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Hydrology of Poorly Drained Coastal Watersheds in Eastern North Carolina

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Abstract. *A 10,000 ha lower coastal plain land near Plymouth in eastern North Carolina has been intensively monitored since 1996 to measure hydro-meteorological parameters including outflows and quality of water drained from fields and subwatersheds with varying land management practices. This study summarized the data for a six-year period (1996-2001) for a 2950 ha forested, a 710 ha agricultural subwatershed and a 8140 ha watershed comprised of agricultural, forested, and riparian lands. The period covered a wide range of weather conditions from a dry year with annual rainfall of 775 mm in 2001 to a wet year with 1512 mm of rain in 1996 with two hurricanes. While 1998 with 1242 mm of annual rain experienced a wet winter and a prolonged dry summer-fall, the conditions were opposite in 1999 (1302 mm of rain) with a dry winter-spring and three hurricanes in the summer and fall. A near normal rainfall (1219 mm of rain) was observed in year 2000. The average annual PET for the site was estimated to be 1000 mm. Variability in annual rainfall was found to have greater effect than the land use type on annual outflows drained from these three watersheds. The average annual runoff/rainfall ratio for the managed pine forest watershed was the lowest compared to two other watersheds. Both the magnitude and frequency of peak flow rates were highest for the agricultural watershed, as expected. Average annual ET, calculated as difference of rainfall and outflow, was 922mm, 714 mm, and 727 mm for forested, agricultural and mixed land use watersheds, respectively. Annual ET estimated by the method suggested by Zhang et al. (2001) were in close agreement with the water balance for all six years when a plant-available water coefficient value of 3.0 was used for the managed pine forest. However, further tests of this ET model are suggested in other watersheds. These results will be valuable for estimating nutrient exports from the watershed as well as verifying watershed scale hydrologic and water quality models.*

Keywords. Drainage outflows, Evapotranspiration, Penman-Monteith PET, Water Balance.

Introduction

A lower coastal plain watershed in North Carolina may be visualized as a mosaic of mostly rectangular fields or blocks of fields defined by low-gradient ditches and/or canals that drain to a common outlet. The individual fields or blocks may have different soil types, land uses including some wetlands and pocosins in some cases, drainage and related water management systems, and management practices. These lands are typical of those that have been drained for agriculture and silviculture in the southern coastal plains (Skaggs et al., 1994).

Quality of fresh water outflows drained from these watersheds into North Carolina coastal rivers and estuaries, such as the Neuse, has been frequently blamed for problems related to excessive nutrients, primarily nitrogen but also phosphorus. In recent years, land managers and planners are frequently challenged with the task of obtaining reliable estimates of nutrient discharges needed for water quality management and regulatory purposes. An accurate knowledge on stream flow discharge or "outflow" as a result of rainfall and other related processes of hydrologic balance is necessary for both quantifying the watershed nutrient discharges and calibration of hydrologic models.

The hydrology and drainage outflow characteristics of the coastal watersheds have been described by various authors (Amatya et al., 1996; 1997; Chescheir et al., 2001; Skaggs et al., 1980). In the natural state watersheds on these lands are characterized by shallow water tables, which respond rapidly to rainfall and evapotranspiration (ET). Skaggs et al. (1991) conducted a long-term computer simulation study of pocosin hydrology using DRAINMOD (Skaggs, 1978) in eastern North Carolina. The authors reported that conversion from natural pocosin vegetation to a managed pine forest with a deeper rooting zone decreased predicted annual outflow by about 9%. Conversion to agricultural uses increased predicted average outflow by 7% compared to natural conditions. Konyha et al. (1988) also used DRAINMOD with a stream routing model to evaluate the effects of in-stream transport on watershed outflow rates. Most of these studies, however, are either based on modeling or only on a field scale monitoring that do not take into account the effects of land use and in-stream transport processes on outflow and nutrient export from fields to the watershed outlet. A watershed scale study is being conducted on a 10,000 ha coastal plain landscape for determining cumulative effects of land use and management practices on watershed outflows and nutrient export. The main objective of this paper is to quantify and evaluate the hydrology and water balance of three watersheds with different areas and land use practices using measured hydro-meteorologic data for a period covering the years from 1996 to 2001.

Study Site and Methods

The study site comprising of three watersheds (S4, T4, and C7) is on an intensively instrumented 10000 ha landscape located near the town of Plymouth in Washington County, NC (Fig. 1). The site is drained by two primary outlets on Kendricks Creek, which flows to the Albemarle Sound in the north. The first outlet located at C7 drains about 8140 ha of land in the southern portion of the site, whose boundary is shown by a thick line in Figure 1. The remaining 1860 ha of land in the north and northwest drains to the second outlet at T5, about 1.5 km north of C7 (Fig.1). The soils are very poorly drained and primarily consist of both mineral (Portsmouth and Cape Fear) and organic (Belhaven and Pungo) soil types. Land uses include cropland (36%), managed forested lands (52%), unmanaged forested wetlands and riparian areas (11%) and areas covered by buildings, lawns, roads, etc (about 1%), typical for the coastal region.

