The Nature Conservancy: Assessment of Scenario Modeling for Best Management Practices on Agricultural Lands

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Recommended Course of Action

The goal of this report is to provide The Nature Conservancy of Washington an analysis of models that can be used to identify agricultural working lands that contribute to bacterial pollution loading and negatively impact water quality for salmon and shellfish in the Puget Sound Ecoregion. To answer this question five models were compared and contrasted, with one model selected. The selected model was then applied to one watershed within the Puget Sound Ecoregion to create a best practices format for running the model and how to apply it to the other watersheds. The results of the model were also analyzed to determine the general effectiveness of the model.

The final recommendation of this report is that the ArcSWAT - Soil Water Retention Tool - model be used for analysis throughout the Puget Sound Ecoregion. Due to the complexity of inputs needed to accurately operate ArcSWAT this report also recommends additional research be done, specifically looking at current grazing practices (number of days per year animals are present on pasture land) and manure fertilizer applications (amount of fertilizer applied and how often). This data is needed to accurately create predictive models within the region and effective answers about the role potential best management practices have on bacteria loading in the watershed.

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Introduction

Non-point source pollution poses a significant threat to water quality in the United States and agricultural lands have been pinpointed as one of the main causes of problems in lakes and rivers (Sommerlot, Nejadhashemi, and Wozniki, 2013). Non-point source pollution can be reduced by implementing best management practices (BMPs). BMPs are useful because they assist in meeting water quality criteria without disturbing environmental quality. Though useful and beneficial, the results of implementing BMPs is difficult because the pollution extends far beyond the source. Pollution extent is very much related to climatic events as well as site specific conditions such as topography, soils, and landuse (Lee et.al, 2009).

The Greater Puget Trough Ecoregion (the region comprised of the Puget Sound and surrounding drainages) is a complex and varied environment containing major metropolitan areas as well as extensive parks and wilderness areas. The area is also home to many interrelated landuses, some which benefit each other and some that conflict with each other (LandScope Washington, 2014). This report focuses on the conflicts between the harvested aquatic and farmed terrestrial systems in which many people in the region are dependent on for both food and livelihood (Table 1).

In this report The Nature Conservancy (TNC) of Washington is a "conservation organization with a stated mission of "to conserve the lands and waters on which all life depends" (The Nature Conservancy, 2014) - has partnered with the University of Washington Master of GIS program to look at specific social-ecological issues surrounding the impacts of runoff from agricultural lands on wild salmon stocks and shellfish beds throughout the Greater Puget Trough Ecoregion. The intersection of these two subjects is of interest because of the conflicts produced between agricultural lands, humans and shellfish beds. In 2014 approximately 19% of shellfish beds in Washington State were closed due to some form of fecal bacteria - with livestock contributing a significant portion to the total impacts (Puget Sound Partnership, 2014). TNC proposed the question this report addresses: Is(are) there a model(s) that can be used to identify agricultural working lands where best management practices (BMPs) could reduce pollution loading (specifically bacteria) to improve water quality for salmon and shellfish in the Puget Sound (Jamie Robertson pers. Comm.) (Figure 1).

Addressing this question was broken into two components:

1. Researching and analyzing models to determine which are best suited for answering the specific questions of interest.
2. Applying the model to a specific watershed - with the time available the decision was made to not analyze the entire Puget Sound ecoregion and instead focus on one watershed - to determine how the model works, develop best practices for the model inputs, and perform a sensitivity analysis on the model outputs.

Table 1 - Social Ecological Systems Table

Scales	Biophysical	Economic	Social
Puget Trough Ecoregion	Puget Sound total suspended sediment is 75% of the total of the Columbia River and sediments can carry many pathogens[1]	Salmon harvests have been on the decline due to pollutants impacting reproductive rates[2]	Recreational, financial and cultural (i.e. tribes) impacts across region. This also plays a role in regional politics, regional tourism and recreation, tribe/non-tribe conflict, and impacts to standard of living across region
County Government agencies and NGO Stakeholders	County governments and water conservation districts will have to collaborate with TNC in order to most effectively implement any BMP suggestions made for the WRIAs where the suggestions are made.	BMP - Cost share incentives for agricultural practices [3] Potential financial hardships of overburdening farmers with BMPs. BMPs must allow for sustainable/local working lands.	Communicate with local farmers about their current practices and educate them on how to better their practices. Monitor, test and regulate, and enforce water quality may cause friction socially.
Focal Scale Watershed: **WRIA 1 - Nooksack** **WRIA 3 - Lower Skagit-Samish**	Contaminants from upstream enter Puget Sound and contaminate shellfish habitats Skagit River one of the highest contributors of phosphorus, nitrogen and suspended sediment in all of Puget Sound. [4] Storm events increase fecal coliform loads into the system.	Shellfish beds in Puget Sound have been closed to harvest due to bacterial contamination possibly due to high fecal coliform pollutants [5]	Recreational, financial and cultural (i.e. tribes) impacts in watershed. This also plays a role in local politics, tourism and recreation, tribe/non-tribe conflict, and impacts to standard of living.
Farm Level	Dairy farms can create surface runoff of sediment, nutrients and bacteria Pollution loads are influenced by type of farm activity, soil type, slope, farm size and proximity to streams [6]	Outreach of Education BMP's[7]	Dairy farms have required plans in place to manage manure in order to protect water quality and apply vegetative practices, such as riparian plantings and buffer maintenance.[8]

[1] USGS. 2007. "Nutrient and Suspended-Sediment Transport and Trends in the Columbia River and Puget Sound Basins 1993-2000" *Scientific Investigations Report*. p 37.

[2] Landahl, J. T., Johnson, L. L., Stein , J.E.Collier, T.K., and U. Varanasi. 1997. "Approaches for determining effects of pollution on fish populations of Puget Sound." *Transactions of the American Fisheries Society*. 126:3, 519-535.

[3] Whatcom County Conservation District. 2014. http://www.whatcomcd.org/

[4] USGS p 42.

[5] Picket, P.D. 1997. "Lower Skagit River Total Maiximum Daily Load Water Quality Study." *Department of Ecology. Publication* 97-326a.

[6] Environmental Protection Agency. "Washington: South Fork Skagit River" *Water: Nonpoint Source Success Stories*.http://water.ep.gov/nps/success319/wa-skagit/cfm.

[7] Ibid

[8] Ibid

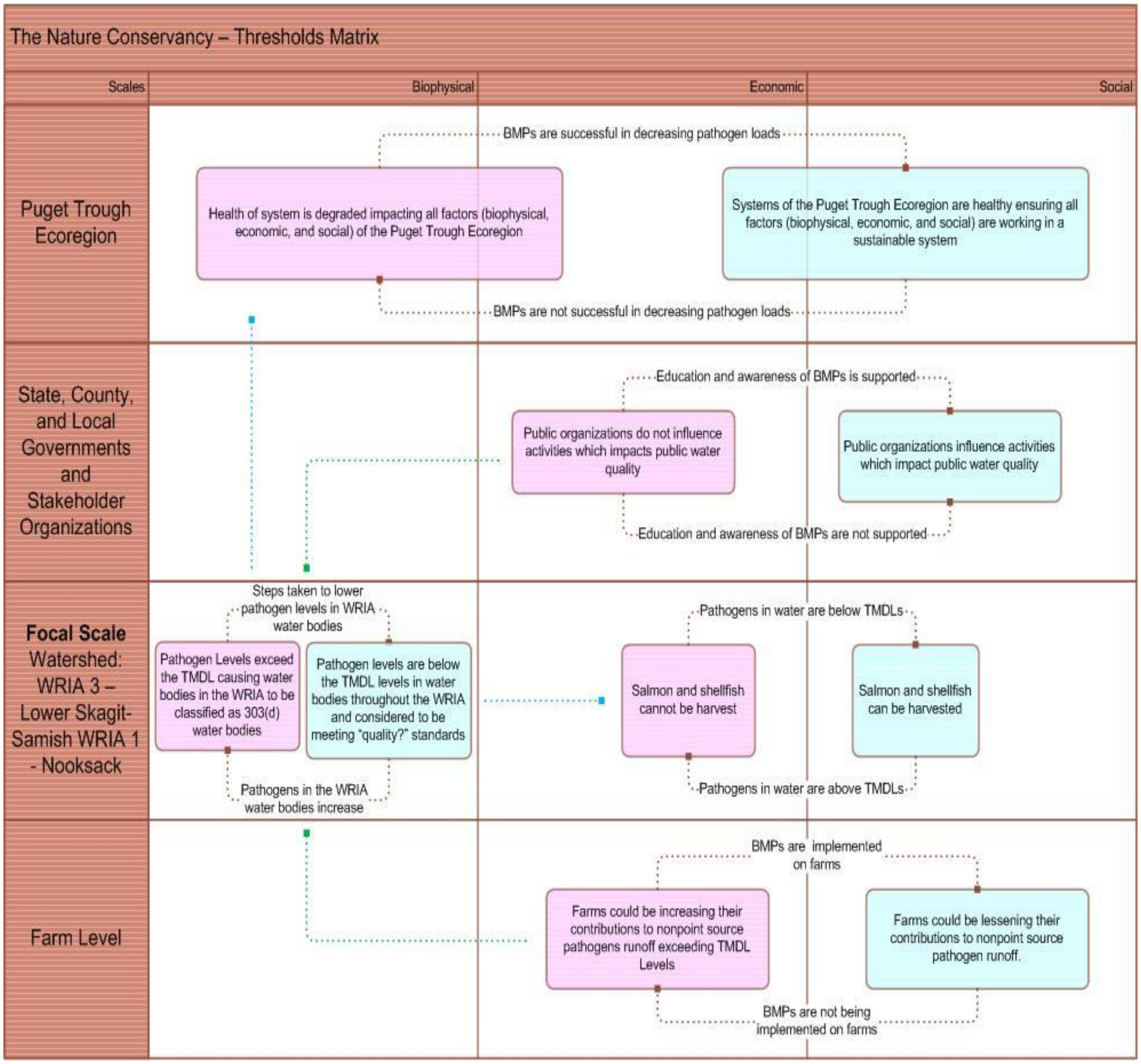


Figure 1 - Threshold Matrix - Relationship between the existing systems

Design and Methods

Preanalysis

An initial meeting with The Nature Conservancy gave a starting point for this project suggesting three models of interest: InVEST, OpenNSPECT, and SPARROW. They also confirmed there was flexibility in choosing a relevant model for the project and were open to other model suggestions. Analysis on the three suggested models was started and that research turned up two other models, ArcSWAT and SUSTAIN, for a total of five models. The five models were analyzed, based on model criteria provided by the Nature Conservancy as well as suggestions from the project team. These criteria are as follows:

1. Ease of use/User experience
2. Simplicity of running of the model
3. Data Availability (Is required data available in the other WRIAs where the model will be run?)
4. Processing needed to obtain usable data
5. Customizable at different scales
6. Answers the TNC questions asked
7. Graphic output
8. Level/Number of Simplifying Assumptions
9. Cost
10. Deals with pathogen data directly or requires manipulation of sediment data

In addition to these criteria the models were analyzed using a model comparison table that includes a model description, data requirements, model outputs, and a brief description of how the model applies to the project (Appendix A).

OpenNSPECT

The Nonpoint Source Pollution and Erosion Comparison Tool (NSPECT) is a model that ties together landuse and pollutants by modeling the impacts landuse changes have on pollutant concentrations. The model is broken into four components, three support models (runoff estimation, pollutant concentration, and sediment concentration) that build data sets for the final assessment and reporting model. The runoff estimation and pollutant concentration models make use of landuse data that are already built into the model and should be capable of representing any impacts on pollutant concentrations when BMPs are altered. However, the default acceptable coded landuses the model recognizes are not representative of what TNC is looking for. This means a key component for making this model relevant would be calculating pollution coefficients for any landuse type not included in the defaults, as well as calculating another coefficient for that landuse when any BMP is applied to it in the model. These calculations are needed so the model can produce an accurate accounting of the runoff. Without proper pollution coefficients - along with the appropriate runoff values shown by the Soil Conservation Science (SCS) curve numbers and the Revised Universal Soil Loss Equation (RUSLE) values - the model will not produce results that will hold any certainty in their values.

Also of note, OpenNSPECT does not run through ArcGIS, it uses MapWindow GIS to run all operations (NOAA Coastal Services Center, 2014).

SPARROW

The Spatially Referenced Regression On Watershed (SPARROW) model developed by the United States Geological Society (USGS) uses regression modeling to identify relationships between water quality records and pollutant sources. The regression modeling provides estimates of pollutant contributions based on statistical analysis of watershed sources and transporting properties and monitoring stations records. It then uses a process-based approach to account for pollutant loading modeling transport from surface water to stream network and then stream network to a final waterway. The program has been used to analyze nutrient loading from national scales to single watersheds and can be used to account for bacterial loading if long term continuous monitoring data is available. It then runs statistical analyses for surface water and stream transport impacts for both large and small scales. These analyses are performed on individual segments within a stream network (USGS, 2011).

