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Implications of Different DEMs on Watershed Runoffs Estimations

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Abstract

Watershed modelling tools like ArcSWAT, an ArcGIS extension of Soil and Water Assessment tool (SWAT), are useful to watershed managers in many ways. One particular use is analyzing model outputs for decision making related to waterway restoration and mitigation, which is often undertaken to improve water quality in streams. The present study evaluates the use of digital elevation model (DEM) at 10 meter, 30 meter, and 100 meter pixel size on non-point runoff predictions for three sub-watersheds in Raritan River Basin in New Jersey. These three watersheds include: Bound Brook, Lamington River, and Lawrence Brook watersheds. ArcSWAT is utilized to investigate the difference due to DEM variation in predicting monthly estimates of pollutant loads including ammonium (NH_4), nitrite (NO_2) and sediment transported with water out of a watershed. Using land use/cover, slope and soil data for 2012, monthly pollutant loads are calculated for each sub-basin in the watershed over a 10-year simulation period (2012-2022) in ArcSWAT. Overall statistical and spatial results show that ArcSWAT results are sensitive to changes in DEM pixel size for watershed modeling. The results show that total sum of monthly runoffs including NH_4, NO_2 and sediment differ among the three different DEMs. Moreover, the spatial pattern of input (in sub-catchments) also changes among the three DEMs for most watersheds. This indicates that watershed managers need to supplement model predictions with field measurements before making substantial investments in stream restoration programs.

Keywords

Runoffs, DEM, SWAT, Stream Restoration, Watershed Characteristics, Watershed Modeling

1. Introduction

ArcSWAT is commonly used to estimate water quality outcomes under various land management practices within its corresponding watershed [1] [2] [3]. SWAT is developed by the USDA Agricultural Research Service, is a continuous, distributed parameter, daily time step model used to assess the effects of land management practices on the hydrology, nutrients, sediments, and non-point source pollutant transport in watersheds under various slope, soils, and land use/cover conditions in a continuous-time framework [1] [4]. One of the functionalities of the SWAT model is to divide a watershed into sub-basins and then further divide each sub-basin into hydrological response units (HRUs). SWAT represents a realistic projection given specific biophysical features such as land use/cover, soil, topography, hydrology, climate, and policy effects at sub-watershed area [5].

In predicting surface runoff, the hydrological process requires determination of topographic characteristics [6]. The spatial patterns in such systems are heavily based upon the attributes such as slope and the area per slope length. DEMs are used as digital raster based map of the land surface area [6] [7]. DEMs are implemented as a topographic representation in ArcSWAT and serve as a crucial data layer to define physical parameters such as area, slope and slope length for each sub-basin within the watershed. The quality of the ArcSWAT model performance in predicting future scenarios depends upon how well the model inputs represent the relevant characteristics of the watershed. In general, there is a tradeoff between the DEM resolution and fine scale details for simulation, the accuracy of the data and computing speed [6]. Due to this tradeoff, users often select coarse resolution of DEM to speed up the simulations. It has been suggested that lower resolution in spatial input data results in segmented watersheds while higher resolution allows better delineation of flat surfaces [6] [8].

The quality of spatial input data is crucial for model development and accuracy [9]. Several studies analyzed the significance of scale effects on the quality of natural system processes and predictions [6] [8] [10] [11] [12]. Lin [13], analyzed the impact of different resolutions of DEMs. These DEMs are collected from different data sources to evaluate the sensitivity of SWAT output for three runoffs: sediment, total phosphorous (TP) and total nitrogen (TN). The results of their study suggest that SWAT is sensitive to the grid size effects due to the variations in DEM. The use of small grid size improves the model outcomes for 90 meter and 30 meter grid size but does not improve the results for 5 meter DEM. Another study investigated that difference in scales are minimal in small watershed, however in large scale watersheds there is an increased amount of uncertainty in stream flow outputs due to scale variation [11].

In ArcSWAT, multiple HRUs are calculated and generated based upon topography of the landscape. The HRUs derived through the use of DEM help in investigating the spatial variation in input, output, and flow of water pollutants in catchments [14] [15]. In order to capture the changes in watershed management on water quality outcomes, the model must reflect the quality and accuracy of such input data in the model [15]. Still, watershed managers use various DEMs in analyzing the watershed health under various stream restoration programs.

To date, no such study existed for the Raritan River watershed to help watershed management to identify the suitable and efficient scale for predicting watershed quality outcomes. The Raritan River watershed's uniquely diverse activities and physiography make water resource management a complex issue to address and prove to be a challenge to state and local regulators working to maintain its integrity. This complex socio-ecological system consists of abiotic, biotic, and anthropogenic entities that provide a range of ecosystem services. In this regard, this paper investigates the impact of the three different cell sizes in the digital elevation model on simulated NH_4, NO_2 and sediment outputs of three watersheds: Bound Brook, Lamington River and Lawrence Brook watersheds of Raritan River Basin in New Jersey by using the Soil and Water Assessment Tool (SWAT) in ArcGIS. The present study analyzed the sensitivity of ArcSWAT outputs on three DEM resolutions: 10 m, 30 m and 100 m. The suitability and selection of these resolutions is based upon the results from several studies [9] [13] [16] [17] [18]. The relationship between resolution and runoff is important to understand the specific scale that is useful to achieve optimal results in simulation [19]. The literature of Raritan River Basin currently lacks methods for systematically analyzing the effect of grid size on statistical and spatial characterization of the land surface and associated hydrological response in terms of watershed quality parameters. The relationship between the hydrological spatial data input and associated hydrological response at different scales is not well understood. In this regard, the novelty of this paper is to provide the knowledge on scale assessment of elevation data in hydrological simulation.

The primary goal of this study is to demonstrate the sensitivity of the ArcSWAT model due to a change in topographic parameter and to provide a better understanding to assess the impacts of land surface variation due to flow direction changes with changing DEMs on surface water quality. Accordingly, the objective of this research is not only to project surface water quality outcome, but to provide an answer to a research question: if the change in resolution of surface patterns affecting water quality output in water quality modeling for small watersheds.

