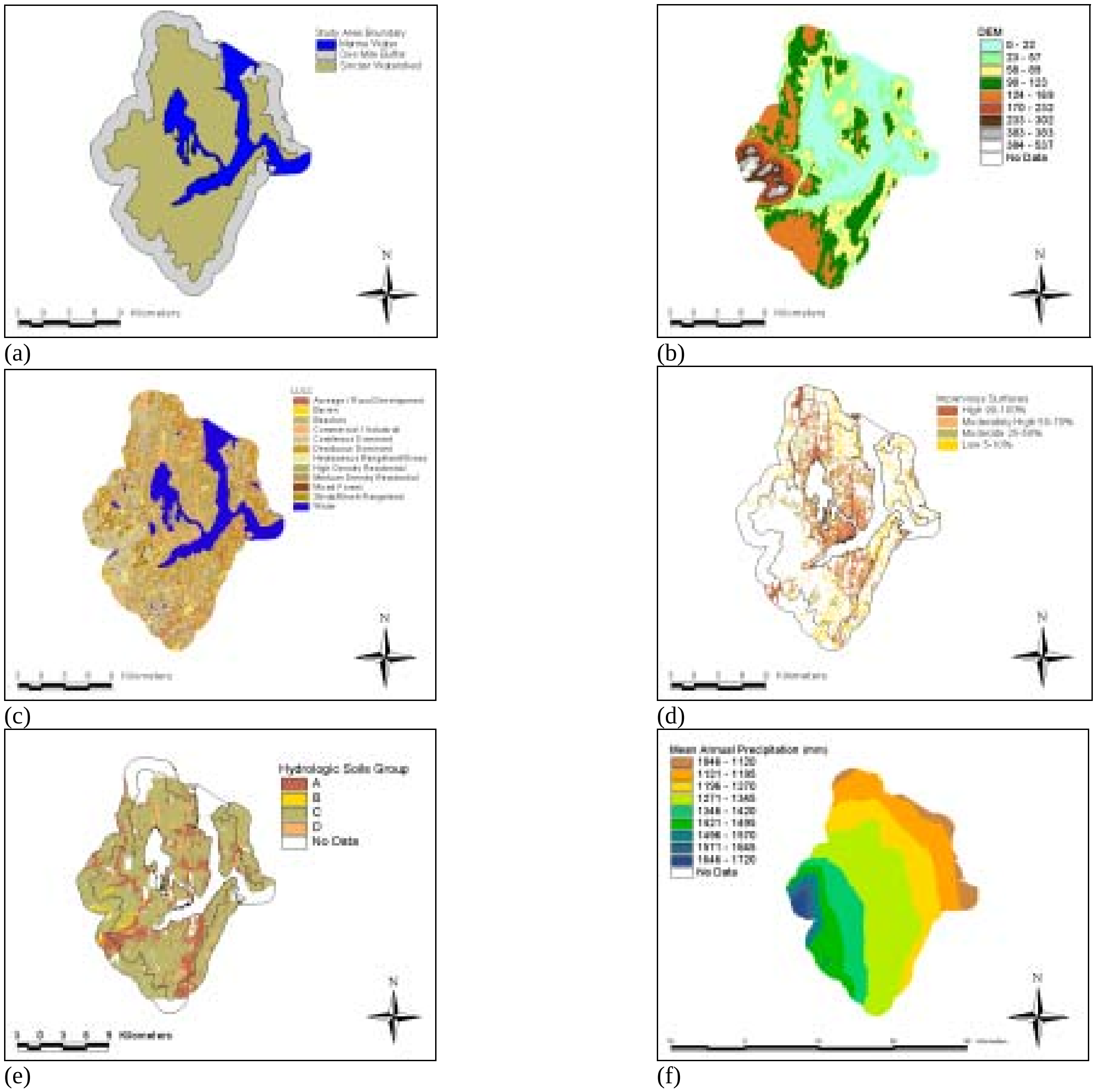

Figure 2. (a) Map, (b) DEM, (c) LULC, (d) percent impervious cover, (e) representative soils data, and (f) mean annual precipitation data for the ENVVEST project study area.

