THE USE OF SCENARIO ANALYSIS TO ASSESS FUTURE LANDSCAPE CHANGE ON WATERSHED CONDITION IN THE PACIFIC NORTHWEST (USA)

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Abstract. The ability to assess, report, and forecast the life support functions of ecosystems is absolutely critical to our capacity to make informed decisions which will maintain the sustainable nature of our environmental services and secure these resources into the future. Scenario analysis combined with landscape sciences can be used to characterize uncertainties, test possible impacts and evaluate responses, assist strategic planning and policy formulation, and structure current knowledge to scope the range of potential future conditions. In this study, potential impacts from three wide-ranging scenarios in a large regional area in the northwest United States are compared to current conditions (ca. 1990) of the region in terms of a set of processes that are modeled in a geographic information system (GIS). 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 the basin. Landscape metrics in conjunction with hydrological process models were used to examine the contribution

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of land use/land cover to water and sediment yield and identify subwatersheds within the Willamette River Basin (Oregon, USA) that would be most affected in the year 2050 relative to three possible future scenarios which include inherent differences related to conservation, planning, and open development. Specifically, this study provides one example of the use of landscape sciences for environmental assessment that examines the impact of both urban and agricultural development in a large river basin. In particular, it attempts to (1) answer questions that relate to future scenarios that describe contrary positions related to urban development, (2) provide information which can be used to assess the potential changes of the landscape relative to human use, and (3) provide options that could be useful for sustainable management of natural resources and thus minimize future hydrologic and environmental impacts.

1. Introduction

In a traditional sense, security has always represented individual or collective safety achieved through protection of border and political sovereignty and cast in state, regional, or national interests. Concern over the environment has now expanded the need to include it into security policy, especially as it affects strategic renewable resources. Environmental problems related to depletion and scarcity are now seen as threats to human livelihood and thus can contribute to social and economic inequality which can lead to tension or in a worse case can result in open conflict. Land degradation, water quality and quantity, climate change, and the management and distribution of natural resources (e.g. water, forests, oil and minerals) are factors which can either directly contribute to conflict or can be intrinsically linked to social outcomes which result in poverty, migration, infectious diseases, and declining economic productivity.

The ability to assess, report, and forecast the life support functions of ecosystems is absolutely critical to our capacity to make informed decisions which will maintain the sustainable nature of our environmental services and secure these resources into the future (SCEP, 1970). It is from this perspective that we have used the state of Oregon and particularly the Willamette River basin to demonstrate the integration of advanced technologies (such as satellite remote sensing and land cover characterization, large digital primary datasets, spatial statistics, and process models) with landscape ecological theory to examine

impacts in environmental processes. Specifically, this study provides one example of the use of landscape sciences for environmental assessment that examines the impact of both urban and agricultural development in a large regional area in the northwest United States. In particular, it attempts to (1) answer questions that relate to future scenarios that describe contrary positions related to urban development, (2) provide information which can be used to assess the potential changes of the landscape relative to human use, and (3) provide options that could be useful for sustainable management of natural resources and thus minimize future hydrologic and environmental impacts.

In this study, potential impacts from three wide-ranging scenarios are compared to current conditions of a region in terms of a set of processes that are modeled in a geographic information system (GIS). Alternative futures land-scape analysis involves (1) describing development patterns and significant human and natural processes that affect a particular geographic area of concern; (2) constructing GIS models to simulate these processes and patterns; (3) creating changes in the landscape by forecasting and by design; (4) and evaluating how the changes affect pattern and process using models (US Environmental Protection Agency, 2000). 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 the basin. Landscape metrics describing spatial composition and spatial configuration were computed using the Analytical Tools Interface for Landscape Assessments (ATtILA) tool (Ebert and Wade, 2004). The landscape metrics generated from ATtILA were used in conjunction with the Automated Geospatial Watershed Assessment (AGWA) tool (Hernandez et al., 2005) to examine the contribution of land use/land cover to water and sediment yield 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, planning, and open development.

2. Materials and Methods

2.1. WILLAMETTE RIVER BASIN

Oregon is the 10th largest of the U.S. states (Figure 1). It comprises an area of 251,418 km^2 and is bounded by the Pacific Ocean on the west and the states of Nevada and California on the south, Washington on the north, and Idaho on the east. The major landforms in Oregon include the Coast Ranges and the Cascade Range, a region which includes the snow-capped and glaciated peaks of Mount Hood and Mount Jefferson (Omernik and Gallant, 1986, Thorson et al., 2003). The Willamette River Valley is a substantial basin which empties into the

