A USER GUIDE FOR MODELING WATERSHED-SCALE IMPACTS OF ONSITE WASTEWATER SYSTEMS: CASE STUDIES OF IMPACTS OF ONSITE SYSTEMS IN TURKEY CREEK WATERSHED, COLORADO

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Abstract

The primary objective of this research project is to develop a user-friendly Guidance Document for the selection and application of watershed modeling tools for simulating impacts of onsite-wastewater (OWS) pollutants at the watershed scale. Model selection was done based on review of potential of each model for assessing current wastewater management problems / scenarios, particularly the relative contribution of sources including onsite wastewater systems (OWS). Model capabilities were assessed through literature review with focus on relevance to OWS. Watershed Analysis and Risk Management Framework (WARMF) is adapted to simulate OWS loading directly to the subsurface and is best suited to simulate OWS pollutants. A case study is included for Turkey Creek watershed, in Colorado. This watershed is impacted from decentralized wastewater treatment systems. The model was calibrated for hydrology, phosphorus and nitrate concentrations. We implemented the software program UCODE for model-sensitivity analysis and parameter estimation based on daily stream flow measurements. The work on hydrology, phosphorus and nitrate modeling was aimed at determining which parameters used in WARMF are critical for calibration and identify parameters that can be determined by calibration, estimating optimal parameter values, identifying conditions such as loading rate and soil properties under which stream concentrations could be most sensitive to septic system effluent discharge rate through sensitivity analysis. Sensitivity analysis using an auto calibration tool called UCODE indicated that simulated stream flow is most sensitive to seven of the twenty parameters evaluated. These seven parameters are hydraulic conductivity, field capacity, total porosity, precipitation weighting factor, evaporation magnitude, evaporation skewness and snow melting rates for forested areas. Phosphorus concentration was found to be highly sensitive to initial P concentration in the soil, soil adsorption and sediment detachment and transport parameters. Unlike phosphorous, nitrate concentration was not sensitive to sediment transport parameters, however, there was a significant increase in stream nitrate concentration as a result of increased loading from increased population and increased effluent ammonium concentration. The effect of septic tank effluent nitrate concentration increased with increasing nitrification. Other factors such as cation exchange capacity, initial base saturation and leaf composition were also relevant.

Introduction

In many non-agricultural watersheds with residential development where water quality is currently impaired, decentralized wastewater systems are perceived as the primary contributor. However, there is rarely monitoring results or other direct evidence of contamination. As a result, decisions regarding wastewater infrastructure are often made based upon an absence of information regarding the relative contribution of decentralized systems, as compared to other sources of pollutants. Modeling tools that range from screening level GIS assessment models to comprehensive multimedia flow and transport models have recently become available. Watershed-scale models can be useful tools for assessing the impacts of onsite wastewater systems (OWS). Because the hydrology and chemical transport processes at the watershed scale are so complex, generally numerical models are necessary to provide a rigorous assessment of OWS impacts. Thus, a User Guide is essential to provide guidance on data requirements, simulation and calibration mechanics, and output capabilities of selected models.

Selection of the appropriate model depends on the intended use of the model and the desired output. The ideal model for quantitative watershed-scale assessments involving OWS should be able to handle all the hydrologic and transport processes. This includes precipitation, snowmelt, evapotranspiration, infiltration and runoff, stream flow, ground-water flow, and subsurface transport, including advection, dispersion, and possibly reactions. Given that the vast majority of OWS include soil treatment of effluent, to represent OWS accurately, a model must allow for a subsurface dispersal of liquid effluent with a specified chemical composition.

It is critical that a model include the relevant chemical reactions in soil, ground water and surface water. For nitrogen, this includes the transformation of nitrogen once it enters the soil (nitrification from ammonium to nitrate, and denitrification of nitrate to gaseous nitrogen). Sorption of ammonium ion to soils also may be important. For phosphorus, the most important reactions are sorption to soils (i.e., to metal oxides) and precipitation to a typically immobile solid phase. Both pollutants may also be taken up by plants if the rooting depth is sufficient but may be released later on decomposition if not harvested. Organic contaminants, including pharmaceuticals, will undergo biochemical degradation, sorption to soils, and perhaps other loss mechanisms. Metals will undergo sorption and precipitation to a solid phase. Viruses may sorb to soil or air-water interfaces, deactivate, be killed through predation by other microbes, and be filtered or strained by the soil. The common reactions for all pollutants are sorption, decay or degradation to another chemical species, and irreversible removal from the aqueous phase (e.g., chemical precipitation for P, straining for virus, etc). These reactions can be very complex, and can include nonequilibrium reactions, non-linear reactions, irreversible reactions other-than-first-order reactions (e.g., denitrification is sometimes reported as a half-order reaction). However, practically speaking, models designed for application at the watershed scale cannot simulate this level of chemical complexity, nor is it feasible to obtain all model input parameters required to simulate such complex processes at the watershed scale. It is therefore minimally sufficient to consider the following: linear first-order reversible sorption; and first-order degradation including treating chemical precipitation, irreversible sorption, or other losses as a first-order loss term.

In addition, because it is usually important to assess the impacts of OWS compared to other pollutant sources, a model recommended for general use should also be able to account for the hydrologic and chemical processes of the most likely non-OWS sources. At a minimum, these include: processes related to agricultural activity, sediment and chemical runoff due to erosion from urbanization or mining, and point source loading to streams (from industrial sources, or upstream wastewater treatment plant loading). Atmospheric deposition (of N, for example) might be an important process to consider in some settings.

Model selection will always be linked closely to the question at hand including the decision(s) being made and the importance of making correct decisions. Selection of models that can be applied to Onsite Wastewater Systems (OWS) requires evaluation of key features of the models and ability to handle non-point source pollution from OWS. Emphasis has to be given to models that can simulate the most common wastewater pollutants, especially nitrogen and phosphates both at a field and watershed scale. Sediment transport should also be considered since transport and fate of sediments and nutrients are intimately related. The models included in the initial review include AGNPS, ANNAGNPS, ANSWERS-2000, CREAMS-WT, GLEAMS, HSPF, MIKE-SHE, SWAT, MODFLOW, SWMM, WARMF, WMS and GIS Screening Models. In general, models such AGNPS, ANSWERS-2000, ANNAGNPS, CREAMS-Wt, GLEAMS, SWAT and HSPF have similar routines for nutrient transformation. Nitrogen, phosphorus, and pesticides in these models are based on routines developed for the CREAMS/GLEAMS models including biochemical processes and groundwater loading. However none of theses models explicitly account for OWS. AGNPS and ANSWERS-2000 are primarily surface runoff models and do not handle subsurface flow well, therefore are not suited to simulate OWS pollutants. Models like ANNAGNPS, CREAMS-WT and GLEAMS have routines to simulate subsurface flow and leaching but subsurface flow and leaching do not contribute to stream flows. Although these models can be good to simulate the effect of OWS pollutants on ground water, they are not suited to simulate the impact of OWS pollutants on stream flow. On the other hand, models like SWAT and HSPF have routines to simulate lateral and ground water contributions to stream flow. Although these models don't explicitly account for OWS pollutants, they can still be used using the non-point and point source routines features of the models. Compared to WARMF, HSPF and SWAT model do not explicitly account for OWS. Application of a watershed-scale decision-support tool such as WARMF can enable analysis of wastewater management scenarios and provide critical insight into the water quality benefits of management options.

