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Original Research Article

Understanding the spatial distribution of hydrologic sensitive areas in the landscape using soil topographic index approach[☆]

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ABSTRACT

Maintaining healthy watershed is pivotal to ensure sustainability in water resources thereby improving the carrying capacity of the earth. Understanding and identifying the spatial variability of hydrologically sensitive areas (HSAs) in a watershed is an important step to prioritizing the landscape to maintain water sustainability with limited resources. A spatial technique known as Soil Topographic Index (STI) was used to identify HSAs in the landscape. This study was conducted in Clinton and Tewksbury Townships in New Jersey, United States. Three different scenarios (STI > =9, STI > =10, and STI > =11) were conducted to understand the spatial distribution of HSAs in the watershed. The following conclusions were derived from this study. Firstly, a more detail representation of HSAs in the watershed was observed when applying the STI technique with a fine scale light detection and ranging (LiDAR) digitial elevation model. Secondly, all three scenarios consistently identified perennial stream corridors as HSAs; therefore, it is important to protect perennial stream corridors through implementation of various land use controls. Thirdly, this study analyzes the land use pattern of HSAs under the three scenarios and identifies the HSAs for high intensity land uses such as agriculture and urban to be the high priority locations for implementing best management practices for water quality improvements. The procedures developed in this study can be applied to watersheds in other parts of the world with similar physiographic characteristics.

1. Introduction

Healthy Watersheds Initiative (HWI) is a new watershed program introduced by the United States Environmental Protection Agency (USEPA) in 2009. The program intended to protect water resources from contamination by identifying, conserving and protecting the highest quality watersheds and their intact components; and protecting the key watershed processes and habitat required for healthy aquatic ecosystems (USEPA, 2010). HWI acknowledges the dynamic characteristics of water and aquatic ecosystems and their interconnections with the landscape, and protects all integral hydrologic, geomorphic, and other processes as a whole interconnected system. HWI strategies call for prioritization in protection and restoration of healthy watersheds. However, these strategies should be cost-effective because of limited availability of funding and resources for protection and restoration. Protecting healthy watersheds provides numerous benefits including sufficient clean water to support healthy aquatic ecosystems, habitat for fish and wildlife, safe drinking water, and better human health. Moreover, it helps to reduce the vulnerability of water resources to future land use and climate change impacts because it would subsequently decrease the cost of adaptation (USEPA, 2011).

Land use changes have substantial impact on water resources which needs to be addressed carefully when implementing HWI. Rapid urbanization has altered the landscape during last three decades in the United States (USDA, 2015). One illustrative example of such changes is found in New Jersey which has the highest population density in the United States. During 1986–2007, the urban land use in New Jersey has increased by 26.8%, which is a massive 130,817 ha of land adding to the state's pre 1986 urban footprint, while the population has increased only by 14% to finally reach 8.5 million during the same time period (Hasse & Lathrop, 2010). During the same period, New Jersey lost 24% of its agricultural lands, 7% of its forest lands and 5% of its wetlands to urban development (Hasse & Lathrop, 2010). Land use changes greatly alter watershed hydrology, which leads to nonpoint source pollution that degrades water quality, breaks down the stream integrity, and causes public concerns on water chemistry and biotic health issues of streams (Qiu et al., 2014).

Urbanization changes the land uses in a watershed, which leads to water resource degradation, however, its impacts on water resources vary across different parts of the watershed. For example, urbanization

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Fig. 1. Location of study area (Clinton and Tewksbury Townships) in New Jersey, US.

occurred close to the streams has far greater impact than away from the streams. To cope with the complicated hydrological interaction between streams and various parts of a watershed, researchers developed different techniques such as principal component analysis, positive matrix factorization, simple export coefficient modeling, statistical modeling (SPARROW), and physically based watershed modeling (SWAT) to identify critical source areas in the watershed that have most significant impacts on water quality in streams. However, most of these techniques require extensive input data as well as in-depth modeling knowledge. Therefore, we are proposing a simple terrain based approach that adopts the variable source area (VSA) hydrology concept to assess contributions of different parts of a watershed to runoff generation and identify these critical source areas. The term VSA usually attributed to Hewlett and Hibbert (1967) and is based on a saturation-excess hydrological process that explains how runoff is generated from relatively small saturated areas in a watershed (Hewlett, 1982). VSAs contribute to the increase or decrease of the saturation areas in a watershed and it varies with respect to change in time and storm intensity. While VSAs represent a dynamic pattern of saturated area actively contributing to runoff generation in a watershed during a storm event, hydrologically sensitive areas (HSAs) are defined as parts of VSAs which are more susceptible to produce runoff compared to other parts of watershed (Walter et al., 2000).

