Geomorphic Constraints on Hydrologic Responses to Urbanization among Small Tributaries to a Fall Zone Stream

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Contact me:

Motivation

Geomorphic characteristics of watersheds influence both patterns of urban development and hydrological response to development. This research is designed to evaluate geomorphic and urban controls on catchment hydrology.

NW Branch of the Anacostia River, an Urbanized Fall Zone Stream

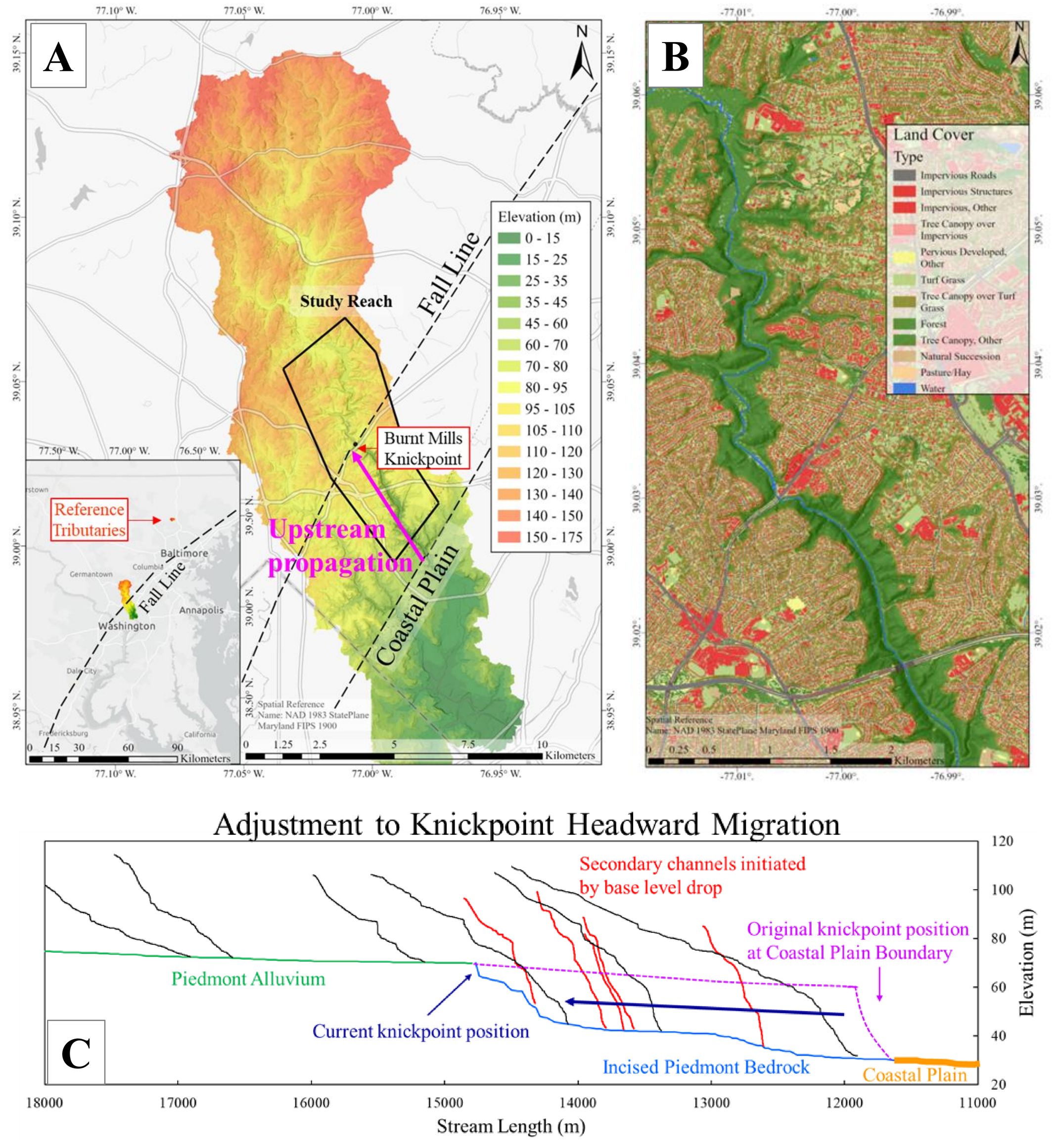
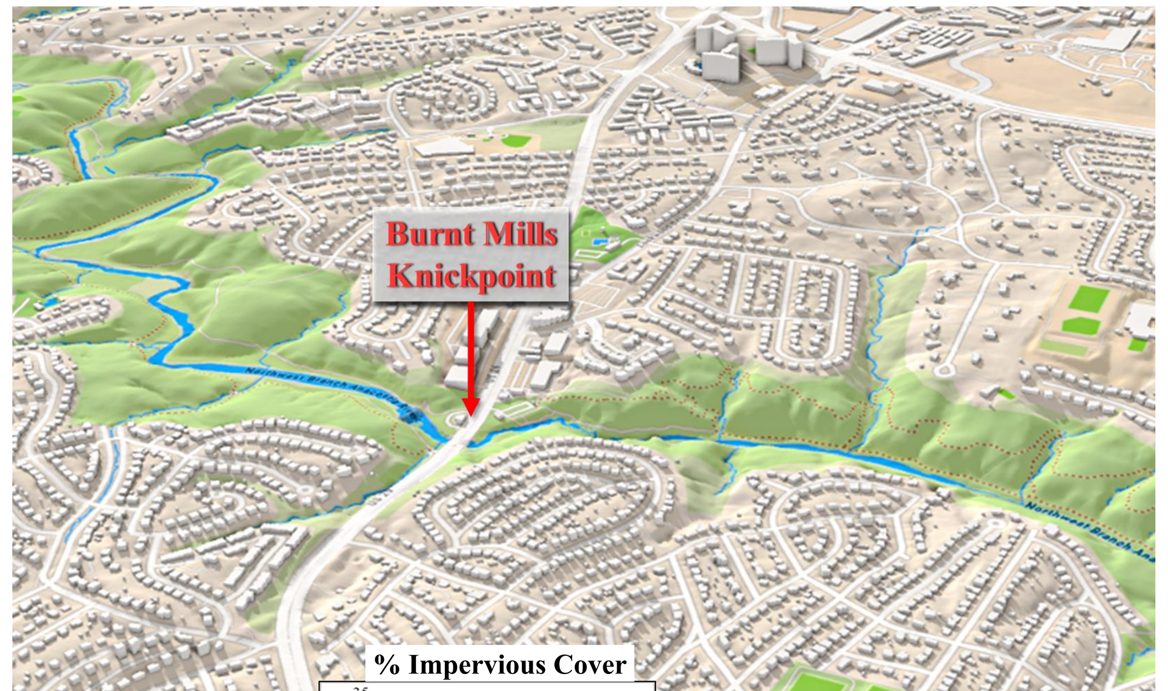
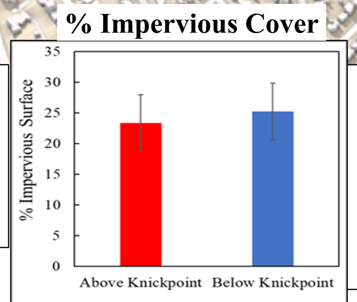


