Modeling Phosphorus Transport in the Blue River Watershed, Summit County, Colorado

Paula Jo Lemonds and John E. McCray

Abstract

Lake Dillon in Summit County, Colorado, is a primary drinking-water reservoir for Denver. Eutrophication of Lake Dillon is a concern, primarily due to phosphorus (P) loading. There is little agriculture in the watershed. Thus, many local officials attribute the P loading to onsite wastewater systems (OWS). A watershed modeling effort using the SWAT model is underway to understand the potential influence of various point and nonpoint sources of P in the Blue River watershed (the most developed of three watersheds that supply Lake Dillon). The watershed model was calibrated to measured flow rates and P concentrations. The hydrologic model results are most sensitive to the physical parameters of snowmelt, and orographic effects on precipitation and evapotranspiration. However, uncertainties in chemical-hydrologic parameters preclude a rigorous assignment of relative contributions of various P sources. Rather, the effort has resulted in a better understanding of P chemical parameters required to simulate watershed-scale transport. The model was most sensitive to the P sorption coefficient, the P availability index, and the P enrichment ratio (a measure of P in runoff sediments compared to immobile sediments). Modeling results indicate that OWS are not significant sources of P to Lake Dillon.

Keywords: watershed, modeling, phosphorus, wastewater, hydrology, SWAT

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Introduction

Numerical models are useful tools because they allow a quantitative assessment of the environmental impacts of wastewater pollutants and improve understanding of watershed-scale pollutant transport. Projecting future water quantity and quality is especially important in developing communities that rely on shallow groundwater as a source of drinking water while disposing of wastewater in the shallow subsurface. Some models capable of simulating watershed-scale pollutant transport include Soil and Water Assessment Tool (SWAT) (Arnold 1998), MIKESHE (Danish Hydraulic Institute 1999), Watershed Analysis Risk Management Framework (WARMF) (Chen et al. 1999) and Hydrologic Simulation Program – Fortran (HSPF) (Bicknell et al. 1996). SWAT was used for this effort because it is a public-domain model that can incorporate large amounts of data and simulate many hydrologic processes.

Several watershed-scale models have been developed using SWAT (Arnold et al. 1999, Arnold and Allen 1996, Fontaine et al. 2002, Manguerra and Engel 1998, Santhi et al. 2001, Srinivasan et al. 1998). However, these projects did not specifically address the watershed-scale impacts of wastewater pollutants from onsite wastewater systems (OWS). The goals of this study are to accurately simulate mountain watershed hydrology and to quantify the impacts of OWS-derived phosphorus (P) in the Lake Dillon Watershed.

The study area is the Lake Dillon watershed located in Summit County, Colorado (Figure 1). Lake Dillon is the main drinking-water storage reservoir for Denver. Towns in the watershed include Frisco, Dillon, Silverthorne, Breckenridge, and Blue River.

Model Setup

The ArcView Interface for SWAT was used in model development. Subwatersheds were delineated using SWAT and a USGS 300-m resolution, 1-degree Digital

Elevation Model (DEM). Information extracted and calculated from the DEM includes overland slope, slope length, and elevation corrections for precipitation and evapotranspiration. The subwatershed delineation is illustrated in Figure 1.

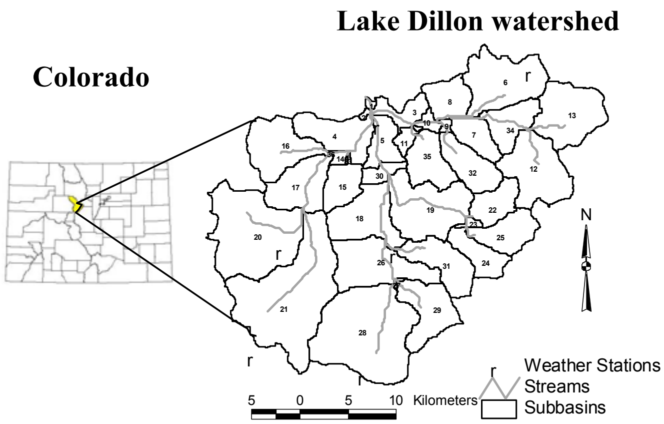

Figure 1. The study area is the Lake Dillon watershed in Summit County, Colorado.

The land-use information was derived from 1:250,000-scale Landuse/Landcover Geographic Information Retrieval Analysis System (GIRAS) spatial data. The land use/land cover digital data were collected by the USGS and converted to ARC/INFO by the USEPA. This information was used when simulating infiltration, runoff, ET, and natural sources of nutrients.