The following goals are met in order to achieve the primary objective of this study.

1) Use spatially determined surface changes to simulate impacts on the transport of NH_4, NO_2 and sediment in the selected sub-watersheds in Raritan River Watershed.

2) Analyze and compare the outcomes and relative importance of DEM of different sizes on surface water quality predictions of ArcSWAT.

2. Methodology

2.1. Study Area

The Raritan River Basin intersects three of New Jersey's physiographic regions—

the Highlands, Piedmont, and Coastal Plain. Each of these regions has distinct geologic and soil characteristics. These characteristics affect soil drainage, surface water runoff, ground water recharge, and land use/cover development patterns throughout the Basin. The Raritan River Basin is a 1105 square mile drainage area and serves as an important source of drinking water for the central portion of New Jersey. Municipalities within the Raritan River Basin have been developing at a rapid pace, increasing the amount of impervious surface, reducing riverine buffers, and increasing storm water loads in rivers and streams which makes this a study system recognizable across the globe. Three sub watersheds as shown in **Figure 1** were selected for analysis within the Raritan Basin: Bound Brook (Highly Urbanized), Lamington River (Mostly Forested), and Lawrence Brook (Moderately Urbanized and Forested).

2.2. Input Data for ArcSWAT

All the spatial input files including raster and polygon files are projected in NAD_1983_StatePlane_New_Jersey_FIPS_2900_Feet and 1:250,000 scale format is used.

DEM

DEM data for 100 m, 30 m, and 10 m are collected for each watershed in the study area to compare runoff results for each grid size. 100 m and 30m data are collected from National Elevation Dataset (NED) of U.S. Geological Survey (USGS) and 10 meter is collected from New Jersey Department of Environmental Protection (NJDEP).

Land use/ cover

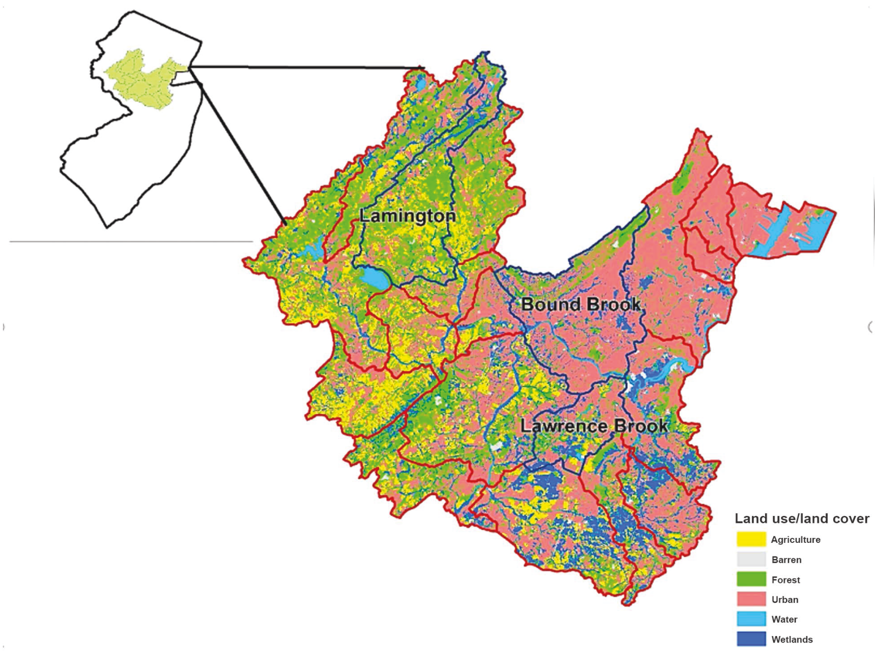


Figure 1. Land use/cover for the Raritan River watershed, New Jersey, 2012. Source: NJ Department of Environmental Protection (NJDEP), 2012.

The most recent land use/cover data for the year 2012 is used and collected from New Jersey Department of Environmental Protection (NJDEP). The six land use/cover classes and their definitions utilized in the dataset are shown in Table 1 and Figures A1-A3 in Appendix.

Streams

Data on streams are delineated through the ArcSWAT Watershed delineation based on digital elevation model (DEM) raster for the Raritan River watershed. Three resolution of 100 meter, 30 meters, and 10 meters for each watershed are used for the elevation. ArcSWAT draws the location of the stream network based upon the flow direction and accumulation using DEM grid.

Soil

The Soil Survey Geographic (SSURGO) database is used in ArcSWAT in defining the HRUs. The SSURGO data is collected from USDA, NRCS, and New Jersey Office of Geographic Information Systems. SSURGO data provides smaller polygons (soil map units) and higher resolution with fine details. Each soil map unit represents a soil type in each watershed (Figures A1-A3 in Appendix).

Slope

In ArcSWAT multiple slope classes in percentage using 100 meter, 30 meter, and 10 meter DEMs are used to define the HRUs. The slope is broken down into four classes (1%, 5%, 25% and more than 25%) to represent the variation in topography of the Raritan River watershed (Figures A1-A3 in Appendix).

Weather Data

Weather data are obtained from weather database from first order stations in ArcSWAT, which has the weather data from the year 1960 to 2010. The data on rainfall, temperature, relative humidity, solar radiation and wind speed are simulated using the weather generator function in ArcSWAT for each sub-basin.

2.3. ArcSWAT Model

The ArcSWAT model processes overview is shown in Figure 2. The ArcSWAT model is set up using data on the three watersheds including: Bound Brook, Lamington River, and Lawrence Brook in Raritan River watershed, New Jersey. For each watershed 100, 30, and 10 meter resolution digital elevation model (DEM), land use/cover for 2012, soil type, and local meteorological conditions are used. A DEM is the input used to delineate the watershed sub-basins using topography, such as overland slope and slope length (in meters) to analyze the drainage patterns of the landscape and define the area of the sub-basin in the watershed. ArcSWAT delineated the physical characteristics of the watershed such as size, boundaries, and stream network based upon the digital elevation model (DEM), and divided the watershed into hydrologically and spatially connected sub-basins.