Drainage systems on the site include a network of field ditches and canals, which divide the watersheds into a mosaic of regularly shaped fields and blocks of fields (Fig. 1). Field ditches, which provide both surface and subsurface drainage, are spaced 80 to 100 m apart and range in depth from 1.0 to 1.5 m on agricultural lands and 0.6 to 1.2 m on forested lands. Tile drainage has been installed on some of the agricultural lands. Field ditches drain to a network of collector and main canals, all of which eventually lead to the watershed outlets. Some of the forested lands do not have field ditches. The study site has flashboard riser facilities for controlled drainage on about 50% of the land.

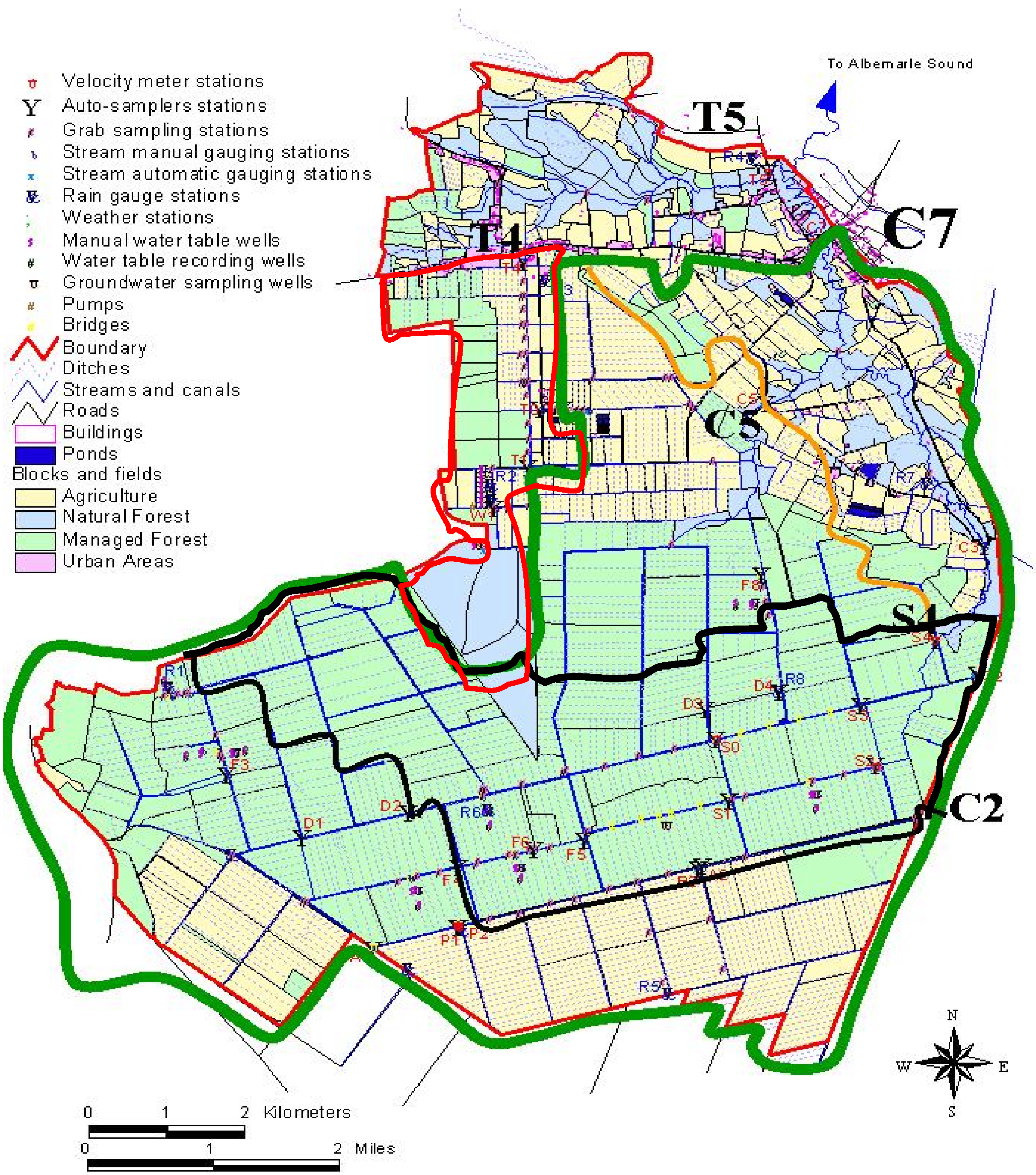

Figure 1. A map of the 10,000 ha lower coastal plain study site showing watersheds S4, T4, and C7 boundaries along with drainage network and monitoring stations.