The soil attributes were taken from the State Soil Geographic (STATSGO) Database, which was developed by the National Cooperative Soil Survey (USDA-NRCS Soil Survey 2002). In the STATSGO database, soil attributes are stored in polygon format. Each polygon includes multiple soil series with information on its areal percentage of the polygon. In the SWAT ArcView Interface, the dominant soil series is selected, and the interface extracts properties for the model from a relational database. Examples of the properties extracted include soil texture, bulk density, hydraulic conductivity, available water capacity, organic carbon, and total depth of soil. These parameters are used in computations for infiltration, runoff, groundwater flow, and P transport.

Precipitation and temperature data were available from the National Climatic Data Center (NCDC) and the Natural Resources Conservation Service's (NRCS) Snowpack Telemetry (SNOTEL) Data Network. Six stations were available within the Lake Dillon watershed. Daily precipitation and minimum/maximum temperature values were incorporated into the model.

Other information defined in initial model setup included wastewater treatment plant point-source discharges into the Blue River and its tributaries, Lake Dillon water levels, reservoir outflow, and surface area of the reservoir. Information specific to each subwatershed, including stream-water chemical properties, groundwater-flow properties, stream-routing parameters, consumptive water use, and agricultural diversions were included. For details on the model setup and simulation parameters, the reader is referred to Lemonds (2003).

Incorporation of OWS

Currently, no algorithms exist in SWAT to specifically simulate OWS. Therefore, a fertilizer management practice was used to simulate OWS input. The mass input rate of OWS pollutants was set equal to the mass of nutrient input by the fertilizer. OWS inputs were established from reviews of OWS effluent flow rates and water-quality parameters completed by Kirkland (2001).

Fertilizer application input parameters were adjusted in SWAT to achieve the appropriate inorganic P mass input rate to the subsurface based on the number of OWS in each subwatershed. It was assumed that implementing the fertilizer management practice in seven-day intervals would adequately represent OWS effluent processes. SWAT allows the user to apply the fertilizer into the first soil layer. As a result, the simulated OWS nutrients are not affected by runoff and are allowed to percolate through the vadose zone. The source of percolation is the natural precipitation, which is orders of magnitude greater than OWS effluent input.

Results

Prior to simulating nutrient transport, physical hydrologic input parameters were adjusted to calibrate the model to stream flow rates. Adequate calibration of the physical hydrologic system was critical to simulating nutrient transport.

Hydrology Simulation and Calibration

Measured streamflow was obtained from two USGS gaging stations on the Blue River: one near the headwaters and the other located approximately one half mile upstream of Lake Dillon. The model simulation was executed for 11 years (1990-2000). The first two years were not used for model evaluation because parameters such as soil water content and residue cover are initially not in equilibrium with actual physical conditions (Fontaine et al. 2002; Santhi et al. 2001). Prior to calibration, comparison of annual-average streamflow data to simulated values show an under-prediction of flow (Figure 2).

Because SWAT was developed for watersheds in non-mountainous terrains, special adjustments were necessary to accurately simulate hydrologic processes that are strongly affected by elevation changes characteristic of this watershed. Fontaine et al. (2002), who applied SWAT to the mountainous Wind River Basin in Wyoming, discovered that orographic processes were very important. Processes that are affected by elevation include evapotranspiration, precipitation and snowmelt/snow-formation processes.

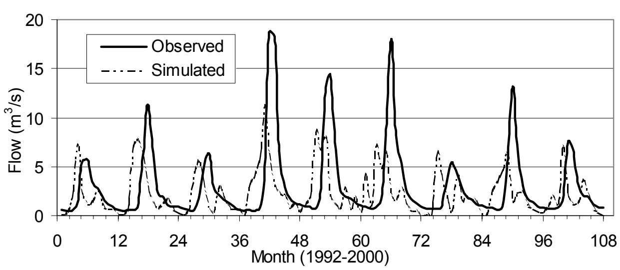

Figure 2. Initial simulation of monthly streamflow.

Lapse Rates and Elevation Bands

Elevation in the Lake Dillon watershed ranges from 2681m to 4350m (8796-14,272ft). To account for the orographic effects on precipitation and temperature (and thus evapotranspiration and snow processes), algorithms for elevation bands and lapse rates were used. In addition, several empirical parameters related to snowmelt and snow formation were adjusted.