Using ArcSWAT, each of the three sub-watersheds is partitioned into sub-basins using sub-basin outlet locations. This division spatially connects each sub-basin

Table 1. Land use/covers classes and their description ((NJDEP, 2012).

Land use/covers	Description
1. Agriculture	Land comprised of cropland and pastureland, orchards, vineyards, nurseries, horticultural areas, sod farms, confined feeding operations, and other agriculture.
2. Barren Land	Consists beaches, bare exposed rock, rockslides, extractive mining, altered lands, transitional areas (sites under construction) and undifferentiated barren lands.
3. Forest	Areas characterized by deciduous forest, coniferous forest, and plantation, mixed forest, bushland/shrub land and severe burned upland vegetation.
4. Urban	Urban areas include residential, commercial and services, industrial and commercial complexes.
5. Water	Areas characterized by streams and canals, natural lakes, artificial lakes, estuaries & other tidal waters, tidal rivers, inland bays and other tidal waters, open tidal bays, dredged lagoon and Atlantic ocean.
6. Wetlands	Include coastal wetlands, interior wetlands and severe burned wetlands.

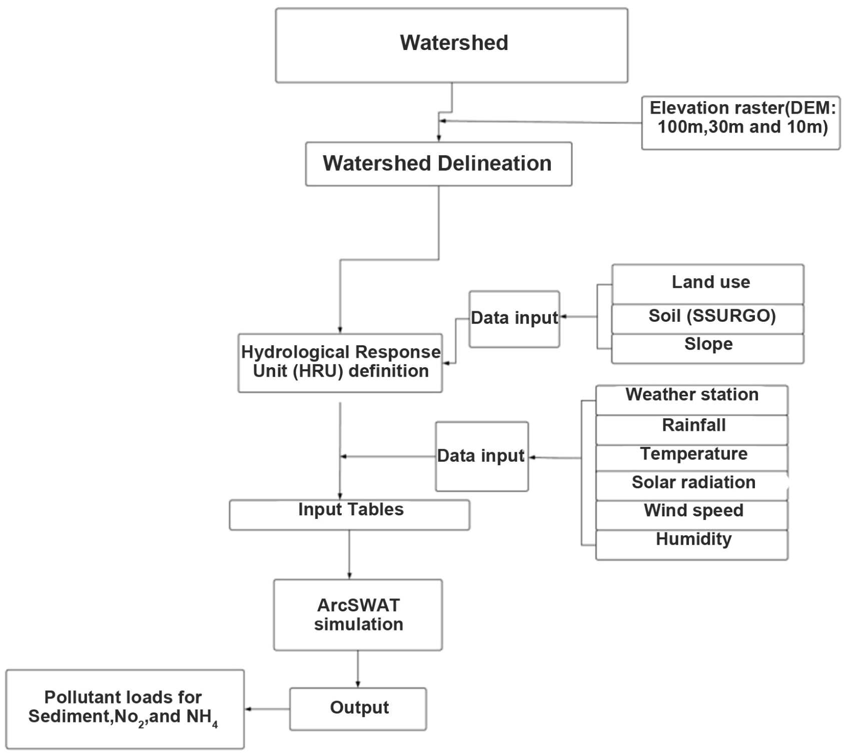


Figure 2. ArcSWAT model procedure for the Raritan River Watershed.

to one another [3]. Land use/cover classes are categorized accordingly to the SWAT code for each type of land use/cover as defined in **Table 2**.

The SSURGO soil data layer is prepared for each sub-watershed and used for the soil database in ArcSWAT. Once the land use/cover data, the SSURGO soil data, and the slope class layers are defined, the data is overlaid to derive unique subbasins. For the distribution of HRUs, multiple HRUs are used for this research. Each HRU in the watershed has a unique combination of land use/cover,

Table 2. Land use/covers classes.

Land use/cover 2012	SWAT land use/cover type
1. Agriculture	Agricultural land generic
2. Barren Land	Barren
3. Forest	Mixed forest
4. Urban	Residential urban areas
5. Water	Water
6. Wetlands	Mixed wetlands

soil type, and slope characteristics. Number of sub-basins are noted with each type of DEM.

ArcSWAT provides the weather database from local stations. ArcSWAT is run monthly over a 10 year time period. The pollutant loading data are extracted from model results. The selection criteria for runoff is the pollutant load releasing out of the watershed rather than the final pollutant load flowing into the watershed. Three pollutants: NH_4, NO_2 and sediment are selected from ArcSWAT output defined in Table 3.

ArcSWAT estimates the sediment yield in each sub basin using the (MUSLE) Modified Universal Soil Loss Equation (1) [20] [21]:

$$\text{Sed} = 11.8 \cdot \left(Q_{\text{surf}} \cdot q_{\text{peak}} \cdot \text{area}_{\text{hru}}\right)^{0.56} \cdot K_{\text{USLE}} \cdot C_{\text{USLE}} \cdot P_{\text{USLE}} \cdot \text{LS}_{\text{USLE}} \cdot \text{CFRG} \quad (1)$$

where Sed is the sediment yield on a given day (metric tons), Q_{surf} is the surface runoff volume (mm H_2O/ha), q_{peak} is the peak runoff rate (m^3/S), area_{hru} is the area of the HRU (ha), K_{USLE} is the USLE (Universal Soil Loss Equation) soil erodibility factor (0.013 metric ton m^2 hr/(m^3-metric ton cm)), C_{USLE} is the USLE cover and management factor, P_{USLE} is the USLE support practice factor, LS_{USLE} is the USLE topographic factor, and CFRG is the coarse fragment factor. The amount of sediment released out of the watershed on a given day is regarded as a function of final concentration in ArcSWAT.