Fig. 1: (A) NWB watershed, black outline indicates the study area. Burnt Mills is the main knickpoint within the Fall Zone. The inset map shows forested reference streams located above the Fall Zone included in the study. (B): Land cover in the study area, note extensive residential development in the flat uplands and deciduous forest in the steep valley adjacent to the stream. (C.) Longitudinal profiles of NWB and study tributaries, located above and below the Burnt Mills knickpoint.

Tributary spacing and morphology differ above and below the knickpoint, but urban structure, age, and % impervious cover are similar





Upstream tribs:
- Wider spacing
- Gentler slopes with floodplains.

Downstream tribs:
- Closer spacing of tributary valleys.
- Steep tributaries, little floodplain development.

Study Catchments:

Urbanized and non-urbanized tributaries above and below the mainstem knickpoint

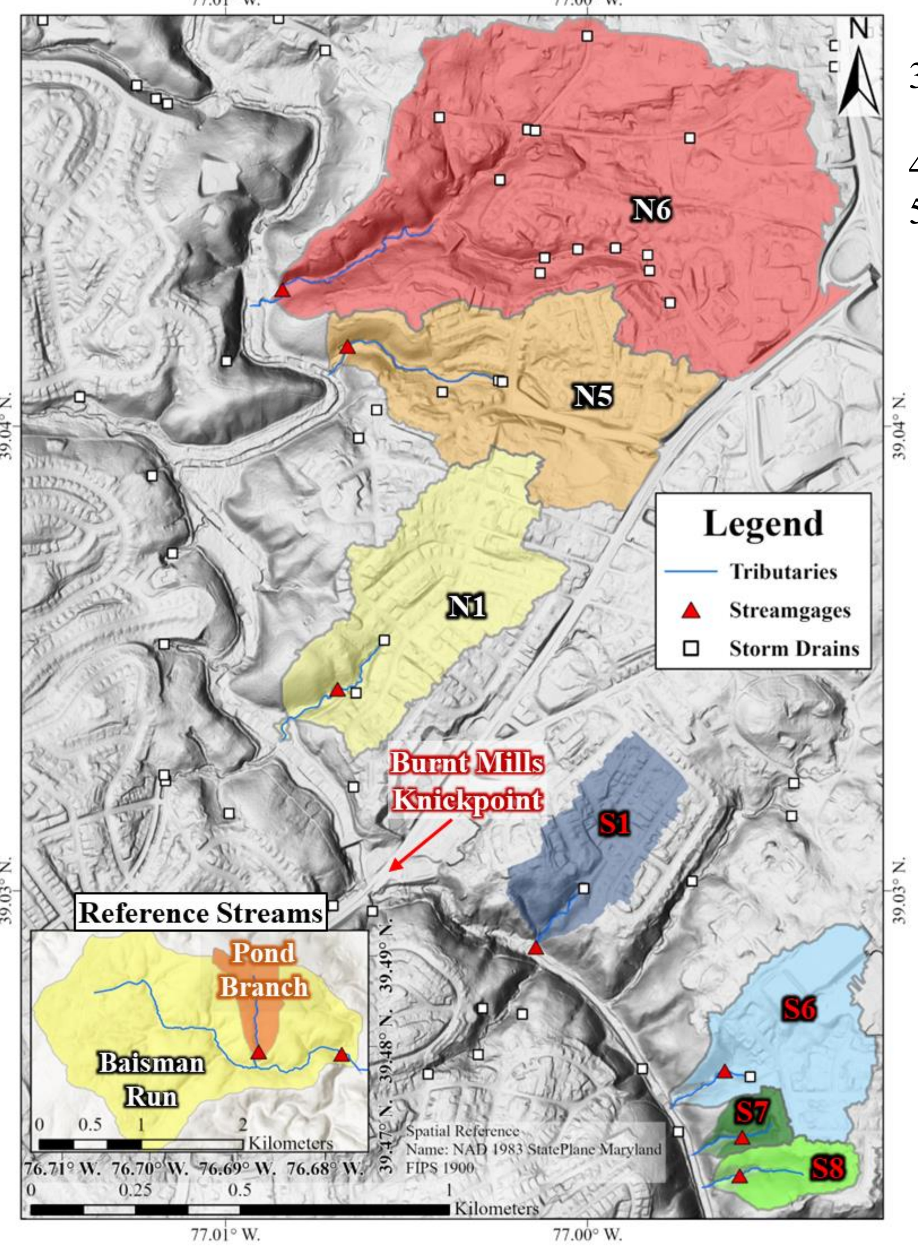


Fig. 2: Gaged study tributaries/catchments with locations of storm drain outfalls. Downstream tributaries S7 & S8 do not receive direct urban runoff. Secondary tributaries are indicated in red.

