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SWAMP GIS: A spatial decision support system for predicting and treating stormwater runoff

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Abstract

SWAMP GIS is a spatially-based decision support system that empowers users in rural areas within Oregon (USA) with tools for predicting and mitigating stormwater runoff. SWAMP GIS is made freely available to all potential users that have an Internet connection. Users can choose from among six maximum 24 hour runoff events and can calculate runoff statistics for a specific area that they trace on top of a digital orthophotograph, or from a contributing area that can SWAMP GIS can create based on a user-specified point or polygon. Predicted stormwater runoff for the area of interest is based on Natural Resources Conservation Service methodology and involves spatial databases representing rainfall amount, landscape terrain, hydrologic soil groups, and land cover categories. SWAMP GIS users can then use a runoff reduction tool to investigate the affects of 17 different stormwater runoff mitigation strategies. The runoff reduction tool can assist in determining which runoff mitigation strategy might be most advantageous given the characteristics of the landscape surrounding an area of interest. SWAMP GIS brings spatial technology and approaches for stormwater runoff prediction and reduction to users that might otherwise lack the GIS resources and expertise necessary for stormwater analysis. We describe the SWAMP GIS decision support tool and the design of spatial geoprocessing tools for runoff estimation. We also provide examples of tool applications for predicting and mitigating storm water runoff within rural areas.

Keywords: geographic information systems, runoff, mitigation, treatment

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Introduction

As land is developed and converted to housing and other uses, rainfall which once infiltrated into the ground now flows over hard surfaces until it reaches soils that allow infiltration or is intercepted by a stream or storm water system. Storm water runoff can have significant impacts on the environment as pollutants can be transported and introduced in other areas, including nearby streams. Additionally, storm water management systems are an expensive method of addressing storm water impacts. There are many alternatives that can reduce runoff and reduce environmental impacts but providing this information to planners and land managers in a way that encourages interest and adoption of alternatives can be challenging.

We've designed a spatially-based decision support system that allows users to predict storm runoff values in a study area that includes watersheds along the entire Oregon (USA) coastline and in several sub-basins in southern Oregon. The decision support system is named StormWater Assessment and Management Process (SWAMP) GIS and is freely available through an Internet mapping interface. Many communities within the study area are positioned in rural areas and lack the resources for a dedicated geographic information system (GIS). In some instances, the cost of GIS software alone is prohibitive to rural organizations, and staffing resources for GIS analysts and training may be minimal if not nonexistent. One of the goals of SWAMP GIS was to provide rural communities with an accessible GIS-based storm runoff analysis tool that did not require purchase of a software license. A second goal was to make the runoff analysis tool flexible to support several methods of investigation yet designed in such a way that GIS expertise was not necessary to produce output.

SWAMP GIS allows users to indicate an area of interest on a digital orthophotograph and to choose among six maximum 24 hour rainfall amounts representing a specific return period. Geoprocessing then accesses multiple spatial layers representing topography, soil properties, and land cover to predict storm runoff volume. The output information can then be fed into an on-line Stormwater Runoff Reduction Tool that displays runoff information and allows users to explore potential runoff reduction practices within their area of interest. The influence of potential runoff reduction practices is calculated in terms of potential runoff volume treated and helps users to weigh alternative practices quantitatively. Our objectives in this manuscript are to describe the decision support tool and the design of geoprocessing tools for runoff estimation. We also provide examples of tool applications for predicting and mitigating storm water runoff.

Methodology

SWAMP GIS is built upon ESRI's ArcGIS Server technology that makes GIS capabilities available through an on-line mapping interface. GIS data layers and software for SWAMP GIS are stored on a computer server on the Oregon State University (OSU) campus that can be accessed by anyone with Internet accessibility. One advantage of this approach is that on-line users have access to GIS functionality without having GIS expertise, building supporting databases, or purchasing a GIS software license. GIS geoprocessing tools are functions that allows for spatial database manipulation and analysis. The tools are built within the server environment as services that are made available through the on-line mapping interface. Though typically not all GIS functionality can be made available through the server environment, many core GIS functions are possible.

The SWAMP study area is over 930,000 ha and includes all sixth-field watersheds that border the Oregon coastline and two entire sub-basins in the southwestern portion of Oregon. An initial mapping interface within SWAMP GIS breaks the study area into four geographic portions and prompts users to select one
of the portions to work within (Figure 1). These areas typically feature many smaller, rural communities where access to spatial tools for runoff prediction and mitigation are likely not available. In addition, rainfall is frequent during the winter months along the Oregon coast and potential stormwater runoff can be significant at times.