HSAs play a critical role in watershed hydrology, therefore, land uses inside HSAs have more dominant impacts on water quality than land uses in non-HSAs of a watershed. The concept of HSAs helps relate the watershed scale problems to various smaller areas in the watershed that potentially contribute water pollution. Identification of HSAs helps optimize the utilization of resources and provides a cost effective way to control pollutants transported by runoff into streams.

Considerable research has been using HSA approach to understand watershed hydrology and prioritize the watershed for water quality improvement. Soil Topographic Index(STI) is a terrain-based technique often used to quantify the runoff generation potential and define HSAs (Walter et al., 2002). Giri, Qiu, and Zhang (2016) used STI technique and HSA concept and created a regional scale model to understand the relationship between land uses and water quality in Northern New Jersey watersheds. They used STI value greater than equal to 10 to delineate HSAs in their study and analyzed the correlation between land uses and water quality. Anderson, Groffman, and Walter (2015) used STI technique to understand the distribution of denitrification rate across a small mixed land use watershed in Central New York. They found a positive correlation between STI and denitrification. Qiu et al. (2014) delineated HSAs using STI and assessed the effectiveness of five land use controls in protecting HSAs from urban development in three Municipalities in New Jersey. They considered the areas with STI greater than or equal to nine to be HSAs in the watershed. Results suggested that out of five land use controls, wetlands protection was most effective in protecting HSAs in the watershed. Buchanan et al. (2014) used STI to estimate soil water distribution at five agricultural fields in Central New York. Results depicted that STI was correlated well with the soil moisture distribution in the agricultural fields. Qiu (2009) used STI to predict runoff generation area in the Neshanic River Watershed in New Jersey and found that STI was effective in determining runoff generation area in the watershed. Other studies also have used STI approach and HSA technique to investigate hydrology and water quality in different watersheds (Agnew et al., 2006; Herron & Hairsine, 1998; Lyon et al., 2006; Walter et al., 2000).

The aforementioned literatures depict the importance of HSAs in the watershed to protect water quality. The spatial variation of HSAs would further facilitate prioritizing accurate runoff generation locations and their land uses to control nonpoint source pollutions with limited resources. For example, perennial stream corridors, upland areas, riparian zones would be identified as HSAs when using a lower STI threshold value, however, only perennial stream corridors would be identified as HSAs when using a higher STI threshold value. If there is a budget constraint, watershed managers would focus on their efforts to conserve perennial stream corridor identified using the higher STI threshold value instead of various land uses identified using the lower STI threshold value. The spatial variation of HSAs in a watershed would help watershed managers prioritize their efforts to manage land uses for water quality improvement. In this study, spatial variation of HSAs will be analyzed to characterize land uses within HSAs. Different STI threshold values were used to delineate HSAs in Clinton and Tewksbury Townships to assess the changes in land use characteristics within HSAs that dominantly contribute pollution to streams.

2. Materials and methods

2.1. Study area

This study was conducted in Clinton and Tewksbury Townships located in Hunterdon County, New Jersey (Fig. 1). Tewksbury Township is located in Highlands region of New Jersey where approximately 70% of the township is in its Preservation Area and remaining 30% in its Planning Area (http://www.nj.gov/dep/highlands/highlands_map.pdf). Clinton Township is located across both Highlands and Piedmont physiographic regions (http://www.clintontwpnj.com/modules/showdocument.aspx?documentid=124). These Highlands region is regulated through the Highlands Water Protection and Planning Act to protect, enhance, and restore natural resources of Highlands, particularly, water resources (New Jersey Highlands Council, 2010). The elevation in the study area ranges from 36 m (m) to 311 m above the mean sea level. The slope of the study area fluctuates between 3% and 40%.