SWAT and WARMF have been used to some extent to evaluate the impact of OWS pollutants. Pradhan et al (2005) used the SWAT model to evaluate fate and transport of nitrogen derived from OWS using the fertilizer input routine in SWAT. Weintraub et al. (2004) used WARMF model as a tool for tracking fate and transport of nutrients from OWS. A watershed modeling using the SWAT model was performed to understand the potential influence of various point and non-point sources of P in the Blue River watershed in Colorado (Lemonds and McCray, 2003). The watershed model was calibrated to measured flow rates and P concentrations. Fertilizer management routine was used to simulate OWS input in SWAT. The mass input rate of OWS pollutants was set equal to the mass of nutrient input by the fertilizer. Because simulations with OWS contributions showed little change in the concentration of P in the stream, OWS are not believed to be the primary source of P in the lake. Instead, P in runoff sediments is the most likely contributor to surface water (Lemonds and McCray, 2003). The three dimensional MODFLOW ground water flow model from the US Geological Survey has been used along with GIS to quantify septic system nitrogen loadings to receiving waters (Sham et al., 1995). Morgan and Everett (2005) used MODFLOW-MT3D in conjunction with optimization model to estimate the optimal loading of nitrate from decentralized wastewater treatment systems to an aquifer.

Case study: Turkey Creek Watershed Hydrology and Water Quality Calibration and Parameter Sensitivity, Scenario Evaluation

The model selected to simulate OWS based on suitability requires good calibration to be used as a decision tool. Watershed models simplify field conditions, thus the underlying assumptions and inputs used influence the model results. Generally, parameter estimates must be improved through calibration before a model is used for decision making related to management of water resources.

Trial-and-error calibration is frequently used to estimate model parameters. However, it is time consuming and subjective, and does not include a procedure for seeking optimal values, nor provide associated calibration statistics for model analysis. In this study, the sensitivity of simulated equivalents of field observations to input-parameter values has been used to identify the most important input parameters for hydrology and water quality. Non-linear regression was used to estimate the values of those parameters for the Watershed Analysis Risk Management Framework (WARMF) model. WARMF is a decision support system developed for watershed modeling and total maximum daily load (TMDL) calculation (Chen et al., 2001). The most important task that needs to be accomplished before calibration is reducing the number of parameters that are used during the parameter estimation stage. Parameter sensitivity analysis is applied to identify parameters of WARMF model that contribute most to the variability of stream flow, and thus, those that should be calibrated and reduce calibrable parameters of WARMF. A universal inverse code, UCODE_2005 (Poeter et al., 2005) was used for identifying important parameters and estimating their values. UCODE calculates sensitivity of model output to values for input parameters and correlations. Insensitive and correlated parameters can be omitted from the parameter estimation to reduce the number of parameters by simply fixing their values. UCODE performs inverse modeling, and calculates parameter values that minimize a weighted least-squares objective function using nonlinear regression (Poeter et al., 2005). The objective function is the sum of weighted-squared-residuals.

Description of watershed

The 126 square-kilometer Turkey Creek watershed (TCW) is located in Jefferson County, approximately 30 km southwest of Denver, Colorado. The topography is mostly steep with elevations ranging from about 1800 m to 3200 m. A Digital Elevation Model (DEM) from the USGS database was used to define the topography (Figure 1). Land-use data were derived from the 1992 National Land Cover Dataset (NLCD). The land cover map for TCW is shown in Figure 2. Agricultural land accounts for only 0.35% of TCW, thus crop rotation from year to year is not significant in TCW. Bossong et al. (2003) estimate that forest canopy covers 60 to 70 percent of TCW. The 1992 NLCD data shows that forest covers about 67% of TCW. Thus, there has been no considerable land use change in the watershed in recent years. Meteorological data were obtained from National Climatic Data Center (NCDC) (NCDC, 2007). Stream discharge data from two USGS stream gaging stations were used to calibrate the WARMF model. The two stations have USGS gage numbers 06710995 (old station) and 06710992 (new station), on Turkey Creek at the mouth of the canyon near Morrison and Turkey Creek near Indian Hills, respectively. Station 06710995 operated from April 1998 to April 2001 and was discontinued in lieu of the new, up-graded station, which operated from April 2001 to the current year, 2007.

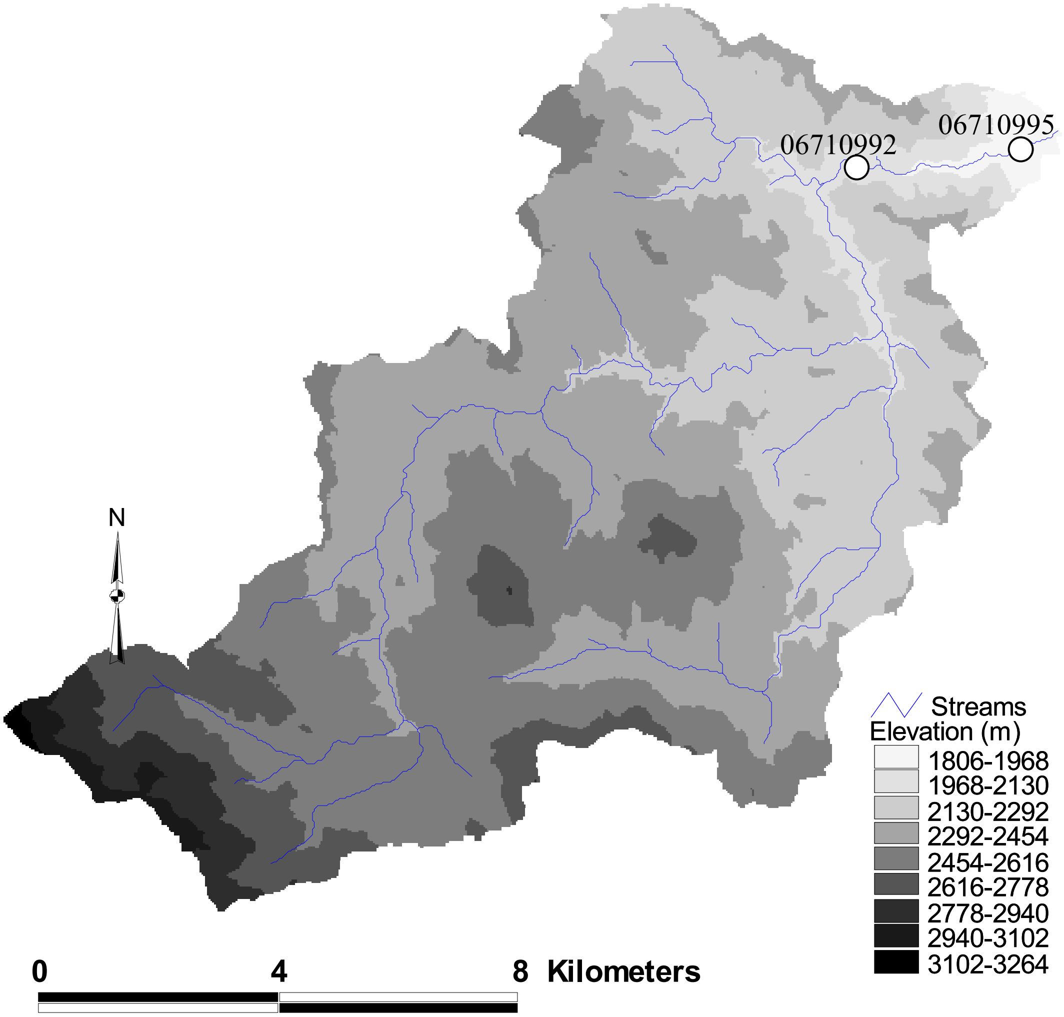

Figure 1. Digital Elevation Model for Turkey Creek Watershed, Colorado.

