

The Use of Scenario Analysis to Assess Water Ecosystem Services in Response to Future Land Use Change in the Willamette River Basin, Oregon

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Abstract. Human pressures on the natural resources of the United States have resulted in many unintended changes in our ecosystems, e.g., loss of biodiversity, habitat degradation, increases in the number of endangered species, and increases in contamination and water pollution. Environmental managers are concerned about broad-scale changes in land use and landscape pattern and their cumulative impact on hydrologic and ecological processes that affect stream conditions. The type of land use and land cover has direct consequences for most ecosystem services, including water quantity and water quality, erosion control, and biodiversity. As human pressure continues to increase, ecosystem services worldwide are projected to suffer continued loss and degradation, thus reducing the capacity of ecosystems to provide essential goods and services that contribute to human well-being [1]. The ability to assess, report, and forecast the life support functions of ecosystems is absolutely critical to our capacity to make informed decisions that will maintain the sustainable nature of our environment and secure these resources into the future. This study presents an integrated approach to identify areas with potential water quality problems as a result of land cover change projected by stakeholders within a moderately large river basin in the Pacific Northwest (USA). A process-based hydrologic watershed model was used to examine the contribution of land use/land cover to sediment yield, and nitrate and phosphorus loadings, and identify subwatersheds within the Willamette River Basin that would be most affected in the year 2050 relative to three possible future scenarios, which include inherent differences related to conservation, existing planning trends, and open development. Thus, the objective of this study was to evaluate the effects of alternative future scenarios that describe varying degrees of urban development and human use on hydrological response related to water quality. Results of this study suggest that the amount of forest along streams and agriculture consistently explained a high percentage of variation in nutrients. The AGWA-SWAT model was used to simulate change in sediment yield, nitrate and phosphorus transported with surface runoff for the three future scenarios. With regard to nitrate, the greatest increase was associated with subwatersheds with agricultural land use and urban areas. Although the model predicted some

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improvement in basin headwaters for all scenarios, nitrate loadings are expected to decrease under the conservation scenario. The largest decrease was observed in the Coast Range. With regard to phosphorus loadings, the greatest reduction was observed in subwatersheds draining predominantly forest areas. The greatest increase was observed under the open development scenario in subwatersheds with agricultural land use. Urbanization and agriculture are presumed to be the major environmental stressors affecting watershed condition of the Willamette River Basin.

Keywords: Ecosystem services, hydrological process models, scenario analysis, Willamette River, alternative futures, watershed assessment, sediment yield, nitrate, phosphorus, nutrients

Introduction

Sustainable societies are dependent on the goods and services provided by ecosystems, including clean air and water, productive soils, and the production of food and fiber [1]. Ecosystem services have been defined as basic outputs of ecological functions or processes that directly or indirectly contribute to human health and well-being (including economic prosperity). The United Nations initiated the Millennium Ecosystem Assessment to assess the consequences of ecosystem change to human well-being and provide the scientific basis for action needed to enhance the conservation and sustainable use of those systems. Their findings provided a state-of-the-art appraisal of the condition and trends in the world's ecosystems and the services they provide, as well as the call for action to conserve and use them sustainably. It is the provision of these basic services and their probability for continuation that serve as core ingredients to the concept of human and environmental sustainability. The dilemma before us is to recognize and anticipate change in ecosystem services, in all of its forms, and to understand the impacts to human society before they reach levels of imminent threat.

This study presents a modeling approach integrated with scenario analysis [2] to identify areas with potential water quality problems in the Willamette River Basin, Oregon. Water quality is an important hydrological service produced by terrestrial ecosystem effects on freshwater [3]. A hydrological process model and land use future scenarios were used to examine the contribution of land use/land cover to sediment yield, and nitrate and phosphorus loadings, and to identify subwatersheds within the Willamette River Basin that would be most affected in the year 2050 relative to three possible future scenarios including differences related to conservation, planning, and open development.

1. Materials and Methods

1.1. Willamette River Basin

The Willamette River Basin is the 13th largest river in the contiguous 48 states and produces more water per land area than any of the larger rivers of the United States [4]. Its total annual discharge makes up 12 to 15 percent of the total flow of the Columbia River [5]. The Willamette River Basin is 290 km long and 29,728 km² in area, bounded on the west by the Coast Range and on the east by the Cascade Mountain Range. The basin centroid is 45° N latitude and 123° W longitude. The basin makes up 12 percent

of the Oregon state land area and contains 68 percent of the state's population (figure 1).



Figure 1. Location of the Willamette River Basin, Oregon.

Across the basin, average annual air temperature ranges from 4°C to 19°C depending on elevation. In the valley, mean minimum air temperature in January averages 3°C to 5°C, whereas in the summer monthly means range from 17°C to 20°C. Precipitation averages approximately 100 cm/yr at the lowest elevations and approaches 500 cm/yr near the crests of the Cascade Mountains and Coast Range [5]. Across the Willamette basin, estimates of average precipitation and recharge (surface-water runoff plus groundwater recharge) are 130 cm/yr and 50 cm/yr, respectively [6]. Most of this precipitation (70 to 80 percent) occurs between September and April during the wet season, and less than 5 percent of the precipitation occurs during the dry season in May through August.