Out of the total area, 73% area has slope in the range of 3–15% and rest of the area has slope in the range of 15–40%. The study area contains 20 types of prime farmland soils which covers 28% of the total area. The primary streams in Tewksbury Township are Cold Brook, Hollow Brook, Rockaway Creek, and North Branch while the primary streams and reservoir in Clinton Township are Beaver Brook, Prescott Brook, Rockaway Creek, South Branch, and Round Valley Reservoir. Most of the streams in this study area are classified as Category One (C1), as the water from these streams is designated for drinking purposes (NJDEP, 2010).

The climate in the study area is humid continental. The average temperature during winter and summer in Clinton Township is 0 °C and 22 °C, respectively. The average temperature during winter and summer in Tewksbury Township is −8 °C and 28 °C, respectively. Annual average precipitation in Clinton and Tewksbury Townships is 117 cm (cm) and 133 cm, respectively.

The total watershed area is 17,065 ha, out of which 38.5% is forest, 27% urban lands, 23% agricultural lands, seven percent water, and four and half percent wetlands. Corn and soybean are the primary crops in the study area along with some rye in some parts of the study area. Urban lands are primarily divided into high, medium, and low density residential as well as rural residential area. Out of all types of urban land, low density residential and rural residential areas are predominant in the study area due to exurbanization During 1980s and 1990s (population growth period), when most of the corporates migrated from traditional downtown areas into this study area.

2.2. Soil topographic index

In humid areas, Topographic Wetness Indices (TWIs) are widely applied to estimate relative soil moisture patterns. STI is one of the popular methods to calculate TWI. STI is based on the Topographic Index (TI) introduced by (Beven and Kirkby, 1979) and spatial variation in hydrologically relevant soil properties (Beven,1986). STI functions as a critical indicator to measure the likelihood of a location on the landscape to generate saturation excess runoff and is calculated using the following equation (Buchanan et al., 2014; Walter et al., 2002; Lyon et al., 2004):

$$STI=\ln\left(\frac{\alpha}{tan(\beta)}\right)-\ln\ (T) \tag{1}$$

where α is the upslope contributing area per unit contour length (m), β is the local topographic slope (mm^{-1}), T is the soil transmissivity (m^2 d^{-1}), which can be calculated as:

$$T=K_sD \tag{2}$$

where K_s is the average saturated hydraulic conductivity of topsoil layers (m/day) and D is the topsoil depth to a restrictive layer (m).

The above STI has been applied in several regional modeling studies (Agnew et al., 2006; Buchanan et al., 2014; Lyon et al., 2006a, 2006b; Schneiderman et al., 2007; Easton et al., 2008) in the Northeast of the United States and it has worked reasonably well.

2.2.1. Soil transmissivity

The soil survey geographic database (SSURGO) for Hunterdon County was downloaded from the U.S. Department of Agriculture (USDA) Geospatial Gateway (https://gdg.sc.egov.usda.gov/GDGOrder.aspx). Using the Soil data view add-in tool in geographic information system (GIS), soil saturated hydraulic conductivity and soil depth layers were created. Both layers were then multiplied to form a soil transmissivity layer for the Hunterdon County. Since the study area is located inside the Hunterdon County, therefore, the county transmissivity layer was clipped based on the boundary of the study area.

2.2.2. Wetness index

Wetness index is created based on topography. Fine scale topography data represents a detail complexity of the terrain and facilitates formation of better wetness index. In this study, a light detection and ranging (LiDAR) digitial elevation model (DEM) in a 3-m resolution was used to generate the wetness index. The LiDAR DEM data for the entire New Jersey was downloaded from the New Jersey Geographic Information Network (NJGIN) website (https://njgin.state.nj.us/NJ_NJGINExplorer/jviewer.jsp?pg=lidar). The whole LiDAR DEM was clipped based on the boundary of the study area. The clipped LiDAR

DEM was further processed in System for Automated Geoscientific Analyses (SAGA GIS) package in the R-platform to generate wetness index. Different processes such as fill sinks, calculation of slope of each grid, and catchment area were estimated before generating wetness index. The soil transmissivity layer was added into the wetness index layer in order to generate STI in R-platform. It is very important to ensure that the shape and projection of both LiDAR DEM and transmissivity layers are same before formation of the STI layer in R.