The sediment Outflow in ArcSWAT is calculated as Equation (2) [21]:

$$\text{sed}_{\text{flowout}} = \text{conc}_{\text{sed,f}} \cdot V_{\text{flowout}} \quad (2)$$

where $\text{sed}_{\text{flowout}}$ is the amount of sediment released out of the water with outflow (metric tons), $\text{conc}_{\text{sed,f}}$ is the final sediment concentration (Mg/m^3), and V_{flowout} is the volume of outflow from the impoundment (m^3 of water).

Having the sediment yield calculation, ArcSWAT calculates the amount of sediment released to the main channel as Equation (3) [21]:

$$\text{sed} = \left(\text{sed}' + \text{sed}_{\text{stor},i-1}\right) \cdot \left(1 - \exp\left[\frac{-\text{surlag}}{t_{\text{conc}}}\right]\right) \quad (3)$$

where sed is the amount of sediment discharged to the main channel on a given day (metric tons), sed' is the amount of sediment load generated in the HRU on a given day (metric tons), $\text{sed}_{\text{stor},i\text{-}1}$ is the sediment stored or lagged from the

Table 3. Variables and definitions of pollutant loads in ArcSWAT.

Variable	Definition
NH_4_OUT	Ammonium transported with water out of reach during time step (kg N).
NO_2_OUT	Nitrite transported with water out of reach during time step (kg N).
SED_OUT	Sediment transported with water out of reach during time step (metric tons).

previous day (metric tons), surlag is the surface runoff lag coefficent, and t_{conc} is the time of concentration for the HRU (hrs).

In ArcSWAT, a regression model estimates loadings such as NH_4 and NO_2 as a function of impervious area, land use/cover, and rainfall. The general equation developed in ArcSWAT to predict loadings in watersheds is shown in Equation (4) [21]:

$$Y = \frac{\beta_0 \cdot \left(R_{\text{day}}/25.4\right)^{\beta_1} \cdot \left(\text{DA.imp}_{\text{tot}}/2.59\right)^{\beta_2} \cdot \left(\text{imp}_{\text{tot}} \cdot 100 + 1\right)^{\beta_3} \cdot \beta_4}{2.205} \quad (4)$$

where Y is the total constituent load (kg), R_{day} is precipitation on a given day (mm H_2O), DA is the HRU drainage area (km^2), imp_{tot} is the function of the total area that is impervious, and the β variables are regression coefficients. The conversion factors to implement metric units in equations are used: 25.4 mm/inch, 2.59 km^2/mi^2, and 2.205 lb/kg. ArcSWAT assigns the annual precipitation to each sub-basin by aggregating the monthly precipitation from the weather generator data [21].

2.4. Statistical Analysis

Once the level of monthly NH_4, NO_2, and sediment are calculated for each watershed, the relative performance of 100 m, 30 m and 10 m DEMs is compared considering sum outputs, the minimum, maximum, mean, median, and standard deviation of pollutant runoff yields for each watershed. By using sum outputs of NH_4, NO_2, and sediment, difference and percentage difference are calculated for 100 m, 30 m and 10 m DEMs. By using three DEMs, descriptive statistics and spatial maps of runoffs for each watershed scenario are compared. As suggested in [22], the coefficients of variation (CV) are calculated to compare model efficiency using three DEM grid size. CV also serves as a sensitivity analysis of the model for comparison. CV is calculated as Equation (5):

$$\text{CV} = \frac{\sigma}{\mu} \quad (5)$$

where σ is the standard deviation and μ is a mean.

Estimation for monthly runoff of NH_4, NO_2 and sediment using the 30 m and 10 m DEMs are compared to a reference 100 m DEM for quality assessment of DEM results. Statistical assessment as suggested in [9] is performed to investigate the sensitivity of the DEM in the model. This has been achieved using various statistical parameters including the mean difference (MD), the mean absolute difference (MAD), and the root mean standard difference (RMSD) between

30 m and 10 m DEMs, and 100 m as a base DEM (Equations (6)-(8)).

$$\text{MD} = \frac{1}{n}\sum_{i=1}^{n}\left[(\text{Var})^* - \text{Var}_{100\text{ m}}\right] \quad (6)$$

$$\text{MAD} = \frac{\sum_{i=1}^{n}\left|(\text{Var})^* - \text{Var}_{100\text{ m}}\right|}{n} \quad (7)$$

$$\text{RMSD} = \left\{\frac{1}{n}\sum_{i=1}^{n}\left[(\text{Var})^* - \text{Var}_{100\text{ m}}\right]^2\right\}^{0.5} \quad (8)$$

Here, MAD, MD and RMSD decrease show increasing model accuracy across all DEMS. The RMSD represents the degree to which the value of 10 m and 30 m differs from the reference 100 m DEM value.

3. Results

The ArcSWAT estimated the monthly yield of NH_4, NO_2 and sediment over 10 year time period generated from the different resolutions of DEM combined with land use/cover and soil maps (Table 4). The total sum yield of sediment (tons/hectare) increased with 100 m for all watersheds. NH_4 (kg/hectare) has mixed results showing increase for Lawrence Brook with 10 m, Lamington River with 100 m and Bound Brook with 30 m. Similarly NO_2 (kg/hectare) has mixed results showing slight increase for Lawrence Brook with 30 m, Lamington River with 10 m and Bound Brook with 100 m (Table 4). Overall, significant percentage difference was shown between 30 m and 100 m across all pollutants except NH_4 for Bound Brook. This difference resulted due to different numbers of sub-basins with variation in DEMs for most sub-watersheds (Table 4). The impacts of DEM resolution on model efficiency are investigated using coefficient of variation (CV) (Tables 5-7). With three DEMs, fixed scales of land use/cover and soil maps (1:250,000) are used in ArcSWAT analysis. CV indicates how sensitive the model is to the DEM pixel size on which the runoffs are simulated in ArcSWAT. The results show the changes in value of CV. This indicates that the model is sensitive to the scale variation (Tables 5-7).

Table 4. Total sum, difference, and % difference in sediment, NH_4, and NO_2 in 10 m, 30 m, and 100 m DEMs for Lawrence Brook, Lamington River, and Bound Brook.