Columbia River near the city of Portland and is situated between the Coast and Cascade ranges. According to US Census records, nearly 70% of Oregon's population lived in the Willamette Valley in 1990. Most of the Willamette Valley is urban, privately owned, and used heavily for agriculture. Much of Oregon's economy is directed by activities that occur in the counties that comprise this river valley and thus the economy of the study area is based most notably on the forest products, tourism, agriculture/livestock, and more recently, the electronics industries. The mountainous areas in the eastern half of Oregon are primarily managed by the federal government (e.g. US Forest Service) while most of the lower-elevation plateau areas are agriculturally based private land which support dryland wheat farming, fruit orchards, and livestock ranching operations. Annual precipitation in the study area varies greatly, from less than 25–460 cm and elevations range from sea level on the coast to as high as 3,426 m at Mount Hood. Approximately 3.5 million people reside within the state of Oregon, most of whom live in the cities and suburbs along or adjacent to Interstate 5, including Portland, Salem, Eugene, Albany, Corvallis, and Medford. There are also many smaller towns along the Pacific Coast on US Route 101, such as Florence, Lincoln City, Newport, and Coos Bay as well many state recreation areas and parks.

By the year 2050, the number of people who inhabit the Willamette River Basin is expected to double which undoubtedly will place huge demands on existing environmental services and has the potential to threaten the security and sustainable management of natural resources. Digital data were collected from a variety of public sources, e.g. Oregon State University and US Environmental Protection Agency (Heggem et al., 2003). The baseline condition of ca. 1990 was selected and a set of land cover/land use maps were developed by Baker et al. (2004) 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 which 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. The Conservation Scenario is the most ecosystem protection and restoration oriented, the Plan Trend Scenario reflects the most likely census predictions with zoning options designed to accommodate growth, and the Development Scenario is the least conservation and most market-economy positioned option. All three scenarios assume the same level of population increase, i.e. 2.0–3.9 million by 2050.

Figure 1. Location of the study area.

TABLE 1. Alternative-future scenarios in the Willamette River Basin, Oregon in the year 2050. (Adapted from Baker et al., 2004.)

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

2.2. APPROACH

The general approach used in this study was carried out in three steps. The first step consisted of evaluating the entire state of Oregon using descriptive landscape metrics in 3 km grids. Landsat Thematic Mapper (TM) data were the basis in production of the statewide land cover grids (Baker et al., 2004). The data set contained 65 classes of land use/land cover in 30 m resolution pixels and was aggregated into a National Land Cover Data 21-class system (Anderson et al., 1976; Vogelmann et al., 2001). The land cover grids were also reprojected from NAD27 datum to NAD83 to be consistent with the other data utilized for the ATtILA landscape metric analysis and AGWA watershed assessment. ATtILA was used to compute the landscape metrics across the state and from the initial analysis of 65 metrics it was determined that 11 metrics representing three families of measurement, i.e. landscape characteristics, riparian characteristics, and human stressors, were the most diagnostic (Table 2). Landscape characteristics are related to land cover proportions (e.g. percentage of

TABLE 2. Eleven most diagnostic landscape metrics applied to Oregon. (Adapted from Ebert and Wade, 2004.)

I. Landscape characteristics	
A. Land cover proportions	
U-Index	Percentage that is all human land use
N-Index	Percentage that is all natural land use
Pagt	Percentage that is all agricultural use
Purb	Percentage that is all urban use
B. Slope metrics	
AgtSL3	Percentage that has any agricultural use with slopes that are equal to or exceed 3%
II. Riparian characteristics	
Ragt0	Percentage of stream length adjacent to all agricultural use with zero buffer
Rhum0	Percentage of stream length adjacent to all human land use with zero buffer
Rnat0	Percentage of stream length adjacent to all natural land use with zero buffer
III. Human stressors	
P_Load	Phosphorous loading (kg/ha/yr)
N_Load	Nitrogen loading (kg/ha/yr)
Popdens	Population density count/area in km^2

anthropogenic use) and slope metrics (e.g. percentage of agricultural use with slopes that are equal to or exceed 3%). Riparian Characteristics describe land cover adjacent to and near streams (e.g. percentage of stream length adjacent to all human land use with zero buffer). Human stressors are concerned with population, roads, and land use practices (e.g. population density count/area in km^2). Three types of output display were provided once metrics were generated by ATtILA. The first displayed areas ranked by individual metric value, the second ranked areas by a weighted index made up of two or more metrics, and the third displayed a bar chart of selected areas and metrics.