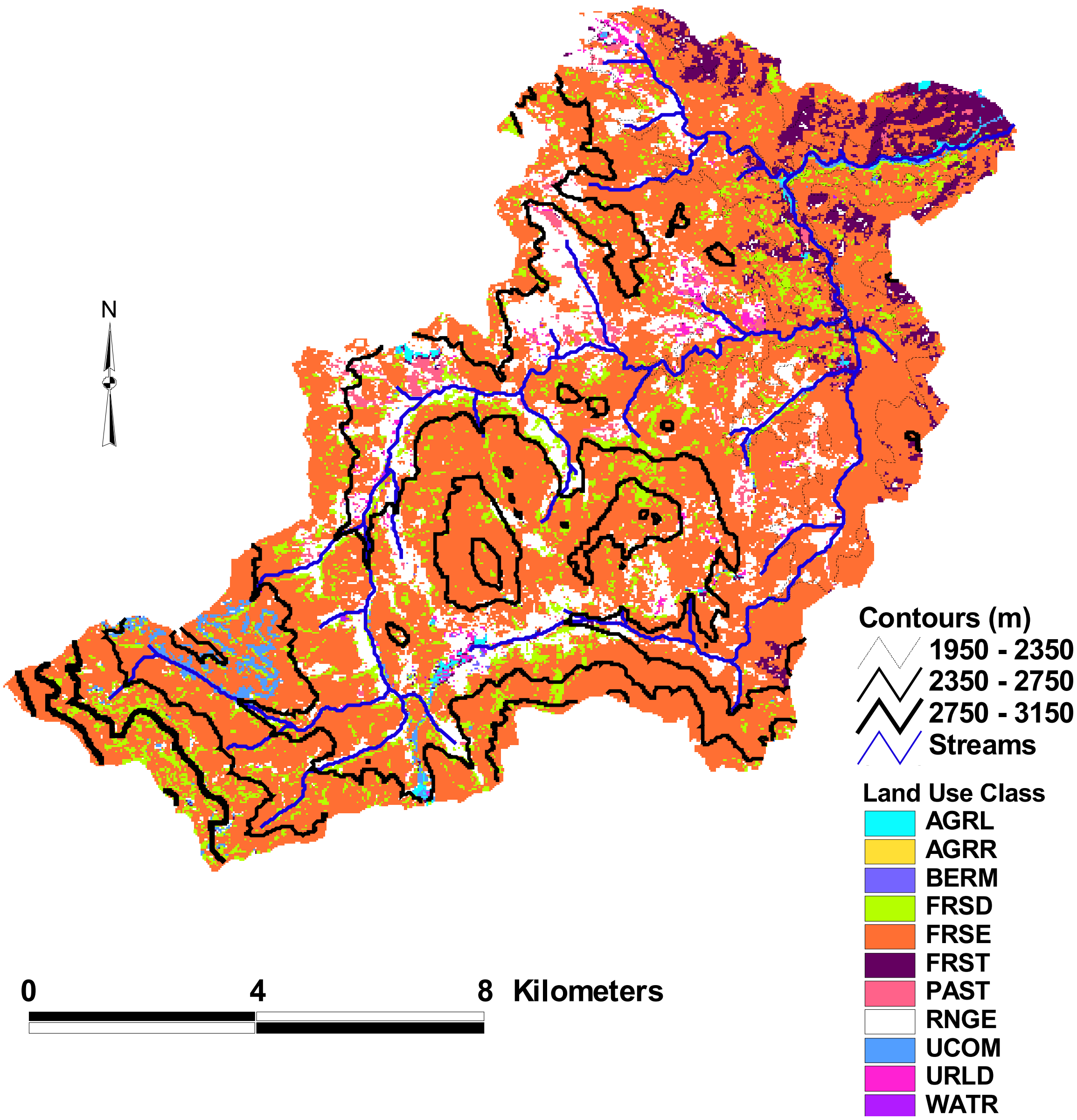

Figure 2. Land Cover Classification for Turkey Creek Watershed, Colorado.

Note: AGRL=Agricultural Land-Generic, AGRR=Agricultural Land-Row Crops, BERM=Bermudagrass, FRSD = Forest-Deciduous, FRSE= Forest-Evergreen, FRST=Forest-Mixed, PAST=Pasture, RNGE= Range-Grasses, UCOM= Commercial, URLD=Residential-Low-Density, WATR=Water

WARMF model

WARMF is a watershed based model that calculates daily runoff, shallow ground water flow, and water quality of a river basin. In WARMF, a river basin is divided into a network of land catchments, stream segments, and lakes (if available) for hydrologic and water-quality simulations. Daily precipitation is partitioned into rain and snow, depending on daily temperature. The model uses a water balance approach. Hydrologic budget for each catchment is calculated resulting in surface runoff and groundwater discharge to river segments. Water is then routed through river segments and surface water bodies (Chen et al., 2001). The percentage of each type of land use is defined for each catchment. Water on impervious surfaces runs off immediately, while water on pervious surfaces may infiltrate, remain on the surface as detention storage, or runoff, depending on relative rates and antecedent soil moisture conditions. Water, that does not infiltrate, either flows overland or forms ponds on the surface.

In WARMF, the catchments can be divided into five soil layers. Each layer can be assigned a separate thickness, initial volumetric soil moisture content, horizontal and vertical hydraulic conductivity, field capacity, and saturated moisture content. A water balance is maintained for each layer. The model calculates infiltration into each layer, lateral inflow into and out of each layer from adjacent catchments, and lateral flow into streams or lakes. Infiltration into a layer depends on the potential vertical infiltration rate, which depends on moisture content of the layer and the amount of water available for infiltration. The lateral flow of water from a layer is based on Darcy's Law, where the hydraulic conductivity is adjusted for water content. The head gradient is approximated to be equal to the land surface elevation gradient, which assumes the water table mimics the land surface topography. The water balance is used to compute the soil moisture content of the layer based on infiltration to the layer; percolation out of the layer, lateral inflow from upstream segments, evapotranspiration from the layer, and lateral outflow from the layer. Darcy's Law is also used for ground water transport between sub-catchments or from sub-catchments to streams as base flow. WARMF uses daily time steps and requires daily records of precipitation, minimum and maximum temperature, cloud cover, dew point temperature, as well as air pressure and wind speed, which are used in the evapotranspiration and snow melt algorithms (Chen et al., 2001).

The mass balance is maintained for each constituent. The model uses mass balance approach and accounts for factors affecting mass balance such as atmospheric deposition, foliar exudation, canopy reactions, snow pack chemistry, leaf litter decomposition, fertilization, livestock exclusion, nutrient uptake by plants, anion and cation adsorption, cation exchange, cation precipitation, nitrification and denitrifcation, and septic systems discharges. WARMF simulates the transport of clay, silt, and sand separately. The transport processes include the detachment of soil particles from the land surface, the suspension and deposition of detached soil particles in the overland flow, and the bed load transport of sand fraction on land. Phosphate is adsorbed by soil; a linear isotherm is used to represent the anion adsorption. Cations can form precipitates with hydroxide ion, which can then fall out of solution. Phosphorus can exist in two forms, the dissolved fraction and the adsorbed fraction. Similarly, a mass balance approach is used for calculating nitrogen. The mass balance approach accounts for factors affecting mass balance such as atmospheric deposition, foliar exudation, canopy reactions, snow pack chemistry, leaf litter decomposition, fertilization, livestock exclusion, nutrient uptake by plants, anion and cation exchange, nitrification and denitrifcation.