Research Questions

1. Are there significant differences in geomorphic characteristics among tributaries located above and below the NWB knickpoint?
2. Is normalized bankfull discharge similar for tributaries above and below the knickpoint? Are these values significantly different than non-urban streams?
3. Is bed grain size in equilibrium with bankfull shear stress? Are both types of tributaries threshold channels?
4. Does depth to bedrock and water storage vary systematically among these tributaries?
5. What are the interactions among development patterns, geomorphic characteristics, stormflow, water storage and baseflow discharge in these catchments?

Tributary Profile Characteristics

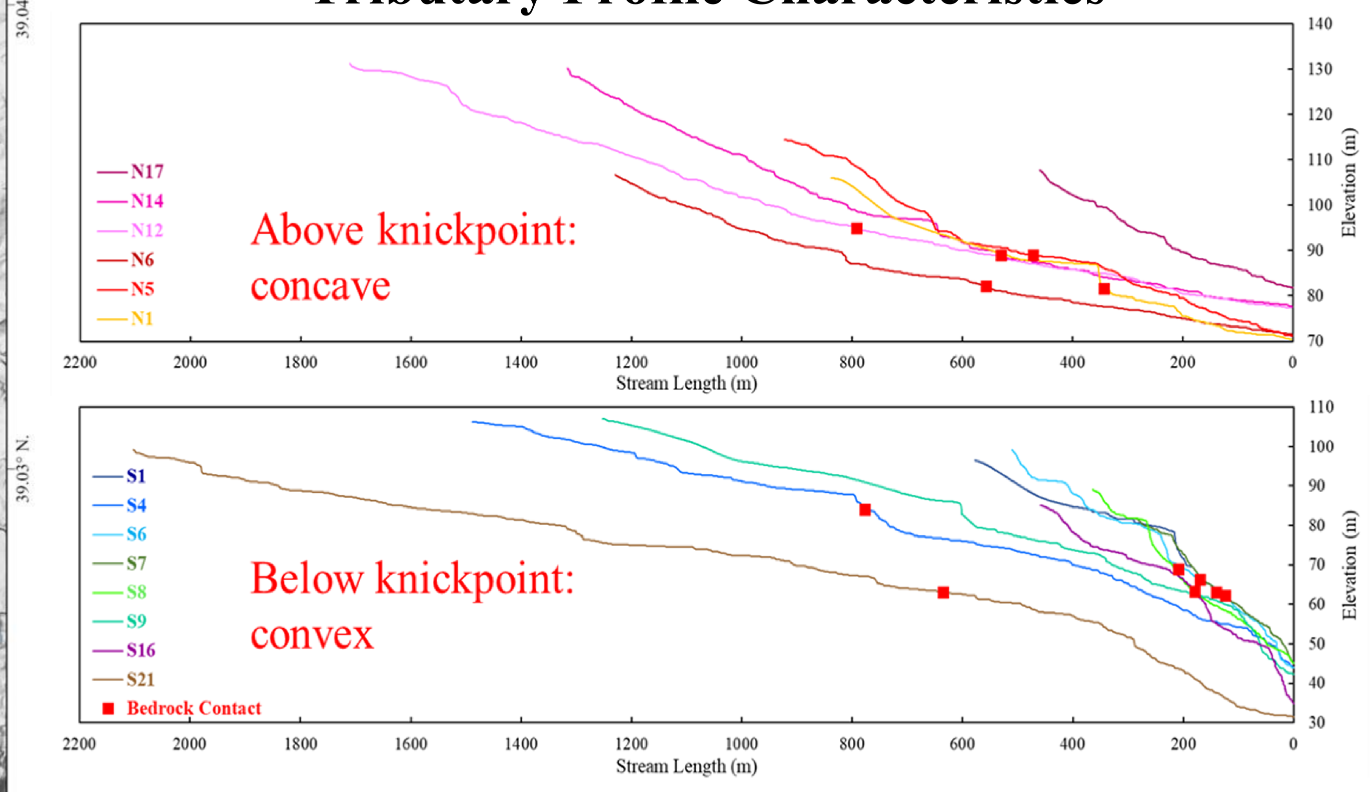


Fig 3: Longitudinal profiles of the NWB tributaries, starting from the drainage divides. The tributaries above the Burnt Mills knickpoint have more concave