Sub-watershed	#of sub-basins	Sediment	NH_4	NO_2
Lawrence Brook				
Total Sum at 10 m	25	171,541.77	27,336.18	411.74
Total Sum at 30 m	24	155,469.05	25,101.87	414.14
Total Sum at 100 m	26	293,419.9	19,580.62	226.90
Difference (10 m & 30 m)		16,072.72	2234.31	2.40
% difference (10 m & 30 m) = 10 m − 30 m/30 m × 100		**10.34%**	**8.90%**	**−0.58%**
Difference (30 m & 100 m)		137,950.85	−5521.25	−187.24
% difference (30 m & 100 m)		**−47.01%**	**28.20%**	**82.52%**

Continued

Lamington River		Sediment	NH_4	NO_2
Total Sum at 10 m	23	586,951.06	29,195.65	34.57
Total Sum at 30 m	23	555,893.93	26,179.36	30.42
Total Sum at 100 m	21	1,514,951	30,267.38	11.68
Difference (10 m & 30 m)		31,057.13	3016.30	4.14
% difference (10 m & 30 m)		**5.59%**	**11.52%**	**13.61%**
= 10 m − 30 m/30 m × 100				
Difference (30 m & 100 m)		959,057.07	4088.02	−18.74
% difference (30 m & 100 m)		**−63.31%**	**−13.51%**	**160.48%**
Bound Brook		**Sediment**	**NH_4**	**NO_2**
Total Sum at 10 m	26	749,899.84	87,756.30	632.55
Total Sum at 30 m	29	762,364.61	95,237.21	1538.94
Total Sum at 100 m	32	1,537,139.59	94,816.47	2051.53
Difference (10 m & 30 m)		12464.80	7480.91	906.39
% difference (10 m & 30 m)		**−1.64%**	**−7.86%**	**−58.90%**
=10 m − 30 m/30 m × 100				
Difference (30 m & 100 m)		774,774.98	−420.73	512.59
% difference (30 m & 100 m) =30 m − 100 m/100 m × 100		**−50.40%**	**0.44%**	**−24.99%**

Table 5. Descriptive statistics of average monthly runoff for Bound Brook 10 meter, 30 meter and 100 meter DEM.

Descriptive. Stats	Sediment	NH_4	NO_2
Bound Brook 10 meter DEM			
Min	0.259	0.004	0.000
Max	8431	662.8	11.29
Median	106.6	2.706	0
Mean	238.4	27.89	0.201
Standard Deviation	437.357	56.765	0.909
Coefficient of variation	1.835	2.035	4.522
Bound Brook 30 meter DEM			
Min	0.271	0.002	0
Max	7183	602.3	28.38
Median	89.03	2.647	0
Mean	217.3	27.14	0.439
Standard Deviation	387.041	53.944	2.030
Coefficient of variation	1.781	1.988	4.624
Bound Brook 100 meter DEM			
Min	13.582	0.032	0.000
Max	1099.648	145.846	9.099

Continued

Median	275.864	1.957	0.000
Mean	331.280	20.435	0.442
Standard Deviation	292.108	36.789	1.686
Coefficient of variation	0.882	1.800	3.814

Table 6. Descriptive statistics of average monthly runoff for Lamington River 10 meter, 30 meter, and 100 meter DEM.

Descriptive. Stats	Sediment	NH_4	NO_2
Lamington 10 meter DEM			
Min	0.077	0.007	0.000
Max	5890.000	306.300	2.162
Median	93.330	1.478	0.000
Mean	210.900	10.490	0.012
Standard Deviation	336.631	23.314	0.071
Coefficient of variation	1.596	2.222	5.917
Lamington 30 meter DEM			
Min	0.075	0.007	0.000
Max	5074	277.800	2.227
Median	88.6	1.323	0
Mean	199.700	9.407	0.011
Standard Deviation	304.188	21.270	0.067
Coefficient of variation	1.523	2.261	6.091
Lamington 100 meter DEM			
Min	65.630	0.071	0.000
Max	1181.896	72.200	0.058
Median	451.892	1.506	0
Mean	497.521	9.407	0.004
Standard Deviation	341.196	17.469	0.013
Coefficient of variation	0.686	1.857	3.332

Table 7. Descriptive statistics of average monthly runoff for Lawrence Brook 10 meter, 30 meter, and 100 meter DEM.

Descriptive. Stats	Sediment	NH_4	NO_2
Lawrence Brook 10 meter DEM			
Min	0.038	0.001	0
Max	1551.000	151.700	9.081
Median	22.370	1.666	0
Mean	56.710	9.037	0.136

Continued

Standard Deviation	100.391	15.939	0.564
Coefficient of variation	1.770	1.764	4.147
Lawrence Brook 30 meter DEM			
Min	0.034	0.003	0.000
Max	1089.000	137.000	8.863
Median	22.460	1.602	0.000
Mean	53.540	8.644	0.143
Standard Deviation	85.851	14.775	0.580
Coefficient of variation	1.603	1.709	4.056
Lawrence Brook 100 meter DEM			
Min	7.281	0.021	0.000
Max	307.347	34.927	1.004
Median	45.095	0.707	0.000
Mean	77.830	5.194	0.060
Standard Deviation	73.997	8.988	0.206
Coefficient of variation	0.951	1.730	3.418

Spatial patterns of pollutant loads for each sub-basin in the watershed over a 10 year simulation period also show variation in the distribution of pollutant runoffs among three sub-watersheds (**Figures 3-5**). DEM is the major spatial data input to assess the prediction of runoff and sediments in the watershed. Results show that spatial concentration pattern of NH_4, NO_2 and sediment have changed across DEMs in most watersheds (**Figures 3-5**). The spatial distribution of watershed pollutants across different sub basins shows DEMs influenced spatial patterns of pollutants by the changing DEM resolution effects.

Root mean square deviation focuses on overall relative measure of similarity of two maps of each DEM grid for pollutants in each watershed, allowing to assess the differences in spatial distribution. Selected results show with 100 m DEM the runoff of NH_4 and NO_2 is stretched out in the central-lower part of the Bound Brook watershed (**Figure 3**) with smooth topography, compared to the northern area exhibited relatively steeper slopes (**Figure 3** & **Figure A1** in **Appendix**).