WARMF accepts septic tank effluent discharged to a soil layer, much like an underground point source. For each catchment, WARMF can accept the input data of population served by septic

(Weintraub, et al 2004). The pollutants discharged undergo treatment in the soil via cation exchange, chemical and biological reactions and plant uptake. Remaining constituents are eventually transported via ground water into surface waters. If a sewer is used instead of decentralized OWS the discharge from wastewater treatment source can be considered as a point source discharge into the streams.

Modeling framework

For the inverse modeling two models (WARMF and UCODE) were coupled. The UCODE model (Poeter and Hill, 1998, Poeter et al., 2005) was used to minimize the objective function and calculate diagnostic statistics such as sensitivity and correlation coefficients. UCODE also calculates parameter sensitivities and does parameter estimation via calibration. The procedures to estimate the hydrologic and water quality parameters are UCODE runs WARMF at the initial or updated parameter values, extracts the model predictions from the WARMF outputs and calculates the objection function value, updates the parameter values using the modified Gauss–Newton method. The process is repeated until the user-specified convergence criterion is met. The convergence is based on a criterion on magnitude of change in the parameter values.

Hydrology calibration and Sensitivity

Sensitivity analysis

The Turkey Creek watershed was divided into 61 catchments. Each of these catchments is represented by a number of parameters that could be set to a value or derived by calibration. Each catchment also has a river segment and associated parameters. WARMF also uses system coefficients that apply uniformly to all catchments in the watershed. Determining parameter values that are both realistic and optimal for such a large number of parameters is not feasible, requiring a reduction of the number of calibrated parameters. Parameters that are estimated through regression were selected using sensitivity analysis using UCODE for both hydrology and water quality. Sensitivity analysis indicated that simulated stream flow is most sensitive to seven of the twenty parameters included in the sensitivity analysis. These seven parameters are hydraulic conductivity, field capacity, saturated soil moisture or total porosity, precipitation weighting factor, evaporation magnitude, evaporation skewness and snow melting rates for forested areas. It is sensible that stream flow is highly sensitive to these parameters because WARMF uses a water balance approach to estimate runoff, and these parameters are particularly relevant to water balance. Precipitation weighting factor, evaporation magnitude, evaporation skewness and snow melting rates directly control the available water, while the remaining parameters dominate the run-off term. In WARMF, if the simulated volume of water in a layer is greater than the volume of saturated soil moisture, the soil layer becomes saturated, and additional water input results in surface runoff. Thus, saturated moisture/porosity is an important factor for surface runoff.

The two USGS gage station namely 06710995 and 06710992 at Turkey Creek at the mouth of the canyon near Morrison and Turkey Creek near Indiana Hills are used in this study for hydrologic calibration. The old station 06710995 had data from April 1998 to April 2001 and the new station has data from April 2001 to the current year. A universal inverse code, UCODE_2005 (Poeter et al., 2005) was used for hydrologic calibration. Using UCODE, it was possible to achieve a good fit to stream flow observations for the Turkey Creek watershed. Simulated daily stream flow matched the observed stream flow fairly well with an R^2 value of 0.85 and Nash-Sutcliffe coefficient of Efficiency (NSE) value of 0.75. The RMSE value, another measure of goodness of fit, was 0.29.

Water Quality: Phosphorus calibration and sensitivity

General

Phosphorus is considered to be the nutrient most responsible for eutrophication. Over the last several decades, agricultural sources of P have been suggested as a contributing factor to water quality degradation (U.S. EPA, 1996). The transport of P in runoff can occur in dissolved and particulate forms. The transport of dissolved phosphorus in runoff occurs due to desorption, dissolution, and extraction of P from soil and plant material. These processes occur as a portion of rainfall interacts with a thin layer of surface soil before leaving the field as runoff (Sharpley 1985). P is more susceptible to movement through sandy soils with low P-sorption capacities (Gotoh and Patrick, 1974; Ozanne et al., 1961). Adsorption of P by soil occurs rapidly, and because of the high binding energy between soil and P, adsorption tends to dominate desorption.

Septic tanks receive wastewater from individual residences, as well as other non-sewered facilities (Crites and Tchobanoglous 1998). Phosphorus removal in septic tanks is largely a physical process, with some chemical precipitation occurring as well. Between 20 and 30% of total phosphorus in raw wastewater is separated out in the form of sludge in a septic tank (Wood 1993). Orthophosphate may also be removed in septic tanks through mineral precipitation reactions (Zanini et al. 1998). Total phosphorus loadings from septic tank effluents have been estimated to be 15 to 17 kg/ha/yr (Lombardo Associates 1980; Gold and Sims 2000). The lower number assumes 170 l/capita/day, three people per household, five households per hectare and a wastewater effluent containing 15 mg-P/l. A soil absorption system is used following treatment in septic tanks. In a soil absorption system, septic tank effluent is discharged via a dispersal system to the soil infiltration zone, the vadose zone, and, ultimately, to ground water. Most of the phosphorus and pathogen removal occurs in the vadose zone (EPA 2002). A modeling study on Phosphorus Transport in the Blue River Watershed, Summit County, Colorado using SWAT model indicated that OWS are not the primary source of P in the lake. Instead, P in runoff sediments is the most likely contributor to surface water (Lemonds and McCray, 2003). Phosphate precipitation and adsorption account for the majority of phosphorus removal in raw municipal wastewater (Tchobanoglous and Schroeder 1987). Phosphorus in wastewater effluent tends to attach itself, or sorbs to soil particles in the unsaturated zone below septic drain fields. It is common for this process to remove 85-95% of phosphorous, and complete removal typically occurs long before effluent reaches surface water (Harman et.al. 1996, Ver Hey, 1987). This may not be the case if distances to surface water are short. Significant phosphorus has been detected in groundwater below some drain fields, and phosphorus plumes have been measured moving down gradient from septic drain fields in sandy shallow aquifers (Harman et.al. 1996, Ver Hey, 1987).

This case study on phosphorus concentration in stream involves parameter sensitivity, calibration and evaluation of scenarios related to OWS. Parameters that need to be estimated should first be selected and then estimated to determine the optimal combination of parameter values that provide the best match between field observation and their equivalent simulated values. It is important to reduce the number of parameters to be estimated, because although use of more parameters can lead to a better correlation between simulated and observed values, it increases the uncertainty associated with the estimated input values and the resulting predictions. Sensitivity analysis can be used to identify insensitive parameters and insensitive parameters can be omitted from the parameter estimation. The objectives in this case study for phosphorus include, determination of which phosphorus parameters used in WARMF are critical for calibration and identify the phosphorus parameters that can be uniquely determined by calibration, use non-linear regression to estimate optimal parameter values and identify conditions such as loading rate and soil properties under which in stream phosphorus concentrations could be most sensitive to septic system effluent discharge rate through sensitivity analysis. The findings are expected to be transferable to WARMF models for similar watersheds and other similar models. A rigorous parameter sensitivity analysis to statistically determine the most important input parameters for nutrients for a watershed model has not been previously presented in the literature. Sensitivity analysis is useful to planning monitoring campaigns that enable successful model studies

Phosphorus parameter selection

While calibrating phosphorous we focused on the model parameters that influence phosphorous concentration only and not the stream flow although we made an initial evaluation of the sensitivity of phosphorous concentration to parameters affecting stream flow. The analysis showed that simulated phosphorous concentration is sensitive to parameters used in flow calibration. The hydrologic parameters that are most sensitive include hydraulic conductivity, field capacity, saturated soil moisture or total porosity, precipitation weighting factor, evaporation magnitude, evaporation skewness and snow melting rates for forested areas. Although P concentration was sensitive to the hydrologic parameters, these parameters were used in stream flow calibration alone and P calibration was done using parameters that do not affect the stream flow, which has been already calibrated. Just like the stream flow parameters, parameters affecting P concentration in WARMF are grouped into river, catchments and system coefficients. River coefficients include parameters in sediment category affecting sediment detachment and transport, parameters in the reactions and adsorption category. Catchment coefficients also include parameters affecting sediment loading and soil properties such, phosphorus adsorption and initial concentrations in the soil. In addition to parameters affecting soil erosion and sediment transport, parameters related to plant nutrient uptake, litter decay rates and septic system discharge quality are included in the system coefficients.