MODEL DESCRIPTIONS

The following sub-sections describe the three methods that were implemented to estimate mean annual surface runoff for the Sinclair and Dyes Inlet watershed. All three groups (*CTC*, ERDC, SSCSD) implemented the simple loss function approach based on a raster data product of percent impervious cover. *CTC* proposed and implemented the curve number approach developed by the Soil Conservation Service (SCS) of the U.S. Department of Agriculture. ERDC proposed and implemented the distributed application of the 'surface runoff function' originally derived by Eagleson (1978).

Percent Impervious Cover Method

This simple empirical approach computes losses as the inverse of the percent impervious cover. Model inputs include raster data products of percent impervious cover and mean annual precipitation. Model output consists of a raster data product of the estimated mean annual surface runoff.

Soil Conservation Service Curve Number Method

Storm runoff volume, or rainfall excess, is estimated using the curve number (CN) approach developed by the Soil Conservation Service (SCS). In the SCS method, both infiltration and surface storage characteristics of a watershed are included in one parameter, the curve number. Parameters used in this method include the actual precipitation depth (*P*), the initial loss including interception, depression storage, and infiltration losses (I_a), the precipitation excess (P_e), and the maximum storage capacity of the soil system (*S*). Subtracting the initial loss, I_a, and the precipitation excess, P_e, from the actual precipitation depth, *P*, gives the value of the accumulated retention (*F*). The CN method is based on the assumption that the ratio of the accumulated retention, *F*, to the maximum storage capacity, *S*, is equal to the ratio of the precipitation excess, P_e, to the quantity of the precipitation depth minus the initial loss ($P - I_a$), as shown below.

$$F/S = (P - I_a - P_e)/S = P_e/(P - I_a)$$

The initial loss, I_a, is often assumed to be twenty percent of the storage capacity, *S*. When the equation is solved for the precipitation excess, P_e (the surface runoff), the following equation is obtained:

$$P_e = (P - 0.2S)^2/(P + 0.8S)$$

The parameter *S* depends on the soil, cover, and use characteristics of the drainage area. Instead of assigning values of *S* directly to the appropriate characteristics, the parameter was transformed for the purpose of convenience to a CN from 1 to 100. For units expressed in inches, the storage parameter is calculated as:

$$S = 1000/CN - 10$$

Curve Numbers are assigned for different land use/cover types, hydrological conditions, and hydrologic soil groups. For each subwatershed throughout the study area, a weighted average of the appropriate curve numbers is calculated. Model inputs include land use data, soils data, annual precipitation data, and runoff coefficients. Model output consists of an estimate of runoff volume for each subwatershed.

Distributed Application of Eagleson (1978)

Eagleson (1978) approximated the ponding time of the Philip (1969) infiltration equation for $i >> A_o$, where *i* is the assumed uniform rainfall intensity and the term A_o in the Philip infiltration equation incorporates the gravitational infiltration and water table influence. The Philip infiltration equation was subsequently integrated over the duration of a rainstorm of uniform intensity, yielding a first order approximation for the depth of surface runoff in terms of storm intensity, storm duration, surface retention capacity, and initial soil moisture. Assuming initial soil moisture is at its space and time average for the given climate soil system, the storm duration and uniform rainfall intensity are independent, and exponential probability density functions for storm duration and storm rainfall intensity, Eagleson (1978) derived the cumulative distribution function for rainfall excess. This distribution was subsequently utilized to formulate the 'surface runoff function', an expression for the fraction of mean annual precipitation becoming mean annual surface runoff, in terms of physically meaningful climate and soil parameters. The 'surface runoff function' of Eagleson (1978) is given by

$$E[R_{S_A}]/E[P_A] = M_I + (1 - M_I)\{e^{-G-2\sigma}\,\Gamma(\sigma+1)/\sigma^{\sigma} - E[E_r]/m_H\}$$

where $E[\ ]$, R_{S_A}, P_A, M_I, G, σ, Γ, E_r, and m_H represent the expected value of [ ], annual surface runoff, annual precipitation, fraction of area which is impermeable, gravitational infiltration parameter, capillary infiltration parameter, gamma function, storm surface retention, and mean storm depth, respectively. Model inputs include raster data products of land use and land cover, percent impervious cover, soils, and a computational mask, as well as, possibly distributed, estimates for the mean storm depth, average storm duration, average storm intensity, average time between storms, the time and spatial average effective soil moisture, surface retention capacity, effective porosity, saturated hydraulic conductivity, suction, pore size distribution index, pore disconnectedness index, depth to water table, and effective transpiring leaf area per unit of land surface, among others. Model output consists of a raster data product of the estimated surface runoff function.