The 11 ATtILA metrics identified the Willamette River Basin as the most anthropogenically modified feature in the entire state of Oregon. In a preceding study, the future Willamette River scenarios were determined with input from local stakeholders and the land cover grids were modified accordingly to reflect their desired future conditions (Hulse et al., 2004). These land cover grids for the three alternative futures were then subject to evaluation relative to surface hydrologic endpoints of concern using AGWA. The AGWA tool (Miller et al., 2007; Hernandez et al., 2005) is a multipurpose hydrologic analysis system for use by watershed, natural resource, and land use managers and scientists in performing watershed- and basin-scale studies. It was used in this study to evaluate the relative hydrologic consequences of anticipated future urban and suburban development. AGWA, as with ATtILA, is an extension for the Environmental Systems Research Institute's ArcView versions 3.X (ESRI, 2001), a widely used and relatively inexpensive PC-based GIS software package. The GIS framework is ideally suited for watershed-based analysis, which relies heavily on landscape information for both deriving model inputs and presenting model results. Both the ATtILA and AGWA tools are designed to support landscape assessment at multiple spatial and temporal scales and provide the functionality to conduct all phases of a watershed assessment. Both tools also use widely available standardized spatial data to develop the input parameter files and provide tabular statistics and graphic data displays. AGWA utilizes two widely used watershed hydrologic models: the Soil Water Assessment Tool (SWAT; Arnold et al., 1994); and a customized version of the KINematic runoff and EROSion model (KINEROS2; Smith et al., 1995). SWAT is a continuous simulation model for use in large (river-basin scale) watersheds such as the Willamette River Basin whereas KINEROS2 is an event-driven model designed for small arid, semi-arid, and urban watersheds.   Data requirements for both models include elevation, land cover, soils, and precipitation data. Our modeling approach involved running SWAT using the 1990 baseline land cover to parameterize the model to determine reference condition. The Willamette River basin boundary was delineated using an outlet point located at the Portland USGS stream flow gauge. The Willamette River is

fully regulated by seven water reservoirs in the larger tributaries in the Coast Range and Cascade Mountains; therefore, it was necessary to incorporate all of them in the analysis to have a better understanding of the regimes along the river. In addition, because SWAT requires that water reservoirs be placed on the main channel network, it was necessary to use a small Contributing Source Area (CSA) value. Several attempts using different CSA values were necessary to generate the drainage network that would be dense enough to place all seven water reservoirs on the main channel network. At the end of the iteration process, a CSA of 1% of the total area of the Willamette Basin was used to generate the stream channel network and 111 subwatersheds. The hydrologic model was run for a 25-year period (1977–2001) following a 1-year warm up period that used data from 1976 to 1977. The warm up period establishes appropriate initial conditions for soil water storage. The 25-year period was divided into two parts to perform calibration (1977–1991) and validation (1992–2001) of the hydrological model. Calibration of the model was carried out against USGS data from four stations along the Willamette River (station # 14211720 at Portland; station #14191000 at Salem; station # 14174000 at Albany; and station # 14152000 at Jasper near Eugene, see Figure 2).

Two criteria were used to assess yearly runoff simulated by SWAT. The first criterion is the model efficiency of Nash and Sutcliffe (1970), which Sevat and Dezetter (1991) found to be the best objective function for reflecting the overall fit of a hydrograph. Model efficiency expresses the fraction of the measured streamflow variance that is reproduced by the model. For annual streamflow, model efficiency may be expressed as

$$E = 1 - \frac{\sum \left(Q_{obs} - Q_{sim}\right)^2}{\sum \left(Q_{obs} - Q_{mean}\right)^2} \tag{1}$$

where E is the coefficient of efficiency, Q_{obs} is the observed annual streamflow (mm); Q_{sim} is the simulated annual streamflow (mm); and Q_{mean} is the mean observed annual streamflow during the evaluation period. The value of E in Eq. (1) may range from minus infinity to one, with one representing a perfect fit data. According to common practice (Van Liew and Garbrecht, 2003), simulation results are considered to be good for values of E greater than 0.75, while for values of E between 0.75 and 0.36 the simulation results are considered to be satisfactory. For this study, E values less than 0.36 were considered to be unsatisfactory. The second criterion is regression analyses. The regression analyses of the calibration data show how well the calculations of the model matched the data used to calibrate it. The regression of the validation data shows how accurately the predictions of the calibrated model match the subsequent measurements.
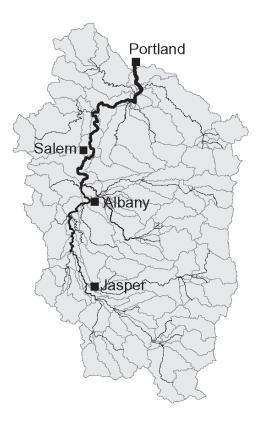
Figure 2. Location of USGS streamflow gauges.

To determine the impact of projected land cover future scenarios on the hydrologic regime of the Willamette River Basin, the 25-year period hydrologic simulation was performed using each of the three 2050 land cover scenarios to develop parameter inputs. Simulations for the future conditions were carried out using optimized parameters from the baseline conditions. Climate, and in particular precipitation, is a major source of uncertainty in hydrologic modeling. Changing climate and its associated impacts on basin hydrology, however, are a significant concern associated with future predictions. The future scenario simulations were run using precipitation and temperature from the 25-year simulation period. This treatment of climate is the most practical means of deriving climatic inputs for future simulations, and has the added benefit of eliminating climatic variations from assessments of hydrologic response to landscape change. Average annual outputs from the three alternative futures were differenced from the baseline values to compute percent change in average daily values in surface runoff, percolation, sediment yield, streamflow discharge, and sediment concentration over the 60-year period. The results

focus on the relative magnitude and spatial distribution of the computed changes and the ability to provide contemporary environmental assessment with plausible predictions related to the benefits (or subsequently the consequences) of visualizing future environments and their likely impacts.