Sensitivity analysis

Sensitivity analysis was done using UCODE for parameters affecting P concentration only. Sensitivity analysis for all phosphorus parameters indicates that P concentration is most sensitive to 13 parameters out of the 31 parameters included in the sensitivity analysis. Out of the 13 most sensitive parameters 9 were related to soil erosion and sediment transport. The most sensitive parameters related sediment detachment and transport include detachment velocity exponent, initial sediment depth, specific gravity, and sediment settling rate, particle diameter, bank stability factor, detachment velocity multiplier, and vegetation factor and bed diffusion rate. An initial parameter sensitivity analysis showed that sediment concentration in stream is sensitive to these parameters. The remaining 4 sensitive parameters are related to adsorption, initial concentration of phosphorus in the soil and plant uptake. It is reasonable that phosphorus concentration is highly sensitive to adsorption and sediment detachment parameters because phosphorus adheres to sediment particles and is transported to streams.

Parameter Estimation

Most of the parameters were not included in parameter estimation because of insensitivity. Those parameters, which are not sensitive, were set to a value. Because the model is not sensitive to these parameters using a fixed value does not have a large impact on calibration. Some parameters were not included due to parameter correlation. Thirteen parameters of the 31 parameters included in the sensitivity analysis had a higher sensitivity. As stated above, nine of them were related to soil erosion and sediment transport. The sediment parameters were also set to parameter values that yielded a reasonable loading from WARMF model compared to ranges reported in literature for sediment loading for different land cover types. The remaining 4 sensitive parameters, adsorption isotherm for soil, in stream adsorption isotherm and initial concentration of phosphorus in the soil were included in the regression. The plant uptake parameter had a relatively lower sensitivity and was not included in the regression.

Water-quality data collected within flow calibration period 1998 through 2003 were used to guide the water quality calibration. The data was obtained from United States Geological Survey site (USGS, 2001) and from a report on investigation of the fate of individual sewage disposal system effluent in Turkey Creek Basin, Colorado (Dano et al, 2004). A good correspondence is exhibited between observed P concentration and concentration simulated by WARMF using optimal parameter values with an R^2 value of 0.69.

Effect of septic discharge

P concentration in stream was not sensitive to septic tank effluent P concentration at the optimal parameter values. Thus, further analysis was done to see if P concentration in stream could be sensitive to septic tank effluent P concentration if other soil properties affecting P transport such as adsorption were altered. Parameters that were used in regression were varied and the sensitivity of P concentration in stream to septic tank effluent P concentration was evaluated. The parameters that were altered are those that were most relevant and that were estimated through calibration namely, soil adsorption isotherm, the initial concentration of phosphorus in the soil and sediment transport related parameters such as detachment velocity exponent, detachment velocity multiplier, and vegetation factor. Out of the parameters tested, the stream P concentration became most sensitive to septic effluent discharge concentration especially when soil adsorption is changed followed by stream sediment adsorption. The results showed that P concentration in stream was sensitive to septic tank effluent P concentration at a lower soil P adsorption than at the optimal value determined through calibration.

Scenario Evaluation

The calibrated model was used to evaluate prediction scenarios. Both scenarios are related to loading rates. The first scenario (scenario 1) involved evaluation of the impact of residential development and increase in population using septic tanks on stream P concentration. The population of Turkey Creek, which is currently about 11,000, and the area under residential houses, was doubled. Total P concentration for the base scenario and scenario 1 and the difference between the two is shown in figure 3. The increase in average stream P concentration as a result of population increase was only 4%.

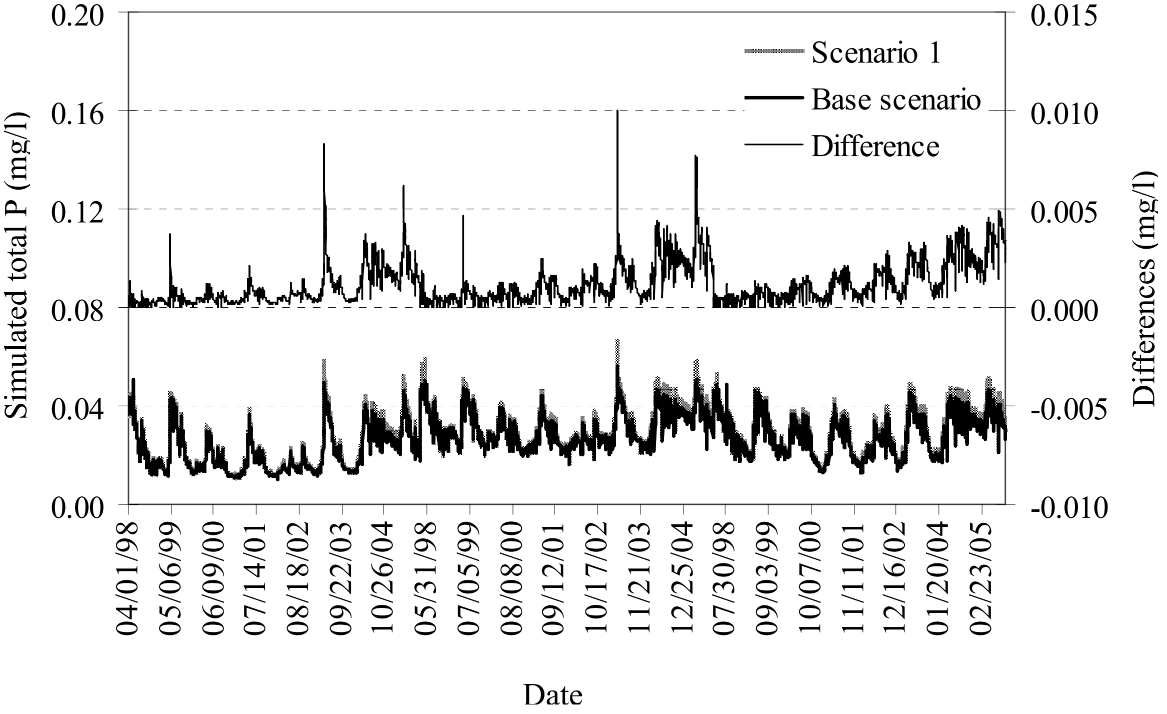

Figure 3. Comparison of stream P concentration for two population levels

The second scenario (scenario 2) also involved increased loading as a result high concentration discharge. Total P concentration for the base scenario and scenario 2 is shown in Figure 4. McCray et al (2003) developed cumulative frequency distributions (CFDs) for OWS effluent concentrations of N and P based on data gathered from existing studies reported in the literature. For the base scenario a median (50%) value (10 mg/l) from the CFDs was used. For scenario 2, concentration of 22 mg/l representing 100% cumulative frequency values (maximum values reported) was used. An increase in P concentration in septic effluent from the standard 10 mg/l to 22 mg/ (scenario 2) caused a 5% increase in stream P concentration, which is slightly higher than the increase in scenario 1 (4%). The two scenarios presented above demonstrate the effect of increased loading as a result of population increase and increased septic effluent concentration.

