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Climate Change and Watershed Hydrology—Heavier Precipitation Influence on Stormwater Runoff

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Abstract: Stormwater runoff in the USA is a main driver of non-point source pollution and other major problems for urbanizing areas, and runoff effects will be exacerbated by the increased frequency and intensity of heavier storm events that are projected as climate changes. The purpose of this paper is to consider how increased rainfall from storms could influence direct stormwater runoff in urbanizing watersheds. As part of a recent research project in coastal Beaufort County, South Carolina, USA, we applied the Stormwater Runoff Modeling System (SWARM) to model various combinations of development levels and climate change scenarios. SWARM single-event output showed dramatic increases in runoff volume and rate, in some cases almost doubling under moderate climate change scenario and tripling under severe climate change scenario. In all cases, modeled impacts from climate change exceeded those of development. By quantifying stormwater runoff based on climate change scenarios within the context of development, the findings add to the recognition that they must be considered together when projecting changes in watershed hydrology and that climate change effects potentially exceed those of development.

Keywords: stormwater runoff; modeling; climate change; watershed hydrology

1. Introduction

Half of the Earth's human population lives in urban areas [1], and the impervious surfaces associated with urbanization decrease infiltration of rainfall into soils and increase surface runoff, effects that will be amplified by heavier storms that are projected to be very likely with climate change [2,3]. For the continental United States (USA) from 1958 to 2012, the depth of the heaviest 1% of storms increased in every region; for the southeast, the increase was 27% [4].

In the USA, stormwater runoff is a main driver of non-point source pollution in urbanized areas [5]. Runoff picks up contaminants that accumulate on impervious surfaces and delivers them to the receiving waterways [6], and increasing development increases contaminant concentrations (e.g., chemicals, bacteria, viruses) [7–12]. In areas with no stormwater systems, contaminated runoff flows unfiltered into the water, and in areas with combined sewer systems where the same pipe handles stormwater and sewage, heavy storm events cause overflows which increase the contamination [13]. Already, high runoff events from heavier storms overwhelms the drainage infrastructure in the USA, and this will only become worse with increased urbanization and heavier rains [14].

USA coastal areas are growing rapidly with the greatest rate of increase occurring in the southeast [15], where the development pressures result in a "less forested landscape and large increases in the developed footprint" [11,16]. Growth will increase the amount of impervious surfaces, intensifying the negative impacts of development by converting even more rainfall to stormwater runoff [11,17]. In addition, flooding, already directly linked to heavy storms, is expected to increase with the projected increases in heavier rainfall [14].

The purpose of this paper is to consider how heavier events may influence stormwater runoff. Additionally, since the impervious surfaces of urbanization are an important means by which developed lands modify hydrologic flow [18], we look at the effect of heavier rains within the context of development.

As part of a recent research project in coastal Beaufort County, South Carolina (SC), USA, we applied the Stormwater Runoff Modeling System (SWARM) in four watersheds to model direct runoff using various combinations of development and climate change scenarios. Beaufort County is a rapidly-developing coastal community very concerned about the threat of stormwater degrading its estuarine environment. The study sites are within areas considered important to the county and have waterways identified as sensitive to runoff volume [19].

By quantifying direct runoff based on climate change scenarios within the context of development, this paper will contribute to the understanding of the resulting potential changes in runoff and related watershed hydrology. Additionally, SWARM output can assist in resource management initial assessments on where limited resources should be placed for mitigating runoff impacts from current and projected development levels, as well as to gain insight of what might be expected from the frequent and heavier storms as climate changes.

2. Methods

2.1. Study Sites

Four watersheds were chosen for evaluation within Beaufort County, SC, USA: Okatie, May, Battery, and Wallace. Watershed boundaries were provided by the Beaufort County government and evaluated using light detection and ranging (LIDAR) and topography maps (Figure 1). The watersheds were characterized by primary drivers of runoff: area, levels of development, land use, and soil types. ESRI ArcGIS 10.3 software (Redlands, CA, USA) was used to obtain area for each watershed. Impervious cover percent, an indicator of development level, was calculated using methods established in the stormwater runoff modeling system, SWARM [11]. Land use was classified using the 2010 C-CAP Regional Land Cover spatial layer provided by NOAA's Office for Coastal Management, Coastal Change Analysis Program [20]. Soil types were sorted into the appropriate hydrologic soil groups using a soil spatial layer provided by the U.S. Department of Agriculture [21].