2.3. Hydrologic Sensitive Areas (HSAs)

There are different approaches to delineate HSAs in a watershed including average saturation probability method (Agnew et al., 2006), the controlling specific storm event method (Lyon et al., 2006), and a methods focusing on 20% of watershed area using a high STI (Herron & Hairsine, 1998). However, a very simple and convincing approach is to select a STI threshold value and use that STI threshold value to delineate HSAs in the watershed. Qiu (2009) used this approach successfully in Neshanic River Watershed in New Jersey to delineate HSAs for conservation buffer planning and riparian restoration. Therefore, in this study similar approach was used to delineate HSAs in the study area. We used three different STI threshold values (9, 10, and 11) to delineate and analyze spatial variability of HSAs in the study area. The quantitative meaning of STI 9 is the runoff producing ranking of the area in the watershed based on topography and soil transmissivity. Similarly, the quantitative meaning of STI 10 and STI 11 is interpreted. Higher STI value means greater capacity to generate runoff in the landscape.

2.4. Land use metrics within HSAs

In order to understand the variability of land uses within HSAs, a 2007 land use data was used to extract the land uses inside each HSA scenario using python 2.7.3. The 2007 land use data was the most recent land use data available in the public domain for the study area. The 2007 land use layer was created by visually interpreting color infrared digital imagery (NJDEP, 2010). Each image was examined and based on the photo signature, these image were classified into different land use categories. A modified Anderson Level I land use classification system (http://www.state.nj.us/dep/gis/digidownload/metadata/lulc02/anderson2002.html) was used to categorize the land uses into agricultural, forest, urban, barren lands, wetlands, and water. In this study, the barren lands that represent the transitional lands to urban uses were in a small amount and were combined to represent as urban land, in order to better assess the land use patterns within HSAs.

3. Results and discussions

The STI value for the study area ranges from one to 30. The area with the STI value of one represents the area with the lowest potential to generate runoff and of 30 depicts the highest potential to produce runoff in the study area. Although various criteria can be applied to delineate HSA, this study calculated and presented three different HSA scenarios based on the STI threshold values of 9, 10 and 11, where Scenario One represents HSAs as the areas with STI that is greater than to equal to the threshold value of 9, Scenario Two depicts the threshold value of 10, and Scenario Three represents the threshold value of 11. Approximately, 37.5%, 24.0%, and 17.0% of the study area are the HSAs under Scenarios One, Two and Three, respectively. The total amount of HSAs under Scenarios One, Two, and Three are 6,396.5 ha, 4,136.0 ha, and 2,868.0 ha, respectively and their spatial distribution is presented in Fig. 2. The lower STI threshold value, the larger HSAs, which is evident by greater HSA areas (green color) in Fig. 2a than in Fig. 2b and c.

Different salient features are observed from the spatial distribution of HSAs in the study area. Firstly, the representation of HSAs in three scenarios is in minute detail when using the STI technique with a fine scale LiDAR DEM. This improvement in identifying HSAs would help policymakers and watershed managers to be more effective in implementing different land use controls such as stream corridor ordinance, farmland preservation, open space preservation, wetland protection, and steep slope ordinance to protect HSAs and improve overall watershed management goals. Secondly, greater amount of HSAs are observed along the streams as well as in uplands in the study area for Scenario One when compared to in Scenarios Two and Three. As the STI threshold value is increased from 9 to 10 and then to 11, most of the upland areas and riparian zones are eliminated from the identified HSAs. The HSAs under Scenario Three only contains the perennial stream corridor and some upland areas, which indicates that perennial stream corridors should be given higher priority for protection. Under any resource constraint, the spatial variability of HSAs would further help prioritize the landscape to control non-point source pollutions and improve water quality.

Land uses in the study area are categorized into agricultural lands, forest, urban lands, water, and wetlands under three HSA scenarios. In Scenario One, forest is the primary land use within HSAs that is accounted for 28.2% of the HSAs, followed by agriculture lands (26.1%), urban lands (21.9%), water (17.6%), and wetlands (6.3%) (Fig. 3). In Scenario Two, water was the primary land use within HSAs (27.1%), followed by forest (24.3%), agricultural lands (21.4%), urban lands (20.3%), and wetlands (6.9%). The results suggest that the delineated HSAs are likely to contain more saturated areas such as water since HSAs are the areas in landscape having higher propensity to generate runoff. For Scenario Three, a similar trend as for Scenario Two was observed except the agricultural lands and urban are switched their rankings.