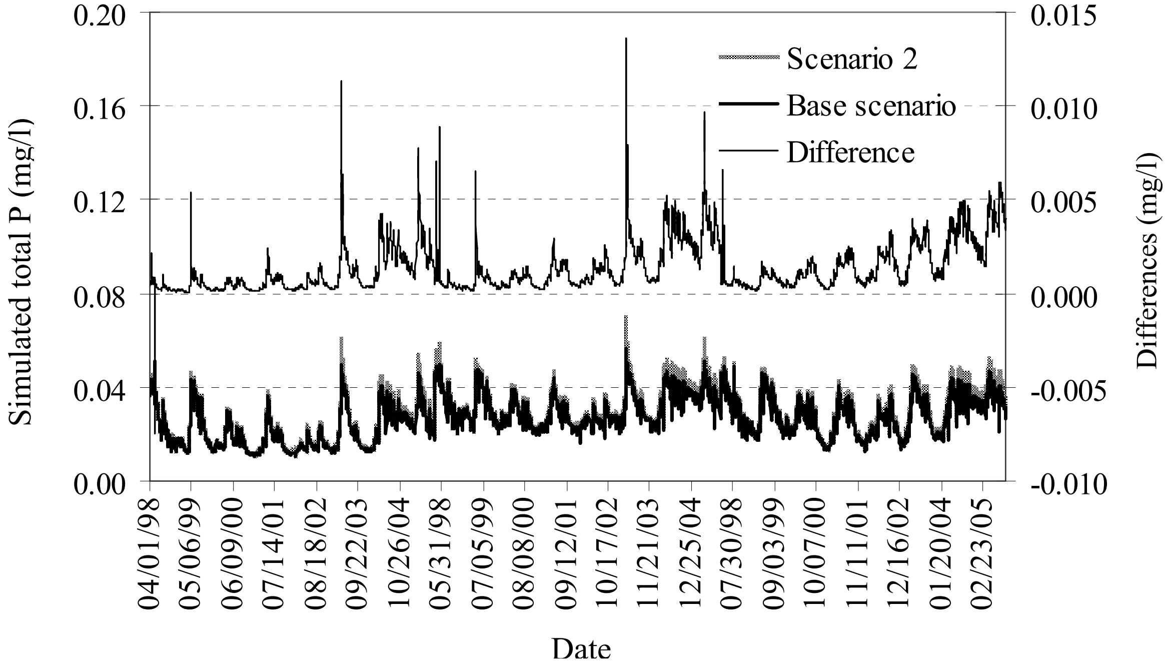

Figure 4. Comparison of stream P concentration for two effluent levels

Water Quality: Nitrate calibration and sensitivity

General

The principal form of nitrogen found in ground and surface water is nitrate. Nitrogen, in nitrate form, is a direct risk to human and livestock health if it reaches high concentration in drinking water. It can also cause ecological damage in lakes and rivers through eutrophication. The U.S. Environmental Protection Agency (EPA) has established a level of 10 mg/l as the drinking water standard for nitrate for public water systems. The anthropogenic sources are the ones that most often cause an increase in the amount of nitrate to an undesirable level. Agriculture is very much at the center of non-point source concern. Septic systems are another sources of anthropogenic source of nitrogen contamination. Ammonium is the major for nitrogen discharge from septic tank effluent; however, it is eventually converted to nitrate in the soil.

On-site systems could be one of the major anthropogenic sources of nutrients (Buetow, 2002; Robertson and Blowes, 1995) in a watershed. Septic systems are considered as one of the major causes for groundwater pollution. McCray et al (2003) developed cumulative frequency distributions (CFDs) for OWS effluent concentrations of nitrogen from septic tanks based on data gathered from existing studies reported in the literature. The results give a range for septic tank effluent concentration from 17 to 178 mg N/L for ammonium, 0 to 1.94 mg N/L for nitrate, 9.4 to 15 mg N/L for organic N, and 12 to 453 mg N/L for total N. Groundwater contamination with nitrogen from on-site systems occurs due to poor purification of the effluent as a result of inherent insufficient biochemical and physical process e.g. denitrification and ammonium adsorption of traditional septic system design.

The objectives in this case study for nitrate include, determination of which parameters used in WARMF are critical for calibration and identify the parameters that can be determined by calibration, use of non-linear regression to estimate optimal parameter values, identifying parameters that control the effect of septic system effluent discharge rate on stream nitrate concentration and evaluating the effect of factors such as population growth and septic effluent concentration on stream nitrate concentration.

Nitrate parameter selection

Just like phosphorus, we focused on the model parameters that influence nitrate concentration only and not the stream flow while calibrating nitrate although we made an initial evaluation of the sensitivity of nitrate concentration to parameters affecting stream flow. The analysis showed that simulated nitrate concentration is sensitive to parameters used in flow calibration. Parameters affecting nitrate concentration in WARMF are grouped into river, catchments and system coefficients. River coefficients include parameters in sediment category affecting sediment detachment and transport and parameters in the reactions and adsorption category. Catchment coefficients also include parameters affecting sediment loading and soil properties such, ammonium adsorption and initial concentrations in the soil and parameters in the reactions such as nitrification and denitrifcation. In addition to parameters affecting soil erosion and sediment transport, parameters related to land use, plant nutrient uptake, litter decay rates and septic system discharge quality are included in the system coefficients.

Sensitivity Analysis

Sensitivity analysis was done using UCODE for parameters affecting nitrate concentration only. Sensitivity analysis for all nitrate related parameters indicate that nitrate concentration is most sensitive to 13 parameters out of the 49 parameters. Of the 13 most sensitive parameters four are related to soil properties, two are related to the concentration of leachable ions, two are septic effluent concentration of ammonium and nitrate and the remaining parameters are related land use, and litter fall rate and decay rates. The soil related parameters are cation exchange capacity, nitrification rate, initial base saturation for ammonium, and initial concentration of ammonium in the soil. The land use or crop related parameters are, leaf composition of ammonium, trunk composition of ammonium, plant productivity, litter fall rate and litter decay rate. The septic system effluent concentration parameters are the concentration of ammonium and nitrate in the effluent. The concentration of leachable ions includes the fraction ammonia that forms organic acid during humus decay (humus leachable ions) and the rate coefficient for wash out of nonstructural ions in litter relative to amount of throughfall (nonstructural leachable ions). Unlike phosphorous nitrate concentration is not dependent on sediment loading to the streams.

Parameter Estimation

Most of the parameters were not included in parameter estimation because of insensitivity and correlation. Those parameters, which are not sensitive, were set to a value. Of the soil related parameters, the cation exchange capacity (the most sensitive parameter) was estimated via calibration, the rest were set to a value based on literature. The land use related parameters (leaf and trunk composition of ammonium, plant productivity, litter fall rate and litter decay rate) were also correlated. Thus, only the litter fall rate was estimated while the remaining were set to a value. The nitrate concentration in stream is also sensitive to septic system effluent ammonium and nitrate concentrations however, it is not reasonable to calibrate these parameters because they are known quantities which can be set to a value based on data. McCray et al (2003) developed cumulative frequency distributions (CFDs) for OWS effluent concentrations of N and P based on data gathered from existing studies reported in the literature. The results give a range for septic tank effluent concentration from 17 to 178 mg N/L for ammonium. Nitrate-N concentrations are much lower, as is expected since nitrification would not transform ammonium to nitrate in the anaerobic conditions of the septic tank. The median value reported in this study; 58 and 0.2 mg N/l for ammonium and nitrate were used in this study. The concentration of leachable ions includes the fraction ammonia that forms organic acid during humus decay (humus leachable ions) and the rate coefficient for wash out of nonstructural ions in litter relative to amount of throughfall (nonstructural leachable ions) were also set to a value. Finally, only two parameters, one representing soil property and another representing land use were used.

