The Effects of Change of Land Use on Trends in Stream Flow

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Introduction

The task of investigating the effects of change of land use on trends in stream flow is one of several being performed by ICPRB with funding support from Maryland Department of Natural Resources - Water Resources Administration under the general subject of conservation and freshwater inflows to the Chesapeake Bay. The two major issues addressed in this task are: (1) the relative consumptive loss of water with differences in land use, and (2) changes in the runoff hydrograph with differences in land use. The first addresses the relative total volumes of runoff, and the second, the temporal distribution of that runoff. The methods and results described in this report will be useful in determining expected trends in stream flow as the population and industrial activity expand in the Chesapeake Bay basin.

It was originally intended to use, as project data, the long-term stream flow records at: Point of Rocks on the Potomac, Jug Bridge on the Monocacy River, and the Occoquan Reservoir on the Occoquan Creek. Upon closer examination, reasons for not using these sub-basins for analysis became apparent. No reliable records in sufficient detail or accuracy existed for the upper Potomac flows which would show the effects of changes in the land use from forest to agriculture. The same reason holds for abandoning the Monocacy, and it was not felt that the degree of agricultural-to-suburban land use conversion was large enough to significantly affect the flows from the whole sub-basin. The record of flows which was obtained for the Occoquan was found not to be the readings of a single gage over the apparent period of record. Instead, it included area proportional correlations with several gages in the sub-basin in recent years and correlations with a gage on the Rappahannock River for the earlier years.

After examination of a number of stream flow records, two sub-basins in the Maryland suburbs of Washington, D.C. were selected for analysis.

Review of Literature

Studies of the relationship between changes in ground cover (land use) and the resulting stream flow characteristics are reported in the professional literature. Many of them focus on the two major issues addressed in this work: the relative change in runoff volume, and changes in the shape of the runoff hydrograph.

Among those that addressed volume changes, Newson 1979, describes the results of ten years of study on the Plynlimon experimental catchment in Great Britain, where complete afforestation can more than double the loss from a grassland catchment. This is a high rainfall area and much of the lost stream flow is through evaporation of rain intercepted on the forest canopy. Stoner 1985, investigating the effects of forestry on water quality observed that conifers reduced the flow in rivers and yield of reservoirs in Wales. Deciduous species such as larch had a lesser effect than evergreens such as sitka spruce. Gash, et al. 1978, refer to a work by Hibbert 1967, which summarizes the results of 39 published catchment experiments from the U.S. and elsewhere, and showed that clear felling increased stream flow by amounts ranging from the rainfall equivalent of 35 mm to 450 mm. The rate of water loss from a wet forest canopy is greater than if that same water reached the soil, with only a fraction of it having the opportunity of returning directly to the air as transpiration. The implication is that forests, with their relatively greater foliage have more potential for catchment loss (evaporation plus transpiration) than cropland.

A study by Verry 1983, concluded that storm flow volumes from rain during the first two years after clear cutting aspen in north central Minnesota increased as much as 170%. However, those flows declined to approximately pre-cutting volumes in the third year. Brozka 1982, found that the first year increase in flow after the clear cutting of an oak-hickory forest was 95%. He also reported that nitrate-nitrogen in the runoff increased for that period. Douglas 1983, developed models to simulate stream flow increase from harvested hardwood and pine forests as a function of the reduction in basal area. The relative effects of different forestry harvesting techniques are reported by Reikerk 1983. Flow volume increased 250% with conventional practices, and 117% with minimum disturbance harvesting; while in one experimental plot weed vegetation after harvest continued significant water consumption. Doty found similar robustness in water consumption in an ohia forest on the island of Hawaii where the mature trees were dying, but where there was an emergent understory and plentiful forest litter on the ground.

Among those studies that addressed changes in the shape of the runoff hydrograph; Newson 1979, reported an average reduction of peak flows by mature forest when compared to non-forest, and time-to-peak was longer with forested as opposed to non-forested land. Brush 1986, correlated high rates of sedimentation in Furnace Bay at the head of the Cheaspeake with high flows in the post-European settlement era, and uniformly low rates in the preceding 1400 years. If sedimentation rates are an approximate representation of peak flows, her work indicates that higher peaks followed land clearance for agriculture. Verry 1983, also reports that the clear-cutting of aspen in Minnesota increased peak discharge by as much as 250% during the first year. Peaks then decreased toward pre-cutting levels in subsequent years. In his study of dying forest trees on Hawaii, Doty 1983, reports that there was no observed change in peak flow (probably because of the remaining understory). The models of watershed response to cutting developed by Douglas 1983, indicated both increased peak flow and decreased time-to-peak.