The agricultural and urban lands are generally considered to be high intensity land uses because anthropogenic interference is in its maximum in these uses. On the contrary, water, wetlands, and forest is considered to be low intensity land uses where anthropogenic interference is in its minimum. 48% of HSAs under Scenario One are in high intensity land use, 41.7% under Scenario Two and 33.4% under Scenario Three. The percentage of agricultural land uses within HSAs decreases much faster than of urban lands as the more stringent criteria, i.e. the larger STI threshold value, is used to identify and define HSAs. As the HSAs become more easily saturated under Scenario three, they would become more difficult to farming. However, saturated landscape is much less a concern for most urban development. Significant intrusion of high intensity land uses into HSAs would signify the deterioration of landscape conditions that would lead to water quality degradation. The low intensity land uses with HSAs shall be protected from further intrusion by high intensity land uses and the high intensity land uses within HSAs shall be given high priority for implementing best management practices.

4. Conclusions

Maintaining healthy watershed is a difficult task due to increased anthropogenic activities in the landscape. Different innovative programs such as HWI help achieve overall water quality goals. With limited resources, the understanding of spatial distribution of HSAs in the landscape and their land uses helps prioritize conservation measures that control non-point source pollution and support these programs.

In this study, the STI technique was used to delineate HSAs in the study area. A STI layer was developed by using LiDAR DEM which represents topography and SURRGGO soil data which characterizes soil saturated hydraulic conductivity and depth to restrictive layer. The STI threshold values of 9, 10, and 11 were used to create three HSA scenarios for detailed analysis in this study. The whole process was performed using SAGA GIS in R- platform. A python script was used to categorize the land uses within each HSA scenario based on the most