Water quality has been a major environmental concern since the late 1920s [5]. The Willamette River was one of the 50 sites studied as part of the National Water Quality Assessment (NAWQA) program led by the U.S. Geological Survey [7].

Overall, nutrients and contaminants in the Willamette River were ranked as typical of concentrations found in other NAWQA sites. Nitrate-nitrogen concentrations ranged from 0.054 to 22 mg/L in 98 percent of the samples, and increased as the area of agricultural land increased [7]. Soluble reactive phosphorus concentrations in streams ranged from 0.01 to 0.93 mg/L in 89 percent of the samples.

Three alternative visions for the future of the region were presented in 10-year increments through 2050 [8]. All three 2050 future alternatives start from the same initial landscape configuration, represented by land use/land cover ca. 1990. These were based on basin stakeholder input regarding policies for urban and rural residential, agriculture, forestry, and natural lands and their associated water uses. The alternative future scenarios are intended not as predictions, but rather to bracket a range of plausible options for future land and water use in the Willamette River Basin.

By the year 2050, the number of people who inhabit the Willamette River Basin is expected to double. This increase will undoubtedly place significant demands on existing ecosystem services and has the potential to threaten the security and sustainable management of basin natural resources. The baseline condition of circa 1990 was selected and a set of land cover/land use maps were developed by Baker et al. [8] for the year 2050 based on current land management and projected census growth. For the purpose of this study, the 2050 maps were selected for three scenarios that reflected important contradictions in desired future policy based on stakeholder input. The scenarios are listed in table 1 and basically reflect changes in population within the watershed, patterns of growth, and development practices and constraints.

Table 1. Alternative-future scenarios in the Willamette River Basin, Oregon in the year 2050 (adapted from [8]).

| | |
|-------------------|--|
| Conservation 2050 | Places greater priority on ecosystem protection and restoration, although still reflecting a plausible balance between ecological, social, and economic considerations as defined by citizen stakeholders. |
| Plan Trend 2050 | Assumes existing comprehensive land use plans are implemented as written, with few exceptions, and recent trends continue. |
| Development 2050 | Assumes current land use policies are relaxed and greater reliance on market-oriented approaches to land and water use. |

1.2. Approach

The general approach used in this study was carried out in two steps. The first step consisted of applying the Automated Geospatial Watershed Assessment (AGWA) Tool [9] to parameterize the Soil Water Assessment Tool (SWAT) [10]. The second step consisted of evaluating the effects of alternative future scenarios on water quality in the year 2050 relative to three possible future scenarios that include inherent differences related to conservation, planning, and open development.

1.3. Description of AGWA

The AGWA tool uses widely available standardized spatial data sets to develop input parameter files for the KINEROS2 [11] and SWAT watershed runoff and erosion models. Using digital data in combination with the automated functionality of AGWA greatly reduces the time required to use these two models. The user selects an outlet from which AGWA delineates and discretizes the watershed using the digital elevation model. The watershed elements are then intersected with the soil, land cover, and

precipitation (uniform or distributed) data layers to derive initial model input parameters. The model is then run, and the results are imported back into AGWA for visual display. AGWA is available in both ArcView [12] and ArcGIS versions [13] and is designed to provide qualitative estimates of runoff, erosion, and several measures of water quality relative to landscape change. Decision makers can use it to identify problem areas where management activities can be focused, or to anticipate sensitive areas where concerted planning efforts could be applied to ameliorate impacted conditions.

1.4. Model Description

A detailed theoretical description of SWAT and its major components can be found in Neitsch et al. [14] (http://www.brc.tamus.edu/swat/soft_model.html). Previous applications of SWAT for flow and/or pollutant loadings have compared favorably with measured data for a variety of watershed scales [15-18].

The Willamette River Basin boundary was delineated using an outlet point located at the Portland USGS stream flow gauge. A Contributing Source Area (CSA) of 1 percent of the total area of the Willamette basin was used to generate the stream channel network and 111 subwatersheds.

Daily precipitation and maximum and minimum temperature were obtained for 68 stations from the Oregon Climate Service database. Solar radiation, wind speed, and relative humidity were generated internally with the built-in weather generator developed for the contiguous United States [19].

1.5. Configuration of AGWA-SWAT for Baseline and Future Scenarios

A detailed description of the calibration and validation of the SWAT model for surface runoff can be found in Kepner et al. [18]. Long-term calibration for sediment and nutrients could not be done because there were not enough data available with which to calibrate the model. The model was run for a 25-year period (1977–2001) following a one-year model initiation period that used data from 1976 to 1977. The initiation period established appropriate initial conditions for soil water storage. The 25-year period was divided into two parts to perform calibration and validation of the hydrological model using observed runoff data [18]. The calibration and validation of the model were carried out on the basis of the data for the periods 1977–1991 and 1992–2001, respectively. Calibration of the hydrologic model was conducted against USGS data from four gauging stations along the Willamette River. Several studies have demonstrated that the AGWA interface can successfully select initial input parameter values for SWAT without calibration in a wide variety of hydrologic systems and geographic locations using readily available GIS databases [20-22, 18].