One of the primary data layers within SWAMP GIS is a 10 m resolution digital elevation model (DEM). This is currently the highest resolution DEM available that is continuous throughout the SWAMP study areas. One of the primary functions of the SWAMP GIS tool is to allow a user to draw a point or polygon within the mapping interface, and to have the upslope contributing area be defined and used in subsequent runoff calculations.

SWAMP GIS uses the Natural Resources Conservation Service (NRCS) method to predict total runoff. The potential maximum water storage capacity of soils is first calculated according to a curve number:

Equation (1)

\[ S = (100 / CN) -1 \]

where \( S \) = storage capacity

\( CN \) = curve number

Curve numbers range from 0 to 100 with 0 indicating no runoff and 100 indicating no infiltration capacity. Runoff depth across an area is then calculated:

Equation (2)

\[ Q_{\text{depth}} = (P_g - 0.2 \times S)^2 / (P_g + 0.8 \times S) \]

where \( Q_{\text{depth}} \) = runoff depth

\( P_g \) = gross rainfall

Curve numbers reflect the relative amount of runoff expected from a land area based on hydrologic soil group and land cover. Impervious surfaces such as asphalt and concrete will have higher curve numbers than vegetated land cover such as grass fields or forests. Soils are split into four primary groups (A, B, C, and D) that provide a gradient approximation of infiltration rates. Soil group A has relatively high infiltration rates and low runoff potential whereas soil group D has slow infiltration rates and high runoff potential. We accessed GIS layers of hydrologic soil groups for the SWAMP study area through the NRCS (NRCS 2011).

Land cover data was available through the National Oceanic and Atmospheric Administration’s (NOAA) Coastal Change Analysis Program (CCAP) which featured land cover categories created from 2001 Landsat Thematic Mapper satellite imagery (NOAA 2011). We used runoff curve numbers based on unique combinations of NRCS hydrologic soil groups and land cover types that had been recommended in previous research (NOAA 2008).

Maximum 24 hour rainfall spatial data were accessed through the Oregon Climate Service and are based on analysis of annual maximums (Schaefer et al. 2008). Return periods include 24 hour rainfall maximums for 6 month, 2 years, 10 years, 25 years, 50 years, and 100 years.
The primary SWAMP GIS interface contains a map that identifies four study areas: the north coast, south coast, Umpqua basin, and Rogue basin. Text on top of the primary map informs users that the Identify tool can be clicked on one of the study areas in order to access a GIS interface that is specific to that study area. Regardless of which study area is chosen, a similar mapping interface appears but one that has the extent of a specific study area as its spatial extent. Twenty-three spatial data layers are made available and can be toggled on or off from view by the user. Many of the spatial data layers are provided to help users locate their area of interest including rivers, highways, city limits, urban growth boundaries, and a half-meter resolution digital orthophotograph. The digital orthophotograph is stored on a separate server on the OSU campus and is ported into the SWAMP GIS interface as an additional map service. Given the tremendous file size of the digital orthophotograph, the map service porting provides a significant advantage in not requiring storage of the orthophotograph on the SWAMP GIS server. Other layers such as elevation contours and soil water infiltration are made available to help users learn more about the landscape in their area of interest. In addition, layers that are part of the stormwater runoff calculations are also provided: land cover, hydrologic soil groups, and a layer for each of the six maximum rainfall return intervals.

A set of navigation tools enables users to pan across or zoom into the map interface. The identify tool lets users click on vector GIS layers and view database attributes, such as city names that are affiliated with a urban growth boundary, or names of prominent streams, roads, and water bodies. In addition, a measure tool makes it possible to return a set of map coordinates for any point on the data layers that is clicked on. Other measure tool options include a polyline tool that returns the linear distance associated with a sequence of user mouse clicks on the map interface, and a polygon tool that returns the perimeter and area of any polygon feature drawn by a user.