A geographic information system (GIS) was developed by digitizing data on field areas, major category of land use type, stream, canal, lateral ditches, road, and other important ground features from 1:4800 orthophotos and verified by field reconnaissance. (Fig. 1). Hydro-meteorologic monitoring stations were also added later as separate GIS layers (Fig.1). Major soil types and their hydraulic properties were identified using NRCS soil survey data base (SCS 1981; Kleiss et al., 1993). Land uses, soil types, water management practices, fertilizer applications, location and characteristics of riparian buffer areas, and detailed information on crops and cultural practices were documented for the entire site (Lebo et al., 2000; Shelby, 2002; Paugh et al., 1999; Breve, 1994). General information on soils, land use distribution and drainage systems on each of the three watersheds of the study site is shown in Table 1.

Table 1. Soils and land use distributions on three watersheds.

Water-shed	Drainage Area (ha)	Major Soil Types	Major Land Use Type	Drainage Type
S4	2950	Mineral (Portsmouth, Cape Fear, Wasda) and Organic (Pungo, Belhaven) soils	85% - Managed forest 15% - Second growth pine and hardwood	Mostly drained by lateral parallel ditches, collector canal and stream
T4	710	Portsmouth, Wasda, Cape Fear, Roanoke and Belhaven soils	25% - Mixed pine forest 11% - Wetland 64% - Crop lands, swine farm, pasture and lagoon	Tile drainage, open ditches, collector ditches and canals, and undrained wetland
C7	8140	All types in S4 and Roanoke, Arapahoe, and Tomotley soils	60% - Mixed forests 34% - Agricultural lands 6% - Wetland and riparian forests	Some tile drainage, open ditches, collector ditches and canals, undrained lands

Meteorology

Rainfall. Rainfall is being continuously measured by automatic tipping bucket gauges that are connected to each of the two weather stations (R2 and R6) shown in Figure 1. The data are being stored on half-hourly basis by the data loggers of the CR10X weather station. The gauge at R2 is located at a standard height above the open ground whereas the gauge at R6 is located above the tree canopy on a 22 m tall tower equipped with the CR10X weather station. Moreover, there is also an automatic gauge at a standard height in an open area near R6. Rainfall is being measured with automatic tipping bucket rain gauges at six additional locations (R1, R3, R4, R5, R7, and R8) distributed on the site (Fig. 1). All of these stations are also equipped with manual rain gauges as backups. Breakpoint rain data from each of the stations were processed to obtain daily, monthly and annual rain amounts.

Other weather parameters and evapotranspiration. The weather station at the managed forest site (R6) is mounted on a 22 m tower that can adjust the elevation of the instruments. The instruments are currently located 9 m above the ground surface (2 m above average canopy height of 7 m). The sensors are raised every year before the beginning of the growing season to maintain at about 2m above the average tree canopy. The weather station at the agricultural water management site (R2) is mounted on a 3 m tower. The stations at R2 and R6 measure air temperature, soil temperature, relative humidity, solar radiation, wind speed, and wind direction every 30 seconds and store the average values in the data loggers on an half-hourly basis. The data from two different weather stations (R2 and R6) were used to estimate Penman-Monteith based daily potential evapotranspiration (ET) for short crop and forest reference vegetation, respectively. Details of the weather stations are described by Amatya et al. (2000a).

Potential ET (PET) for the short crop was estimated for a 12-cm height standard grass reference in the Penman-Monteith method using daily weather data (Jensen et al., 1990). Similarly, the Penman-Monteith PET of the forest vegetation was estimated using a maximum canopy stomatal conductance value (80 mmoles m^{-2} sec^{-1}) measured at a pine forest in another coastal plain study (Amatya and Skaggs, 2001) with the estimated Leaf Area Index (LAI). The total daily LAI estimated using intermittent measurements and the published seasonal variation (McCarthy and Skaggs, 1992) varied from about 3.8 to 6.6 m^2/ m^2 during the study period. The method used daily weather data measured above the tree canopy. Annual ET for watersheds with forest, short crop as grass, and mixed vegetation was estimated using annual rainfall and PET with a vegetation factor (w) to reflect the plant available water capacity in the method suggested by Zhang et al. (2001). All data were processed using EXCEL spreadsheets and FORTRAN utility programs for estimating PET as suggested by Jensen et al. (1990).