Water-quality data collected within flow calibration period 1998 through 2003 were used to guide the water quality calibration. The data was obtained from United States Geological Survey site (USGS, 2001) and from a report on investigation of the fate of individual sewage disposal system effluent in Turkey Creek Basin, Colorado (Dano et al, 2004). A good correspondence is exhibited between observed nitrate concentration and concentration simulated by WARMF using optimal parameter values. A graph of simulated versus observed concentrations shows a reasonable fit between observed and simulated concentrations with an R^2 value of 0.51.

Effect of septic discharge

Unlike phosphorus, nitrate concentration is sensitive to septic tank effluent ammonium concentration at the optimal parameter values. Scenarios related septic loadings were evaluated to further understand the impact of septic systems on nitrate concentration in surface water.

Scenario Evaluation

The scenarios evaluated are related to loading rates. The first scenario involved evaluation of the increase in population using septic tanks on stream nitrate concentration. The population of **T**urkey **C**reek, which is currently about 11,000, and the area under residential houses, was increased. Two population levels were evaluated; a 50% increase (16,500 people) and a 100% increase (22,000 people). Nitrate concentration for the two population levels and the % change in nitrate concentration as a result of the change in population level from 11, 000 to 16,500 and 22,000 is shown in Figure 5. The increase in average stream nitrate concentration was 12 and 23% for a population level of 16,500 and 22,000 respectively compared to the base condition (11,000).

The second scenario involving increased loading as a result high concentration in septic effluent discharge for the existing or base population level (11,000). Total nitrate concentration for the base condition with effluent concentration of 58 mg/l representative of standard septic system and a new scenario with effluent a higher concentration of 178 mg/l based on McCray et al (2003) is shown in Figure 6. Figure 6 also shows the change in actual concentration and the percent change in stream concentration from base condition. The average increase stream nitrate concentration as a result of increased effluent concentration level from 58 mg/l to 178 mg/l is 33%.

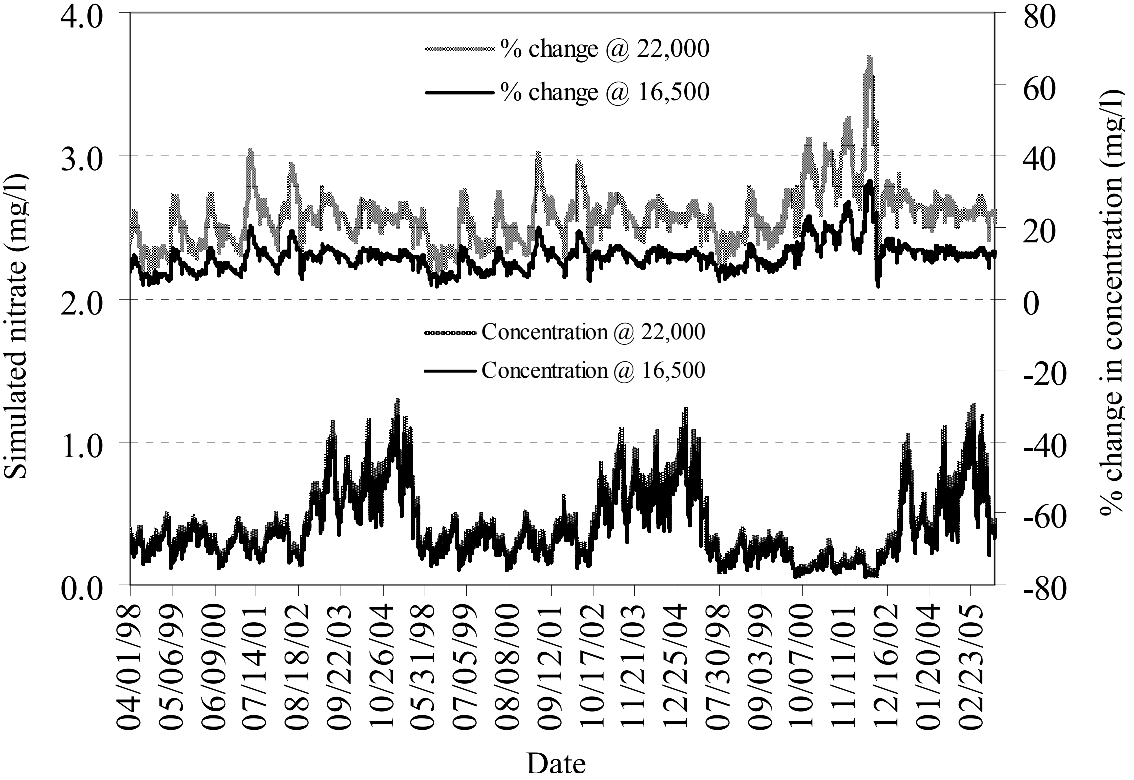

Figure 5. Concentration and % change in concentration for two population levels

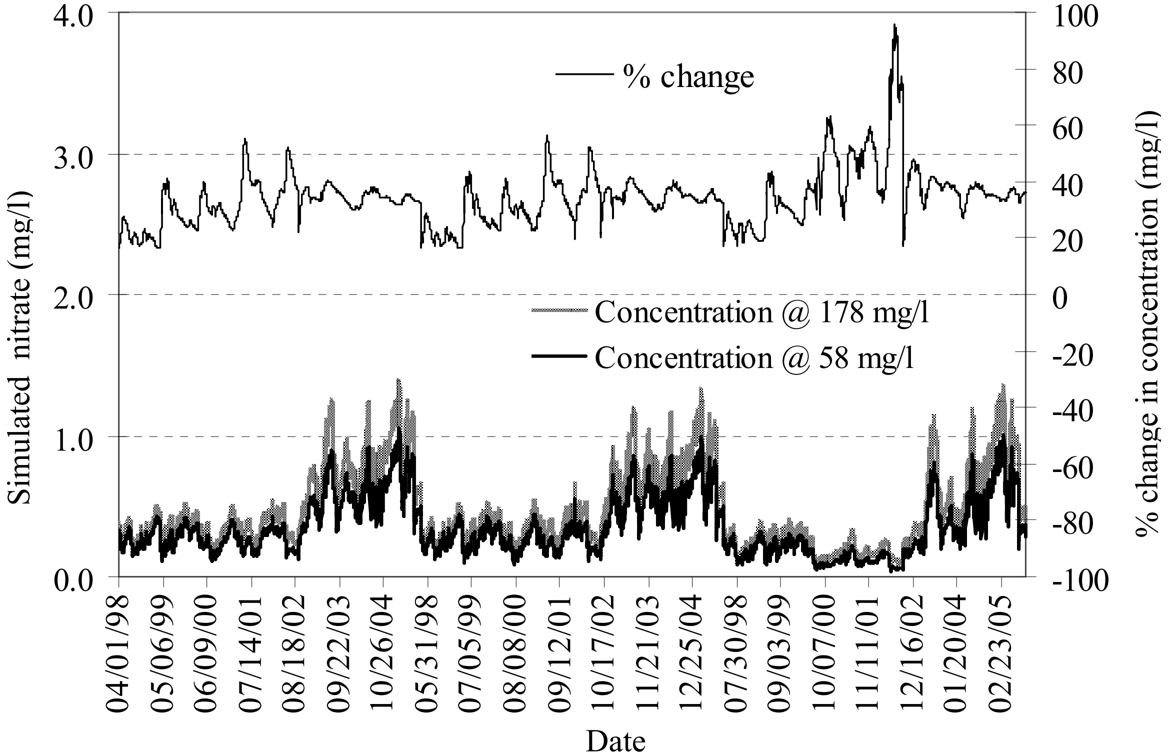

Figure 6. Concentration and % change in concentration for two effluent ammonium concentration levels