3.   Results

3.1. ANALYSIS OF LAND COVER CHANGE

3.1.1. *Baseline scenario*

The percent of land cover distribution within the Willamette Basin for ca. 1990 is depicted in Figure 3. Forest land cover accounts for 69% of the land cover in the basin, with evergreen forest the predominant forest type. Wetland land cover types are found primarily in the northern part of the basin near Portland accounting for less than 1% of the total land cover, most of it in shrub wetlands. Agricultural land cover types comprise 19% of the total land cover. Pasture/hay and row crops are the dominant agricultural land uses in the central valley of the Willamette Basin. Urban land cover types account for 5% of the total land use. Shrub land cover comprises 5%, barren land cover types 1% and natural grasslands less than 1% of the total land cover, respectively.
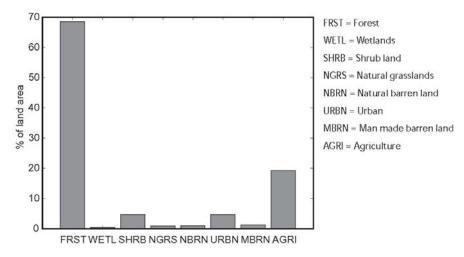

Figure 3. Percent land cover distribution for ca. 1990.

One of the most informative indicators of environmental impact is the extent to which humans have changed the natural vegetation to crops or urban land cover. The human use intensity index (U-Index) comprises agriculture and urban areas; the spatial distribution of it is depicted in Figure 4a. Urban areas

are relatively minor (5%), in terms of total area, and agricultural areas are more extensive (19%). Most of the human land use has occurred in the central valley of the basin. The regional pattern of human use is reflected in the watershed rankings over the region. In Figure 4a, the accompanying bar chart shows that the highest U-Index value for a watershed is about 94%, which means that 94% of that watershed has agriculture or urban land cover. The lowest value is 0.03%, and the median value is about 11%. The proportion of area with urban or agriculture land cover exceeds 50% in about 29 watersheds, and about 53 watersheds have U-Index less than 10%. Higher elevations appear to have been less impacted by conversions to agricultural or urban land cover. The bar chart gives some details about the distribution of human use intensity among watersheds. About 3% of the watersheds have been almost completely converted to agricultural land. These are located in the fertile central valley of the Willamette Basin. About 52% of the watersheds have only small amounts of agriculture. These watersheds are primarily located in the mountainous areas.
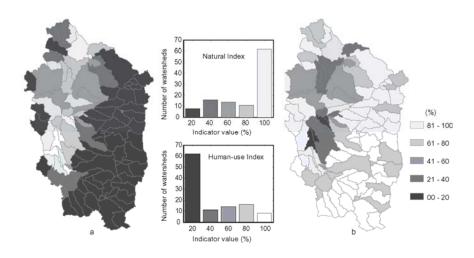

Figure 4. (a) Human-use Intensity Index and (b) Natural Land Use Index.

The spatial patterns are evident in the map of all natural land use (anything except urban and agriculture) (Figure 4b). The largest areas of natural land cover are found in the Cascade Mountains and along watersheds in coastal areas. About 48% of the subwatersheds are characterized as having all natural land use (Figure 4b). As expected, the Natural Index (N-Index) is less than 20% in subwatersheds in the Willamette Valley close to urban areas.

3.1.2. Scenario analysis

This section on trajectories of land use change for the three scenarios presents data on composition of land cover expressed as percent of land base composed of natural grassland, shrubs, forest, wetland, agriculture, natural barren, man-made barren, and urban. The three alternative scenarios – Conservation 2050, Development 2050 and Plan Trend 2050 – create different patterns of land cover/land use in the Willamette River Basin. The percent of total area and percent change relative to the baseline (ca. 1990) for each alternative scenario and for the eight main land cover/land use classes are presented in Table 3.

TABLE 3. Percent of total area and percent relative change land cover for eight classes.

Land cover	Baseline % of total area	Conservation % of total area and % change	Development % of total area and % change	Plan Trend % of total area and % change
Forest	68.29	68.82	67.78	67.96
		+0.79	–0.75	–0.48
Wetland	0.22	0.56	0.21	0.22
		+158.26	–3.45	+0.0043
Shrubs	4.45	4.57	5.13	4.23
		+2.83	+15.27	–4.87
Natural grassland	0.63	2.28	0.60	0.57
		+260.92	–4.73	–9.82
Natural barren	0.65	0.53	0.57	0.54
		–19.22	–13.26	–17.90
Urban	4.44	5.59	6.74	5.67
		+25.87	+51.81	+27.75
Man-made barren	1.01	0.90	1.31	1.01
		–10.69	+29.44	–0.11
Agriculture	18.96	15.34	16.32	18.45
		–19.07	–13.91	–2.67

+ Values indicate an increment from baseline conditions

Patterns of natural vegetation across the Willamette River Basin reflect the properties of both the lowlands and upland regions. Future scenarios depict relatively minor changes in natural vegetation for the basin as a whole. Distributions of major land uses are unlikely to change greatly; for instance, changes vary from 1 to 4% of total area. As a result, the magnitudes of change by areal proportion will be relative minor, with greatest differences being the composition of agricultural land use.