Having estimations of runoff of sediment, NH_4, and NO_2 over 2012-2022, ArcSWAT is used here as a decision tool to test the effect of the DEM on the mean monthly runoff of sediment, NH_4 and NO_2. Most of the results show some variation in runoff due to difference in DEMs. When 100m DEM used as a reference, mean difference (MD), mean absolute difference (MAD), and especially root mean square difference (RMSD) revealed a significant change in terms of model sensitivity in predicting sediment. The results show no variation in overall relative sensitivity with NO_2 with change in DEMs (**Tables 8-10**).

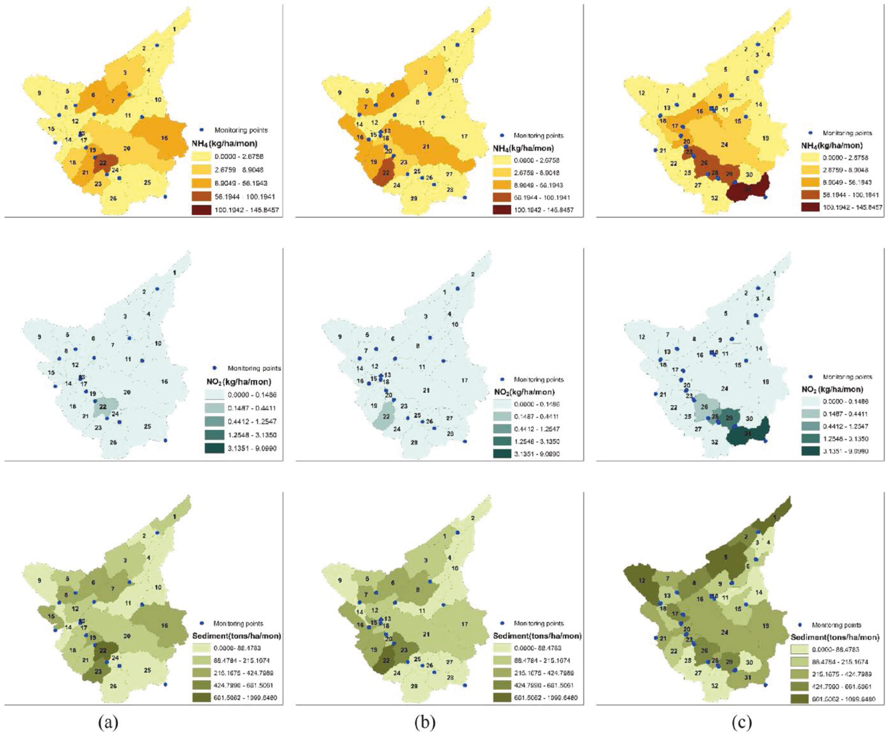


Figure 3. NH_4, NO_2 and sediment yields from each sub-basin as estimated by ArcSWAT. (a) Bound Brook 10 meter DEM; (b) Bound Brook 30 meter DEM; (c) Bound Brook 100 meter DEM.

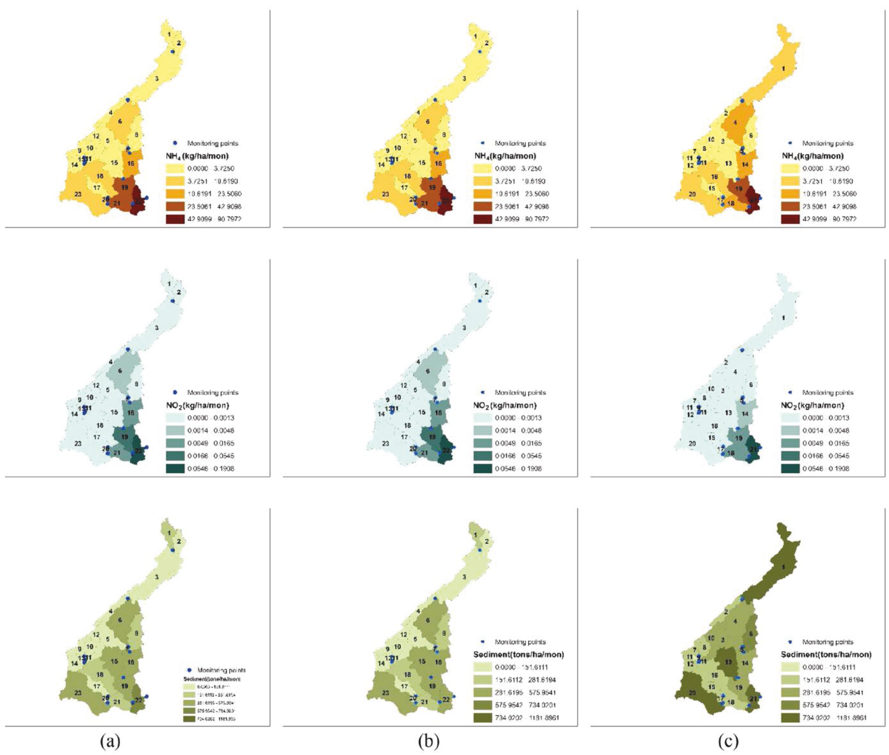
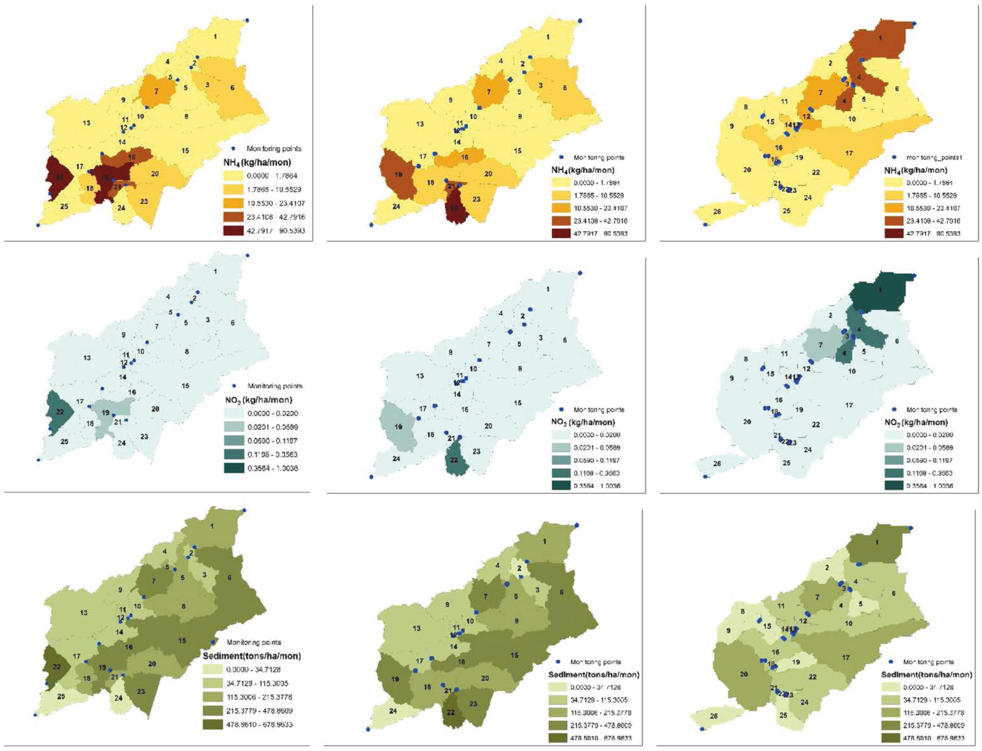