2.2. Stormwater Runoff Modeling

The modeling system integrates area, land use, soil type, elevation, precipitation amount, and temporal distribution to calculate runoff volume and runoff rate over time for individual storm events. The system (SWARM) targets watersheds fitting easily within hydrologic units of 12-digit codes and has been calibrated for low-gradient topography of the southeast coastal plain. SWARM is based on curve number and unit hydrograph methods and algorithms of the U.S. Department of Agriculture (USDA), Natural Resources Conservation Service, which are described in Part 630 of the National Engineering Handbook and are widely used in the USA for modeling stormwater runoff [22]. We modified USDA methods related to peak rate factors, travel time formulas, curve numbers, and the initial abstraction ratio. To test the modeling system, we used U.S. Geological Survey (USGS) gauged data for discharge and precipitation from one forested and two urbanized watersheds. Similar to watersheds used in establishing SWARM, the test watersheds were located in the southeast coastal plain. Validation results for both undeveloped and developed test watersheds showed that SWARM captured the major drivers of runoff: modeled volumes and peak rates were within 16% and 9%, respectively, of the USGS gauged data. Methods (including calibrations, validations, and sensitivity analysis) and applications are fully described in two peer-reviewed publications [11,23].

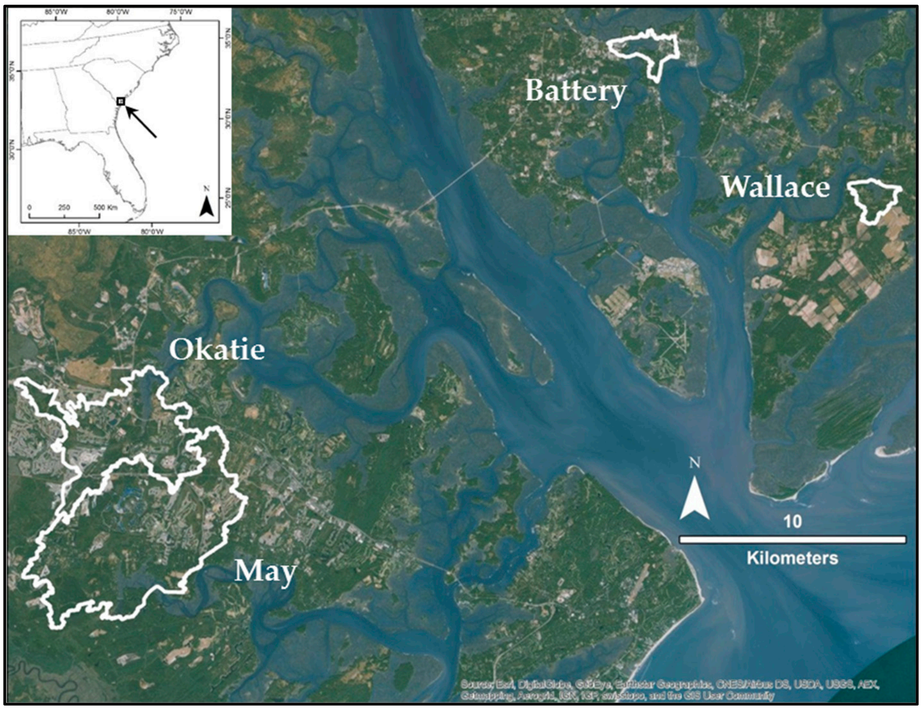

Figure 1. Study watersheds, Beaufort County, South Carolina, USA.

SWARM is a simple modeling system, and the inputs required for volume calculation are watershed total area and the ratios of each land class area and each soil group area to the total area (Table 1). The additional inputs required for rate over time calculations and hydrograph construction include field and digital elevation map data used for determining the time of concentration. The SWARM methods article provides a full description of all volume, rate, and time calculations and equations [23].

For this paper, the modeled base storm event is a 24 h, 49.5 mm (1.95 in) rainfall which is the 95th percentile rain for Beaufort County and is used in stormwater regulations for the county [24]. The rainfall amount is increased for the climate scenarios (see Subsection 2.4). For hydrograph construction, our temporal distribution for the storm event is the National Oceanic and Atmospheric Administration Type III, 1st quartile, 30% distribution [25].