SWAT estimates the initial concentration of mineral nitrate based on the soil properties at individual sub-basins. Therefore, no adjustments were made to initial concentration of mineral nitrate. The initial concentration for mineral phosphorus in the soil upper layer for each different land use was set at the appropriate levels based on available literature.

2. Results

2.1. Watershed Hydrology

To determine the spatial distribution of sediment yield, and nitrate and phosphorus loadings, calculations were carried out on a water-year basis (October–September) and results are shown as average annual values over the 25-year period.

The mean spatial daily suspended sediment concentration averaged over the 25-year simulation period is shown in figure 2 for the model channel reaches. Notice that mean suspended sediment concentration for the Cascade Mountain tributaries are lower than the Coastal Mountain tributaries. The largest concentrations occur along the Willamette River near Portland and the mean daily concentrations averaged over the 25-year simulation period vary from 16 gm/m^3 to 25 gm/m^3 . However, an observed daily concentration over 100 gm/m^3 was recorded in the 2000 water year. The 1981 and 2000 water year sedigraphs are shown in figure 2; notice that the model predicted the overall trend of daily suspended sediment concentration at Portland.

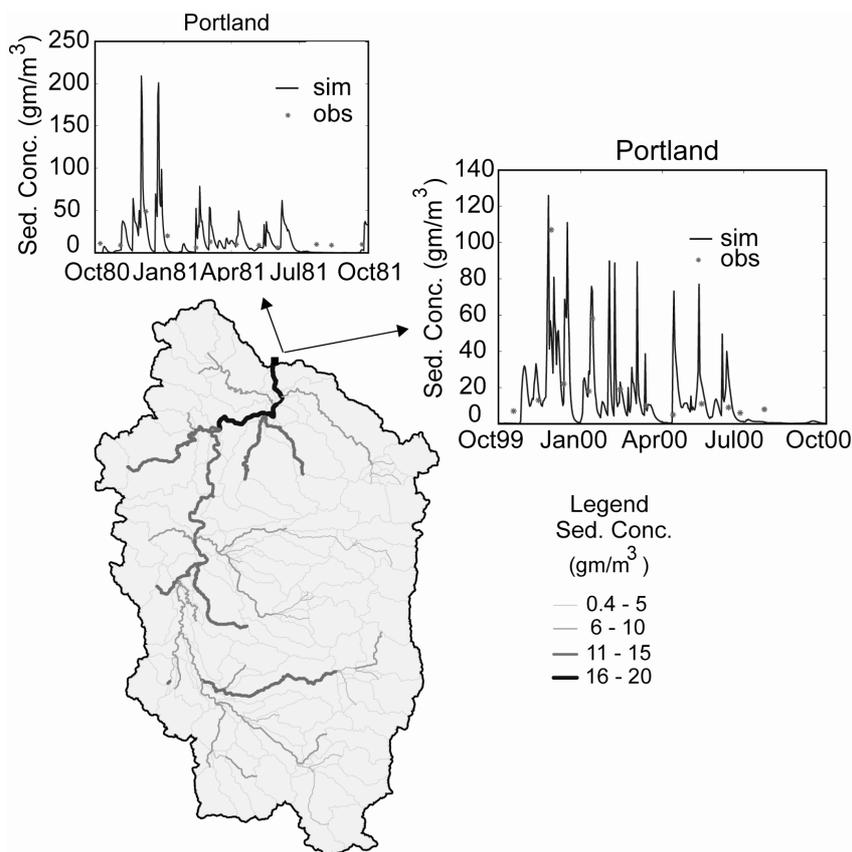


Figure 2. Spatial distribution of mean daily sediment concentration in channel reaches averaged over a 25-year simulation period.

Suspended sediment is important to characterize water quality because nutrients, such as phosphorus and nitrogen, and toxic constituents, such as dioxin and chlorinated pesticides, can be transported in association with fine sediments.

Average annual nitrate loading averaged over the 25-year simulation period is shown in figure 3. The variability of average annual nitrate loadings ranged from 0.2 to 2.5 (kg N/ha). The lowest loading was detected in forested areas and the highest loading in urban areas, particularly near the city of Portland. Figures 4 and 5 contain additional detail about the results of daily mineral nitrate concentration from the period 1989–2001 at the Portland USGS streamflow gauge. Since there were not enough data with which to calibrate the nutrient component of the model, all results were compared on a relative basis. Based on figure 4, it can be argued that the SWAT model was able to capture the overall trend of observed averaged daily mineral nitrate concentration; however, the correlation coefficient between simulated and observed average daily mineral nitrate yielded a value of 0.31.