Hydrology

Drainage water quantity and quality at the field edge are being determined from measurements at the outlets of 12 agricultural fields, 11 managed forested areas and one natural forested wetland site (Fig. 1). Field scale monitoring includes flow measurement and surface water quality sampling from field ditches or collector canals and water table measurement and shallow groundwater sampling in the field. Instrumentation at each flow measurement and surface water quality sampling station includes sharp crested V-notch weirs, water level recorders (located upstream and downstream of the weir), automatic samplers, and microprocessors to store the data and control the samplers. Gauging and sampling stations are located at 30 locations on selected in-stream canals and natural streams to determine water and nutrient outflow rates and their transport through the canal and stream network (Fig. 1). Monitoring equipment include canal water level recorders, automatic samplers for water quality, sharp crested V-notch weirs, trapezoidal flumes, open channels, and Doppler velocity meters. Details of the field and in-stream monitoring equipment and procedures have been described by Chescheir et al. (1998).

Watershed S4 outlet. The outlet of watershed S4, which drains approximately 2950 ha of forest (Fig. 1), is a dual span 1.18 m wide 120^o V-notch weir. The weirs installed on a riser structure discharge into a 2.28m diameter corrugated metal pipe (CMP) culvert located immediately downstream. Stage heights upstream and downstream of the V-notch weir were continuously recorded to estimate flow rates both during the free flow and submerged conditions. The flow rates obtained by using the weir equations for a short period with high submergence were calibrated using a Doppler based continuous velocity meter installed at the downstream end of the outlet culvert. Analysis of data indicated that use of the weir equation alone for estimating flow rates during high weir submergence, generally caused by summer tropical storms and hurricanes, may lead to underestimates of outflow rates on these flat watersheds (Amatya et al., 1998). Daily flows were summed to obtain monthly and annual outflows.

Watershed T4 outlet. The outlet of watershed (T4) draining 710 ha of mostly agricultural land is a 200-meter long uniform straight open channel section that drains through dual concrete box culverts under US 64 highway (Fig. 1). Stages at upstream and downstream sections of the stretch have been continuously measured using a data logger since June 1996 to compute flow rates using Manning equation for slope-area method. The errors associated with using the Manning's equation in the unsteady state flow conditions in the open channel flows were analyzed by Amatya et al. (1998). To minimize such errors the Doppler based continuous velocity meter was installed in one of the dual span box culverts to measure both the stage and velocity at the exit end. Velocity in the second culvert was assumed the same as in the one where measurement was taken. Then flow rates through the dual box culvert were calculated using the area-velocity method or extrapolated using stage-discharge relationship when needed.

Watershed C7 outlet. Measurement of flow rates at this station, which is one of the two primary outlets of the 10,000 ha watershed, were first conducted using continuous stage measurements upstream and downstream of a dual span 3m wide and 3 m high concrete culverts under NC Highway 64E. This outlet drained about 8140 ha of the lands, primarily in the south of the watershed. Later data were supplemented by Doppler based continuous velocity measurements at the end of one of the box culverts. The velocity measured in one of the box culverts throughout the measurement period was assumed the same in other two for total flow computation purposes. Flow rates were estimated using the average velocity and cross-sectional area of flow in the culverts. Relationships were developed for stage and velocity, which were used to compute flow rates for the periods when only the stage data were available and velocity data were missing. Flow rates for very low flow periods were adjusted based on manual flow measurements. Wind effects on computation of flow rates were not considered. However, tidal effect, which is a possibility at this location near the sound, was assumed to be included in the velocity measurements.

All data on rainfall, stage discharge, flow rates, and seasonal and annual outflows were processed and computed using EXCEL spreadsheets in personal computers and NEXS spreadsheets in UNIX system and FORTRAN based utility programs.

Results

Rainfall

Annual rainfall measured at each of the six gauges (R1, R2, R3, R6, R7 and R8) spread across the three watersheds (S4, T4 and C7) is plotted for the six-year (1996-2001) period in Figure 2. Data for R7 was not yet available in 1996. Average rainfall from the long-term (1951-90) data at Plymouth (Office of the State Climatologist, 2000) is also shown.

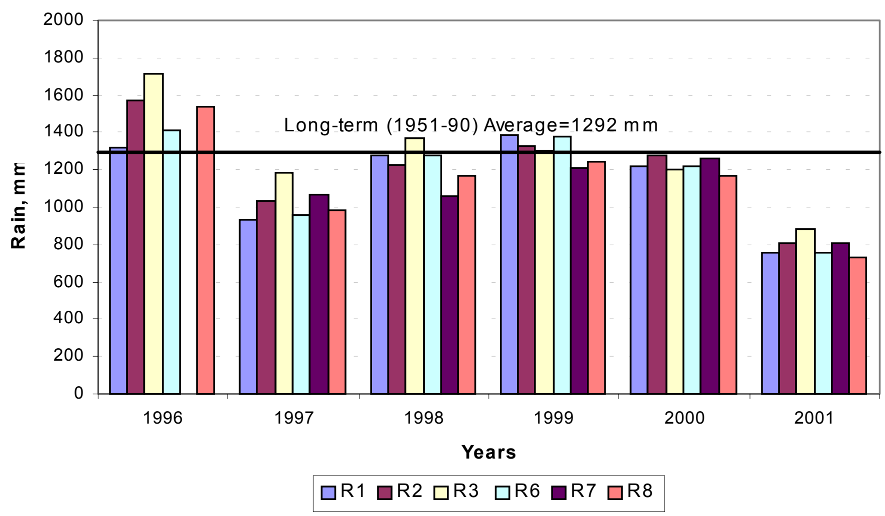

Figure 2. Annual rainfall measured over a six-year (1996-01) period at six stations on the study site.