2.3. Development Levels

We used two development levels for each of the watersheds: Current and Build-out. Current is based on present land use in each watershed. For the Build-out level, we projected additional watershed development in the four developed land classes by transferring all land areas not presently developed (i.e., cultivated, forested, pasture/grass, and brush) to the four developed classes, with the amount added to each class based upon its current level in relation to the other three developed classes (Table 1). Wetland remained the same in Build-out because it is generally protected from development.

Table 1. Input required for calculating stormwater runoff volume: area, land use, and hydrologic soil group. Watershed entries for each land use category and each hydrologic soil group are proportional to the total area. For soils, A is the most permeable group and D the least permeable. 'Current Land Use' shows proportions at existing levels. 'Build-out Land Use' shows proportions when all undeveloped dry land is transitioned to the developed state.

Category	Description	Current Land Use				Build-out Land Use			
		Wallace	Battery	Okatie	May	Wallace	Battery	Okatie	May
Area	Hectares	241	288	2296	4378	241	288	2296	4378
Land Use	Developed-High	0.000	0.068	0.006	0.001	0.000	0.089	0.009	0.004
	Developed-Medium	0.000	0.100	0.071	0.026	0.000	0.132	0.110	0.066
	Developed-Low	0.005	0.174	0.166	0.098	0.367	0.229	0.258	0.251
	Developed-Open	0.003	0.224	0.160	0.112	0.180	0.294	0.248	0.286
	Cultivated	0.039	0.000	0.011	0.016	0	0	0	0
	Forested	0.297	0.151	0.125	0.228	0	0	0	0
	Pasture/Grass	0.062	0.003	0.032	0.049	0	0	0	0
	Brush	0.142	0.023	0.055	0.077	0	0	0	0
	Wetland	0.448	0.198	0.344	0.369	0.448	0.198	0.344	0.369
	Water	0.004	0.059	0.030	0.025	0.004	0.059	0.030	0.025
Hydrologic Soil Group	A	0.093	0.583	0.033	0.041	0.093	0.583	0.033	0.041
	B	0.206	0.151	0.054	0.221	0.206	0.151	0.054	0.221
	C	0.192	0.060	0.469	0.277	0.192	0.060	0.469	0.277
	D	0.509	0.207	0.444	0.462	0.509	0.207	0.444	0.462

2.4. Climate Scenarios

For the climate change scenarios, we based our modeling on general predictions of increasing frequency and intensity of heavy storms [2]. Our default modeling with SWARM at present climatic conditions uses average antecedent runoff conditions (ARC). ARC is the collective term for causes of runoff variability including "rainfall intensity and duration, total rainfall, soil moisture conditions, cover density, stage of growth, and temperature" [26]. ARC is divided into three classes: I for dry conditions, II for average conditions (default ARC for SWARM modeling), and III for wetter conditions. Our climate change scenarios include a range of wetter conditions. For this paper, we are using two scenarios: moderate and severe. Moderate climate change scenario consists of a 10% increase in rainfall (from 49.5 mm to 54.5 mm) and an ARC halfway between ARC II and ARC III. The severe scenario consists of a 20% increase in rainfall (from 49.5 mm to 59.4 mm) and ARC III. These scenarios are only two of numerous possibilities [27]. We use them to model runoff at Current and Build-out levels.

3. Results

3.1. Watershed Characteristics

The four watersheds differed in characteristics relevant to runoff (Table 2). The two larger watersheds, Okatie, at 2296 hectares (ha), and May at 4378 ha, were an order of magnitude larger than the two smaller watersheds, Wallace, at 241 ha, and Battery, at 288 ha. In environmental and ecological research, the percent of impervious cover is often used as an indicator for the level of development [6,8,28], and we use that to explore impacts of urbanization on runoff: the higher the percent of impervious cover, the higher the degree of development. Impervious cover calculations are based on percentages used for the developed land classes (High-90, Medium-70, Low-45, Open-15) and are derived from those used by the USDA and the Coastal Change Analysis Program [11,20,29]. The two smaller watersheds showed the greater range in impervious cover—Wallace was the least developed at 1% impervious cover, and Battery was the most developed at 30%. The two larger watersheds fall in between—May and Okatie, at 13% and 23% impervious cover, respectively. Due to the low-gradient coastal location, wetlands are a large portion of the watersheds, occupying from 20% (Battery) to 45% (Wallace) of the total areas.