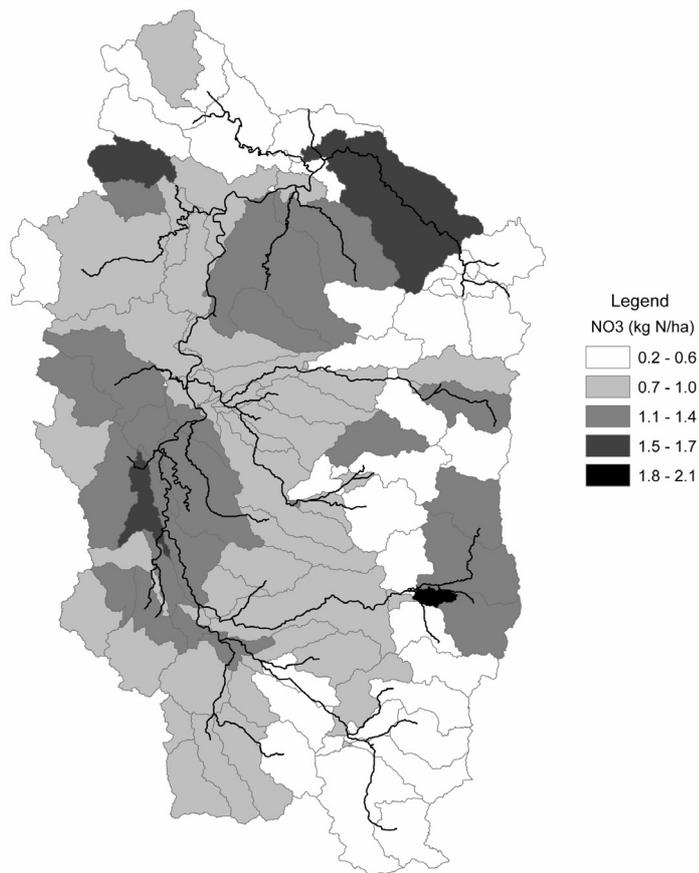


Figure 3. Spatial distribution of average annual nitrate loading over a 25-year simulation in upland model elements (black lines are channels, gray lines are subwatershed boundaries).

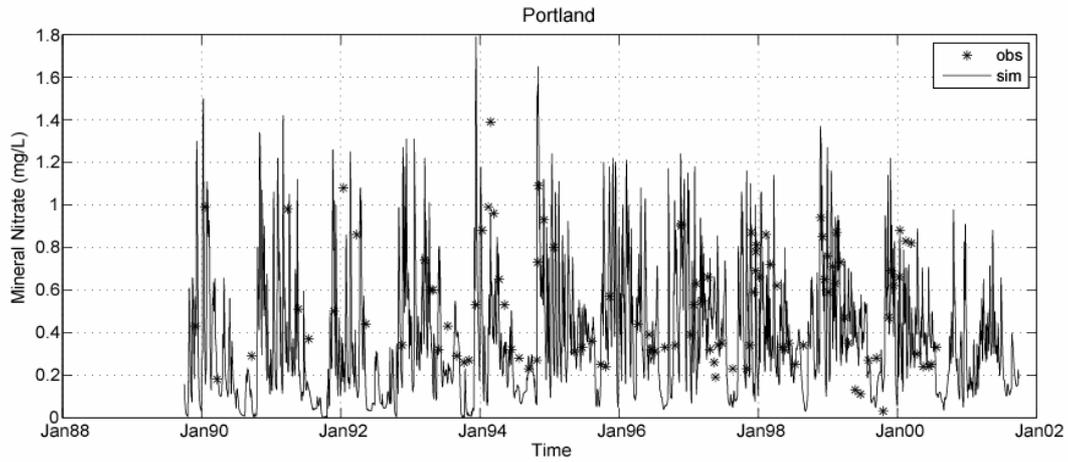


Figure 4. Observed and simulated daily nitrate concentration for the period 1989–2001 at Portland USGS streamflow gauge.

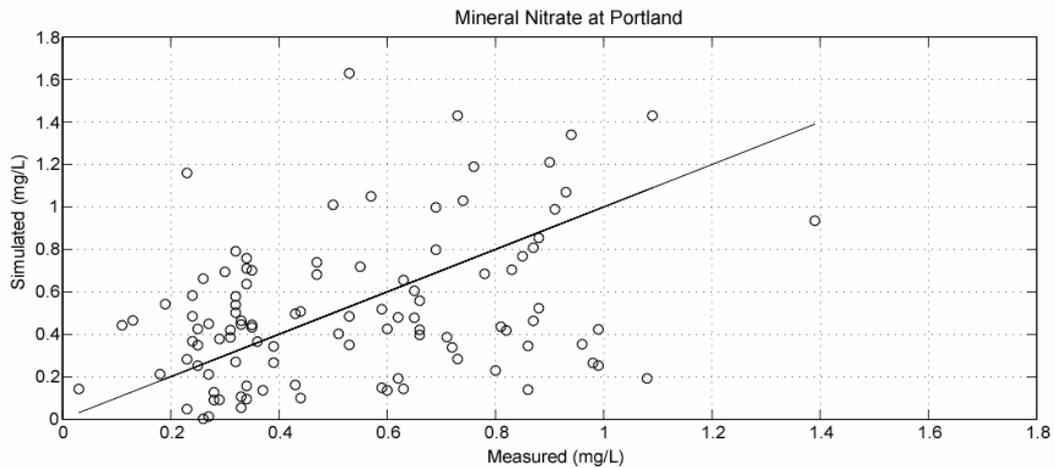


Figure 5. Scattergram of observed and simulated daily mineral nitrate concentration from the period 1989–2001 at the Portland USGS streamflow gauge.