Figure 4. NH_4, NO_2 and sediment yields from each sub-basin as estimated by ArcSWAT. (a) Lamington 10 meter DEM (b) Lamington 30 meter DEM (c) Lamington 100 meter DEM.



(a) (b) (c)

Figure 5. NH_4, NO_2 and sediment yields from each sub-basin as estimated by ArcSWAT. (a) Lawrence Brook 10 meter DEM (b) Lawrence Brook 30 meter DEM (c) Lawrence Brook 100 meter DEM.

Table 8. Effect of the 10 meter and 30 meter DEM on the prediction quality of sediment, NH_4 and NO_2 in Bound Brook watershed.

Statistics	100 m	30 m	10 m
Sediment			
Mean	**331.28**	**217.3**	**238.4**
MD		**−163.27**	**−168.96**
MAD		**163.32**	**169.01**
RMSD		**9673.16**	**9476.92**
NH_4			
Mean	**20.43**	**27.14**	**27.89**
MD		**0.32**	**0.46**
MAD		**0.32**	**0.46**
RMSD		**19.07**	**25.73**
NO_2			
Mean	**0.442**	**0.439**	**0.20**
MD		**−0.00**	**−0.00**
MAD		**0.00**	**0.00**
RMSD		**0.00**	**0.06**

Table 9. Effect of the 10 meter and 30 meter DEM on the prediction quality of sediment, NH_4 and NO_2 in Lamington River Watershed.

Statistics	100 m	30 m	10 m
Sediment			
Mean	**497.52**	**199.70**	**210.90**
MD		**−201.12**	**−193.56**
MAD		**201.19**	**193.66**
RMSD		**10,605.97**	**10,212.52**
NH_4			
Mean	**9.41**	**9.41**	**10.49**
MD		**0.02**	**0.051**
MAD		**0.02**	**0.05**
RMSD		**0.97**	**2.70**
NO_2			
Mean	**0.004**	**0.01**	**0.01**
MD		**0.00**	**0.00**
MAD		**0.00**	**0.00**
RMSD		**0.00**	**0.00**

Table 10. Effect of the 10 meter and 30 meter DEM on the prediction quality of sediment, NH_4 and NO_2 in Lawrence Brook Watershed.

Statistics	100 m	30 m	10 m
Sediment			
Mean	**77.83**	**53.54**	**56.71**
MD		**−4.25**	**−3.18**
MAD		**4.25**	**3.18**
RMSD		**229.06**	**175.12**
NH_4			
Mean	**5.194**	**8.644**	**9.037**
MD		**0.04**	**0.05**
MAD		**0.04**	**0.05**
RMSD		**2.186**	**2.88**
NO_2			
Mean	**0.06**	**0.14**	**0.14**
MD		**0.00**	**0.00**
MAD		**0.00**	**0.00**
RMSD		**0.00**	**0.00**

4. Conclusions

Simulation results over a 10-year time period showed that runoff predictions vary with variation in DEM pixel size. This shows that for small watersheds with little change in topography over the area with changing resolution up to 10 m DEM does affect the runoff production by using the ArcSWAT. Results show that such a noticeable impact of the DEM size are important for selection of parameters in hydrological models for watersheds that are small and have smooth topography, which are known to result into low weighting in the interception, infiltration and retention [9].

In order to investigate the differences in DEM accuracy in small watersheds, research to incorporate fine resolution such as 1 m DEM may induce changes in the estimated outputs since the topographic parameters are computed at the HRU level which may smooth the shape of topographic features. The pixel size of the DEM is important in model sensitivity for SWAT predictions.

The scale variation in different DEMs affects the land surface and hydrological simulation. As the grid size decreases the surface area is more precisely calibrated but it can also differed by the size of the watershed and quality of the employed DEM.

This new knowledge on the impact of the DEM size on NH_4, NO_2 and sediment levels should inform researchers in optimizing parameter generation and input data preparation as well as the efficiency of SWAT model with difference in data quality. In particular, this study shows that the extra precision of DEM size is justified to obtain more accurate prediction in case of small watersheds with less variation in topography for Raritan River Basin.