3.2. WATERSHED HYDROLOGY

3.2.1. Calibration

The observed water year and predicted runoff obtained from the calibration run at the main watershed outlet and at three USGS flow gauging stations along the Willamette River were compared and are shown in Figure 5.
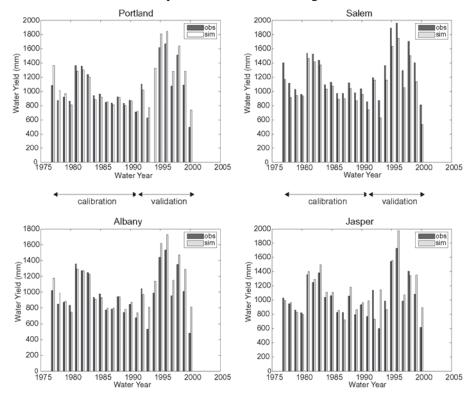

Figure 5. Simulated and observed water yield for the calibration and validation periods at four USGS streamflow stations.

The results of model efficiency and all regression analyses are presented in Table 4. The slope of the regression lines for the calibrations indicates that there is some bias in the model; i.e. some processes and/or phenomena are not accounted for adequately in the model. Notice that the largest bias is at Jasper, which is indicated by the largest deviation from unity of the slope of regression lines. The reasonably constant value of the square root of mean square residual (RMSE) indicates that there is a similar data scatter about each of these four regression lines. This could be interpreted as no degradation of uncertainty among the four USGS stations.

TABLE 4. Model efficiency and statistics from Ordinary Least Square regression analyses for the calibrations and validation periods.

Location	Period	E	Slope	Intercept	R^2	RMSE
Portland	1977–1991	0.75	0.94	68	0.89	98
	1992–2001	0.83	1.02	116	0.97	112
Salem	1977–1991	0.72	0.93	–10	0.96	57
	1992–2001	0.70	0.97	–167	0.98	80
Albany	1977–1991	0.88	0.90	104	0.94	68
	1992–2001	0.65	0.91	266	0.95	119
Jasper	1977–1991	0.88	1.16	–134	0.97	56
	1992–2001	0.42	0.74	390	0.75	262

A high value of the average of the Nash and Sutcliffe model efficiency (0.81) and a high average coefficient of determination (0.88) suggest that the model was accurately calibrated for predicting runoff from the Willamette Basin.

3.2.2. *Validation*

The model validation was carried out by comparing the observed surface runoff with the simulated runoff over the 1992–2001 water year period (Figure 5). A fairly good agreement was obtained throughout the validation period. However, the distribution of the predicted runoff values about the 1:1 line revealed that the data scatter about the regression lines at Portland and Jasper has been reversed. Regression analysis between the observed and predicted runoff values resulted in a high average value (0.91) of the coefficient of determination (r^2) and a slope of near unity, which indicated a close relationship between measured and predicted runoff. The average efficiency coefficient for the validation period (0.65) decreased 20% from the calibration period (0.81). In addition, the average RMSE of the validation period for the four USGS stations is twice as much as the calibration period. This could be interpreted as an increment in the uncertainty from all sources.

Based on the calibration and validation analyses, we assume that the model is adequate for effective planning and evaluation of future alternative scenarios.

3.2.3. *Spatial distribution of hydrological processes*

Among the various hydrological processes taking place in the Willamette River Basin, surface runoff, percolation, stream flow discharge, sediment yield and sediment concentration are of particular interests. To determine the spatial distribution of these water balance components, calculations were performed on a water year basis and results for surface runoff, percolation, and sediment yield

are shown as average annual values averaged over the 25-year period and for streamflow discharge and sediment concentration results are shown as average daily values averaged over the 25-year period of simulation. Land use and plant cover structure are important factors in formation of runoff. The time lapse of watershed reaction on rainfall is greater in the presence of forest or rich plant cover, and the maximum runoff is reduced in comparison with barren soil or urban areas. Based on Figure 6a the spatial distribution of overland surface runoff follows very closely the spatial distribution of the Human-use Index depicted in Figure 4a; i.e. highly populated areas are associated with areas producing high overland flow volumes. Except that natural barren areas such as those in high elevation areas of the Cascade Mountains produced on average 380 mm/yr. Overland flow volumes ranged in the average from 10 mm/yr in forested areas to 449 mm/yr in some urban areas.
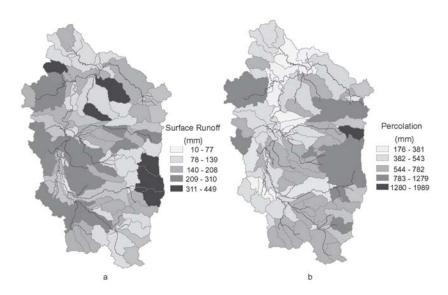

Figure 6. (a) Spatial distribution of average annual surface runoff and (b) and average annual percolation.