Figure 6 depicts the spatial distribution of average annual soluble phosphorus loading averaged over a 25-year period simulation. Soluble phosphorus yields were highest in agricultural land. The observed and simulated daily soluble phosphorus concentrations from the period 1989–2001 at the Portland USGS streamflow gauge is shown in figure 7. It is apparent that the model was able to simulate the overall trend, primarily the low concentrations. The scattergram of observed and simulated daily soluble phosphorus concentration for the period 1989–2001 at Portland is shown in figure 8; the correlation coefficient is 0.17.

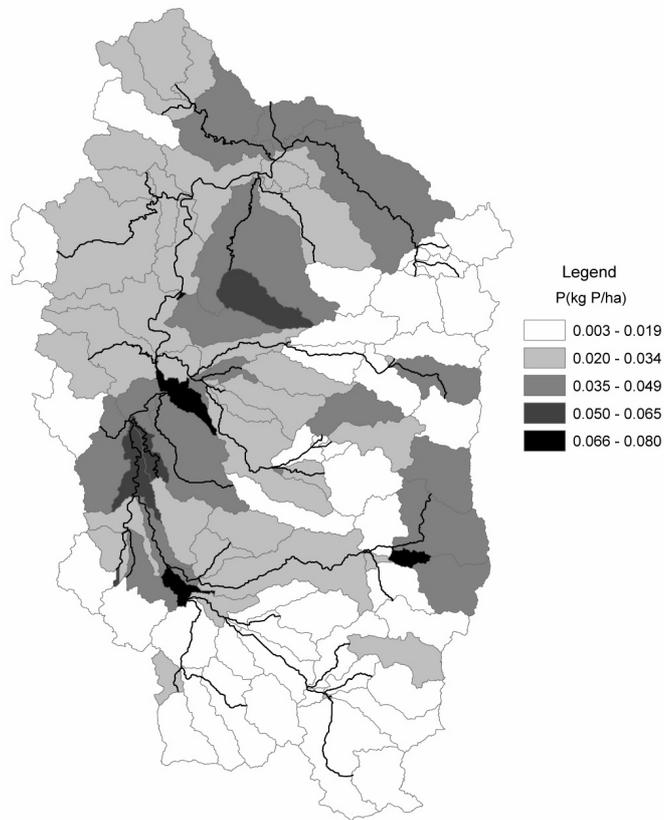


Figure 6. Spatial distribution of average annual phosphorus loading over a 25-year simulation in upland model elements (black lines are channels, gray lines are subwatershed boundaries).

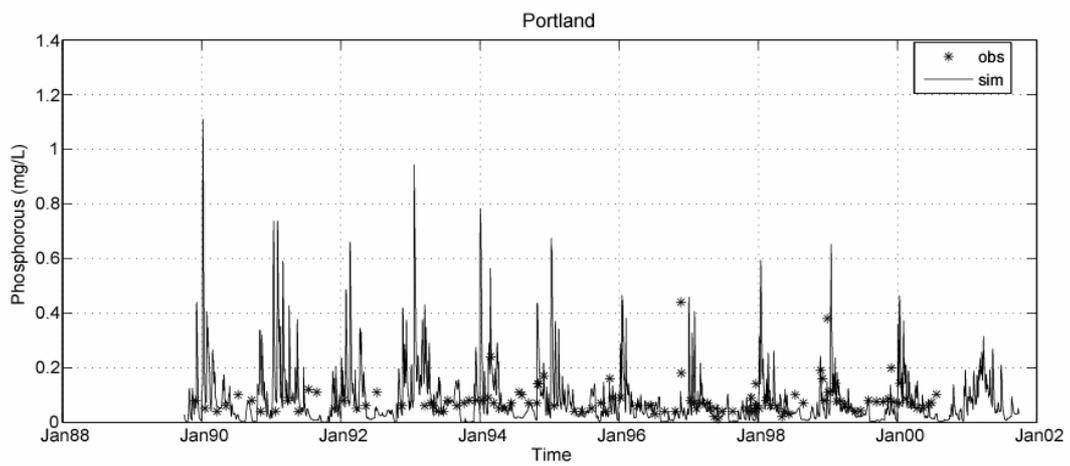


Figure 7. Observed and simulated daily soluble phosphorus concentration for the period 1989–2001 at the Portland USGS streamflow gauge.