Table 2. Study watershed characteristics. Area units are hectares. 'IC' is Impervious Cover and is associated with developed lands, 'Developed' is the urbanized portion of the total watershed; 'Undeveloped' is the non-urbanized portion; 'Wetland' is the marsh portion, 'Water' is the open water portion. 'HSG' is Hydrologic Soil Group, and C and D are the least permeable of the soil groups.

Watershed	Area (ha)	IC (%)	Developed	Undeveloped	Wetland	Water	HSG (C+D)
Wallace	241	1	1%	54%	45%	0%	70%
Battery	288	30	57%	17%	20%	6%	27%
Okatie	2296	23	40%	22%	35%	3%	91%
May	4378	13	24%	37%	37%	2%	74%

Soil types sort into four hydrologic soil groups (HSG): A, B, C, and D. HSG A and B soils have high and moderate infiltration rates, respectively, and have high permeability to rainfall. HSG C and D soils have low and very low infiltration rates, respectively, and have low permeability to rainfall [29]. The watersheds have a large proportion of low permeability soils, with 70% and greater C and D soils, except for Battery, which only has 27%. This is due in part to the large proportion of wetlands in each watershed; wetland soils are classified as HSG D.

3.2. Modeled Runoff Measurements

Results are provided for four key measurements related to runoff: initial abstraction, runoff volume, runoff ratio, and peak runoff rate (Table 3, Figures 2 and 3). Initial abstraction, measured in millimeters, indicates the amount of rainfall required in order for runoff to begin in a specific watershed. Runoff volume, measured in cubic meters, is the actual modeled amount of runoff from the specified rainfall. Runoff ratio is the ratio of runoff to rainfall and shows the portion of the rainfall that is converted to runoff. Peak rate, measured in cubic meters per second, quantifies the largest flow rate during the runoff event and is the highest point on the hydrograph curve. Results for these four measurements are presented for the two development levels and then for the two climate change scenarios within each development level. For both runoff volume and peak rate, the watershed area is an important drive and, thus, relative comparisons between watersheds are precluded. Since the initial abstraction and runoff ratio are not based on area, comparisons can be made. Initial abstraction provides an indication of a watershed's runoff potential, and the greater the initial abstraction, the lower the runoff potential. Runoff ratio is based on the specific storm event modeled, showing the proportional runoff, and the higher the ratio, the higher the proportion of rainfall that is converted to runoff.

Table 3. Modeling results for the study watersheds with climate change scenarios shown within the context of each of the two development levels for each watershed. The Current and Build-out development levels are based on the 24 h 49.5 mm storm event at average antecedent runoff conditions (ARC). Moderate and severe climate change scenarios are based on a 10% increase in rain at semi-wetter ARC and a 20% increase in rain at wetter ARC, respectively. 'IC' is impervious cover, an indicator for development; 'I_a' is initial abstraction and is the rainfall depth at which runoff occurs; 'Volume' is the quantity of runoff presented in cubic meters; 'Ratio' is the proportion of rainfall that is converted to runoff; and 'Peak' is the highest flow rate for the rain event expressed as cubic meters per second.

Watershed	IC (%)	Category	I_a (mm)	Stormwater Runoff		
				Volume (m^3)	Ratio	Peak rate (m^3/s)
Wallace	1	**Current Development**	**7.8**	**21,142**	**0.18**	**0.40**
		Moderate Climate Change	5.0	39,775	0.30	0.76
		Severe Climate Change	2.7	69,839	0.49	1.37
	35	**Build-out Development**	**4.3**	**37,909**	**0.32**	**0.72**
		Moderate Climate Change	2.7	60,646	0.46	1.18
		Severe Climate Change	1.5	92,693	0.65	1.86

Table 3. *Cont.*

Watershed	IC (%)	Category	I_a (mm)	Stormwater Runoff		
				Volume (m^3)	Ratio	Peak rate (m^3/s)
Battery	30	**Current Development**	**5.4**	**36,853**	**0.26**	**0.78**
		Moderate Climate Change	3.5	62,551	0.40	1.35
		Severe Climate Change	1.9	100,858	0.59	2.26
	40	**Build-out Development**	**3.1**	**57,857**	**0.41**	**1.25**
		Moderate Climate Change	2.0	85,909	0.55	1.90
		Severe Climate Change	1.1	122,453	0.72	2.80
Okatie	23	**Current Development**	**4.8**	**328,255**	**0.29**	**3.27**
		Moderate Climate Change	3.1	539,843	0.43	5.40
		Severe Climate Change	1.6	846,241	0.62	8.45
	36	**Build-out Development**	**3.7**	**400,719**	**0.35**	**4.02**
		Moderate Climate Change	2.4	621,445	0.50	6.21
		Severe Climate Change	1.3	922,765	0.68	9.22
May	13	**Current Development**	**6.1**	**502,875**	**0.23**	**4.95**
		Moderate Climate Change	3.9	879,314	0.37	8.62
		Severe Climate Change	2.1	1,454,969	0.56	14.24
	33	**Build-out Development**	**4.0**	**729,857**	**0.34**	**7.16**
		Moderate Climate Change	2.5	1,147,637	0.48	11.24
		Severe Climate Change	1.4	1,726,224	0.66	16.88