The third scenario evaluated was average stream concentration at different soil nitrification rates. There is a relatively high correlation between septic effluent ammonium concentration and other parameters that were found sensitive, namely, the nitrification rate, the base saturation for ammonium, cation exchange capacity, initial concentration of ammonium in the soil, the leaf composition of ammonium, non-structural and humus leachable ions, the litter fall rate and the crop productivity in that order. The correlation implies that the effect of ammonium concentration on stream nitrate concentration is dependent on the values used for these parameters. So the effect of septic tank effluent concentration was evaluated at different levels of nitrification (the parameter which was found to have the highest correlation with the septic effluent ammonium concentration among parameters that are sensitive). Figure 7 shows that the effect of septic tank effluent ammonium concentration increases with increasing nitrification rate. The results also show an increasing sensitivity (CSS) of stream nitrate concentration to septic tank effluent nitrate concentration and sum of squared error (SSE) with increasing nitrification rates. The effect of nitrification rate on stream concentration was evaluated for two different septic tank effluent concentration of ammonium (58 mg/l and 178 mg/l). The nitrification rates were obtained from McCray et al (2003). McCray et al (2003) developed cumulative frequency distributions (CFDs) nitrification and denitrification based on literature. The results show that a CFD of first-order nitrification rates ranging from 0.0768 to 211 per day with a median rate of 2.9 per day. The results also show a higher sensitivity (CSS) of stream nitrate concentration to septic tank effluent nitrate concentration and sum of squared error (SSE) for the higher level of effluent concentration (178 mg/l) as compared to base scenario (58 mg/l). The results also show that the average nitrate concentration is considerably higher at higher nitrification rate for both effluent concentration levels.

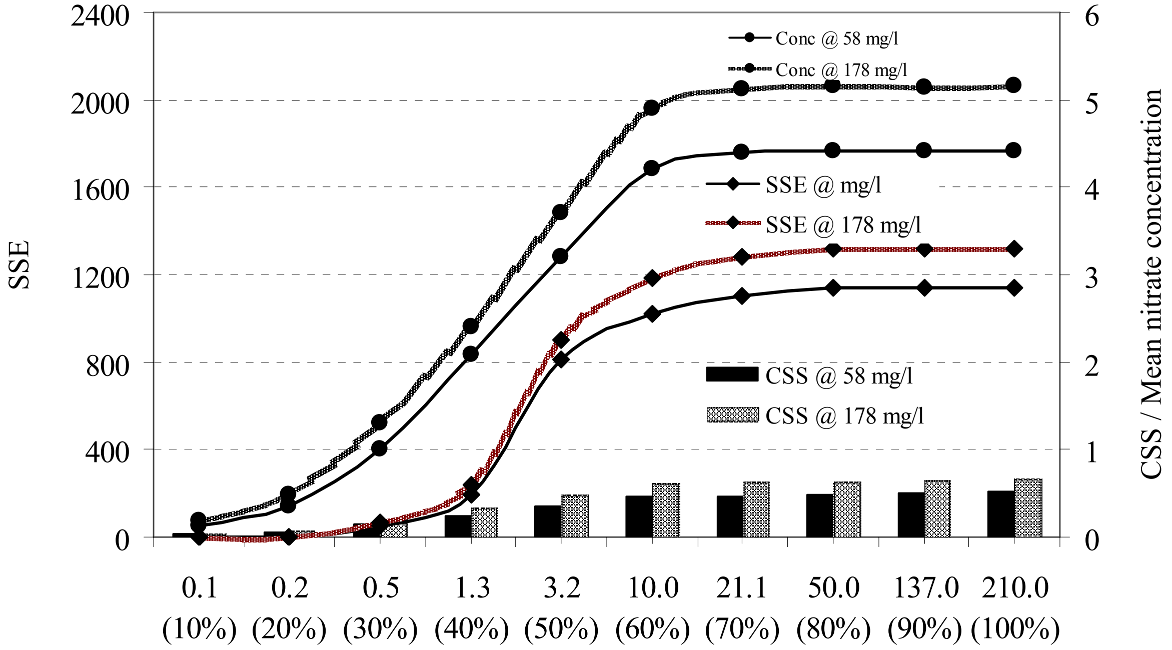

Figure 7. Sensitivities and mean concentrations for two effluent concentration levels at different nitrification levels.

Summary and Conclusion

Selection of the appropriate model depends on the intended use of the model and the desired output. For assessing OWS impacts the watershed model should have routines for simulating both water quality and water quantity. The model must be able to simulate pollutants relevant to OWS such as nitrogen and phosphorus. WARMF model was chosen in this study based on these attributes and it capability to simulate OWS directly.

Model users need to identify both hydrology and water quality parameters that are most relevant for calibration. This paper describes sensitivity analysis and parameter estimation for WARMF model of the Turkey Creek Watershed in Colorado for hydrology and water quality using automated calibration and uncertainty software called UCODE. Parameter sensitivity analysis was applied to identify parameters of WARMF model that contribute most to the variability of stream flow and water quality, and thus, those that should be calibrated and reduce calibrable parameters of WARMF. It also provides information on input-parameter sensitivity which is useful to model users. The simulated stream flow is most sensitive to seven parameters, namely, hydraulic conductivity, field capacity, total porosity, precipitation weighting factor, evaporation magnitude, evaporation skewness and snow melting rates for forested areas.

Phosphorus concentration was found to be highly sensitive to initial P concentration in the soil, soil adsorption and sediment detachment and transport parameters. Thus, controlling sediment transport can play a role in controlling phosphorus transport. The modeling study showed that stream P concentration is not sensitive to the septic tank effluent concentration at optimal parameter values. There was no significant increase in stream P concentration as a result of increased loading from increased population and increased effluent P concentration. This shows that the contribution of the septic discharge to P concentration in stream is minimal if the soil treatment units function well. The results agree with previous studies, which have also indicated high degree of phosphate sorption and complexation regardless of these high contributions from septic systems. The study also shows P removal from septic effluent is dependent on soil adsorption. The effect of septic tank effluent P concentration increased with decreasing soil adsorption rate followed by stream sediment adsorption rates and the vegetation factor. Thus P concentration in stream could be a concern only when there are failing soil treatment systems associated with inappropriate location of systems in areas with inadequate separation distances to stream water and insufficient adsorption in the vadose zone.

Nitrates concentration was found to be highly sensitive to parameters related to soil properties (cation exchange capacity, nitrification rate, initial base saturation for ammonia, and initial concentration of ammonia in the soil), concentration of leachable ions, septic effluent concentration of ammonium parameters are related land use (leaf composition of ammonia, trunk composition of ammonia, plant productivity), litter fall rate and litter decay rate and the septic system effluent concentration parameters are the concentration of ammonium and nitrate in the effluent .The modeling study showed that stream nitrate concentration is not sensitive to sediment transport parameters unlike phosphorus. There was a significant increase in stream nitrate concentration as a result of increased loading from increased population and increased effluent ammonium concentration. The effect of septic tank effluent nitrate concentration increased with increasing nitrification rate.

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