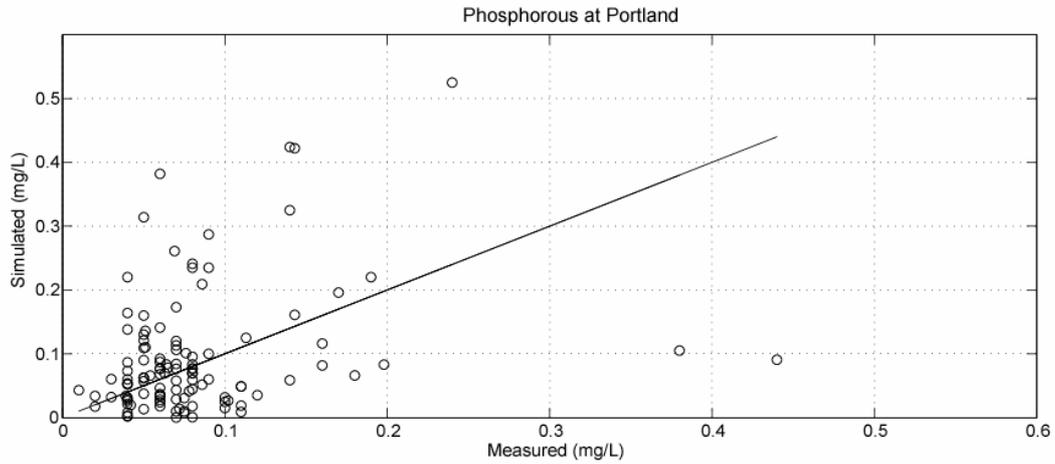


Figure 8. Scattergram of observed and simulated daily soluble phosphorus concentration for the period 1989–2001 at the Portland USGS streamflow gauge.

2.2. Alternative Future Analyses/Temporal and Spatial Variation

To evaluate each alternative future, the calibrated hydrologic model was run using each of the three 2050 land cover scenarios to develop parameter inputs. Average annual outputs for sediment yield, nitrate and phosphorus loadings, and average daily estimates for sediment concentration from the three alternative futures were differenced from the baseline values to compute percent change over the 60-year period. Results from the simulation runs are given in table 2 and figures 9–12. These figures show the relative departure from the 1990 baseline year and illustrate the spatial variability of changes to the surface water quality. In general, the simulation results indicate that land cover changes associated with future development will moderately alter the water quality conditions of the basin. Changes are primarily associated with increasing urbanization and the associated replacement of vegetated surfaces with impervious ones.

Table 2. Simulated average annual sediment yield, nitrate, and phosphorus for the 1990 baseline and future conditions and predicted relative change for each of the three development scenarios at the watershed outlet.

| Water Quality Components | Baseline 1990 | Simulated Percent Relative Change 1990–2050 | | |
|----------------------------|---------------|---|-------------|------------|
| | | Conservation | Development | Plan Trend |
| Sediment Yield (t/ha) | 36.69 | 32.22 | 33.70 | 36.42 |
| | | -12.18% | -8.15% | -0.74% |
| Nitrate (kg/ha) | 0.785 | 0.772 | 0.788 | 0.789 |
| | | -1.66% | +0.38% | +0.51% |
| Soluble Phosphorus (kg/ha) | 0.025 | 0.025 | 0.026 | 0.025 |
| | | 0% | +4.00% | 0% |

Sediment yield and erosion are directly related to runoff volume and velocity. The percent change in sediment yield and sediment concentration simulated with SWAT displayed a high degree of spatial variability across the basin and among the three scenarios (figures 9 and 10). Subwatersheds with the greatest increase in sediment yield do not necessarily correspond with those exhibiting the greatest change in surface

runoff; however, those model elements in the northern headwaters and in the valley generally showed the greatest increase in sediment yield. Sediment yield at the outlet of the watershed decreases an average 12 percent under Conservation 2050, 8 percent under Development 2050, and approximately 1 percent under Plan Trend 2050 scenarios (table 2). Furthermore, channel reach sediment concentrations are shown in figure 10; notice that the maximum percent change increases occurred under the Development 2050 and Plan Trend 2050 with 1 percent and 0.5 percent change, respectively (figures 10b, 10c). The largest maximum reduction of sediment concentration with 1 percent was perceived under the Conservation 2050 scenario, and the smallest maximum reduction was detected under the Development 2050 with 0.25 percent reduction. Notice that under the Conservation 2050 scenario no increase of sediment concentration was detected (figure 10a). The channel reach sediment concentration map provides some understanding about the sediment dynamics occurring between land cover and channels. For instance, forest management practices that change forest conditions will inevitably change channel conditions and must therefore be carefully tailored to mitigate adverse impacts on riverine habitat.

There has been concern about the water quality within the Willamette River Basin for several years in response to the continuing expansion of agricultural land and urban development. Among the many problems caused by water pollution, nutrient loading is one of the most serious and widespread in the basin. For example, during 1991, about 63,000 tons of nitrogen and 20,000 tons of phosphorus fertilizer were applied in the Willamette basin [23]. These elements are essential nutrients for aquatic plants; however, in high concentrations, they can cause excessive growth that constricts stream channels. When introduced to the landscape in dissolved form, phosphorus and nitrogen show different responses to runoff processes. Nitrogen, which is generally more abundant, tends to be highly mobile in the soil and subsoil, moving with the flow of soil water and groundwater to receiving water bodies. In contrast, phosphorus tends to be retained in the soil, being released to the groundwater very slowly.