MODEL APPLICATIONS AND RESULTS

The three methods described above were each applied to estimate mean annual surface runoff for the Sinclair and Dyes Inlet watershed. The results from the application of the three methods are summarized in the Table 1 and Figure 3 below. For the distributed application of Eagleson (1978), Monte Carlo Simulation (MCS) was utilized to account for parameter uncertainty. In particular, the results below for the distributed application of Eagleson (1978) are the mean resulting from 2,500 MCSs.

Table 1. Comparison of mean annual surface runoff estimates from the three methods for selected watersheds.

			Mean Annual Surface Runoff		
Stream Name	**Drainage Area km^2**	**Mean Annual Rainfall m^3**	**% Impervious Cover Method m^3**	**SCS CN Method m^3**	**Eagleson (1978) Method m^3**
Anderson Creek	5.24	7,147,458	815,666	6,614,771	615,141
Barker Creek	10.18	12,824,971	6,303,863	12,403,029	4,052,545
Blackjack Creek	34.26	44,814,409	15,305,583	41,066,130	9,231,068
Chico Creek	42.12	60,103,397	8,274,248	55,296,111	4,986,843
Clear Creek	22.02	26,772,511	13,326,794	26,203,299	9,702,875
Gorst Creek	24.31	34,805,707	4,435,769	31,643,276	4,100,400
Illahee Creek	3.23	4,092,700	1,437,729	3,696,288	902,613
Kock Creek	1.39	1,800,542	1,334,868	1,756,601	960,270
Mosher Creek	4.38	5,668,341	3,734,120	5,395,675	2,512,928
Ross Creek	5.05	6,634,419	2,735,824	6,226,452	1,908,459
Strawberry Creek	7.68	9,716,977	4,621,304	9,164,232	2,877,948
Wilson Creek	4.99	6,414,940	4,438,452	5,803,766	3,223,458

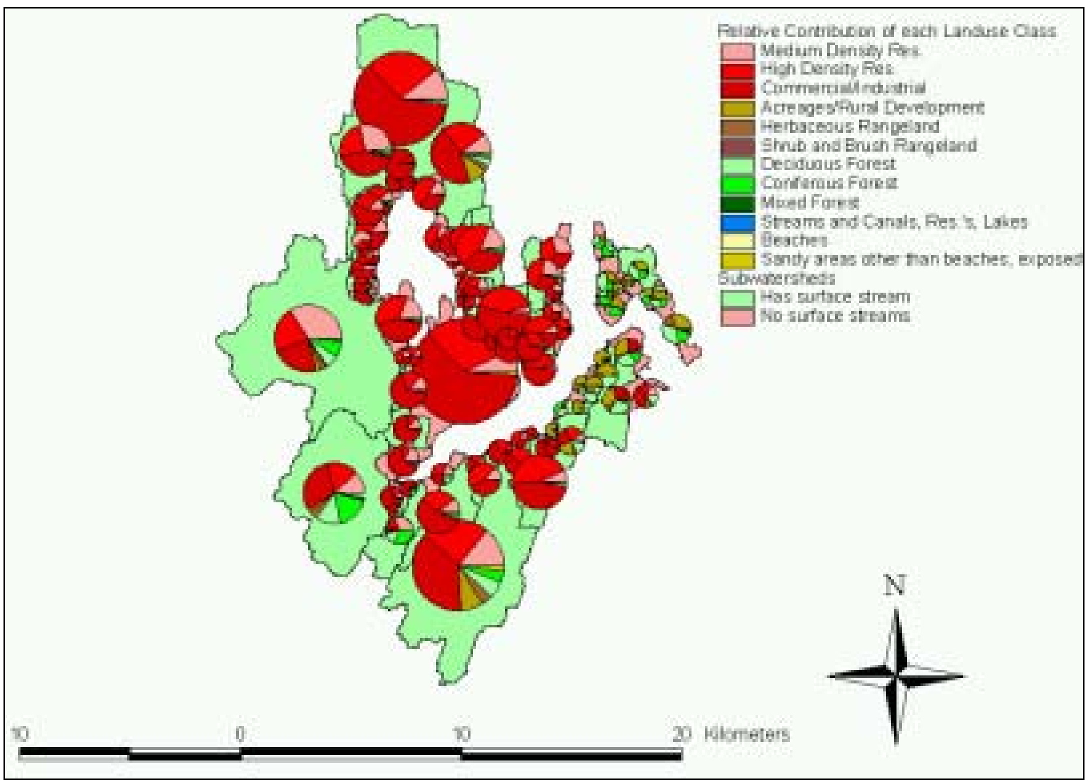

Figure 3. Estimates of mean annual surface runoff resulting from the application of the distributed application of Eagleson (1978) symbolized to show the relative magnitude of mean annual surface runoff and the relative contribution of each landuse class within a given watershed.