Limitations of this model are the availability of long term consistent data within the Washington State watersheds which could cause uncertainty and inaccuracy of load estimates. Another limitation of the model is the absence of sufficient load coefficient data by landuse type to the detail requested by the Nature Conservancy for this study. This model is also not scenario based, it relies on statistical calculations and not the physical aspect of the landscape. Finally, it doesn't involve any GIS in its general process or results and requires coding to produce a spatial aspect (USGS, 2011).

SUSTAIN

The SUSTAIN (System for Urban Stormwater Treatment and Analysis Integration Model) model was created by the Environmental Protection Agency (EPA) and is composed of different modules: framework manager, BMP siting tool, land module, BMP module, conveyance module, optimization module, and post-processor. The SUSTAIN model was designed to provide an "objective analysis of management alternatives among multiple interacting and competing factors." (Lai et al, 2007) All of the modules are designed to work with ArcGIS,as well as work together but do not necessarily build to one final output (Shoemaker, 2011).

The most interesting aspect of the SUSTAIN model is the ability allow the user to specify the exact locations of BMP plans. The model analysis produces outputs with information about the expected impacts and costs from the implementation of BMP's defined in the model parameters which may be able to assist in analyzing what BMP practices make the most sense and where. This could make it possible to create targeted BMP recommendations for given parcels (or perhaps a given landuse) instead of analyzing broad based changes for all landuse types (Shoemaker, 2011).

Similar to other models, SUSTAIN is not specifically programmed to handle pathogens, so sedimentation would need to be used to evaluate this important concern of the Nature Conservancy. Also, pollution coefficients are needed to represent changes for a given BMP and would need to be located, calculated and applied for the SUSTAIN model to accurately produce results to represent the impacts proposed changes may have. Another major concern is whether or not SUSTAIN, a model designed for the urban environment, will work for the agrarian environments of this project. One area this limitation appears is the BMPs the model can work with are tailored to the urban environment. For example, there is no listed option to include riparian buffers and utilizing conservation tillage on fields, two common agrarian BMPs (Shoemaker, 2011).

InVEST

The InVEST model was created by the Nature Capital Project and is a set of models that can be used, individually or in combination, to simulate various ecological systems. Sample data is provided in the model, but individualized data sets can be introduced into the model to customize the simulation. Overall the InVest models seem simple to run and data seems like it would be easy to acquire since the models provide data sources in the appendices. However, these models, both individually and as a group, do not address the main concern of The Nature Conservancy - the concentration of bacteria being loaded into the rivers. In addition, many of the models pertaining to rivers indicate they are only accurate at the sub-watershed level, and seem like they cannot be customized to represent different scales in a simple way. However, it may be possible to change them using Python scripting. Some models, such as the sedimentation model and the water yield model may be interesting additions to analyze alongside a larger model, since the maps they produce provide a quick and simple look into sedimentation and water yield (Natural Capital Project, 2014).

ArcSWAT

The Soil Water Retention Tool (SWAT) developed jointly by the United States Department of Agriculture (USDA) and Texas A&M Agrilife Research is a comprehensive model that encompasses many tools pertaining to water and landuse quality. Including but not limited to, contaminant retention in various soils, various aspects of hydrology such as surface runoff, groundwater and soil water, erosion and sedimentation including transport of contaminants, water routing and channelization, and the impacts of impoundments such as ponds, potholes, and reservoirs. There is also significant official documentation for this model (three separate documents) as well as significant published literature using ArcSWAT (Arnold et al., 2012, Neitsch et al., 2009, and Winchell et al, 2013).

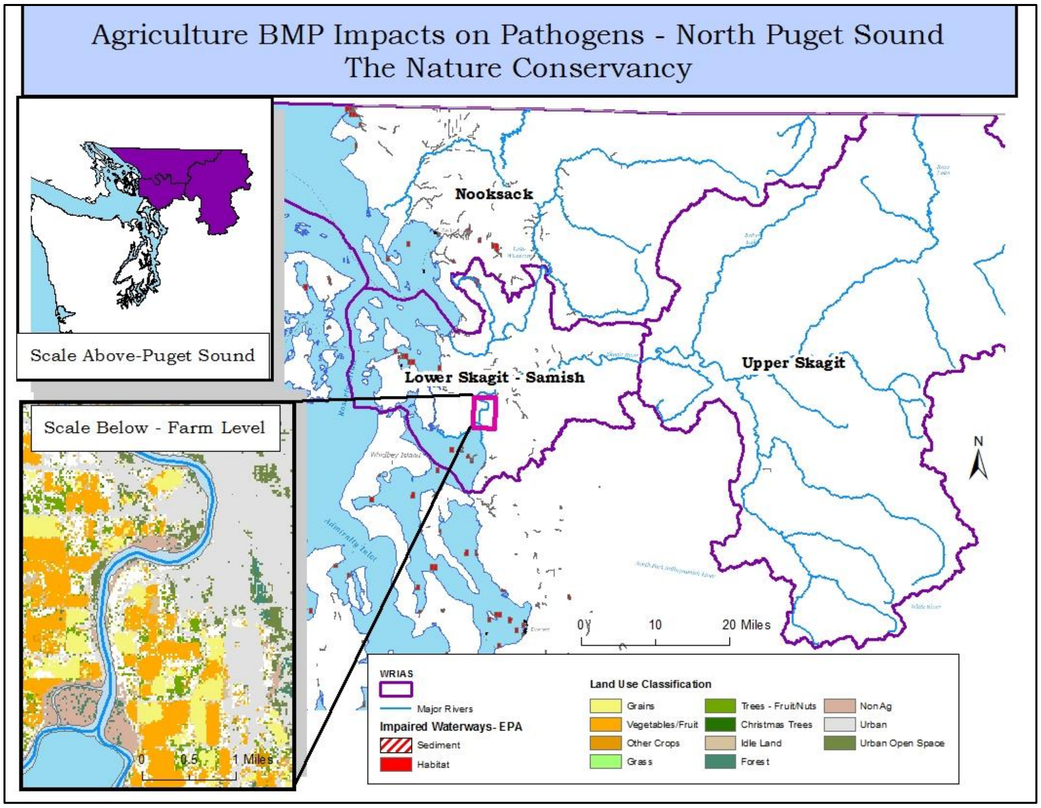
ArcSWAT is contained in one model and can be run at three levels, watershed, sub-watershed, and hydrologic resource units (HRUs). HRUs are specified by the landuse, soil, and slope that is most common in that area. One of the attractive features of ArcSWAT is it analyzes pathogens as well as pesticides and nutrients. The model simulates the transport of bacteria, nutrients and pesticides from land areas to water bodies, analyzing the different aspects of the hydrologic cycle, river flow rate, velocity, and sedimentation, taking into account impoundments such as ponds, reservoirs, wetlands, depressions and potholes. This model is extensive in what outputs it can provide, but the documentation directly states it can be customized to fit the user's needs (Arnold et al., 2012, Neitsch et al., 2009, and Winchell et al, 2013).

Model Recommendation

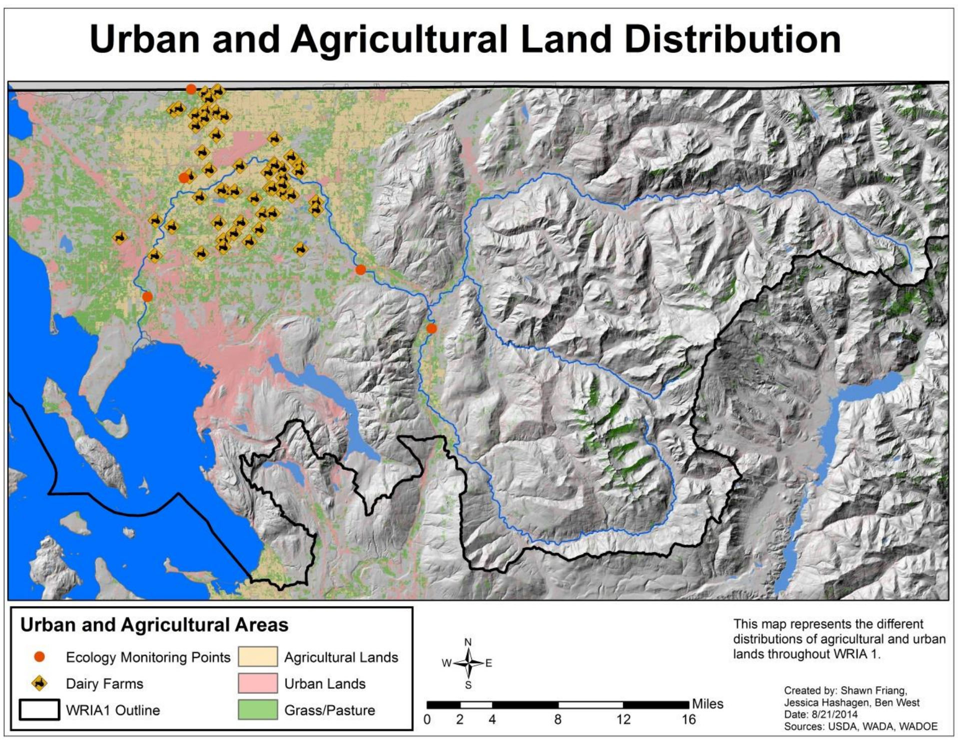
Of the five models reviewed (OpenNSPECT, Sparrow, SUSTAIN, InVEST, and ArcSWAT) our final recommendation for the model of best fit is the ArcSWAT model. The primary reasons this selection was made is ArcSWAT is the only model reviewed with the ability to directly deal with bacteria and not use another measurement (such as sediment) as a proxy. It also focuses on agricultural lands as a primary landuse, and can model different agricultural practices, for example type of fertilizer applications and harvesting method. In addition ArcSWAT models sedimentation, river velocity, and has the capability of modeling the effects of channelization to rivers; all topics of interest to TNC. Other outstanding features of ArcSWAT includes the capability of running the model to different levels of complexity, both scale and amount of information used. Another attractive aspect to this model is the primary output tables can be linked to spatial data created by the model. The tables can also be represented well in charts, tables and graphs, providing a variety of means to represent the data. In conclusion, this model not only seems to provide everything TNC is looking for, it also provides many opportunities to expand the potential scope of the project in the future.

ArcSWAT Model Methodology

Instead of trying to spread our analysis across the entire Puget Sound we instead focused our analysis efforts on one watershed (Map 1). The watershed we chose to analyze was the Nooksack watershed, residing in Washington Resource Inventory Area 1 (WRIA 1), extending east to west between the Cascade Mountain Range and the Puget Sound. Urban, rural and agricultural land uses provide a mix of activities feeding into the stream network. The main waterway in WRIA 1 is the Nooksack River, 75 miles long meandering through the entire watershed and provides drinking water to the City of Bellingham along with other smaller cities in the area (Department of Ecology, 2014).



Map 1 - Sustainable Systems Map - North Puget Sound Watersheds



Map 2 - Urban vs. Agricultural Lands - WRIA 1

Three key factors played a role in the selection of WRIA 1. One factor is because of the limited point source pollution due to a significant agricultural influence and small urban influence. Another factor is a number of dairy farms in the WRIA - and associated grazing - is prevalent in the lower reaches of the watershed. Finally, the number of established monitoring stations present throughout the WRIA made it an attractive option (Map 2).

All of these factors combine to make WRIA 1 a strong candidate to investigate pathogen pollutant sources to the Puget Sound occurring due to agriculture. The Nooksack River lies in a watershed about 100 miles north of Seattle, Washington. While this is remote to the bustling city life, the Nooksack watershed houses one of the most ecologically active regions in the Puget Sound. Shellfish harvesting and salmon fishing are two of the largest recreational and economic activities in the region (Whatcom Conservation District, 2014).

In order to run a model in ArcSWAT there are a minimum of three phases to work through to prepare the model inputs: watershed delineator, HRU analysis, and writing input tables. Each must be completed in order to build the model base.

Watershed Delineation

Watershed delineation is the initial step of the model where the streams within the area of interest are created for the model analysis. Two different approaches to watershed delineation of stream network and sub-basins are available and both were tested. The first method is calculating a stream network based on a 10 meter DEM where the model self-delineates sub-basins and stream networks (USDA , 2014). The other option available is uploading a user defined sub-basins and stream networks into the model. The user defined files can be as complex or as simplified as desired. The more complex the inputs are, the more refined the overall model results will be. The more simplified the inputs are, the coarser the overall model results. The most complex stream basin information was selected from the Washington Department of Ecology (WADOE, 2014) 100k hydrography dataset and the sub-basins were selected from the WADOE water assessment results geodatabase for WRIA 1 (WADOE, 2014).