Mean annual percolation volume estimates range from 176 mm/yr to 1989 mm/yr, the spatial pattern of percolation resembles the Natural Index spatial pattern shown in Figure 4b; i.e. areas with high percolation volumes are associated with forested areas and low percolation volumes with urban and barren areas (Figure 6b).

The mean daily discharge averaged over the 25-year simulation period is shown in Figure 7. The discharge along the Willamette River and its tributaries varies from 3.5 m^3/s to 1400 m^3/s at the Portland USGS stream flow station. Furthermore, to illustrate the flow regime and goodness of fit between observed and simulated daily discharge at Portland and Salem, the hydrographs for 1981 water year are shown in Figure 7. Notice that the model over predicts the peaks during the winter season but in general the model simulates the overall trend.
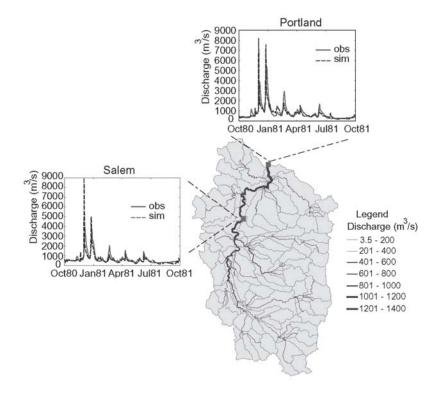

Figure 7. Spatial distribution of average daily discharge for the 25-year period.

Mean discharge for the Willamette River at its mouth averages 917 m^3/s, but varies seasonally from 233 m^3/s in August to over 5,000 m^3/s in December, reflecting the seasonal pattern of precipitation. Much of the summer runoff depends on the high-elevation snowpack because more than 35% of the precipitation occurs as snow above 1,200 m in elevation. As a result of the rain-dominated hydrograph at low elevations and snowmelt-dominated hydrograph at high elevations, stream flows overall are highest in winter and lowest in late summer. The main stem of the Willamette River is not dammed, but there are

seven major flood control reservoirs in the larger tributaries in the Coast Range and Cascade Mountains and many small dams for irrigation or power generation. Reservoirs control approximately 27% of the flow of the Willamette River.

The mean spatial daily suspended sediment concentration averaged over the 25-year simulation period is shown in Figure 8. The largest concentrations occur along the Willamette River near Portland, the mean daily concentrations averaged over the 25-year simulation period vary from 16 gm/m^3 to 25 gm/m^3. However, observed daily concentration over 100 gm/m^3 was recorded on 2000 water year. Moreover, the 1981- and 2000- water year sedigraphs are shown in Figure 8; notice that the model predicted the overall trend of daily suspended sediment concentration at Portland. Suspended sediment is important to characterize water quality because nutrients, such as phosphorous and nitrogen, and toxic constituents, such as dioxin and chlorinated pesticides can be transported in association with fine sediments.
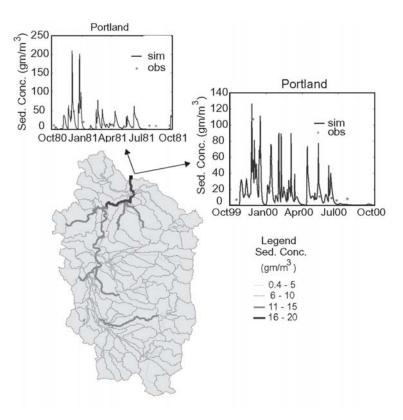

Figure 8. Spatial distribution of average daily sediment concentration for the 25-year period.

3.3. ALTERNATIVE FUTURE ANALYSES

3.3.1. 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 surface runoff, percolation, sediment yield, and average daily estimates for flow discharge and 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 5 and Figures 9–13. These figures show the relative departure from the 1990 baseline year and illustrate the spatial variability of changes to the surface hydrology. In general, the simulation results indicate that land cover changes associated with future development will significantly alter the hydrologic response of the basin. Changes are primarily associated with increasing urbanization and the associated replacement of vegetated surfaces with impervious ones.

In the case of surface runoff the simulations show average increases commensurate with increases in urbanization. There is considerable spatial variability of simulated hydrologic response. Although most subwatershed elements exhibited an increase in surface runoff, other areas showed improvement or decreasing runoff (Figure 9).