One objective of this GIS-based analysis is to identify locations within the study area with potentially high contaminant loadings, relative to other locations within the study area, to support an efficient water quality sampling design. The typical approach for nutrients is to utilize nutrient export coefficients – numbers that are multiplied by the amount (area) of a given land cover type to estimate the amount of nutrients received by waters from that type. Total nitrogen loads were estimated as the product of the area (A_i) of the land cover type *i* times its export coefficient (c_i), obtained from Reckhow et al. (1980), summed across all land-cover types in a given watershed. For other identified contaminants of concern, where mean runoff concentrations are provided as a function of land use; for example, the data provided by Athayde et al. (1983), and others, the total load, *L*, was estimated on a grid cell by cell basis as the product of the mean annual rainfall times the runoff coefficient (for example, the surface runoff function of Eagleson (1978)) times the mean runoff concentration summed across all raster grid cells in a given watershed. Results are summarized in Table 2 below.

Table 2. Constituent load estimates for selected watersheds.

Stream Name	Drainage Area km^2	Mean Annual Rainfall m^3	Constituent Loading				
			Total Nitrogen kg/year	Suspended Solids kg/year	Fecal Coiform col.'s/year	Lead kg/year	Copper kg/year
Anderson Creek	5.24	7,147,458	3,361	14,339	5.69E+13	4.3	6.0
Barker Creek	10.18	12,824,971	14,774	194,038	4.38E+14	41.2	50.5
Blackjack Creek	34.26	44,814,409	37,777	404,416	1.00E+15	89.2	111.9
Chico Creek	42.12	60,103,397	27,640	190,762	6.62E+14	46.2	63.8
Clear Creek	22.02	26,772,511	33,776	493,033	1.21E+15	115.9	141.9
Gorst Creek	24.31	34,805,707	17,633	129,314	3.45E+14	36.2	44.1
Illahee Creek	3.23	4,092,700	3,658	40,074	1.42E+14	9.3	13.1
Kock Creek	1.39	1,800,542	2,938	47,991	1.26E+14	11.3	14.1
Mosher Creek	4.38	5,668,341	8,121	114,148	3.77E+14	26.7	36.4
Ross Creek	5.05	6,634,419	6,661	93,180	2.38E+14	21.9	27.2
Strawberry Creek	7.68	9,716,977	10,464	134,103	4.08E+14	31.2	41.3
Wilson Creek	4.99	6,414,940	9,980	154,210	4.55E+14	36.1	47.2

DISCUSSION

Three GIS-based methods have been applied to estimate mean annual surface runoff for the Sinclair and Dyes Inlet watershed; two simple purely empirical approaches and a "physically-based" method. Results from any one of the three methods could subsequently be used to obtain the estimated load of a given constituent from each subwatershed. Examining the results presented in Table 1, there is a consistent relative difference among the three approaches. The percent impervious cover data for the ENVVEST project study area, shown in Figure 2 (d), is a reclassification of the urban or built-up land denoted in the land use and land cover data for the project study area shown in Figure 2 (c). Hence, for the simple impervious cover method, the footprint of the computed runoff map is identical to the footprint for the impervious cover map. Clearly, the results presented for the SCS CN approach proposed and implemented by *CTC* are dubious, and this method requires significant further refinement. The distributed application of Eagleson (1978) appears to hold the most promise for providing reliable and site-specific estimates of mean annual surface runoff. Current results are qualitative in nature. More reliable estimates will be obtainable when calibration (streamflow) and site-specific export coefficient and mean concentration data become available. Nevertheless, the current GIS-based analysis serves as a useful initial screening level tool. For example, the results from these analyses supported the establishment of a streamflow monitoring program and will also assist in the design of a water quality sampling program and the calibration of a WASP model for Sinclair and Dyes Inlet.

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