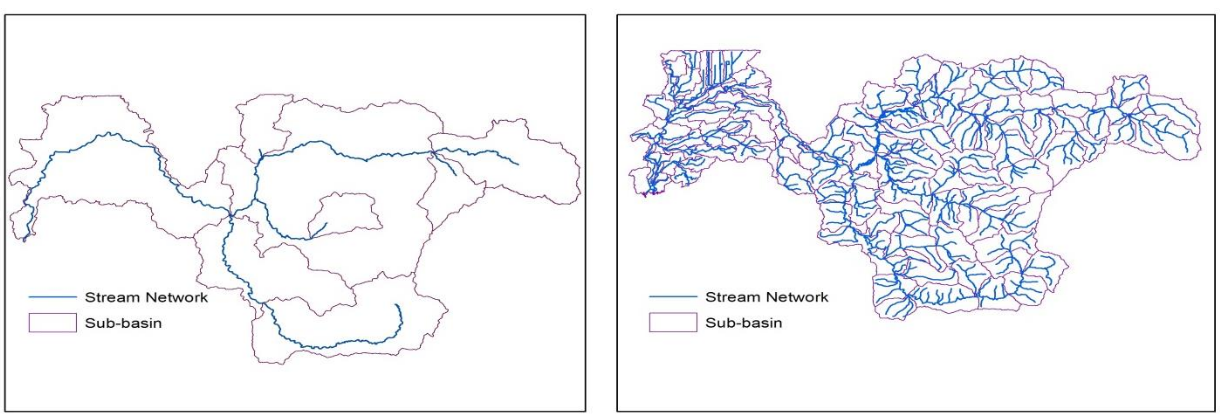


Figure 2 - ArcSWAT delineated and User defined stream networks and sub-basins

The processing time required by the model to self-delineate the watershed is lower in preprocessing (only requires uploading a DEM for the area of interest) and longer in the time for the model to process the stream network and sub-basins. Conversely, the user defined method takes more time initially to create the sub-basins and stream network but decreases processing time (Figure 2). Other decision factors considered for choosing between these two options include level of detail required, processing power of the computer, and size of the watershed of interest.

HRU Analysis

ArcSWAT analyzes surface runoff based on hydrologic resource units (HRUs) which are unique combinations of landuse, soil and slope. The model either assigns one slope to the model or the user can reclassify the DEM into up to five slope classifications. TNC suggested slope classifications of 0-2%, 2-5%, 5-8%, 8-10% and over 10% as much of the agricultural working lands are located on land with less than 8% slope (Jamie Robertson. pers. comm) (Figure 3). Landuse rasters from USDA's Cropscape were uploaded and reclassified using the SWAT landuse definitions (Appendix D). The user can define different landuses, but extensive recoding of data tables is required. STATSGO soil data was used because the other common soil type (SSURGO) had significant gaps in WRIA 1 and throughout the Puget Sound Trough Ecoregion. The STATSGO soil data was downloaded from ArcSWAT's STATSGO database and the STUMID key was used to redefine the soil type and match it to the ArcSWAT database for soil characterization.

Once the three datasets (landuse, soil, and slope) are input and re-classed the model begins to create HRUs. This final step in HRU construction is to determine at what scale the datasets are aggregated. The aggregation used was based on minimum percent coverage of each dataset. To capture all landuses, soils and slope categories a 0% classification for all sliders - meaning all values covering more than 0% of a sub-basin were included - was used for a model run. These inputs created 2106 HRUs for the Nooksack watershed (Map 3).

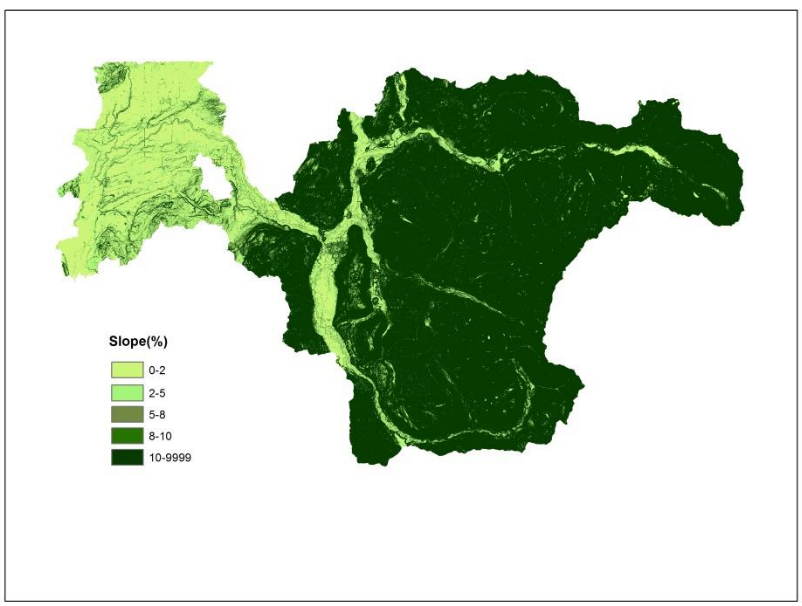


Figure 3 - Slope designations

HRU Definition Detail - Sub-basin 1 - 230 HRUs

Map 3 - Map displaying individual hydrologic resource unit (HRU) assignments for a sub-basin

Writing Input

Weather inputs were selected from the WGEN_US_COOP_1960_2010 because it has the largest number of first and second order monitoring stations, over 18,000 stations and an extensive duration of time monitored. The weather stations provide modeling data for humidity, rainfall, solar radiation, temperature, and wind speed. All categories can be replaced with user provided data as desired.

The default model simulation does not include management actions beyond minimal plant growth simulation for the first year on the landscape. In order to incorporate additional processes edits must be made to management input tables to model agricultural practices. Grazing (from cattle and dairy cows) is prevalent in the Nooksack, covering 8% of the entire watershed, and therefore cattle manure runoff from pasture lands and when it is used for fertilizer on crops has become an area of concern for downstream pollutant loads (Whatcom Conservation District). Bacteria counts for persistent and less persistent bacteria and bacteria partition coefficients are added to the fertilizer database in order to activate the bacteria readings for runoff. Variables were taken from a similar study conducted in Ireland, values used were persistent bacteria at 75,000 cfu/g, less persistent bacteria at 23,000 cfu/g both for cattle manure, and a bacteria partition coefficient of .9 - the coefficient designates likelihood bacteria will be in solution or in soil (Coffey et al. 2010). To test the model calculation of bacteria pollutants grazing operations were set so cattle were on pasture lands 365 days/year and with cows consuming 18 kg of grass and depositing 35 kg of manure. Fertilizer application for crops are usually twice a year (4500 kg/ha Spring and 2200 kg/ha in the Fall) however the model limits the application to 200kg/ha per application. To accommodate this fertilizer application for all crop lands were set to once a month from March to September, for a total 200 kg of manure/ha per application over 6 months.

Model Simulation

ArcSWAT allows the user to define a model simulation time frame starting from 1902 through any point in the future with output intervals of daily, monthly, or yearly. One model simulation run spanned 2002 to 2012 with a three year skipped reporting which allows the model to “warm-up”. The “warm-up” allows the model to “learn” the system before recording scenarios. After the model runs, a summary output table is available to read and display preliminary data. Output tables can be selected for records such as water quality, sediment, flow, reach, sub-basin and management.

Results

Delineating the watershed from a DEM produces major waterways and stream networks (Figure 4). An outlet was chosen at the mouth of the Nooksack River as it empties into Puget Sound to assign the sub-basin for the Nooksack watershed covering 474,835 acres. After the watershed delineation was complete, landuse rasters, soils and slopes were re-classed and layers showing the distribution of these variables are generated and maps can be created (See Figures 5-7).

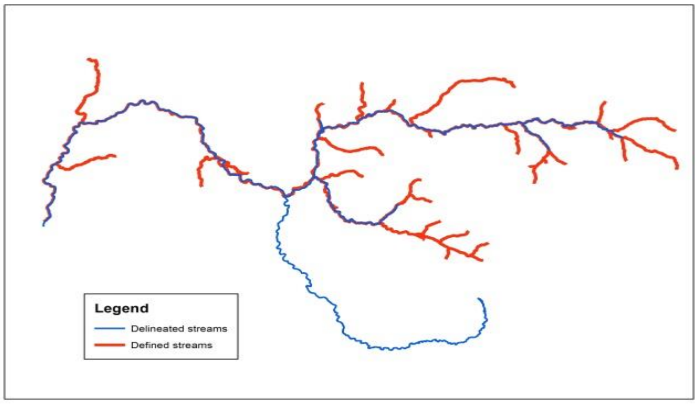


Figure 4 - Stream network delineation

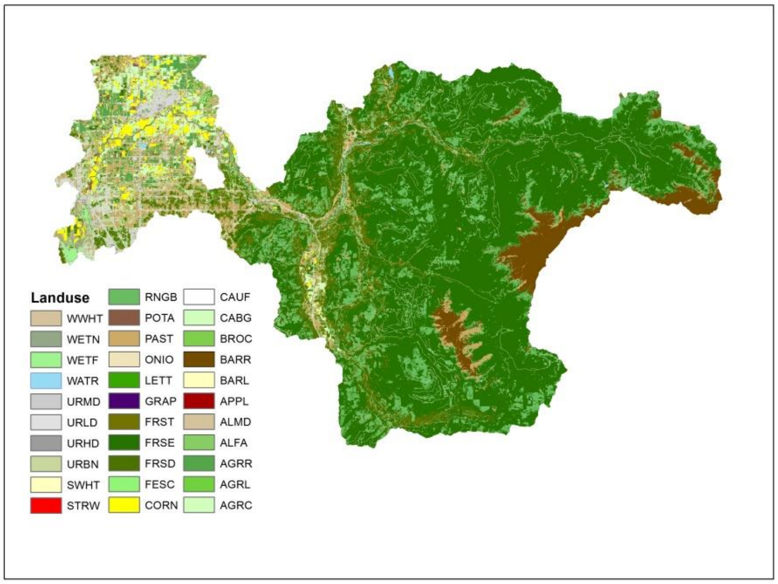


Figure 5 - Landuse Map

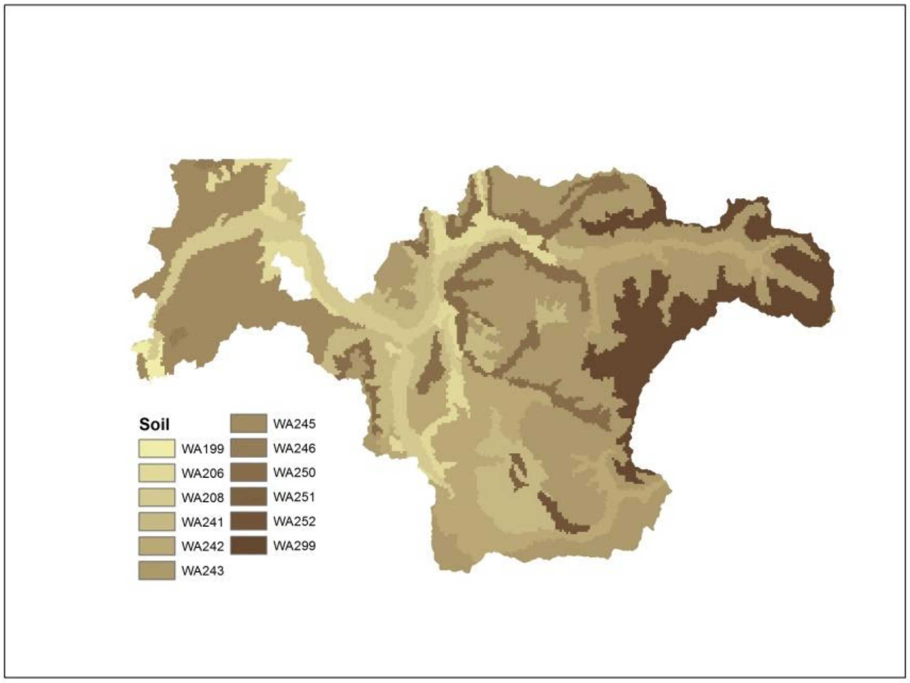


Figure 6 - Soils Map

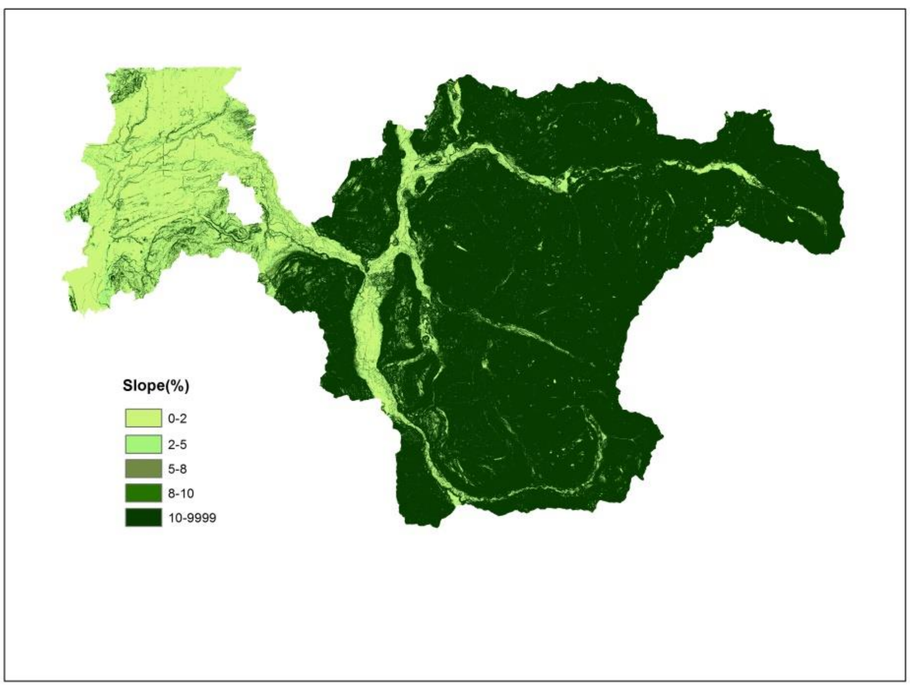


Figure 7 - Slope Map

The model creates a report for the entire watershed and then the sub-basins noting the types of landuses, soils and slope and their respective coverage area. The largest landuse type was forested areas covering almost 300,000 acres. The largest agricultural landuse was corn at 9,143 acres. Pasture land covered 40,026 acres.