The greatest change was simulated for the Development scenario with an average increase of 1.16% over the 1990 baseline Table 5. Simulated increases in surface runoff predominately occur within subwatersheds distributed in the northern reaches of the watershed and along the Willamette Valley near Portland, Oregon City, and Eugene. The root mean square error (RMSE) of the regression analysis for the validation period shown in Table 4, which is an explicit measure of the prediction uncertainty, is larger than the surface runoff predicted relative change for each of the three development scenarios. Thus the hydrologic response of the basin as a consequence of land cover changes associated with future development can be also attributed to model uncertainty.
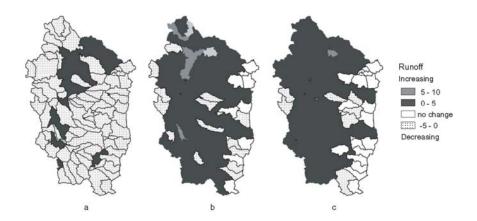
Figure 9. Percent change in surface runoff for future scenarios. (a) Conservation, (b) Development, (c) Plan Trend.

TABLE 5. Simulated average annual surface runoff, percolation, and sediment yield for the 1990 baseline and future conditions and predicted relative change for each of the three development scenarios.

Water balance component	Baseline 1990	Simulated percent relative change 1990–2050		
		Conservation	Development	Plan trend
Surface runoff (mm)	330.98	327.59	334.81	334.18
		–1.02	+1.16	+0.97
Percolation (mm)	655.12	656.27	650.28	653.04
		+0.18	–0.74	–0.32
Sediment yield (t/ha)	36.69	32.22	33.70	36.42
		–12.16	–8.12	–0.72

   Percent change in simulated channel discharge agrees closely with results for surface runoff. Figure 10 shows change in simulated mean daily channel discharge relative to the 1990 baseline for each of the three future scenarios. By mapping this model output for each stream segment in the model area it is possible to visually identify reaches that are anticipated to experience the greatest changes in their hydrologic regime as a result of the land cover/land use change. As such, the simulated changes to the hydrologic regime mapped in Figure 10 can also be viewed as an index of riparian vulnerability to the

unmitigated future development. As in the previous example, channel discharge increased most under the Development 2050 scenario and although the results are spatially variable, the greatest impact seems to be concentrated in the subwatersheds in the northern portion of the basin and along the Willamette Valley where most new development is forecast.
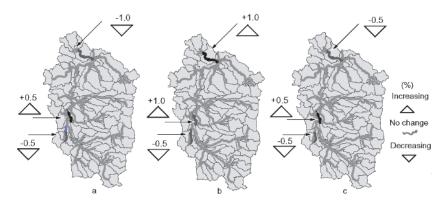

Figure 10. Percent change in discharge for future scenarios. (a) Conservation, (b) Development, and (c) Plan Trend.

Sediment yield and erosion are directly related to runoff volume and velocity. The percent change in sediment yield and sediment concentration simulated with SWAT also displayed a high degree of spatial variability across the basin and between the three scenarios (Figures 11 and 12). 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 on the valley generally showed the greatest increase in sediment yield. Sediment yield decreases on the average 12% under Conservation 2050, whereas in both Development 2050 and Plan Trend 2050 the reduction is 8% and 0.72%, respectively (Table 5). In addition, sediment concentration in the Willamette River is greatest in both Development 2050 and Plan Trend 2050; notice that the greatest reduction in sediment concentration is achieved under the Conservation 2050 scenario (Figure 12). The sediment concentration map may provide 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. It remains apparent, however, that under the Plan Trend 2050 scenario more sediment is expected to erode and be transported offsite than for the other two options (Table 5).
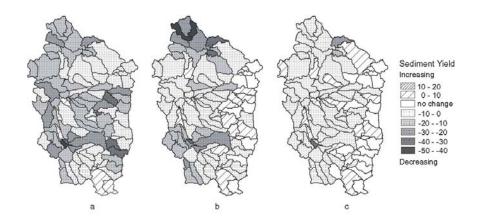
Figure 11. Percent change in sediment yield for future scenarios. (a) Conservation, (b) Development, and (c) Plan Trend.
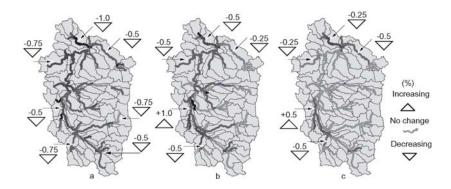

Figure 12. Percent change in sediment concentration for future scenarios. (a) Conservation, (b) Development, and (c) Plan Trend.

Percolation is a hydrologic measure of the water volume that is able to infiltrate into the soil past the root zone to recharge the shallow and/or deep aquifers. Figure 13 displays the simulated change in percolation for the three future scenarios. Although the model predicts some improvement in the watershed headwaters where human inhabitation is most dispersed, overall percolation is expected to decrease in all options as urban impervious surfaces are expanded, especially under the Development 2050 scenario.
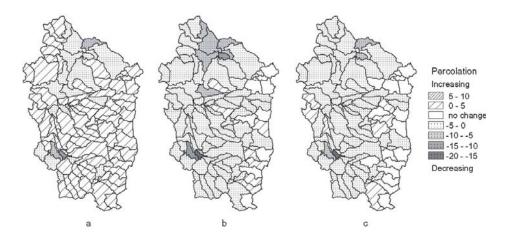
Figure 13. Percent change in percolation for future scenarios. (a) Conservation, (b) Development, and (c) Plan Trend.