Figure 2 clearly shows the spatial variation among the gauges in each year as well as annual variation among the years. The coefficient of variation among the years (21%) was greater than among the stations (7%) in each year. Annual rainfall was greatest in 1996 due to three summer-fall tropical storms (Bertha, Fran, and Josephine) shown in Figure 3. Annual rainfall for 1996 was as much as 21 % (R8) higher than the long-term normal of 1292 mm at Plymouth station. The 2001 average rainfall of 790 mm was 39% lower than the long-term average (1292 mm). This was the lowest rainfall followed by 1026 mm in 1997. The six-year average rainfall ranging from 1079 – 1277 mm at each of the six gauges was lower than the normal (1292 mm), indicating a relatively dry study period. Monthly average rainfall across the six stations is presented in Figure 3. Monthly variation was highest in the year 1999 with a prolonged dry winter-summer followed by a wet late summer and fall period as a result of Hurricanes Dennis, Floyd and Irene. Variation was smallest in the relatively dry year of 1997 (Figure 3). A wet winter-spring was followed by a dry summer-fall in 1998. All months, except for June, had lower than normal average rainfall in 2001. Similarly, the first six months of 1997, 1999, and 2001 (except in June) had relatively lower rainfall than two other years and also consistently lower than the long term normal.

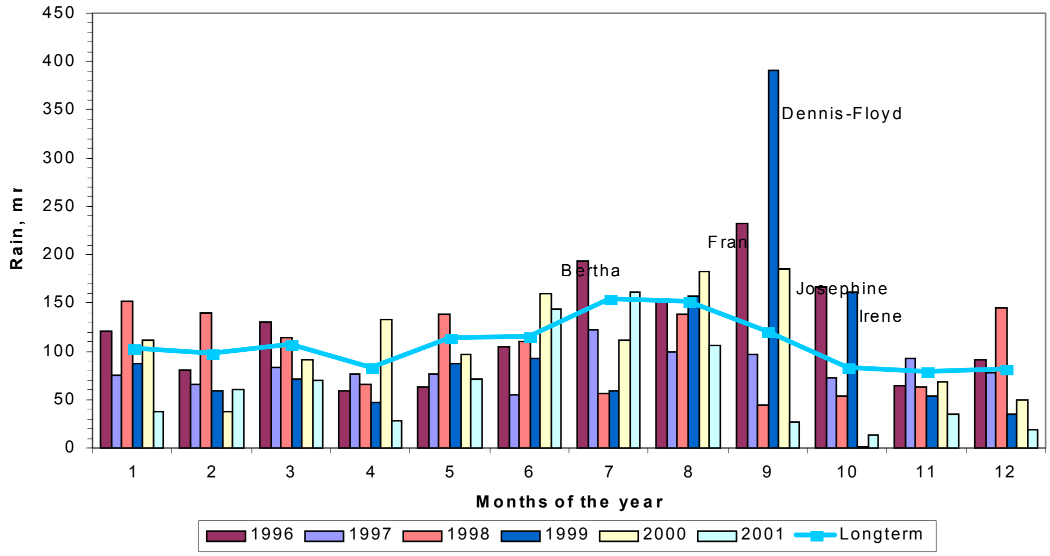

Figure 3. Measured monthly rainfall averaged over six stations for a six-year (1996-01) period.

There was as much as 69 mm difference in the rainfall between the gauges R1 and R2 in June of 1996. A difference of 20-40 mm or more was found to be common between at least two gauges during the summer and fall period. Based on annual data there was no definite pattern in variation of rainfall across the watershed (Fig. 2).

Potential Evapotranspiration

Annual potential evapotranspiration (PET) estimated by the Penman-Monteith method for both the grass and pine forest vegetation is presented in Table 2 for the 1996-2001 period. Annual PET was consistently higher on the forested than at the agricultural site, except for the year 1997. This is due to higher average net radiation measured on pine forest compared to the nearby grass site as reported in an earlier study (Amatya et al., 2000) for 1996-99 period. This was true for the years 2000 and 2001 as well. The greatest difference of 188 mm in PET at two sites was found in the year 2001 with a long dry period based on annual rainfall (Table 2 & Figs. 2 and 3). One reason for this difference may be due to extrapolated data for agricultural site where net radiation data was found to be in error for January to early May. Net radiation was estimated using the solar and net radiation relationship developed for the site from earlier data (Amatya et al., 2000). The annual PET for the watershed (C7) with mixed land use was assumed as average of the data for forested and agricultural watershed. The average annual PET values are consistent with earlier data from the region (Amatya et al., 1996; Skaggs et al., 1994).