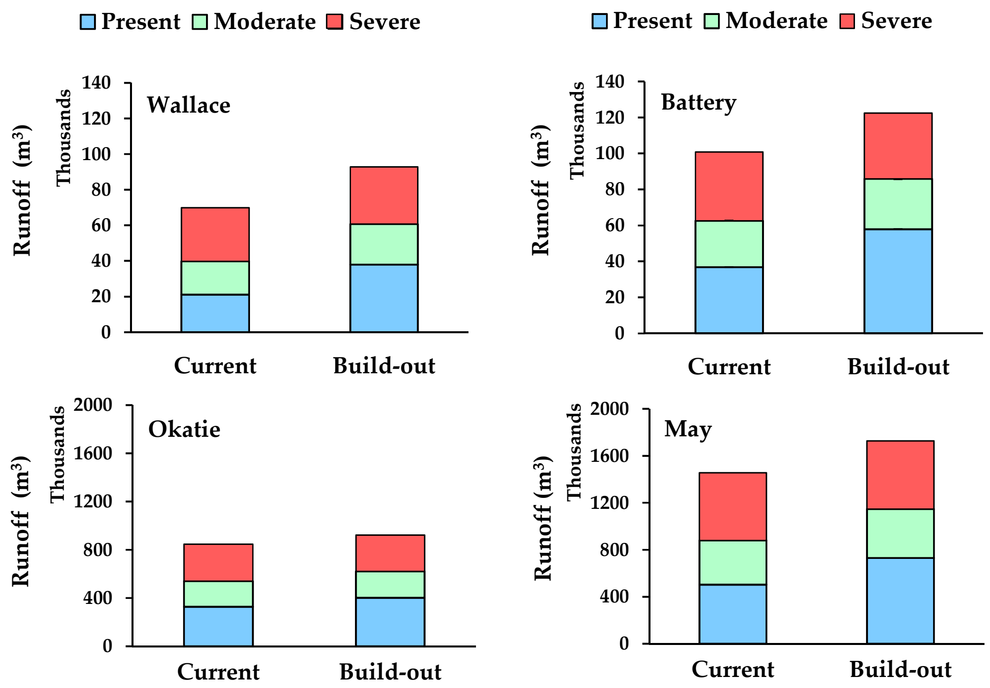

Figure 2. Modeling results for the study watersheds with climate change scenarios shown within the context of both development levels for each watershed; Current is the present development level and Build-out is a higher development level. The *y*-axis is the runoff volume in cubic meters, and the *x*-axis is divided into Current and Build-out development bars, with each bar showing the additive effect of moderate and severe climate change scenarios. Runoff for the Current and Build-out development levels are based on the 24 h 49.5 mm storm event at average antecedent runoff conditions (ARC). Moderate and severe climate change scenarios are based on a 10% increase in rain at the semi-wetter ARC and a 20% increase in rain at the wetter ARC, respectively.