The lapse rates were computed by relating elevation to mean annual temperature and mean annual precipitation at seven meteorological stations in the basin. The temperature decreases 4^{o}C for an increase of 1km in elevation, and annual precipitation increases 5mm for an increase of 1km in elevation. Therefore, the temperature lapse rate was -4^{o}C/1km (R^2=0.91, n=7); the precipitation lapse rate was 5mm/1km (R^2=0.82, n=6). These lapse rates were implemented by dividing the watershed into six elevation bands (2650-4150m) based on the DEM. When lapse rates are defined in SWAT, subbasin temperatures and precipitation are adjusted for each elevation band in a subbasin as a function of the lapse rate and the difference between elevation of the meteorological gaging station and the average elevation specified for the band (Neitsch et al. 2000).

Adjustment of Snowmelt/Snow Accumulation Parameters

Parameters in SWAT that simulate snowmelt processes and control the formation of snow were also adjusted to create a better match to observed streamflow data. The parameters that were modified include a factor that accounts for snow pack characteristics and two empirical factors that account for the melting rate of snow.

A "lagging factor" accounts for temperature characteristics of the snow pack that influence the snow-pack density, snow-pack depth, exposure, and other factors (Neitsch et al. 2001). As the lagging factor approaches 1.0, the mean air temperature on the current day exerts an increasingly greater influence on the snow pack temperature, and the snow pack temperature from the previous day exerts less and less influence (Neitsch et al. 2001). In the model of the Lake Dillon watershed, the value was adjusted to 0.035. This value, which produced the best fit to observed data, is consistent with the findings of Fontaine et al. (2002) who observed values of the lag factor ranging from 0.0 to 0.5 for areas characterized by deep snowpack.

The other two factors influence the empirical relation used for snowmelt. Snowmelt is calculated as a linear function of the difference between the threshold temperature for snowmelt and the average snow-pack maximum air temperature. Two parameters in SWAT represent maximum and minimum melting values that occur on the summer and winter solstices, respectively. For the application of SWAT to the Lake Dillon watershed, these values were adjusted to 3.0 and 2.0 mm H_2O/day-^{o}C, respectively.

Final Hydrology Calibration

The adjustment to snowmelt and snow formation parameters, as well as the inclusion of lapse rates and elevation bands, made a substantial improvement in the simulation of streamflow (Figure 3). The rising limb of each yearly hydrograph begins at the correct time. The recession limb of each yearly hydrograph begins at nearly the correct time. The years of higher discharge show improvement in the timing of the recession limb of the hydrograph (Figures 2 and 3, Months 18, 46, 70, and 92). The only problem that was not completely resolved was that the simulated streamflow approached 0.0 $m^3 s^{-1}$ for 2-3 months of the year. However, an improvement was made from the initial calibration. Comparison of Figures 2 and 3 show that the simulated hydrograph was smoothed considerably and better corresponds to the observed values of streamflow.

Statistics show the numeric improvement made in streamflow simulation. The initial R^2 value of monthly-averaged streamflow was 0.03. The simulation shown in Figure 3 exhibits an R^2 value of 0.70. R^2 values of 0.65 to 0.70 for monthly-averaged streamflow are appropriate considering the numerous potential measurement errors in data collection. For example, spatial variability in rainfall, soils, and land use, errors in measuring streamflow, and errors caused by sampling strategies are potential causes of inaccurate observed values (Santhi et al. 2001).

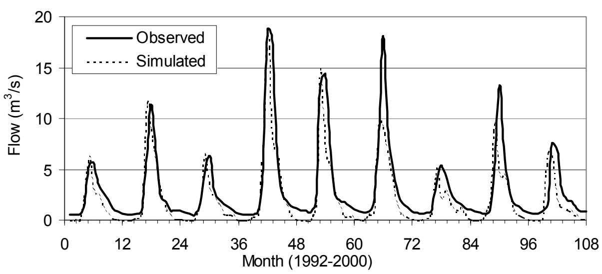

Figure 3. Model calibrated to monthly streamflow.

Phosphorus Calibration

To simulate pollutant transport, it is necessary to know the values for more than a dozen input parameters that influence the reaction, transformation, and interphase partitioning of the pollutants. Unfortunately, the available input data on these parameters, as well as observed data required to calibrate a model, generally are not available in the Lake Dillon watershed.

This is true in most watersheds. Thus, the first step in model improvement should include a sensitivity study to understand the relative importance of these parameters on model output. The next step is to use the parameters that are considered most important (in terms of the influence on the model) to evaluate the performance of the model in simulating actual, but limited, data. This exercise can also lend insight into designing a data-collection plan that would improve model performance.

Sensitivity Study

For the sensitivity study, observed P concentration data for seven years were available at the Blue River station near Lake Dillon (the same location of the measured streamflow data). The observed P data are from the USEPA Storage and Retrieval (STORET) database (USEPA 2002) and from data collected by officials in Summit County, Colorado.