From these assignments the model created HRUs based on how each combination of landuse, soil and slope would respond hydrologically. Based on the inputs, one model run created 14,000 separate HRUs for the watershed with areas from hundreds of acres to under an acre (Figure 8).

Based on this model run all the HRUs were selected to be represented, but the user can choose to run the model only using the dominant landuses, soils or slopes if desired. The HRU report contains detailed information about the landuse, soils and slope for each HRU defined in the watershed noting the exact combination modeled and the total area (ha and acres), percentage of the watershed and percentage of the sub-basin.. This model run used the ArcSWAT database information for the required inputs such as weather (global data from 1960-2010) and other database information specific to the ArcSWAT databases.

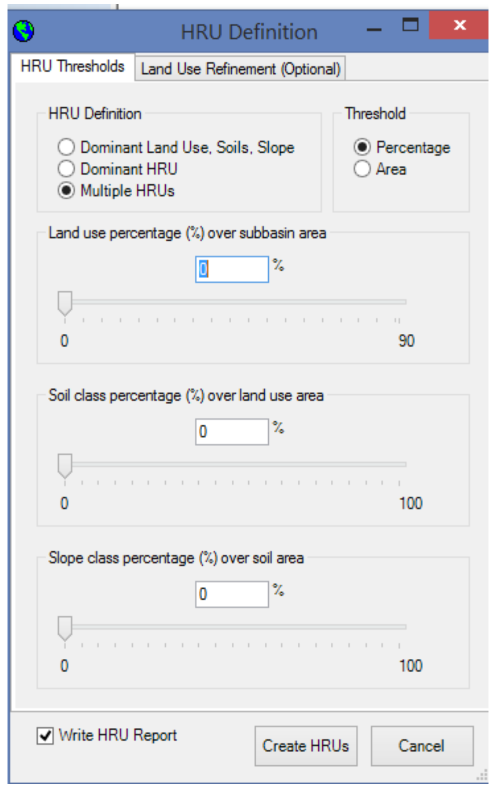
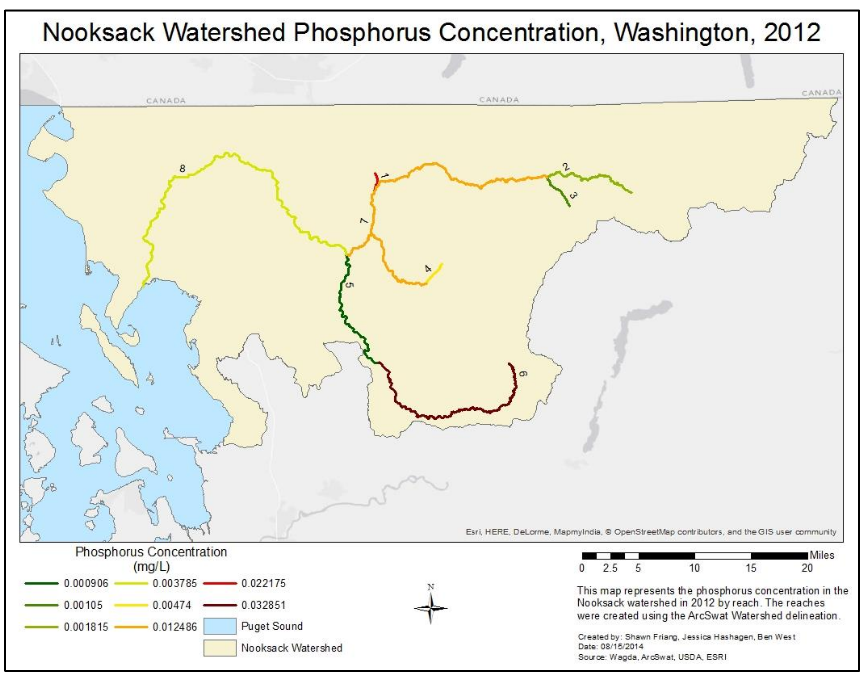
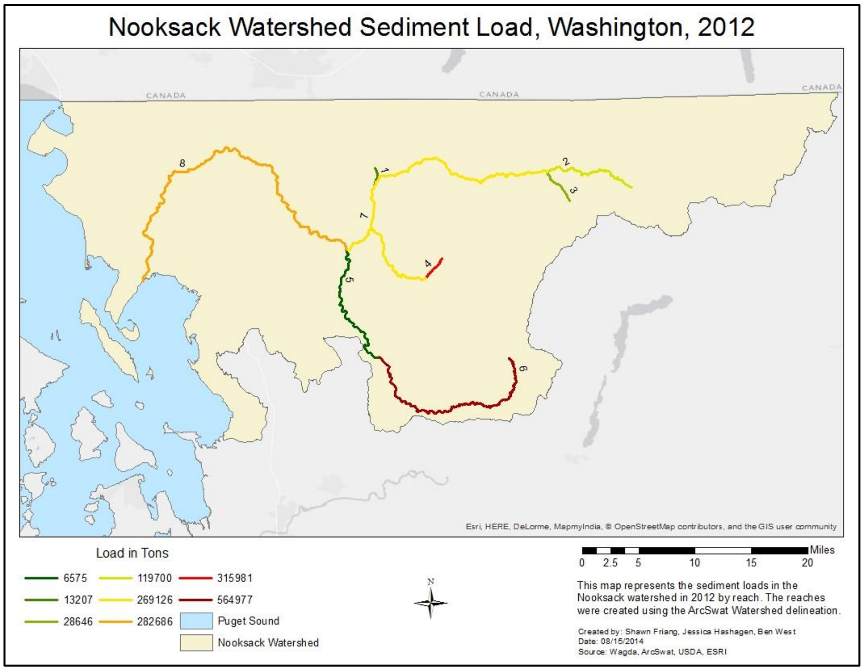


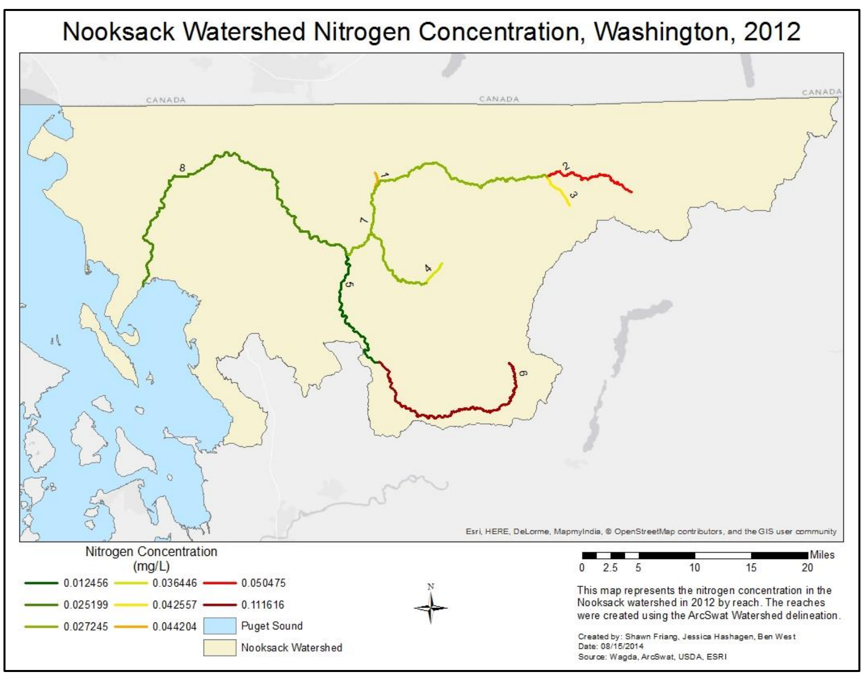
Figure 8 - HRU Definition Model Interface



Map 4 - Nitrogren concentration output by reach



Map 5 - Phosphorus concentration output by reach



Map 6 - Sediment loading output by reach

The model produced monthly summary data for the watershed along with yearly totals. It also produced daily records for all the output tables. While the model produced nitrogen and phosphorus data as well as sediment loads, it did not calculate pesticide or bacteria data with the default inputs (Maps 4-6).

User defined inputs are required to activate the bacteria simulation. Bacteria results from a model run after fertilizer and management inputs reported bacteria levels by HRU and sub-basin. Bacteria reports form the output summary identify average annual changes in persistent and less persistent bacteria in soils in the watershed, transported to the main channel in solution and transported in sediment. HRU output tables include nitrogen, phosphorus and bacteria results by HRU as well as a subset of eighty variables. The management output tables contain results for each crop type and the management practices such as planting, fertilization, harvest and grazing.

Discussion

One of the challenges using the ArcSWAT model is the level of complexity the model is able to accept. The benefit of this is the model is highly tailorable to different systems of interest and specific questions a user is interested in. However, it also present significant problems, in that the model does not easily function as a “plug and play” model - where relatively easy data sets can be input and results are obtained. Instead the ArcSWAT model requires an in depth knowledge of the inputs of interest and the system being studied in order for the user to knowledgeably and accurately modify the tables and other inputs. These modifications include time steps of applications, number of days a pasture is grazed, when crops are harvested, and deposition to name a few. This level of specificity creates complications for application when the system of interest is large, has varying landscapes, and has varying landuses. Perhaps the biggest difficulty is when working with a large system with many landuses, it becomes more difficult to accurately state the processes different land owners are applying to their property.

Due to the flexibility of the model inputs the results can be highly variable. Running the model solely with the baseline data (DEM, landuse raster, soils data, and model supplied weather data) provides a general snapshot of a system of interest, useful for detecting major trends in the system. However, because the model is designed to handle more detailed system descriptions a greater level of detail in the outputs is possible. This means not only is the system described in greater detail but the model will also more accurately predict any scenarios that are applied to the system. By the same token, because there are many variables available to customize there is more room for error in the entry of bad or misapplied data. The result of which would be a mis-representation of the system or scenarios applied to the system. Additional testing not provided by the model is required to perform a sensitivity analysis of the results to confirm they are in fact valid.

After stream network delineation both options use the sub-basin and stream network to calculate stream junctures, outputs, and flow direction. If too complicated a user defined network is input the model has difficulties identifying stream junctures and outputs. However, a sufficiently complicated set of sub-basins and stream networks must be used in order to accurately detect all outputs.

In studying bacteria outputs our group encountered many unanticipated difficulties tackling the complex data sets and level of knowledge required to obtain meaningful results. In order to obtain results from bacteria a number of different steps had to be used. This included specifying which farms were using manure as a fertilizer and how often, as well as identifying which pasture land had cows being grazed on it and the amount of grass intake and manure deposition. Database tables had to be changed to incorporate the decay rates of bacteria as well as identifying a partition coefficient to give the bacteria presence in either soil or solution. However, even all of these steps were not enough to provide significant bacteria readings in the output tables. The final component to achieve results was to define a significantly more detailed sub-basin and stream network on which to run the model. This more accurately represents the system and increases the potential area for interactions between grazing livestock, manure fertilizer applications, and streams. Taking this step is what finally allowed the model to produce measurable amounts of bacteria outputs. Although bacteria outputs were obtained due to time constraints we were not able to take a more analytical look at impacts of what would happen if different BMPs were applied to agricultural lands.

Another impact from the unanticipated difficulties of getting bacteria to be correctly modeled, along with other challenges that made for a steep learning curve with the ArcSWAT model, was there was not sufficient time to implement a systematic testing of BMPs on a system outputting bacteria data.

Simplifying Assumptions

As with all models ArcSWAT is a simplified representation of the real world and in order to work it must make certain assumptions in order to simplify the level of complexity present. A perfect example of a simplification the model must make is the level of complexity allowed by the model in the defined stream network. If too complex a stream network is used, even with flow direction correctly applied, the model has difficulty detecting inlets, outlets, and junctions. Comparing a simplified and complex version of two user defined networks it is possible to see the difficulties the model has (Figure 9). In the more complex network the model cannot even correctly locate the mouth of the river, instead placing the outlet in the middle of the watershed.