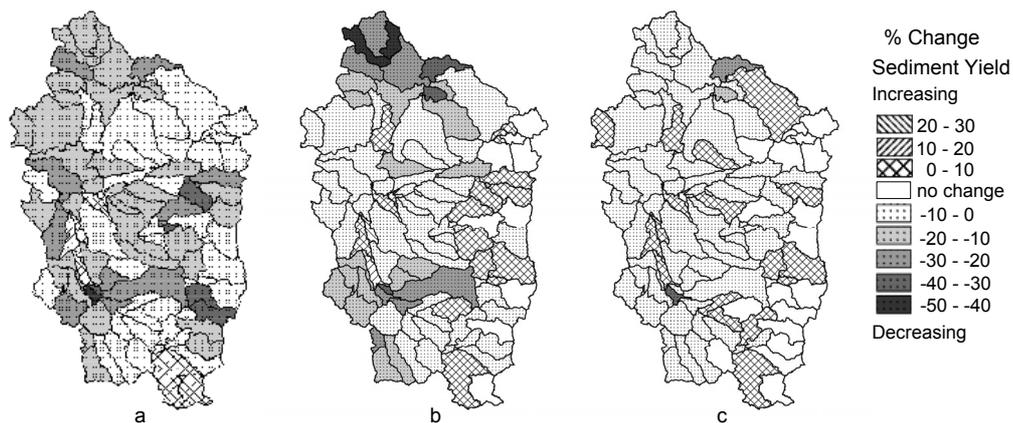


Figure 9. Percent change in sediment yield, 1990–2050, Willamette River Basin; a) Conservation 2050, b) Development 2050, c) Plan Trend 2050.

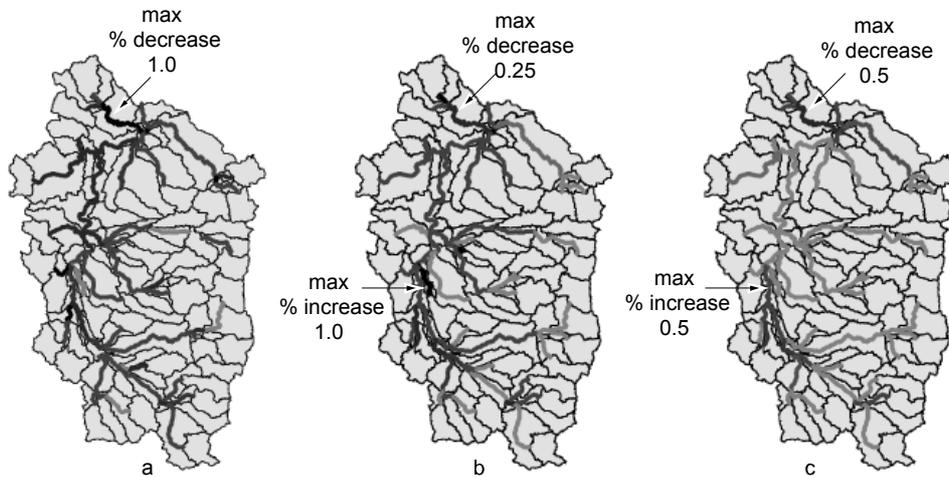


Figure 10. Percent change in model channel reach sediment concentration, 1990–2050, Willamette River Basin; a) Conservation 2050, b) Development 2050, c) Plan Trend 2050.

Percent change differences between the 2050 scenarios and the 1990 baseline are very small based on the nitrate and soluble phosphorus results at the watershed outlet (table 2). The largest percent of the watershed area that realized an increase in sediment, nitrogen, and phosphorus was produced under the Plan Trend 2050 scenario as shown in table 3. Based on the results presented in table 2, at the outlet of the watershed, the largest reduction to sediment yield, nitrogen, and phosphorus was achieved under the Conservation 2050 scenario. However, as shown in figures 11 and 12, a few subwatersheds have an important local effect on the water quality conditions of the basin. With regard to nitrate, the greatest increase is associated with subwatersheds with agricultural land use and urban areas. Although the model predicts some improvement in the basin headwaters for all scenarios, overall nitrate loading is expected to decrease up to 9 percent under the Conservation 2050 scenario (figure 11a). Most of the simulated decrease in this indicator was observed in the Coast Range.

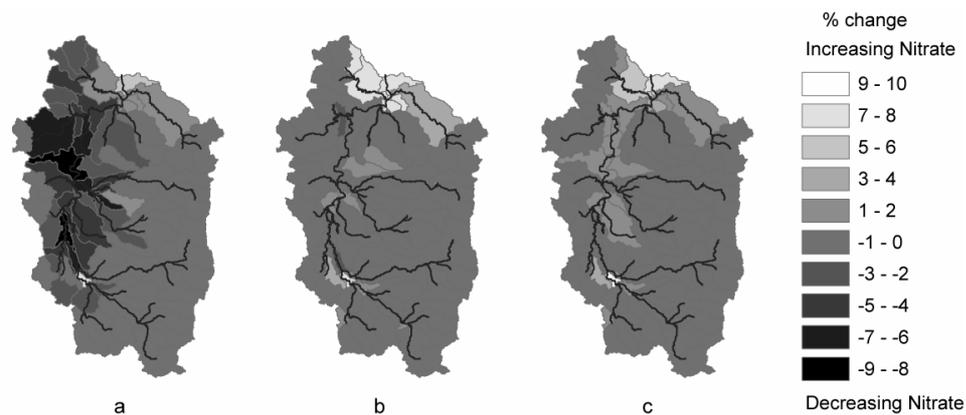


Figure 11. Percent change in nitrate transported with surface runoff, 1990–2050, Willamette River Basin; a) Conservation 2050, b) Development 2050, and c) Plan Trend 2050.