All of the studies mentioned thus far dealt with watershed response to the transition from forest to some other silvicultural or agricultural land use. In a study by Kibler 1981, the impacts of urbanization on flood peaks are analyzed. He reports that peak flows in developed areas are greater than those of natural areas. Further, his conclusions indicate that for rainfall events of frequent return period there is a greater difference in relative peaks between natural and urbanized basins than for events of less frequency.

Development of Hypothesis

The focus of this study is to detect trend, if any, in the volume of flow and shape of the runoff hydrograph as land use changes from rural to (sub)urban. Two catchments in the Potomac River basin are selected and the monthly mean, maximum, and minimum flows for the period of record are analyzed for the existence of trend. The mean monthly flow is a representation of runoff volume. The maximum and minimum flows represent important characteristics of the shape of the runoff hydrograph. Having detected a trend by a statistically valid method, it is tested to determine the degree to which it is significantly different from zero. The trend hypotheses for flow volume and peak flow are that they increase as land use changes from rural to (sub)urban. Base flows (monthly minimums) are likely to decrease because of the flashier runoff with increased land use development.

Selection of Candidate Sub-basins

The sub-basins which were eventually selected for analysis were: (1) Rock Creek above the Sherrill Drive flow gage just inside the District of Columbia, and (2) the Northeast Branch of the Anacostia River above the gage at Riverdale, Maryland. Both of these sub-basins were deemed to be small enough to show changes in flow pattern (if any exists) in response to changes in land use. Both gages had reasonably long records of good quality data, and spanned a period of major land use change. It was difficult to find a sub-basin which met the criteria of significant land use change, absence or minimal presence of water control structures, stable gage location, and long record of good quality data.

Characteristics of Sub-basins Selected for Trend Analysis

	Rock Creek	Northeast Branch
USGS Gage Number	01648000	01649500
Period of Record	Nov 1929 - Sep 1985	Aug 1938 - Sep 1985
Length of Record	56 yrs	47 yrs
Drainage Area	62.2 sq mi	72.8 sq mi

Test for Trend

A nonparametric statistical test was utilized to determine stream flow trends. Referred to as the modified Grand Kendall Tau test for trends in monthly data time series.

Monthly stream flow data exhibits considerable variation. Recognizing the presence as well as the significance of "real" trends in complex stream flow time series requires the rigorous use of valid statistical techniques.

The use of linear regression is widespread, due in part to its easy application with readily available computer codes. Underlying the use of this powerful statistical tool are a number of assumptions about the distribution and structure of the data being analyzed. When these assumptions are violated a severe degradation of the power and significance of commonly employed statistical tests can result. Many steam flow time series violate these assumptions. The distribution of stream flow data is commonly seasonal, skewed, and highly non-normal.

To support valid and rigorous statistical testing for the presence of trends in water quality time series, a nonparametric test statistic known as the Seasonal Kendall Tau was developed (Hirsch, et al. 1982) and has been employed in this work in place of more common tests based on linear regression and other parametric techniques.

The Seasonal Kendall Tau is a nonparametric statistic that can be readily used to test for trends in monthly stream flow time series. As an example, stream flow for June 1972 is compared to the June flow of all later years. If 1972 June flow is greater than for 1973, that comparison is assigned a score of -1, indicating a decrease; an increase in 1973 would be assigned a score of 1, and a tie would receive a score of 0. For every observation, pair-wise comparisons are made with all later observations. Each paired comparison receives a score of -1, 0, or 1. These scores are added together to produce a monthly test statistic for each flow variable.

If there is an increasing trend through time, recent observations will tend to be greater than earlier observations and the value of the test statistic will be significantly greater than zero; if there is a decreasing trend through time the test statistic should be significantly less than zero.

As an example of the interpretation of the significance of trend: if the standardized test statistic for June flow were equal to 2.5 the null hypothesis of no trend would be rejected at the 1% significance level, in favor of the alternative hypothesis of an increasing trend in June flow. The probability that a time series of June flow could produce a test value this high if no "true" trend were present is less than 1 in 100 (see the following table of normal deviations).

Using this statistic the significance of a trend in each month can be evaluated. To assess the significance of trend for the entire period of record (all months collectively) the Kendall Tau statistics for each month are combined into a Grand Kendall Tau. Like the monthly statistic, the significance of this test statistic can be evaluated by comparing it to the standard normal deviate.