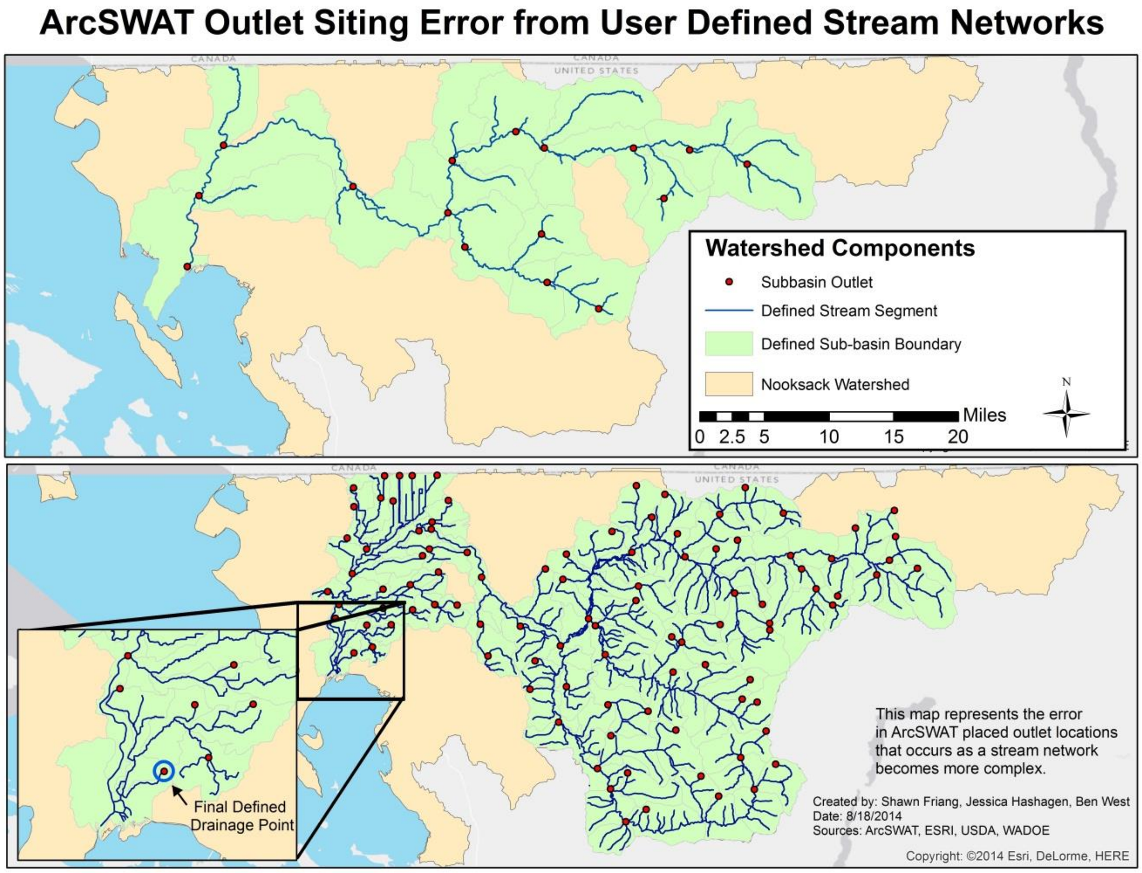


Figure 9 - Model Outlet Comparison – Simple vs. Complex Stream Network

Additional simplifying assumptions include:

- Using the 2012/2013 WSDA LU polygons for ALL years for determining where pasture lands are in Cropscape. It is unclear how accurate this will be, as there does seem to be a significant level of variance from year to year as shown in Table 2.

Table 2 - Pasture land raster complexity comparison

Cell Counts	WSDA Pasture Count in Cropscape by Year
226123	WSDA Pasture - 2013
230002	WSDA Pasture - 2012
92786	WSDA Pasture - 2011
234663	WSDA Pasture - 2010
66951	WSDA Pasture - 2009
64783	WSDA Pasture - 2008
96857	WSDA Pasture - 2007

- Cropscape data changes uses 56x56 cell size for 2007-2009 and 30x30 for 2010-2013. All are now listed in 30x30, but resolution is still lost for the 2007-2009 Cropscape data. Also there were issues with the 2011 data.
- All point source data (probably correctly) must be located on a waterway, the difficulty comes when trying to use sources such as dairy farms which are mostly not directly on waterways.
- Inputs weather tables are accurate
- Does not account for pre-existing conditions in the landscape.

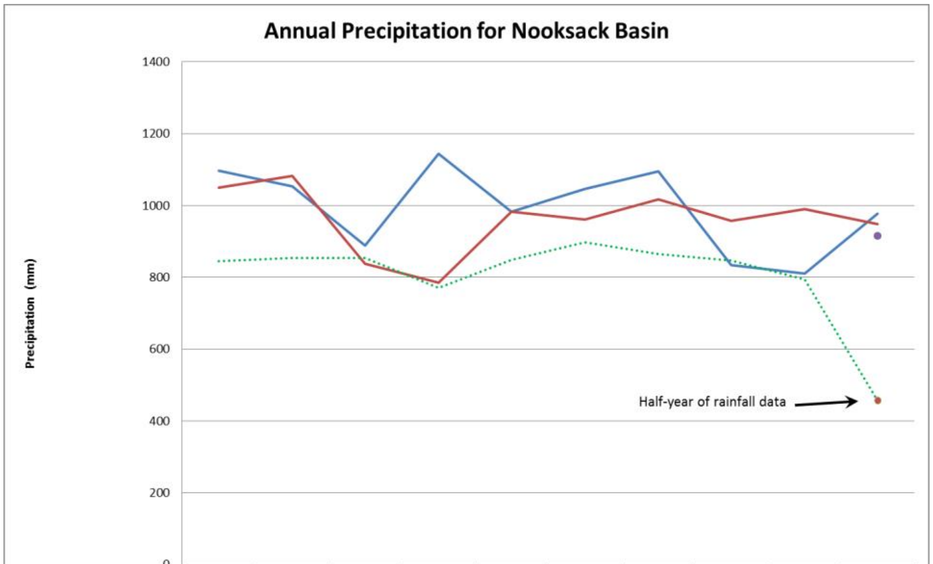
Sensitivity Analysis

In order to provide TNC with adequate information about this model, many tests of the different aspects of the model were performed to determine where the greatest changes in the model outputs would be experienced (Trucano et al, 2006). At each phase of the preparation work - watershed delineation, HRU analysis up through model simulation each option for change was used. All the changes made a difference in the outcomes. This is a positive and negative aspect to this model since one change can impact the results so greatly.

During HRU Definition the user can determine thresholds for landuse, soil and slope representation in HRUs based on percentage or total area of sub-basin. The model documentation suggests using thresholds 10% for landuse, 10% for soils and 20% for slope. The results from applying these thresholds are that the total number of landuse classes were diminished by half and resulted in the loss of most of the agricultural landuses.

Slope changes were made from original slope classification 0-5%, 5-10%, 10-15%, 15-30%, 30-9999% to 0-2%, 2-5%, 5-8%, 8-10%,10-9999% because the Nooksack Watershed is so different from east to west in slope elevation and most agriculture does not take place on land with slopes over about 5%.

Temporal analysis was another concern for a sensitivity analysis. Ten years was chosen for a study period, with one model running a 5 year "skip period" in order to allow the model to come up to speed in simulation. Both methods were attempted and the differences in readings are shown in the following graph (Figure 10)



	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
No Skip	1097.32	1052.59	887.46	1144.32	982.61	1046.49	1094.79	834.72	811.11	977.31
5 yr Skip	1049.17	1082.96	837.94	785.76	982.43	960.51	1017.51	957.48	990.48	948
Actual Precipitation	845.1	853.3	853.3	770.6	847.9	898	864.8	847.1	795	457.4
Full Year										914.8

Figure 10 - Precipitation comparison with and without "skip period" vs. actual precipitation records

Another analysis that was conducted was to run the model on smaller branch of the watershed where the only part of the set-up that was varied was the year landuse represented (a five year “skip period” was used, the base values for weather was utilized, and HRU demarcation was set at 1% for landuse, 10% for slope, and 10% for soil). The outputs were then compared with monitoring station data for the same watershed sub-branch to provide a basic assessment on the accuracy of the model vs. real world results. The value selected for this was sediment because it is a value present in both sets of data, has a continuous monitoring record, and is measured in the same units (mg/L) in the model and the monitoring station. When compiling the sediment data in ArcSWAT there was one primary problem, it’s unclear what the ArcSWAT data represents. If the values in the sub-basin where the monitoring station represent only the values for that sub-basin or if it also incorporates the values for all upstream sub-basins as well. In response two comparisons were made, one comparing only the outputs of the sub-basin the monitoring station is located at the mouth of and one comparing the sum of sediment from all upstream sub-basins from the monitoring station.

The results comparing the monitoring station with the one sub-basin containing the monitoring station (Figure 11) shows that the minimum, maximum of the all the model runs are fairly consistent and those values are consistent with the baseline sediment values of the monitoring station data.

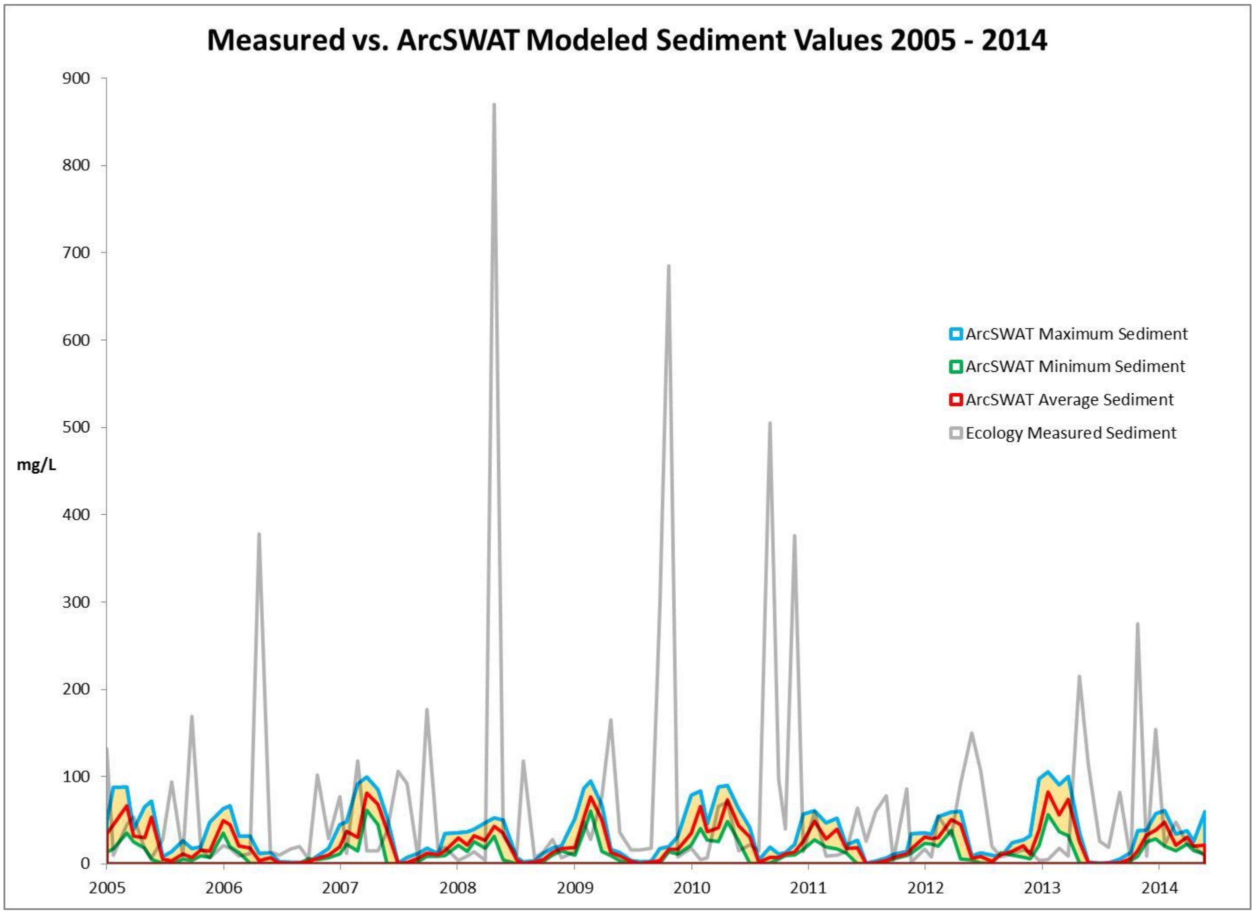


Figure 11 - Sediment output compared to actual records

However, the monitoring station data shows several months with abnormally large amounts of sediment. When this occurs in the spring it is most likely capturing a large or sudden snow melt, but it is less certain what causes the events in the fall. Looking at the rainfall data in Figure 11, there is no clear large rain events that might have triggered abnormally large sediment events. Either way both snow melt and rainfall are both events the model would not account for with the base data provided.

In contrast looking at the chart comparing the sum of all upstream sub-basin sediment and the monitoring station (Figure 12) is very different. Instead of matching the baseflow normal baseflow, the data for all upstream sub-basins more closely matches the extreme events.