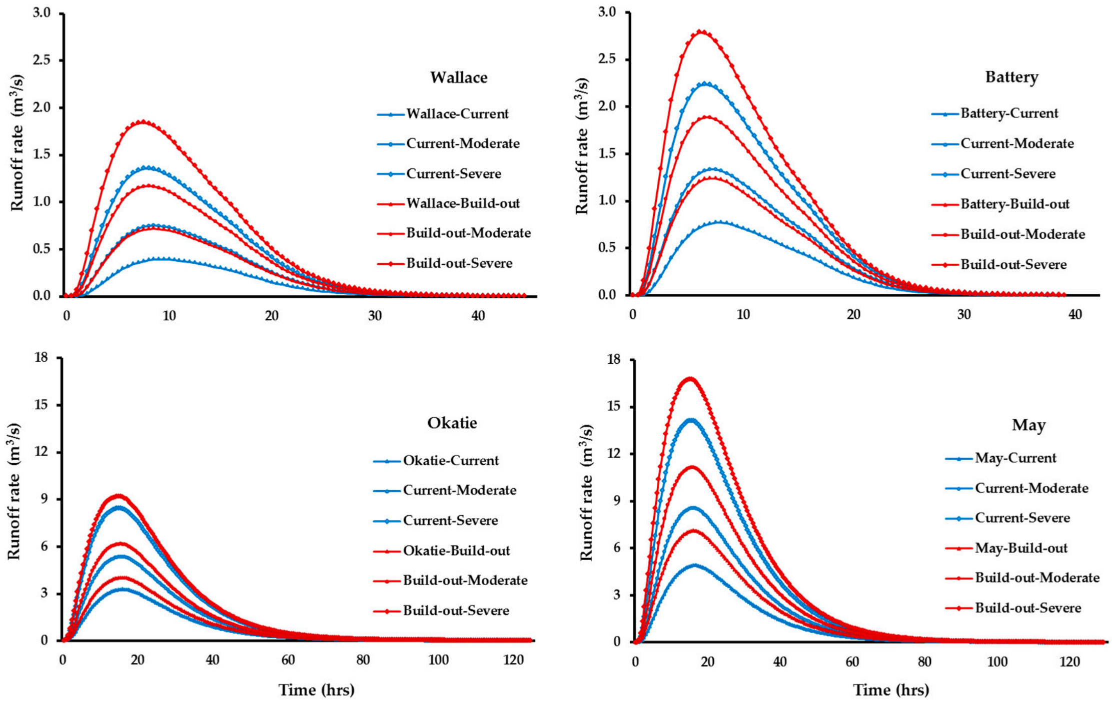

Figure 3. Modeling results for the study watersheds with moderate and severe climate change scenarios shown within the context of the two development levels for each watershed; Current is the present development level and Build-out is a higher development level. Current and Build-out development levels are based on the 24 h 49.5 mm storm event at average antecedent runoff conditions (ARC). Moderate and severe climate change scenarios are based on a 10% increase in rain at the semi-wetter ARC and a 20% increase in rain at the wetter ARC, respectively. The *y*-axis shows runoff rate in cubic meters per second, and the *x*-axis shows runoff time in hours. Distance between points on the hydrograph curves represents a 0.5 h interval.

3.3. Development Influence on Runoff

3.3.1. Development Effect at Current

Wallace, the undeveloped watershed, required the highest amount of rainfall for runoff to occur with an initial abstraction of 7.8 mm; Okatie required the least—4.8 mm—owing to the development level and also due to having the greatest amount of low-permeable soils—91%. Although Battery was the most developed watershed, the preponderance of high permeable soils accounted for a higher initial abstraction than Okatie—5.4 mm. Volume calculated for the rain event was relevant within each watershed; however, comparing runoff volume between the watersheds was difficult owing to the vastly different watershed areas. For example, volume ranged from 21,142 m^3 for Wallace, the smallest watershed at 244 ha, to 502,875 m^3 for May, the largest at 4378 ha. Runoff ratio removed the size effect and provided a meaningful method for comparing relative differences. Wallace retained the largest proportion of the rainfall, converting only 0.18, or 18%, to runoff. Okatie retained the least, converting 29% of the rainfall to runoff. For peak rate, area and development appeared to be the drivers in the smaller watersheds. The smaller and less developed Wallace had a peak rate of 0.40 m^3/s while Battery's rate was practically twice that at 0.78 m^3/s. For the two large watersheds, area was the predominant driver. The peak rates were more than four times greater than those for the two smaller watershed, and the larger May had a higher peak rate than Okatie (May, 4.95 m^3/s, and Okatie, 3.27 m^3/s) even though its development level was lower, with 13% impervious cover compared to Okatie's 23% impervious cover.

3.3.2. Development Effect at Build-out

Transitioning the watersheds to the Build-out level decreased their permeability, which was reflected in the changes in the percent of impervious cover. Wallace, the watershed with the least development, had an increase in impervious cover of 34%—from 1% to 35%. Even the most developed watershed, Battery, had an increase of 10%—from 30% to 40%. Wallace, with the greatest change in impervious cover percent, also showed the greatest changes in the four key measurements. Although Battery impervious cover percent changed the least of the four watersheds, it showed the second greatest relative changes in the measurements, probably due to the high degree of permeable soils which became less permeable with additional development. Partially because Okatie's soils were almost all low permeability, and also because the impervious cover percent change was lower than in May, Okatie showed the least relative change.