Results and Conclusions

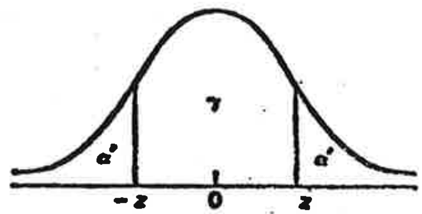
The results of the Kendall Tau test for trends in flow characteristics are tabulated below.

Monthly and Grand Kendall Tau Statistics
for Monthly Stream Flow Data

	Rock Creek '29 - '85			Northeast Br '38 - '85		
Month	Mean	Max	Min	Mean	Max	Min
January	1.17	1.36	.95	.82	.81	.83
February	.85	.97	-.41	.42	.96	.27
March	1.24	1.05	-.64	1.27	1.68	-1.19
April	.85	.21	.00	.61	.77	-.18
May	1.98	2.54	.33	2.21	2.64	.56
June	2.77	1.72	1.92	1.92	1.77	1.07
July	3.06	2.78	1.99	2.55	2.96	1.13
August	2.24	1.78	2.14	.97	.95	.94
September	2.21	1.83	1.70	.52	1.26	-.62
October	1.45	2.89	.86	1.38	2.91	-.92
November	1.36	1.75	-.78	.49	1.04	-1.09
December	1.74	2.59	.49	1.05	1.49	.29
Grand Kendall Tau	6.06	6.22	3.26	4.12	5.58	.32

These results may be compared directly with the following table of Normal Deviations.

Normal Deviations



γ	$\alpha'' = 1 - \gamma$	$\alpha' = \frac{1}{2}(1 - \gamma)$	z
.995	.005	.0025	2.807
.99	.01	.005	2.576
.985	.015	.0075	2.432
.98	.02	.01	2.326
.975	.025	.0125	2.241
.97	.03	.015	2.170
.965	.035	.0175	2.108
.96	.04	.02	2.054
.954	.046	.023	2.000
.95	.05	.025	1.960
.94	.06	.03	1.881
.92	.08	.04	1.751
.9	.1	.05	1.645
.85	.15	.075	1.440
.8	.2	.10	1.282
.75	.25	.125	1.150
.7	.3	.150	1.036
.6	.4	.20	0.842
.5	.5	.25	0.674
.4	.6	.30	0.524
.3	.7	.35	0.385
.2	.8	.40	0.253
.1	.9	.45	0.126

γ = area between $-z$ and z
= confidence coefficient

$\alpha' = \frac{1}{2}(1 - \gamma)$
= area above z
= area below $-z$
= significance level for one-sided test

$\alpha'' = 1 - \gamma = 2\alpha'$
= area beyond $-z$ and z
= significance level for two-sided test

(source: Noether 1971)

For Rock Creek, the Grand Kendall Tau of more than 6 for the monthly mean and maximum flows and more than three for the minimum flows indicates a virtual certainty that there is an increasing trend in these parameter values over the period. The increase in mean indicates greater volume of flow has resulted from increased (sub)urban development. The increasing trend in maximum monthly flow indicates a tendency toward faster more flashy runoff. The season with the greatest likelihood of increasing trend in mean and maximum flows is late spring through summer. The the most significantly positive trend in minimum flow occurs in summer.

Both the volume and peak flow trend results are consistent with expectations. The direction and level of significance of trend in the monthly minimum flows are somewhat surprising. They indicate more residual moisture in the sub-basin. With the presumed lesser amount of catchment rainfall subject to evaporation, and thus a greater amount reaching the soil, not only will there be more instantaneous runoff, but perhaps more water will be entering the soil column and subsequently contributing to base flow. It should be noted that during the early 1960's, two moderately sized dams were built in the catchment and their influence on low flows is not known.

For the Northeast Branch of the Anacostia River, the Grand Kendall Tau of more than 4 for the monthly mean and more than 5 for the monthly maximum flow indicate a virtual certainty that there is an increasing trend in these parameter values over the period. Like the results for Rock Creek, the increase in mean indicates greater volume of flow has resulted from increased (sub)urban development; and the increasing trend in maximum monthly flow indicates a tendency toward faster more flashy runoff. The season with the greatest likelihood of increasing trend in mean and maximum flows is late spring/early summer. The low Tau value of 0.32 for minimum monthly flows does indicate a positive trend, but with less than a 30% degree of certainty. As with mean and maximum flows, the most significantly positive trend in minimum flow occurs in early summer.

Both the volume and peak flow trend results are consistent with expectations. The direction of trend in the monthly minimum flow is a little surprising. However, with the presumed lesser amount of catchment rainfall subject to evaporation, and thus a greater amount reaching the soil, not only will there be more instantaneous runoff, but perhaps more water will be entering the soil column and subsequently contributing to base flow.

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