Outflows

Measured annual outflows (O) for the watersheds S4, T4, and C7 are presented in Table 2 for the periods of measurement. The outflow for T4 watershed began only in late June 1996. Measured stage and velocity data on T4 were unreliable for the first seven months in 2000 and intermittent months in 2001 either due to beaver dams or due to equipment malfunctioning. Data for these months were extrapolated using monthly flow relationship (T4 = 7.36 + 1.71S4) developed from the two watersheds (S4 and T4) for the 1996-99 period to obtain estimates of annual outflow. Estimates of measured flow data from C7 were available only starting in 1998. Estimated daily flow data during very low flow periods were adjusted to match the intermittent manual flow measurements.

Annual outflows from S4 with managed forest were consistently lower than both primarily agricultural watershed T4 and watershed (C7) with mixed land use, as expected. The highest annual outflows from all watersheds were observed in 1996 with three hurricanes resulting in annual rainfall that was highest of all the six years (Figs. 2, 3 & Table 2). The lowest outflows from all watersheds occurred in the year 2001 with the least amount of rainfall. As a result, the annual hydrologic response factor (O/R) in Table 2 varied from as low as 7% in 2001 to 32% in 1996 for S4, with an annual average of 20%. This value is about 30% less than the 10-year (1988-97) average O/R value reported by Amatya and Skaggs (2001) for a 25 ha managed pine forest on a sandy loam soil located south in Carteret County, North Carolina. This was mainly due to difference in average rainfall, which was 1526 mm for the Carteret site compared to only 1167 mm for this site. Other possible reasons are the seepage loss, large surface storage of this larger watershed and difference in soil water properties affecting drainage and ET losses.

Table 2. Estimated annual water balance components for three coastal watersheds.

Site	Years						
	1996	1997	1998	1999	2000	2001	Average
	Forested watershed (S4)						
Rainfall (R), mm	1410	959	1276	1381	1220	757	1167
P-M PET, mm	968	999	1042	1075	1033	1148	1044
Outflow (O), mm	458	144	280	266	276	50	246
(R – O), mm	952	815	996	1115	944	707	922
Estimated ET, mm	955 (874)	778 (731)	942 (871)	997 (919)	915 (848)	677 (651)	895 (816)
((R-O) – ET)/(R-O), %	0	5	5	11	3	4	5
O/R, %	32	15	22	19	23	7	20
ET/PET, %	99	78	90	93	89	59	85
	Agricultural watershed (T4)						
Rainfall (R), mm	1573	1032	1231	1326	1275	806	1207
P-M PET, mm	913	1017	958	982	948	960	963
Outflow (O), mm	842	328	536	513	494	245	493
(R – O), mm	731	704	695	813	781	561	714
Estimated ET, mm	803	713	755	790	761	603	738
((R-O) – ET)/(R-O), %	-10	-1	-9	3	3	-8	-4
O/R, %	54	32	44	39	39	21	38
ET/PET, %	88	70	79	80	80	63	77
	Watershed (C7) with mixed land use						
Rainfall (R), mm	1461	993	1221	1302	1227	771	1162
P-M PET, mm	941	1008	1000	1029	991	1054	1004
Outflow (O), mm			469	514	451	179	403
(R – O), mm			752	788	776	592	727
Estimated ET, mm	801	697	771	807	769	607	742
((R-O) – ET)/(R-O), %			-3	-2	1	-2	-2
O/R, %			38	39	37	10	32
ET/PET, %			77	78	78	58	73

The O/R factors for T4 were much greater with a high of 54% in 1996 and a low of 21% in 2001. The average value was 38%. This value is higher by 7% compared to the average data (31%) reported by Skaggs et al. (1991) using long-term simulation study for a drained agricultural field in the region. The high value in 1996 attributed to potential error in extrapolation of data from January to June, may have biased the average value. Higher outflows than expected during years with seasonal lower rainfall (e.g. 1997, 1998, 1999, and 2001) might have also occurred due to occasional irrigation applications on the croplands of T4 watershed. Other possible reasons are extensive coverage of lands with tile drainage on the southeastern part of T4 as well as harvesting of some forested lands adjacent to the wetland during

1996-97 period. As expected, the values for C7 with 66% forested land and 34% agricultural lands were in between results for S4 and T4, based on four years (1998-2001) of measurements. Watershed S4 yielded the largest coefficient of variation (56%) in annual outflows, followed by T4 (42%) and C7 (38%). However, the coefficient of variation in outflows among the watersheds in each of the years (1998-2001) was similar (between 28 to 33%), except for the below normal year 2001 with 63%. This indicates that the annual rainfall has a greater impact on average annual outflow than the land use conditions, except perhaps for extreme conditions. This was consistent with the results of Skaggs et al. (1991) who reported that the year-to-year variation in annual runoff was much greater than the effects of all other factors considered.