With regard to phosphorus loadings, the greatest reduction in phosphorus loadings was observed in subwatersheds draining predominantly forest areas. However, a maximum 50 percent change increase was observed under the Development 2050 future scenario in northern subwatersheds with agricultural land use (figure 12b).

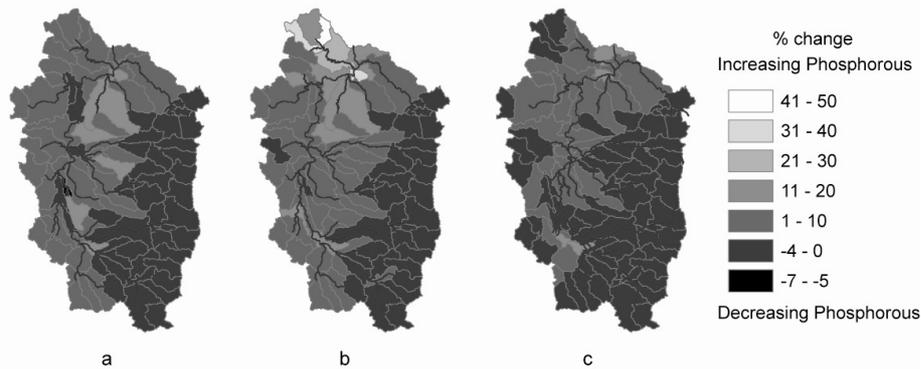


Figure 12. Percent change in phosphorus transported with surface runoff, 1990–2050, Willamette River Basin; a) Conservation 2050, b) Development 2050, and c) Plan Trend 2050.

Table 3. The percent of the watershed area that realized an increase in sediment, nitrogen, and phosphorus for each future scenario.

| Water Quality Components | Conservation (%) | Development (%) | Plan Trend (%) |
|--------------------------|------------------|-----------------|----------------|
| Sediment Yield | 5.53 | 15.33 | 18.86 |
| Nitrate | 9.57 | 43.29 | 62.90 |
| Soluble Phosphorus | 6.06 | 14.73 | 22.66 |

In general, under a future urbanizing environment, the model simulation results appear to indicate that changes in stream condition within the Willamette basin are subtle for all of the forecast scenarios as compared to the 1990 baseline condition. However, some subwatersheds did show some important impacts to the subwatershed water quality. The most notable changes are likely to be increases in the amount of sediment discharge, nitrate, and phosphorus loadings.

3. Summary and Conclusions

For the purpose of this study, negative impacts are considered to be increases in sediment concentration, nitrogen, and phosphorus loadings. The impacts are summarized graphically by percent change relative to the 1990 reference condition for each of the alternative futures using subwatersheds as the comparative unit. Urbanization and agriculture are presumed to be the major environmental stressors affecting watershed condition of the Willamette River Basin.

In general, the Development 2050 scenario has the greatest negative impact on water quality and results in greater simulated sediment concentration, and mineral nitrate transported with surface runoff and soluble phosphorus, especially in the downstream reaches near Portland and reaches along the Willamette Valley. Typically development scenarios favor growth and allow for the largest future population increase within the watershed.

It is important to highlight that under the Conservation 2050 scenario, sediment yield is reduced considerably along the Coast Range Mountains. In regard to water quality, the spatial pattern depicted under the Conservation 2050 scenario suggests an important overall improvement on the environment given that nitrate loadings are decreased along the Willamette Valley and Coastal Range. However, it is also important to note that a small number of subwatersheds with increasing percent change in phosphorus appear in the Conservation 2050 scenario.

This study demonstrates the ability of integrating landscape spatial analysis with hydrological process models to evaluate options for potential future population growth at the river basin and subwatershed scales. Specifically it uses the AGWA tool to examine specific hydrological response endpoints that are considered important indicators related to measuring or accounting for ecosystem services. In this case, a clean, reliable water source available for potable consumption, safe recreation, and industrial/agricultural use is the benefit that humans receive as an ecosystem service and a requisite for sustainable development [3, 24-25].

Collectively, scenario analysis coupled with process models should greatly enhance our ability to analyze benefits related to decision making involving the sustainable use and conservation of our ecosystems and the goods and services they provide. Spatial modeling and analysis tools, such as AGWA, can 1) establish a standard set of measures and approaches for quantifying and monitoring ecosystem services; 2) provide one of the most powerful approaches to quantify and forecast the relative impacts to ecosystem services; and 3) thus improve our combined decision making for the future.

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