Initial abstraction for the watersheds ranged from 3.1 mm to 4.3 mm, indicating that even small rainfalls will generate some runoff. Modeled output for volume and peak rate showed relative changes of more than 50% in Wallace and Battery, and more than 20% in Okatie and May. Direct measurements for all watersheds showed that Build-out produced more volume running off at much faster rates. The additional volume ranged from 16,767 m^3 (Wallace) to 226,983 m^3 (May). Increases in the peak rate range from 0.32 m^3/s (Wallace) to 2.21 m^3/s (May). The spread in range is owing to the different areas of the watersheds.

3.4. Climate Change Influence on Runoff

3.4.1. Climate Change Effect at Current Development

Climate change scenarios affected runoff in the watersheds as a result of increased rainfall and wetter than average antecedent runoff conditions, which decreased overall permeability. Similar to Build-out results, the climate change scenarios showed the greatest relative effect on Wallace and the least on Okatie for the same reasons as previously discussed. However, except for initial abstraction under the moderate scenario for Wallace and Battery, relative changes in the key measures for all watersheds were greater under climate change scenarios than those resulting from the Build-out scenario.

Initial abstraction ranged from 3.1 mm to 5.0 mm under the moderate scenario, and from 1.6 mm to 2.7 mm under the severe scenario. Runoff volume and peak rate for Wallace almost doubled with the moderate scenario and increased by more than three-fold with the severe scenario. Although Okatie had the lowest relative changes, they still were large as volume and peak rate increased by more than half with the moderate scenario and more than doubled with the severe scenario.

As with the Build-out scenario, direct measurements for all watersheds showed that climate change scenarios produced more volume running off at much faster rates. Additional runoff volumes modeled using moderate and severe scenarios ranged from 18,633 m^3 and 48,697 m^3 (Wallace) to 376,439 m^3 and 952,094 m^3 (May). Peak rate increases with moderate and severe scenarios ranged from 0.36 m^3/s and 0.97 m^3/s (Wallace) to 3.67 m^3/s and 9.29 m^3/s (May).

3.4.2. Climate Change Effect at Build-out Development

Relative differences for climate change scenarios at Build-out development were great, but less than those at Current development because watersheds were already at lower levels of permeability created by additional development. Wallace, again, showed the greatest relative changes of the watersheds but the differences from the other three watersheds were quite diminished.

Initial abstraction ranged from 2.0 mm to 2.7 mm under the moderate scenario and from 1.1 mm to 1.5 mm under the severe scenario. For all of the watersheds, volume and peak rate increased by more than half with the moderate scenario (except for volume for Battery which increased by 48%) and more than doubled with the severe scenario.

Although relative changes were less for the climate scenarios applied to the Build-out development level, the actual values were greater primarily due to the decreased watershed permeability from additional development combined with the decreased permeability from the climate change scenarios. Direct measurements for all watersheds showed that climate change scenarios at the Build-out level produced the most volume running off at the fastest rates. Additional runoff volumes modeled using moderate and severe scenarios ranged from 22,737 m^3 and 54,784 m^3 (Wallace) to 417,780 m^3 and 996,367 m^3 (May). Peak rate increases with the moderate and severe scenarios ranged from 0.46 m^3/s and 1.14 m^3/s (Wallace) to 4.08 m^3/s and 9.72 m^3/s (May).

4. Discussion

Coastal development is increasing along the coast of the USA [15]. Communities like Beaufort County, SC, USA are concerned about the impact of stormwater runoff on their receiving waterbodies. In the case of Beaufort County, the receiving waterbodies are treasured tidal creeks and salt marshes which have high ecological and aesthetic value. This includes functioning as aquatic nursery habitats for fish, shrimp, and crabs, feeding grounds for wading birds, and pollutant processing [8]. Previous research has shown that relationships exist between development of the upland and the environmental quality of tidal creeks [7,12,30]. This connection and rapid growth has led to Beaufort County requiring progressive stormwater runoff requirements [31].