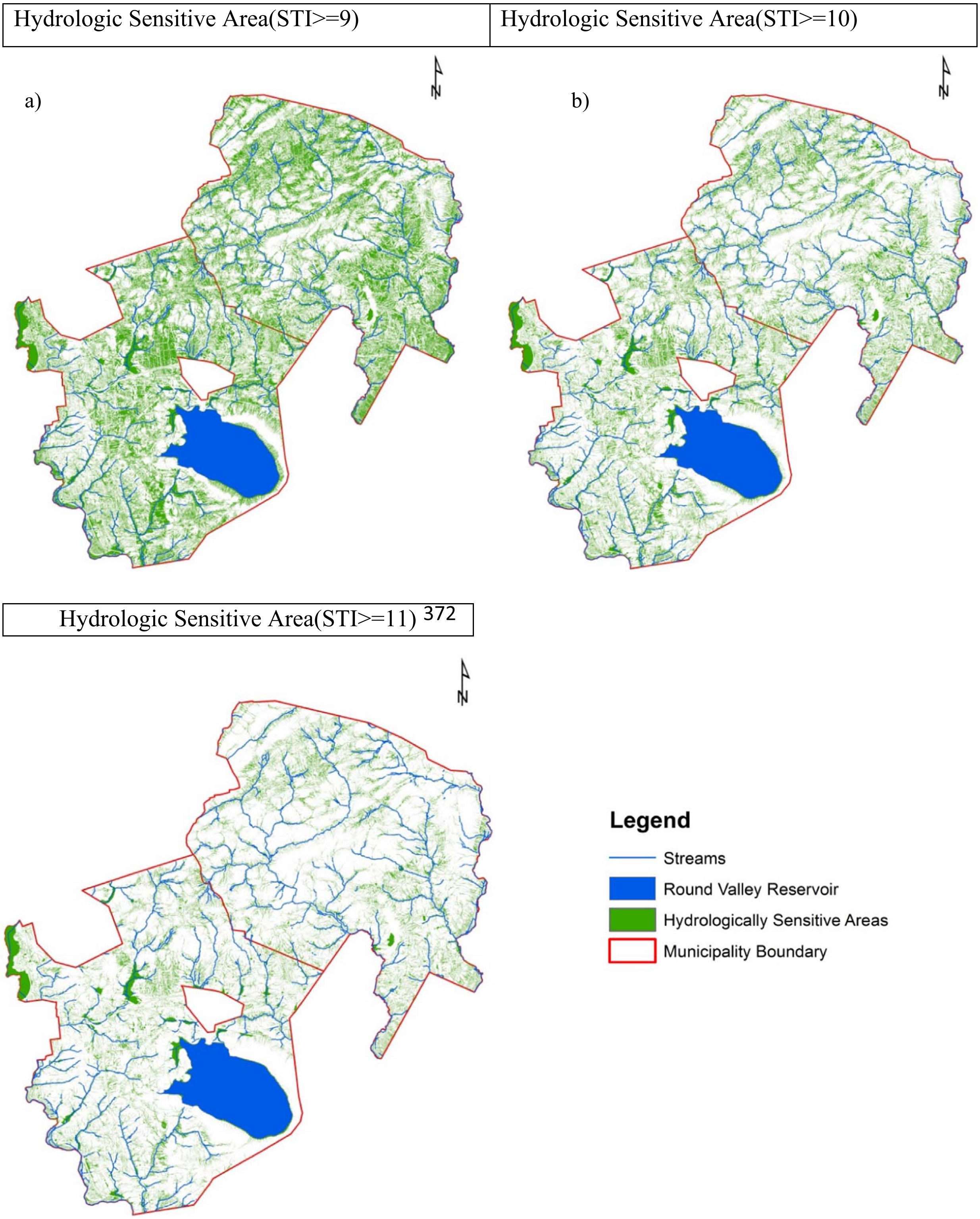

Fig. 2. Spatial distribution of hydrologic sensitive areas for (a) Scenario One (STI > =9), (b) Scenario Two (STI > =10), and (c) Scenario Three (STI > =11) in Clinton and Tewksbury Townships. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

recent available land use data in the study area.

The study presents a detailed representation of HSAs in the study area due to the use of STI technique with a fine scale LiDAR DEM. Such detailed representation of HSAs would increase the efficacy of land use control measures in protecting water quality. Since perennial stream corridors are consistently classified as HSAs under all three scenarios and given the highest priority for protection in terms of maintaining healthy watersheds. The analysis of land use patterns in HSAs provides insights how and where to target the management efforts for water quality improvement. Significant intrusion of high intensity land uses into HSAs would signify the deterioration of landscape conditions that would lead to water quality degradation. Land planning measures should be taken to protect HSAs from the intrusion of high intensity land uses. If there are high intensity land uses in HSAs, those areas

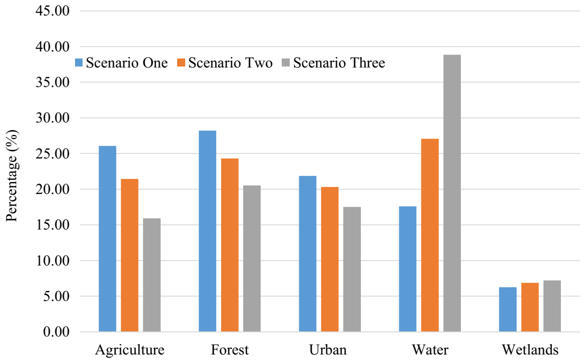

Fig. 3. Distribution of land uses under three hydrologic sensitive area scenarios.

should be prioritized to implement best management practices to minimize their negative impacts on water quality (Qiu et al., 2014). Such targeting approach would further help achieve the HWI's water quality objectives.

The similar technique has been applied in other parts of the world. Burt and Butcher (1985) used the STI technique to predict soil moisture distribution in the hill slope at South Devon, United Kingdom. Mallick, Bhattacharya, and Patel (2009) used a soil wetness technique to estimate soil moisture content in the cropped fields in four States of India, and Hjerdt, McDonnell, Seibert, and Rodhe (2004) used the STI technique to assess the spatial distribution of wetlands in Sweden. Therefore, the method developed in this study can be applicable to other parts of the world especially in the developing countries where spatial data is scarce, water quality is comprised and the necessary land use controls are badly needed. Any application of the method should be built upon a thorough understanding of the physiographic characteristic of the region as this method works best in humid, vegetative and hilling regions.

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