However, notice that under the Conservation 2050 scenario percolation increased up to 5% in some areas along the Coast Range and along the Willamette River; percolation decreased between 4% and 13% under the other two scenarios, particularly, in the southern region of the basin comprising the city of Eugene. On average, the baseline scenario estimates percolation at 655 mm/yr and that this amount will decrease 0.74% under Development 2050 and 0.32% under Plan Trend 2050. In contrast, percolation will increase 0.18% under Conservation 2050 (Table 5).

4.   Summary and Conclusions

Landscape pattern analysis was conducted on a watershed basis across the entire state of Oregon to characterize the heterogeneity of land cover and land use. ATtILA was used to compute the metrics associated with statewide landscape characteristics for the period of circa 1990. From this analysis it was determined that the Willamette River Basin is the most modified hydrological feature relative to human land use within the state of Oregon. Because spatial variability of land cover alters the hydrological structure within a watershed, we then invoked AGWA to examine the watershed response relevant to surface runoff, sediment yield (i.e. soil erosion), and percolation for each subwatershed. The hydrological model was calibrated against total water yield, surface runoff and base flow using measured stream flow records at four permanent flow

gauging stations along the Willamette River over a water year period from 1977 to 1991. Model validation was carried out by comparing observed surface runoff with the simulated runoff over a water year period from 1992 to 2001.

In general, the simulation results for the 2050 alternative future scenarios indicate that land cover changes associated with potential future development will significantly alter the hydrologic response of the basin. Changes are primarily associated with increasing urbanization and the subsequent replacement of vegetated surfaces with impervious ones. Under a future urbanizing environment the model simulation results appear to indicate that changes in stream condition within the Willamette Basin are subtle compared to those from ca. 1990 for most of the stream condition indicators. However, there are some subwatersheds that did show some important impacts to the subwatershed hydrology. The most notable changes are likely to be increases in the amount of surface runoff and sediment discharge, especially in the northern portion of the basin and along the Willamette Valley where most new development is forecast.

For the purpose of this study, negative impacts are considered to be Increases in surface runoff, streamflow discharge, sediment concentration, and decline of percolation volume. 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.

The hydrologic modeling results indicate that negative impacts are likely under all three of the future scenarios as a result of predicted urbanization; however, there is remarkable variation in their specific hydrologic responses, particularly between Development 2050 and Conservation 2050.

In general, the Development 2050 scenario has the greatest negative impact on surface hydrology and water quality and results in greater simulated surface runoff, flow discharge, and sediment concentration, especially in the downstream reaches near Portland and reaches along the Willamette Valley. Additionally, percolation and thus groundwater recharge is most reduced under this scenario. This scenario favors development and allows for the largest future population increase within the watershed.

The Conservation and Plan Trend alternative futures have the least negative impacts to the surface water hydrology. However, it is important to highlight that under the Conservation 2050 scenario, surface runoff and sediment yield are reduced considerably along the Coast Range Mountains. Consequently, percolation is increased within the same subwatersheds. In regard to water quality, the spatial pattern depicted under the Conservation 2050 scenario suggests an important improvement on the environment given that sediment concentration decreased along the Willamette Valley and Coastal Range.

There are of course many ecological and hydrological endpoints in addition to those that were measured in the present study. The endpoints reflect fundamental environmental services and the benefits that people receive from them, e.g. food supply, water purification and supply, wildlife habitat, climate moderation, flood control, forest products, recreation, and carbon and nutrient storage. Those benefits are central to human sustainability, quality of life, and ultimately to security. Conventional definitions of security have now been expanded to include environmental threats thus evoking the term environmental security. Subsequently, environmental security includes the notion that population growth and the inequitable distribution of resources can directly cause competition over resources and that any outcomes resulting in environmental degradation or depletion can therefore become a source of tension at any political or geographical scale (local, national, regional, or global).

This study was initiated to demonstrate the potential of applying landscape sciences to environmental assessment. Specifically, it sought to integrate landscape spatial analysis with hydrological modeling to evaluate the consequences (or benefits) of choice for policy decisions related to the sustainable management of natural resources. Although the Willamette findings are largely intuitive, the authors believe that 1) the process of scenario analysis coupled with the use of spatial analysis tools can develop a better understanding of alternative options for future management of strategic natural resources and 2) the collective technologies provide an ability to quantify and forecast relative impacts to ecosystem services and therefore provides important tools to help both stakeholders and decision-makers make better decisions for improved future options. Lastly, the alternative futures approach and the application of the ATtILA and AGWA tools can be deployed on any variety of landscapes, watersheds, and regions throughout the world and thus provides an important process for watershed assessment of landscape change and impacts to water resources.

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