Daily outflows from agricultural watershed (T4) were much flashier than both the forested (S4) and C7 watershed with mixed land use, as expected (Fig. 4). This is shown by the peak daily flow rates (> 6 mm) that occurred about 1% of time, mostly as a result of hurricanes on all watersheds. A maximum daily outflow of 63 mm for the study period ocurred from watershed T4 as a result of Hurricane Floyd on 9/17/1999 compared to only 12 mm for S4 and 24 mm for C7 watersheds. The impacts of Hurricane Floyd and associated storms on the daily hydrology of these and other watersheds in the area were described in detail by Shelby (2002). Due to small surface storage, higher drainage intensity, and a smaller watershed size, higher peak flow rates occurred more frequently on T4 than on S4 and C7. For example, an outflow depth of 10 mm day^{-1} occurred about 2.4% of the time on T4 compared to only 0.15% and 0.8% on S4 and T4, respectively. Although both T4 and C7 had about similar percent of land uses, peak flow rates on watershed C7 were substantially dampened (Fig. 4) due to large storage of riparian floodplains upstream of the outlet (Fig. 1) and flow routing effects of this large 8140 ha watershed compared to only 710 ha for T4. These results may have large implications in export of nutrient and sediment from these watersheds as shown by Shelby (2002).

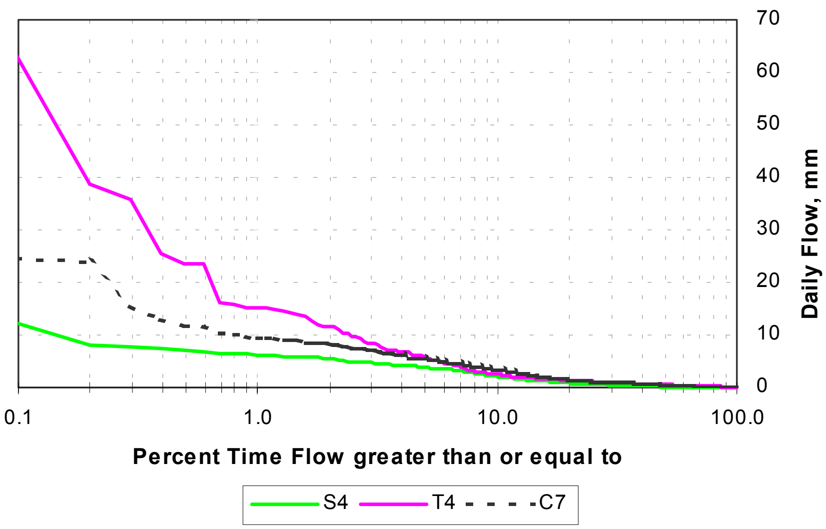

Figure 4. Measured daily flow duration data for three watersheds (S4, T4 and C7) for 1998-2001.

Water Balance

Annual water balance for these coastal watersheds was defined as R (rainfall) = ET (evapotranspiration) + O (outflow) + W (soil water storage). For periods starting and ending with the same water content, W is assumed zero. Vertical seepage on these lands with an impervious layer approximately 2 to 3 m below the soil surface was also assumed negligible (Skaggs et al., 1994; Amatya et al., 1996). Under the assumption that all water including lateral seepage draining from the watershed is measured, the water balance then becomes R = ET + O. Average annual precipitation in the area is about 1292 mm and PET about 1000 mm. Thus the lands are wet because of these local hydrologic processes (Skaggs et al., 1994). Assuming ET = PET for wet conditions without soil water deficits, the long-term average runoff becomes about 292 mm. However, such an assumption depends upon antecedent conditions as affected by year-to-year variation in weather and site-specific conditions as shown by Skaggs et al. (1991).