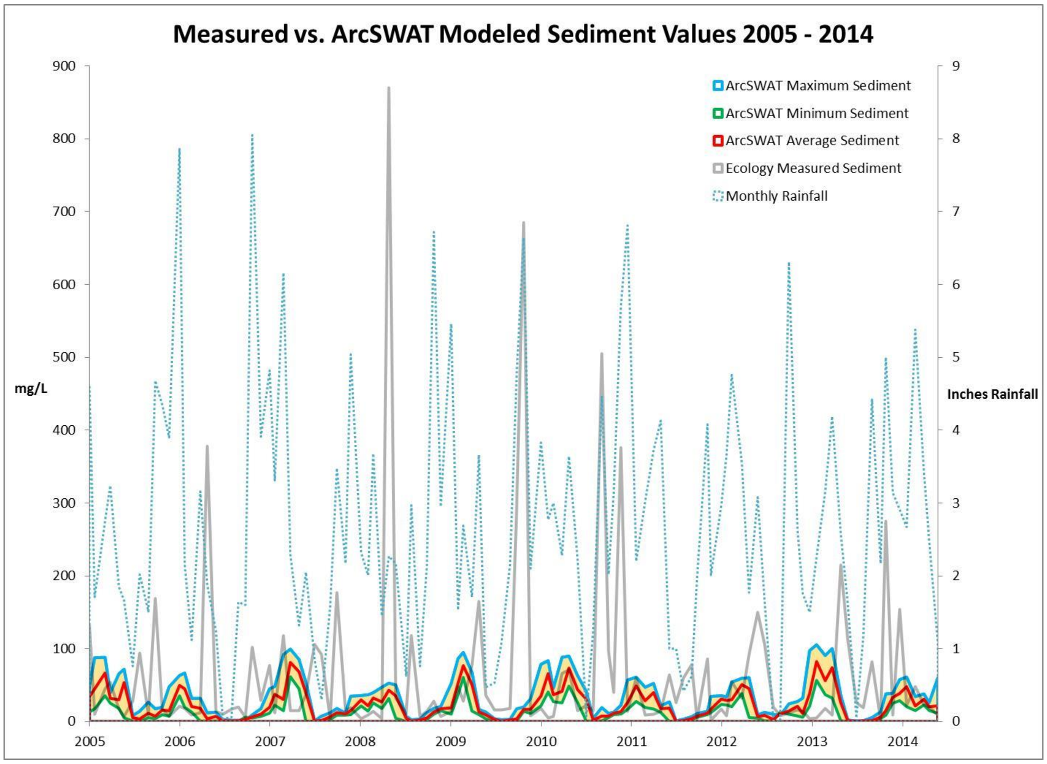


Figure 12 - Sediment comparison with actual rainfall records

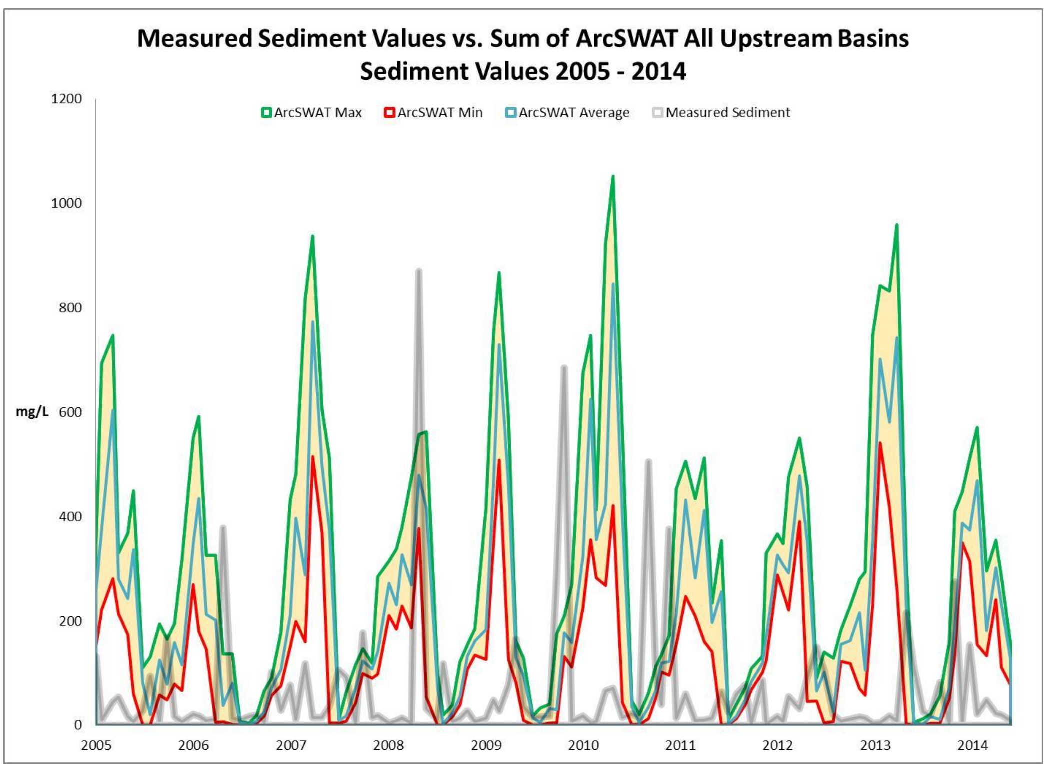


Figure 13 - Combined sub-basin sediment values vs actual records

Business Case and Future Implementation

Business Case

Assisting the Nature Conservancy with the model decision and implementation process, will help the organization put together the scope of a larger project beginning in 2015. With the development of a scope of work, TNC and partners will seek to implement a plan for a Sound-wide analysis, better understanding of BMPs to model, and test these assumptions with on-the-ground projects. For the scope of work The Nature Conservancy needs to determine how much work and where the work needs to be done in a three year period. By doing this project, some of the methods were developed for potential analyses for pathogens and eutrophication which may be able to lead the way for further analyses including temperature and dissolved oxygen. Also, the amount of work that may be needed for the project can be estimated base on the amount of hours the project team has dedicated to the model decision and analysis process.

The financial piece will come later in the project and will be built into the scope of work. The financial burdens that The Nature Conservancy may encounter would be the amount of man hours needed for data processing, field data collection such as monitoring and BMP testing and how they relate to water quality, determining what the BMP's are and where they need to be implemented on the landscape.

This project provides The Nature Conservancy with an overview of five models and how they may or may not be relevant to the criteria they are looking for. One model was determined as the most relevant, ArcSWAT, and this was due to it covering the organizations interests plus much more, including climate change. It also seemed the simplest model with only three basic input layers and three tables. This model offers many opportunities for future implementation. Currently, the model provides information about Nitrogen, Phosphorus, Sedimentation, to name a few. Not only can the model provide outputs of pathogens for non-point sources, point sources can be added to the model run to be included in the outputs. In addition, the model has been running on simulated weather data, all of the weather inputs can be added from local stations which may calculate more accurate readings for sedimentation and evapotranspiration. This model also has the potential of modeling climate change scenarios.

Future Implementation

There are several areas of study that either TNC has expressed interest in for future or that were ideal parts of the future implementation.

Climate Change

The weather input database for ArcSWAT allows for user inputs detailed to include rainfall, temperature, relative humidity, solar radiation, and wind speed, providing an option to apply climate change data to the model once the base inputs are established. Model simulations using climate data could allow for analysis to investigate changes in the levels of the various weather data such as higher wind speeds vs lower wind speeds to play out scenarios just within the climate data and how they could impact water flows downstream and pollutants and sediment. Also various crops and management practices could be modeled using the climate data to establish combinations that could improve water quality and aid in planning for changes that may need to take place in agriculture in light of climate changes.

Best Management Practices

Another key component we did not address was the impacts BMPs have on total outputs. It was unfortunate this aspect of the model was not addressed as the vast majority of our time was spent on learning the in and outs of getting ArcSWAT to output the desired bacteria data. While due to time constraints we did not address BMPs, the model does have a number of preloaded management practices that can be applied. The BMPs are applied by editing the input tables of a specific HRU type (selected by prefered dominant Soil, Slope, and Landuse) within a specific sub-basin. Two of the HRU tables that can edited to include BMPs are ponds and operations. These allow basic BMPs to be applied such as different types of impoundment ponds, residue management, terracing, filter strips, and contouring. Once an HRU has been selected different management techniques can be applied by editing operations. ArcSWAT also contains an additional modeling program called Agricultural Policy Environmental eXtender (APEX) that details the modeling specifications for a host of best management practices (Waidler et al., 2009).

Data Collection

In order to be able to best implement an accurate version of the model, as well as accurately implement and test BMPs in the model, it is recommended that additional data collection be undertaken. Having a greater understanding of ArcSWAT has made it clear that while it is the correct model, ideally additional data should be collected. In terms of the bacteria produced by grazing and application of manure on other agricultural lands this means data about how often livestock is grazed over the course of a year and how often manure is applied as fertilizer to crops.

ArcSWAT Future Implementation

The Nature Conservancy works with various community groups and stakeholder groups (Appendix E) to address conservation issues within the Puget Sound (Jamie Robertson, pers comm). By using ArcSWAT to inform the steps of the collaborative work between groups, the model could be used as a tool to address specific concerns about non-point source pollution from agricultural lands (Appendix F). The Nature Conservancy can utilize ArcSWAT to inform areas of need to create documents to share with local community groups and stakeholders such as the Conservation Districts and the agricultural landowners and serve as starting point to obtain current management practices for the model. Farms using BMPs can be identified and assessed for impacts to pollution loads and areas of concern for possible BMP implementation can be identified. Scenario documentation and model outputs can be shared with stakeholder groups to determine where and what type of BMPs could be implemented. Further steps include taking stakeholder suggestions for BMP types and BMP implementation practices and entered into the model. This process can be further improved by identifying existing or potential monitoring sites that could record impacts from current management practices and new BMP implementation alike. Documentation for proposed sites could be brought back to stakeholder groups for discussion and a possible monitoring program plan could be drawn up. Using ArcSWAT for the modeling of scenarios at each stage of this process feedback to stakeholder groups can be given in weeks instead of months. ArcSWAT also provides outputs to produce maps, charts, and graphics to illustrate the complex systems being addressed so that all parties impacted by these decisions can “see” the possibilities and hopefully make more informed decisions about the future of the agricultural lands in the Nooksack watershed.

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Appendices

Appendix A – Model Comparison Table

MODEL	InVEST - Water Yield	InVest - Nutrient Retention	InVest - Sediment Retention	InVest - Marine Water Quality	InVest - Overlap Analysis**	OpenNSPECT - Runoff Estimation	OpenNSPECT - Pollutant Concentration	OpenNSPECT - Sediment Concentration	OpenNSPECT - Assessment and Reporting	SPARROW	ArcSWAT	SUSTAIN
Description	Insights on how changes in LULC affect annual surface water yield and Hydropower production	Calculates the amount of nutrients retained in each pixel and sums the averages nutrient and export in the sub-watershed	Calculates the avg annual soild loss from each parcel of land in order to determine how much soil may arrive at a particular point of interest. Can also be used to value the landscape maintaining water quality or avoiding reservoir sedimentation.	Calculates the concentration of water quality in response to management decisions	Identify important areas of interest.	Estimates runoff depth and volume	Estimates pollutant loads and concentrations	Estimates sediment loads and concentrations	Assesses the relative impacts of land use changes with scenario analysis	Data needs are for each stream reach in the study area.		System for Urban Stormwater Treatment and Analysis IntegratioN Model
Data Needs												
DEM		X	X			X	X			X	X	X
Land Cover Grid	X	X	X			X	X			X	X	X (NLCD Land Use)