These results are obtained for ArcSWAT model which is based on the definition of HRUs. These results should be applied to other watersheds and models with caution. In ArcSWAT, runoff in each HRU is calculated separately and then added up together to determine the total loadings from the sub-basin [23]. Change (increase or decrease) in HRU area may have produced different results. These results using SWAT application could be extended to other watersheds with similar environmental and hydrological conditions.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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Appendix

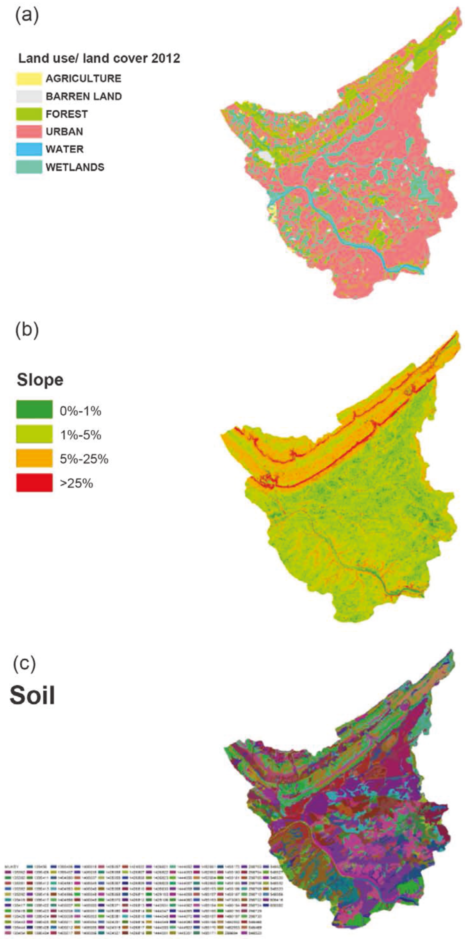

Figure A1. Bound Brook: (a) Land use/cover, (b) Slope and (c) Soil.

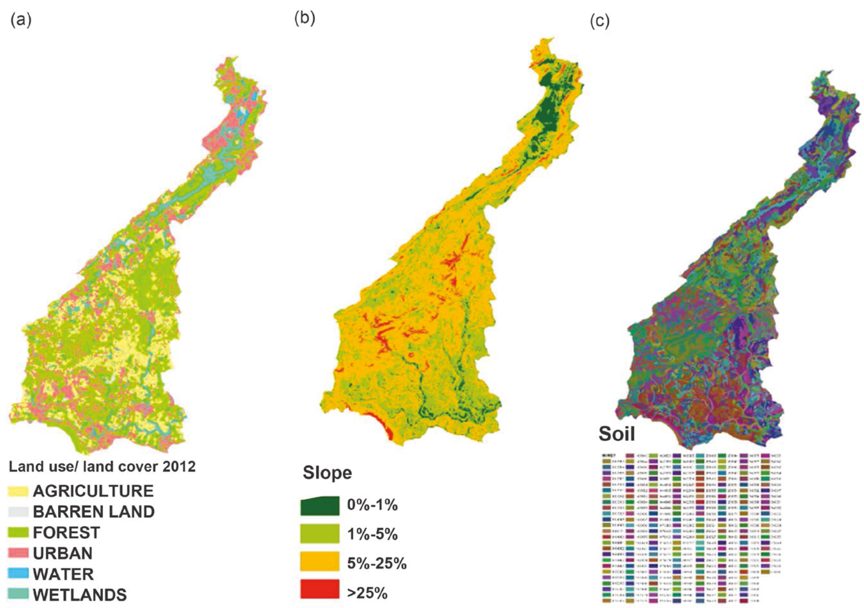

Figure A2. Lamington River: (a) Land use/cover, (b) Slope and (c) Soil.

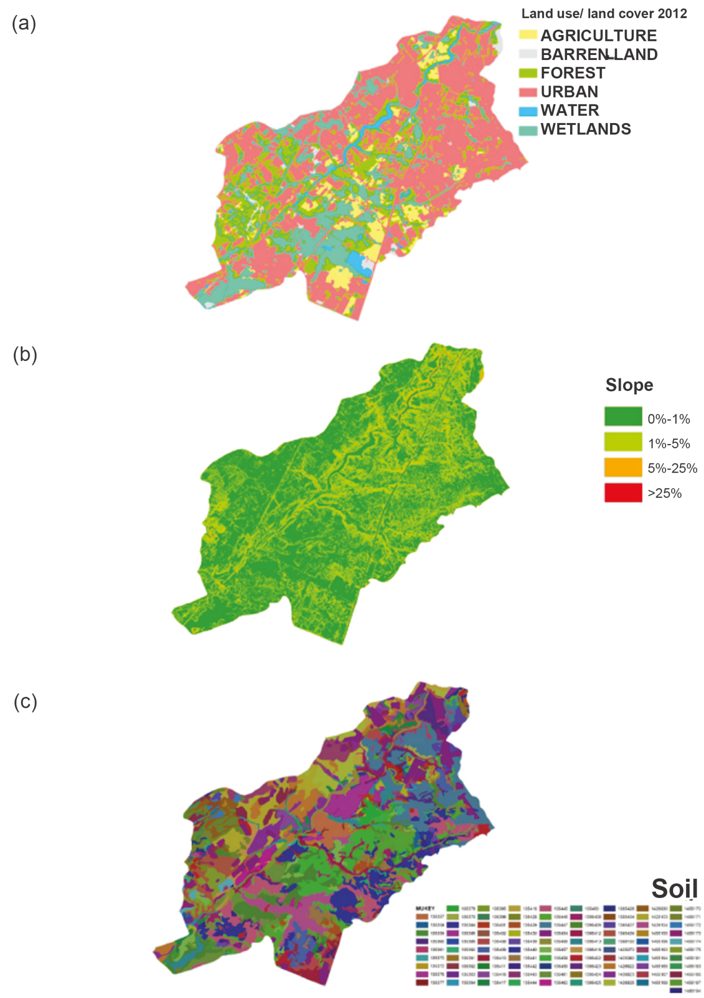

Figure A3. Lawrence Brook (a) Land use/cover, (b) Slope and (c) Soil.