The automated calibration software, UCODE (Poeter and Hill 1998) was used to determine sensitivity of the model to several P transport parameters. Thirteen parameters in SWAT potentially affect P transport (Lemonds 2003). Of these parameters, the model was most sensitive to the P availability index (PAI), which specifies the fraction of fertilizer P that is in solution after a period of rapid reaction with the soil; the P enrichment ratio, which is the ratio of the concentration of P transported with the sediment to the concentration of P in the soil surface layer; the P-soil partitioning coefficient, which is the ratio of the soil concentration of P to the aqueous concentration of P at equilibrium; the initial P concentration in the soil; and the soil bulk density.

Best-Fit Phosphorus Model

Parameters that had little affect on P transport were assigned reasonable values from the literature (Lemonds, 2003). The parameters that most strongly affected the model were adjusted to yield a best-fit to observed values (Table 1). These values are all within reasonable ranges based on literature review (Kirkland 2001, Brady and Weil 1999, Sharpley 1984, Soil Survey of Summit County Area, Colorado 1980).

Figure 4 shows the observed P values versus the best-fit simulated values. The simulation produces P loading values that are generally within a factor of 10 of measured data and usually within a factor of 2. While the match is not rigorous for the entire simulation time, most of the important trends are captured. Simulations with no OWS input of P were also completed. The model-simulated P generally changed by less than 5%. Therefore, OWS is not likely to be an important contributor to P pollution in the Lake Dillon watershed. Rather, natural sources in runoff sediments are likely the most important contributor.

Table 1. P input parameters used in final simulation.

Parameter, Units	Value of Parameter for Best-Fit Model	
P availability index, unitless	0.7	
P-soil partitioning coefficient, m^3Mg^{-1}	175	
P enrichment ratio, unitless	Model calculates for each storm event	
Soil bulk density, $g\ cm^{-3}$	Soil Layer 1	0.80
	Soil Layer 2	0.90
	Soil Layer 3	0.85
	Soil Layer 4	0.9
Initial soluble P soil concentration, mg P kg $soil^{-1}$	Soil Layer 1	5
	Soil Layer 2	2
	Soil Layer 3	2
	Soil Layer 4	2

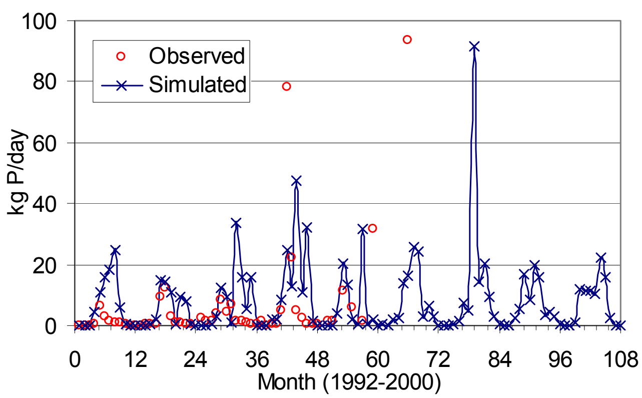

Figure 4. Best-fit model to observed P data.

Conclusions

Using public data that can be easily incorporated using the ArcView interface, SWAT accurately simulated mountain-watershed hydrologic processes. Variables associated with elevation-dependent temperature and precipitation (e.g. orographic) effects and snowmelt were adjusted. The orographic and snowmelt factors are particularly significant in the Lake Dillon watershed, where the elevation varies approximately 2000m.

A sensitivity study was completed to assess the influence of input parameters on simulated P transport. Several model input parameters were adjusted. Simulated P matched the overall trends of the limited measured data along the Blue River upstream of Lake Dillon. Because simulations without 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.

The uncertainty associated with the assignment of some chemical and hydrologic parameters indicates that additional information on the actual values and variability of pollutant-transport input variables is necessary. This is a feasible option, considering that most of the parameters containing approximated values (P soil-partitioning coefficient, mineral P concentration in the soil, and soil bulk density) may be quantified with additional collection and analysis of field data from the Lake Dillon watershed. However, it is not clear that additional measurement would benefit these particular simulations. For example, if parameter values varied greatly over the watershed, it may be impractical to collect enough measurements to obtain accurate values of input parameters. In such cases, sensitivity studies that use the reasonable range of parameters to assess a range in possible model outcomes still can be very useful and may be the only option. Despite the uncertainties related to model inputs, the model performs reasonably well. Thus, the model may be used to investigate different management options, such as using sewers versus OWS for a variety of pollutants, the influence of growth and increased OWS, or evaluating the effect of advanced OWS treatment systems on watershed water quality.

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