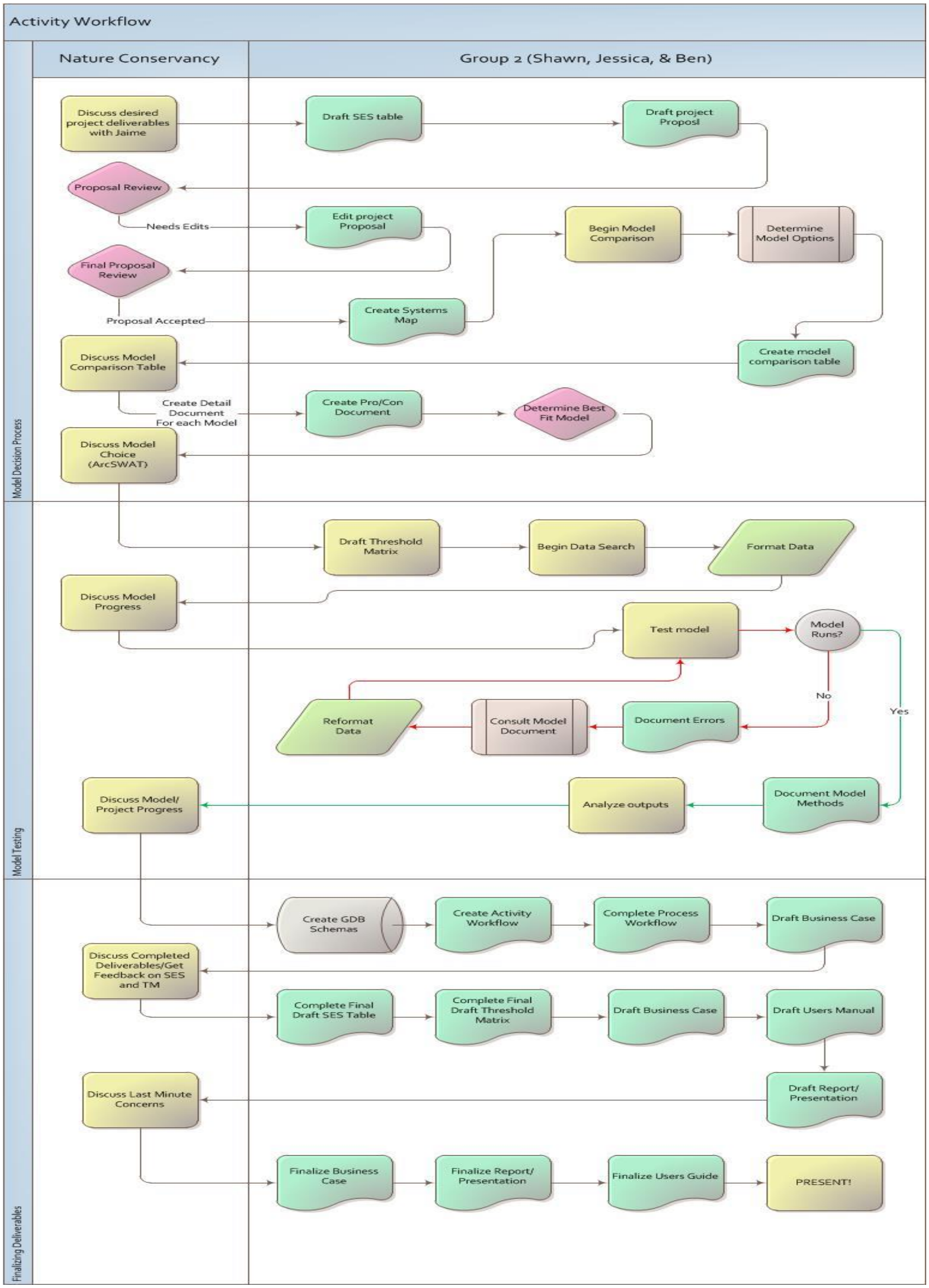
Rainfall Grid/Annual Precipitation	X	X				X	X					
Event Precipitation						X					Precipitation in txt (ASCII) format	
Runoff Curve Numbers						X						
Soils Shapefile						X						X
Rasterized SSURGO Soils Data							X				X	
R-Factor Grid								X (RUSLE)				
Local Pollutant Coefficients										X		
Water Quality Standards										X		
Watershed Shapefle	X	X	X	X	X						X	X (Stream)
Subwatershed	X	X									X	
Biophysical Table	X	X	X									
Percent Imperiousness												X
Urban Land Use												X
Road												X
Ground Water Table Depth												X
Unique Data Requirements List in Cells	Root Restricting Layer Depth	Root Restricting Layer Depth	Rainfall Erosivity Index	Source Point Loading Table	Analysis Data Directory - Point Line or polygon data	Rainfall data is available from: lwf.ncdc.noaa.gov/oa/climate/stationlocator.html, state climate offices: www.ncdc.noaa.gov/oa/climate/stateclimatologists.html	For overlapping datasets with Runoff Estimation the same preprocessing steps apply.	R-factor maps are available from www.nrdc.usda.goc/technical/efotg/ Technical guide (pg. 47) has specific instructions for the additional processing that must be done to the R-Factor maps.	Pollutant grids		Point Discharge Loading - dBASE table	
____________________ __	Plant Available Water Content	Plant Available Water Content	Soil Erodibility	Source point Centroids		Developed using 10-meter DEM re-sampled to a 30-meter grid (possible to use higher resolution		Additional datasets are required if there is a desire to	Sediment/erosion grids	Reach topology - upstrea		

						DEMs)		calculate event-driven sediment yields.		m & downstream nodes, unique reach ID		
__________ __________ __	Average Evapotranspiration	Average Evapotranspiration	Sediment Threshold Table	Grid Cell Depth		Designed to run on Coastal change analysis program (C-CAP) data sets.			Runoff grids	Reach attributes - mean flow, incremental drainage area, total drainage area, nutrient/pathogen source.		
__________ __________ __	Seasonality Factor	Threshold flow accumulation Value	Threshold flow accumulation Value	Decay Coefficient		All input datasets must be in the same projection and grid cells of DEM and land cover data sets must match.			Water quality standards	Contaminant flux - mean annual flux for reach monitoring station, monitoring station lat and long		
__________ __________ __	Demand Table		Sediment Valuation Table	Dispersion Coefficients		Soils data requires extra processing outlined in technical guide.			Analysis unit polygons			
Model Outputs	mean/actual precipitation per pixel (sub) watershed	Mean Runoff index per watershed	Total potential soil loss per pixel in original lond cover	Raster indicating water quality state of pollutant, concentration is the number of organisms/volume	Frequency Raster - number of occurances in a cell	Runoff Volume - In Liters	Accumulated Pollutant (kg)	Accumulated sediment (kg)	Accumulated runoff volume grid (L)	Statistical analysis of results for predicted to residual flux	Too many to list, Many relavant outputs	
	mean/actual evapotranspiration per pixel (sub) watersh	Total Phosphorus/Nitrogen retained by landscap	Total Sediment retained due to direct		Importance score. used if weights are	Runoff depth	Pollutant Concentration (mg/L)	Sediment Concentration (kg/L)	Accumulated pollutant grid(s) (kg)	Reach flux results - upstream yield, incremental		

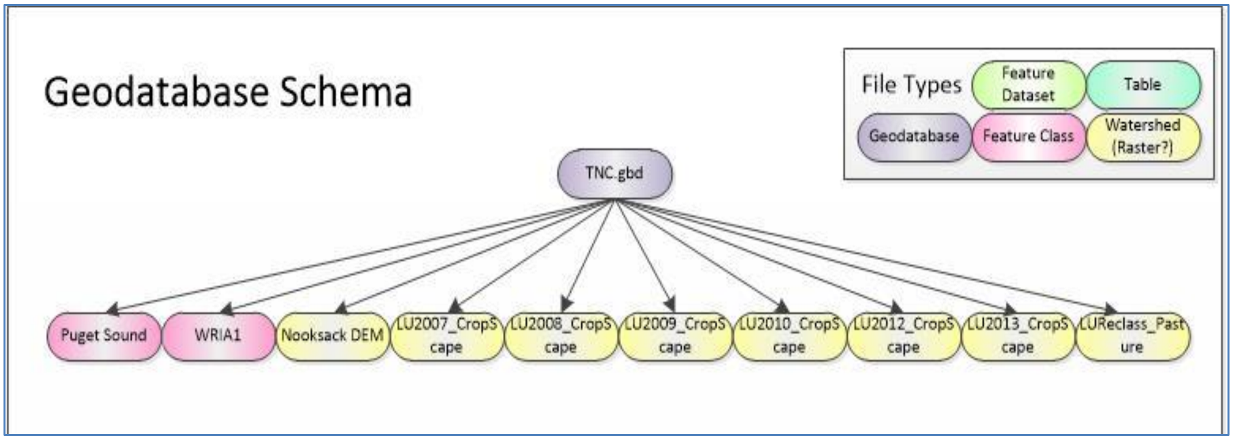
	ed	e	effect of landcover		applied to inputs					yield, flow weighted concentration, reach flux share delivered, source share		
	Mean water yield per pixel (sub) watershed	Total amount of nutrient exported into the stream	Total sediment on the landscape due to sediment filtration through landcover. Effectivly downstream filtered value			Runoff curve number	Comparison to Pollutant Stand (exceeds stand or below standard)		Pollutant concentration grid(s) (mg/L)	Statistical summary of yield by land use		
	Volume of water yield in (sub) watershed	Pixel level map indicating how much load reaches the stream	Total amount of sediment exported from each pixel that reaches the stream						Pollutant assessment grid(s) (exceeds standard or below standard)			
									Accumulated sediment grid (kg)			
			Table of biophysical values for the watershed						Sediment concentration grid (kg/L)			
Model Relavancy to project	Does not measure any contaminants	Only evaluates nitrogen and phosphorus	Does not measure contaminant	Seems like model will allow for the input	This model could allow for makin		The pollutant concentration grids			Addresses pollutant loading for		

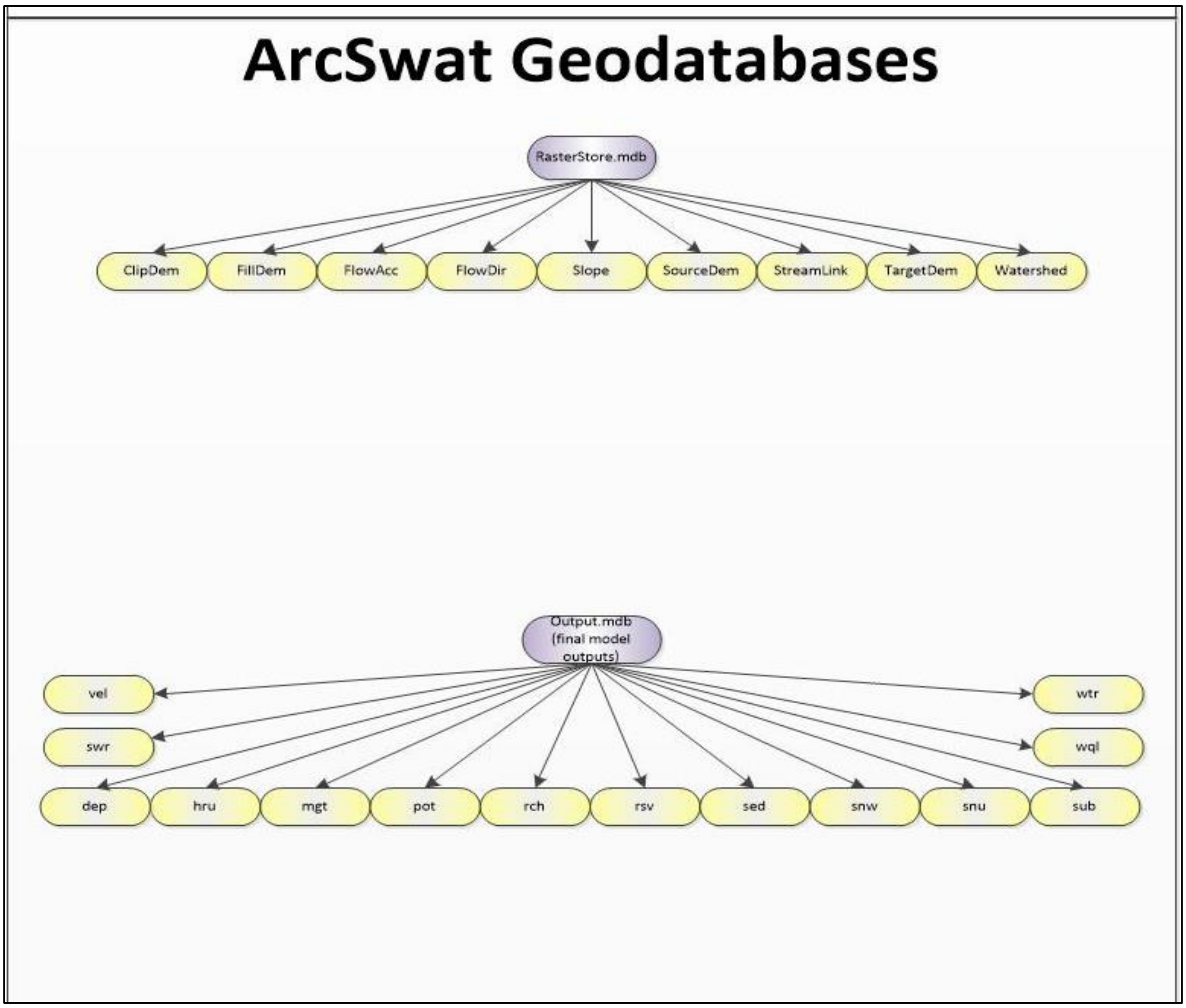
			s but could probably be used or overlaid with a raster/feature class containing contaminant values and a alulation could be performed to determine if sedimentation is exacerbating the issue.	of various pollutants for analysis.	g results of many models in a result with meaning. The relevancy of this model will depend on which model are chosen and the data and outputs used/created		are used as inputs to the water quality assessment and reporting compnent.			surface and stream network. Has been used to study pollutant loading to the watershed level.Provides uncertainty levels of pollutant predictions.		
	Could possibly be relavant to compare with locations of the river that are contaminated with the water yield of pixel in an area of a agricultural location	Model is probably not useful for our purposes since it does not evaluate bacteria	Model could be useful for project purpose	Model sounds as though it is relavant to the project, could be interesting to see if it can be applied to rivers.	Possible relevancy							