Three geoprocessing tools are made available in the map interface. Each tool was built using ESRI’s model builder and python programming. The model builder provides a graphical interface in which to organize individual geoprocessing tools and the sequence in which tools are accessed. Python programming augments the degree to which geoprocessing tool inputs and outputs can be tailored for specific purposes. The first tool is labeled “Create Plot Statistics from Polygon.” The Plot Statistics tool allows users to draw either a single polygon or multiple polygons and to return a file of statistics from databases within the polygon boundary. A drop-down menu prompts for the selection of one of the six 24 hour maximum rainfall events for inclusion in the statistical summary. Upon successful completion of the Plot Statistics tool, output will appear in a Results window in the mapping interface. The output will contain a spatial layer of the polygon(s) drawn by the user and text that indicates which maximum rainfall event was selected. The actual statistical output is contained in a text file in the Results window that offers a download hyperlink. The download hyperlink prompts for a location on the local computer in which to store the statistical output. The statistical output includes the curve number associated with each land cover and soil group combination within the user drawn polygon(s), and the resulting landscape area size, 24 hour maximum rainfall depth, and runoff volume.

The other two geoprocessing tools offer the same choice of six 24 hour maximum rainfall events and produce the same output statistics but differ in how areas that provide the statistics are chosen. The “Create Watershed Statistics from Point” tool prompts users to indicate a single point with a mouse click, or to indicate multiple points. An upslope contributing area, or watershed, is delineated using a flow direction raster database and statistics are generated for the watershed area for the point(s). The “Create Watershed Statistics from Polygon” tool lets users draw a polygon shape or multiple shapes. The upslope contributing area is created for the drawn polygon(s) and statistics are calculated.
The statistical output of each of the three geoprocessing tools can either be viewed in its native text file format, or can be loaded into the Runoff Reduction Tool which is accessible from a link located above the main map interface window. The Runoff Reduction Tool, once activated, prompts users for the location of the text file for uploading. Once uploaded, all unique combinations of land cover and hydrologic soil groups contained within the user drawn polygons are displayed in tabular format, including the curve number associated with each land cover and soil group combination. In addition, the area, 24 hour maximum rain fall depth, and runoff volume are displayed. This summary statistical output appears in an upper section titled "Uploaded Information Table (Pre-construction condition)". The purpose of the pre-construction section is to establish landscape conditions prior to any development or alterations of ground cover within an area of interest. Land cover type and hydrologic soil group can be altered for each of the displayed land cover and soil group combinations by the user clicking on a value. A menu of possible choices for land cover and soil groups then prompts the user to select a change. As curve numbers are available for each combination of land cover and soil group, the curve number is automatically updated and displayed in the summary statistics when a user alters either land cover or soil group. In addition, area, rainfall depth, and runoff volume can also be updated. These updating capabilities enable users to make corrections or modifications to output categories based on their own knowledge of a study area or in order to support investigation. Each of the rows of output information can be individually deleted from the table. At the bottom of the first section of the Runoff Reduction Tool, a set of summary statistics describing the total area of the user drawn polygon(s), the highest rainfall depth, and the total runoff volume are listed, and reflect any changes made by a user to values in the pre-construction section.

A second section of the Runoff Calculator titled "Modifiable Information Table (Post-Construction Condition)" appears below the initial section. This second section is initially populated by the initial land cover and hydrologic soil group values that appear in the pre-construction section of the Runoff Calculator. Area, maximum rainfall depth, and runoff volume statistics are also provided for each row. The post-construction section is provided so that users can modify a landscape to match what might result should development or other alterations occur. Clicking on a land cover opens a menu with land cover alternatives. Alternatives include not only the original land cover categories from CCAP but 12 additional categories that address a gradient of low, medium, and high intensity development and various impervious surfaces such as parking lots, paved roads, and gravel roads. Impervious surface percentages are provided for the eight different levels of development.

As changes are made to the land cover and hydrologic soil group categories in the post-construction section, a summary table at the bottom of this section lists the area, highest rainfall, and total runoff for both pre-construction and post-construction, and calculates the differences between both scenarios. The available runoff to treat is also summarized and represents the difference between the post-construction and pre-construction runoff volume totals. Just below the available runoff to treat is an input area where the user is prompted for the target runoff amount to treat. Once a volume is entered, a button titled "Submit Runoff" will input the target value into the third and final section of the Runoff Calculator Figure.

The final section of the Runoff Calculator is titled "Runoff Reduction Table." This runoff reduction section summarizes the information, including any changes made by the user, in the post-construction scenario. A drop down menu allows a user to add a reduction practice to any of the unique combinations of land cover and hydrologic soil groups. Seventeen potential reduction practices are given as available choices and each is assigned a percentage that describes the relative ability of the practice to reduce runoff. Once a reduction practice has been chosen and the size of the area to be treated has been selected, a summary of the volume treated appears for that land cover and soil group. As changes are made, volume
summaries of the total and target treated runoff are updated, including a volume for the untreated runoff. If two or more are selected, the choice of a reduction practice gets assigned to all treatment rows and the area statistics remain the same.