Studies have identified a relationship between stormwater runoff and the amount of impervious surfaces and low permeable soils [17,32] with which our study agrees. The four study watersheds vary in their size, impervious cover, land use, and soil types. All of these variables have the potential to affect the volume and rate of stormwater runoff. One of the runoff metrics SWARM provides is the initial abstraction or rainfall amount required to initiate runoff which is a useful indicator of relative runoff potential between watersheds. The initial abstraction is not affected by rainfall amount and is based solely on watershed characteristics (i.e., hydrologic soil groups and land use) and antecedent runoff conditions. The initial abstraction is also highly related to the runoff ratio for the modeled scenarios ($r^2 = 0.99$). At the Current level, the initial abstraction was found to be the highest in the most undeveloped watershed, Wallace. The lowest initial abstraction was in the Okatie watershed, with the second highest level of development but the lowest level of permeable soils. This combination of developed surfaces and low permeable soils also results in the lowest relative change in initial abstraction from Current to Build-out scenarios. The highest relative change from Current to Build-out occurred in Wallace, as expected, due to the large amount of land transitioned to developed.

Quantifying runoff volume and peak rate provides useful metrics important for initial understanding of potential for both flooding on the land and for transport of pollutants from the upland into receiving waterbodies [6,17]. These are critical factors for stormwater managers to consider in planning for the future. The hydrographs constructed for each watershed provide a visual representation of the changes in runoff volume and peak rate from building out the watershed, as well as for expected climate changes. The hydrograph curves for the four modeled watersheds reveal a larger relative change in volume (i.e., the area under the curves) from Current to Build-out for Wallace, Battery, and May watersheds compared to the Okatie watershed. This reflects the relatively high initial runoff potential for Okatie resulting from the combination of developed lands and low soil permability. Due to these watershed characteristics, the impact of the Build-out will be less for Okatie than for the other watersheds. For all of the watersheds, the steeper and higher hydrograph curves for the Build-out and the climate change scenarios slopes compared to the Current slopes are an indication of the tremendous impact of additional development and heavier rainfall.

A summary of the relative change in volume and peak rate from Current (2010) to Build-out shows similar patterns to the initial abstraction with a range of 22% (Okatie) to 80% (Wallace). For climate change scenarios at Current, runoff volume and peak rate increased by a range of 64% (Okatie) to 90% (Wallace) for moderate and by a range of 158% (Okatie) to 243% (Wallace) for severe. For climate change scenarios at Build-out, runoff volume and peak rate increased by a range of 48% (Battery) to

64% (Wallace) for moderate and by a range of 112% (Battery) to 158% (Wallace) for severe.. These modeled increases for runoff volume and peak rate need to be mitigated. The use of Best Management Practices (BMP) is a common way to try to mitigate these impacts; however, most BMPs in coastal SC merely detain (rather than retain) the runoff. Beaufort County has implemented a parcel-level infiltration requirement to retain the first 49.5 mm (1.95 in) of rainfall. This should be effective but has yet to be tested, and only applies to unincorporated areas.

The development effect is less than the influence of the climate change scenarios; however, the temporal timeframes are different for these effects. Considering the level of current development, it is possible that watersheds modeled in this study could be built out in the near future—perhaps in five to ten years—and our approach to building out the watersheds was very conservative and assumed similar development patterns to those already in the watershed. Climate will change over longer time periods. Managers are faced with making short-term decisions related to coastal development to limit the impacts from stormwater runoff on receiving waterbodies, but they also need to have the ability to plan for long-term implications from changing climatic conditions.

A conservative approach combined with a simple and robust model can provide local communities with an understanding of the potential changes with which they will be faced. People are migrating to coastal regions all over the world and development of these areas is inevitable. Along the coast of SC, managing stormwater is a requirement; however, it is conducted at the individual development level with no requirement to consider the overall watershed. Coastal stormwater managers need to be cognizant of watershed scale changes that may occur as a result of a changing climate (e.g., heavier rains) within the context of increasing development.

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Abbreviations

The following abbreviations are used in this manuscript:

ARC	Antecedent Runoff Conditions
h	Hour
ha	Hectare
HSG	Hydrologic Soil Group
I_a	Initial abstraction
IC	Impervious Cover
m^3	cubic meter
mm	Millimeter
NRCS	Natural Resources Conservation Service
s	Second
SC	South Carolina
SWARM	Stormwater Runoff Modeling System
U.S.	United States
USA	United States of America
USDA	United States Department of Agriculture
USGS	United States Geological Survey

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