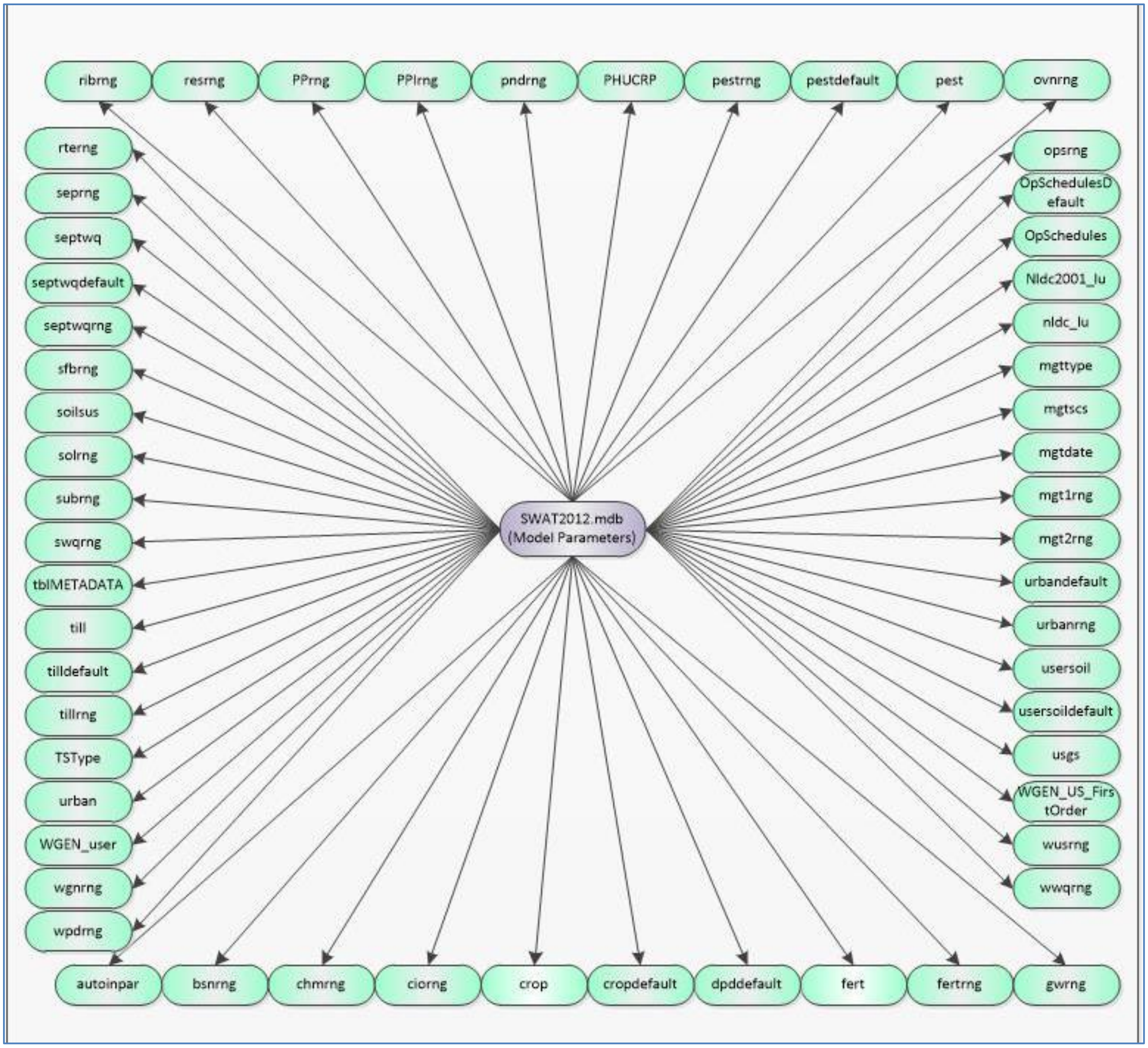
Appendix B – Activity Diagram



Appendix C – Geodatabase Schema



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septwqdefault
septwqrng
sfbrng
soilsus
solrng
subrng
swqrng
tblMETADATA
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tilldefault
tillrng
TSType
urban
WGEN_user
wgnrng
wpdrng
opsrng
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mgttype
mgtscs
mgtdate
mgt1rng
mgt2rng
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urbanrng
usersoil
usersoildefault
usgs
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wusrng
wwqrng
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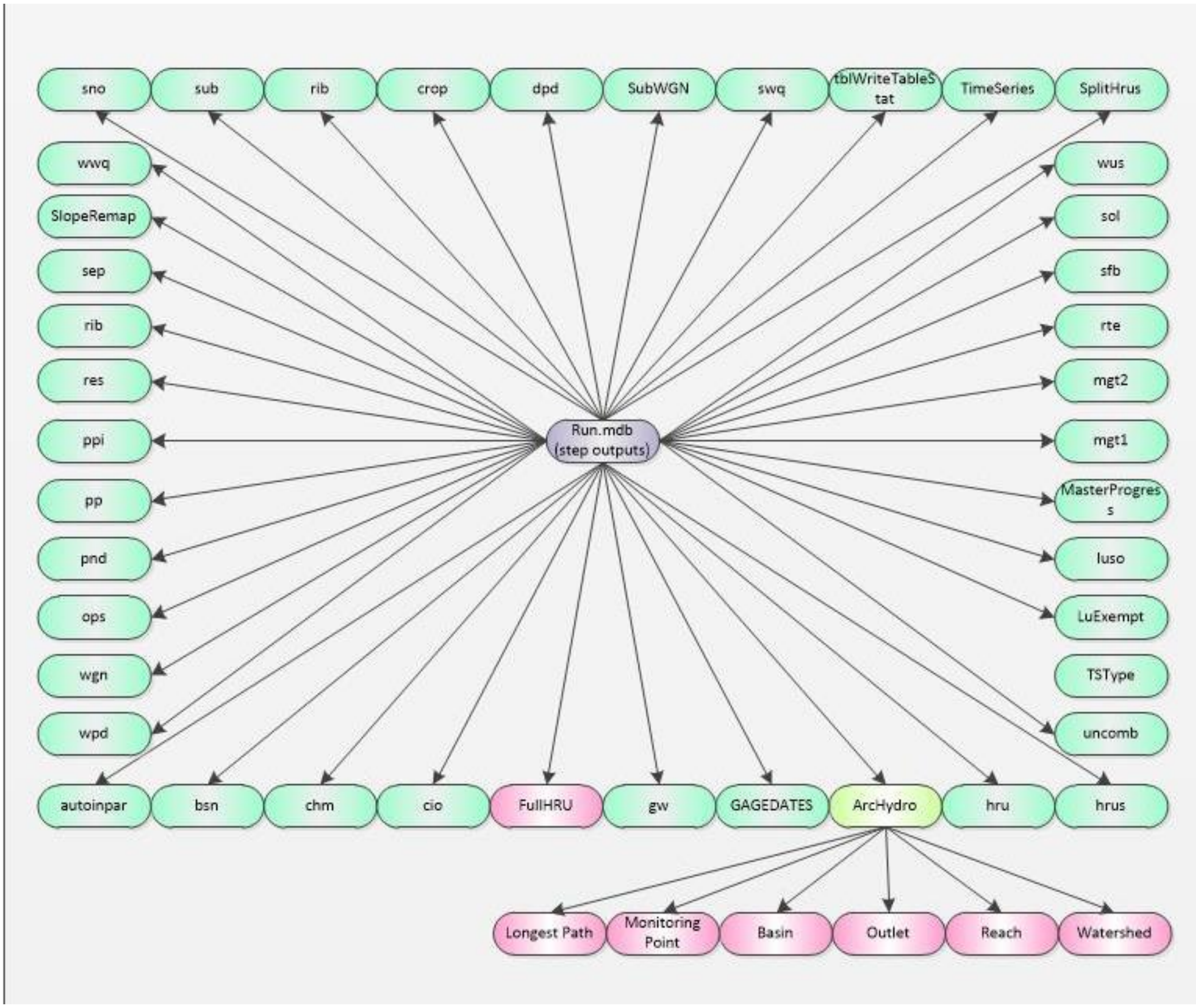
gwrng



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TimeSeries
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wwq
SlopeRemap
sep
rib
res
ppi
pp
pnd
ops
wgn
wpd
wus
sol
sfb
rte
mgt2
mgt1
MasterProgress
luso
LuExempt
TSType
uncomb
Run.mdb (step outputs)
autoinpar
bsn
chm
cio
FullHRU
gw
GAGEDATES
ArcHydro
hru
hrus
Longest Path
Monitoring Point
Basin
Outlet
Reach
Watershed

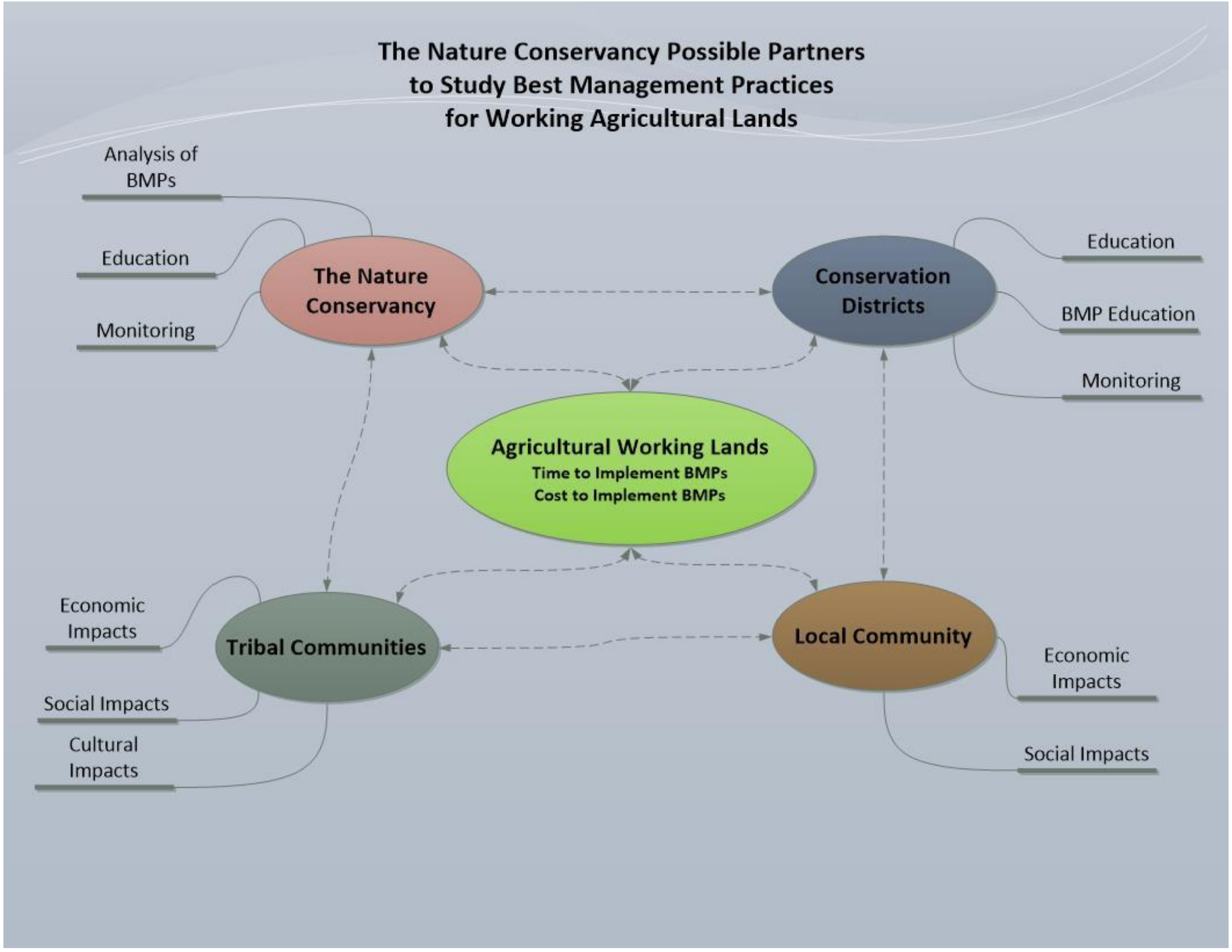
Appendix D – Landuse Classification

VALUE	Final Selected ArcSWAT Value
1	CORN
4	GRSG
5	SOYB
6	SUNF
10	PNUT
12	SCRN
14	AGRC
21	BARL
22	DWHT
23	SWHT
24	WWHT
25	BARL
27	RYE
28	OATS
30	OATS
31	CANP
32	FLAX
33	AGRC
34	AGRC
35	AGRC
36	ALFA
37	AGRC
38	AGRC
39	AGRC
41	SGBT
42	LENT
43	POTA
44	AGRL
46	SPOT
47	AGRL
48	WMEL
49	ONIO
50	CUCM
51	MUNG
52	LENT

53	PEAS
54	TOMA
55	AGRR
56	GRAP
57	CLVA
58	CLVS
59	FESC
60	SWCH
61	BARR
63	FRST
66	ORCD
67	ORCD
68	APPL
69	GRAP
70	FRSE
71	FRST
76	ALMD
77	ORCD
87	WETL
92	WATR
111	WATR
112	BARR
121	URBN
122	URLD
123	URMD
124	URHD
131	BARR
141	FRSD
142	FRSE
143	FRST
152	RNGB
176	PAST
190	WETF
195	WETN
205	SWHT
206	CRRT
207	ASPR
208	ONIO

214	BROC
216	PEPP
218	ORCD
219	LETT
220	ORCD
221	STRW
222	AGRC
223	ORCD
224	FPEA
225	WWHT
226	OATS
227	LETT
229	AGRC
237	WBAR
242	AGRR
243	CABG
244	CAUF
246	RADI
247	RADI
249	AGRC
250	WETN
530	PAST

Appendix E – TNC Potential Partners



Appendix F – ArcSWAT Future Implementation