A fourth tool appears next to the three geoprocessing tools that enables printing of a map that contains the plot or watershed created by the user, and any spatial layers that are made visible. The printing tool prompts for a map title and size. The resulting map includes a legend of visible layers, north arrow, and scale bar.

**Results and Discussion**

We selected a potential area in the Rogue Basin Study area to demonstrate SWAMP GIS output that results from the Plot Statistics geoprocessing tool. A polygon is drawn around an area that contains open space and residential housing (Figure 2). A maximum 24 hour rainfall depth for a 6 month storm event is selected and submitted for processing. A statistics file is produced in the results section and can be downloaded to the local computer and loaded into the Stormwater Runoff Reduction Tool. Current land cover and hydrologic soil group data is displayed in the pre-construction section and, as a demonstration, the grassland cover type has been replaced in its entirety by a medium intensity development characterized by 65% impervious surface (Figure 3). This results in an increase of 5747 ft$^3$ of additional runoff. The runoff is entered into the “Enter target runoff to treat” input box and submitted for evaluation of treatment alternatives. In the Runoff Reduction Table portion of the Runoff Reduction Tool, the medium intensity development category (Med. Int. Dev.) is selected for evaluation. An initial runoff mitigation strategy of vegetated filter strips is selected and applied to 0.5 acres, and a second strategy of rain barrel, rain tank, or cistern is added as a second strategy for 1 acre (Figure 4 Runoff Table Rogue). The 2.7 acre property would hold approximately 20 homes and approximately 1 acre of runoff from the combined roof areas of these homes could be directed into a rain barrel. These practices would result in approximately 2,164 ft$^3$ of runoff being treated.

After completion of the analysis, users can choose the print tool. The print tool prompts users for a map title and size. All spatial layers that are visible as indicated by a check next to a layer name are brought into the map. A legend is provided for all visible layers as well. In this way, users can create records of the spatial databases contained in their various manipulations and produce output that could accompany development plans (Figure 5).

We consider a second potential area in the North Coast SWAMP study area as a demonstration of the Watershed Statistics from Polygon tool. A potential development site is located using a polygon in a coastal area within a forested watershed. A maximum 24 hour rainfall depth for a 10 year storm event is selected and submitted for processing. The output polygon captures the drainage area associated with the initial polygon and generates a stormwater runoff statistics file (Figure 6). The runoff statistics file is uploaded into the Runoff Calculator and indicates that the pre-construction land cover is entirely Evergreen Forest. The post-construction land cover is slated as developed open space which includes parks and golf courses, resulting in nearly 84,000 ft$^3$ of potential additional runoff. Three reduction practices are selected to treat the additional runoff: bioretention, green roof, and vegetated filter strips for limited areas within the post-construction lands. The benefit of these three reduction practice is over 25,000 ft$^3$ of the post-construction runoff being treated (Figure 7).
Conclusions

We've developed a spatially-based decision support system that allows users in rural areas within Oregon to predict stormwater runoff. The SWAMP GIS tool is provided freely all potential users that have an Internet connection. Users can select a specific maximum 24 hour runoff event and generate runoff statistics for a specific area that they draw over a digital orthophotograph, or from a watershed area based on a user specified point or polygon. Runoff estimates are provided based on NRCS runoff formulas and take into account multiple spatial databases. Users can create a map of their study area and can include digital orthophotographs, roads, streams, city limits or any of the 23 spatial databases included in the SWAMP GIS interface.

Different stormwater runoff mitigation strategies can be explored and evaluated by SWAMP GIS users. SWAMP GIS is a freely available spatial technology that provides benefits to landowners and planning departments within rural portions of Oregon. It allows users without spatial resources, such as GIS software or expertise, to conduct their own stormwater analyses, and to explore in a quantitative fashion different runoff reduction strategies. SWAMP GIS tools are based on ESRI's ArcGIS Server capabilities and can be developed for any location in the world given that supporting spatial databases are available.

References


Figure 1. SWAMP GIS initial user interface and study area.

Figure 2. Rogue Basin polygon used to generate runoff estimates.
Figure 3. SWAMP GIS stormwater runoff reduction tool.

Figure 4. SWAMP GIS runoff reduction table.
Rogue Basin Area

Figure 5. Rogue Basin area map.
Figure 6. North Coast user-drawn polygon (top panel) and resulting upslope contributing area (bottom panel).
Figure 7. SWAMP GIS runoff reduction table for North Coast.