In this analysis, since total outflow was measured, annual ET was computed using the water balance (R - O) and was compared with annual ET estimated by the method suggested by Zhang et al. (2001) for long-term annual ET. The calculated water balance components are shown in Table 2 for 1996-2001 for S4 and T4, and for 1998-2001 period for C7 watershed. Rainfall from the gauge at R6 was used for the forested watershed (S4). Using the suggested value of w = 2.0 as the plant-available water coefficient for forest vegetation in Zhang et al. (2001) model, estimated annual ET for the forested watershed S4 (values in parentheses) was consistently lower than the ET using the water balance for all the years (Table 2). However, based on the fact that the years 1996, 1998, 1999 and 2000 were wet or near normal years (Figure 3), the annual ET values for the forest are generally expected near the annual PET because of deeper rooting depths than the agricultural crops. Furthermore, the "w" values suggested by Zhang et al. (2001) are for upland conditions that cover a wide range of climate including tropical, dry, and warm temperate and vegetation ranging from plantation trees to native woodlands, open forests, rain forest, pine trees and conifers. We, therefore, adjusted the plant-available water coefficient, w = 3.0 for the managed pine forest on S4 watershed. This resulted in annual ET values within 11% of the water balance in 1999, with an annual average of 5% (Table 2) that can be attributed to errors and other losses. The average annual ET, thus, computed as 85% of PET, was not only consistent with Zhang et al's data but also consistent with the earlier studies in the region (Amatya et al., 1997; Skaggs et al., 1991).

Rainfall for T4 watershed was obtained from the gauge at R2 and the data from the gauges at R1, R6, R7 and R8 were averaged for the annual rainfall at watershed C7 (Table 2). The values of plant-available water coefficient (w) were assumed to be the same e.g. w= 2.0 for forest and w=0.5 for short grass as suggested by Zhang et al. (2001) for the primarily agricultural watershed T4 and watershed C7 with mixed land use. The forest vegetation on these watersheds is mixed ranging from harvested lands, plantation, and some pine forest to natural hardwood stands on riparian flood plains. Thus the computed annual ET values for watershed T4 varied from as low as 603 mm for the dry year 2001 to 803 mm for the wet year 1996, with a six-year average annual value of 738 mm. The result is nearly consistent with data reported by Zhang et al. (2001) for herbaceous plant catchments. The maximum error in annual water balance (R-O) was –10% in 1996 when flow for the first six months was extrapolated. Although the water balance yielded an average annual error of only –4%, these results should be interpreted cautiously because of some uncertainties in the computation of annual outflows especially in early part of 1996, later part of 2000, and some months of 2001 as discussed earlier. The average annual ET was computed as 77% of total PET. Similarly, the computed annual ET for watershed C7 varied from 807 mm in 1999 to as low as 607 mm in the driest year 2001. These estimates were within an error of 3% compared to the measured water balance for four years. Negative values in errors, especially in the year 1997 for T4 and 1998 and 2001 for both T4 and C7 watersheds are indicative of soil water deficits in those years. These results indicate that the method suggested by Zhang et al. (2001) can be used to estimate annual ET for these humid coastal plain watersheds of North Carolina. The authors, who used Priestlay-Taylor method for PET estimate, suggested that the estimates of annual ET may depend upon the method of PET estimate. We have used the Penman-Monteith method for estimates of PET assuming it the most reliable one of all other methods available in the literature (Jensen et al., 1990).

Conclusions and Recommendations

The six-year (1996-2001) study period on three watersheds of the 10,000 ha lower coastal plain site near Plymouth in North Carolina covered a wide range of weather pattern with an above normal rainfall in 1996 with three hurricanes to a well below normal rainfall in 2001. Variability in rainfall was found to have greater effect than the land use on seasonal and annual outflows drained from three watersheds with different land use and management practices. The average annual runoff/rainfall ratio for the managed pine forest watershed S4 was the lowest compared to two other watersheds. Both the magnitude and frequency of peak flow rates were highest for the agricultural watershed T4, as expected. Despite a similar proportion of land use, flow routing through canals and streams including riparian floodplains reduced both the peak flow rates and annual outflows on large 8140 ha watershed (C7) compared to T4 (710 ha). Average annual ET calculated as the difference of rainfall and outflow was the highest for forested watershed followed by C7 and T4. Annual ET estimated by the method suggested by Zhang et al. (2001) were in close agreement with the water balance for all six years when a plant-available water coefficient value of 3.0 was used for the managed pine forest. Values suggested by Zhang et al. (2001) yielded annual ET values in good agreement with measured water balance for agricultural (T4) and mixed land use (C7) watersheds. The ET model can be used with some calibration for estimating annual ET in the water balance of these coastal watersheds. These results will be useful in estimates of watershed nutrient exports as well as watershed scale hydrologic and water quality modeling (Amatya et al. 1999; Fernandez et al., 2002).

Although the ET model produced reasonable results compared to the measured water balance, it should be further tested for multiple years and sites with varying land uses in other coastal plain watersheds. Since the measurements of outflows on flat coastal plain watersheds is a challenging task, every effort including alternate methods of measurement must be used for accurate estimate of the outflows affecting the water and nutrient balance of these watersheds. Hydrological and water balance studies, as was conducted herein, should be conducted at least for a five-year period to accurately estimate the water budget as affected by the land use and management practices and the varying climatological conditions.

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