profiles than the downstream tributaries below the knickpoint, which steepen moving downstream, following the bedrock/regolith interface. The uppermost bedrock contacts observed in each tributary channel are indicated.

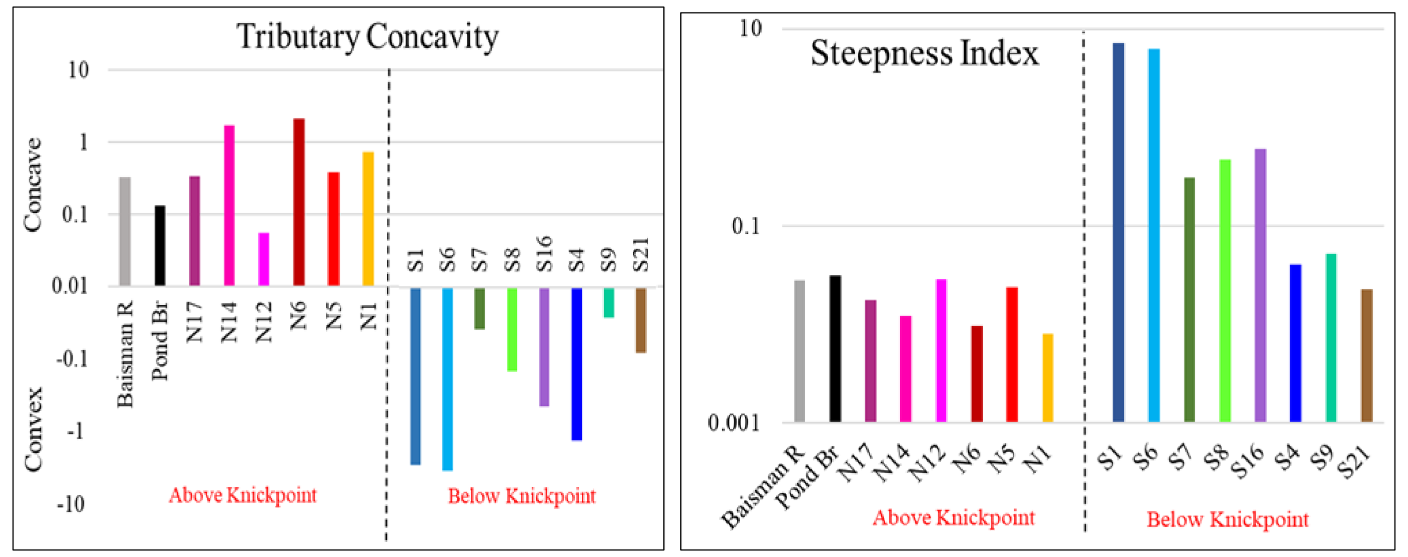


Fig. 4 (Left): Concavity values and steepness indices derived from basin area-slope power law functions: $S = k_s A^{-\theta}$.

S = slope, k_s = steepness index, θ = profile concavity; positive θ is concave, negative θ is convex, and 0 is a straight profile. NWB tributaries above the knickpoint and reference tributaries are concave. Tributaries below the knickpoint are convex. Secondary tributaries below the knickpoint have elevated steepness indices.

Methods

- Stream and basin/hillslope geomorphic analyses using LiDAR-derived digital elevation models processed with ArcGIS.
- Land cover and stormwater network analyses using ArcGIS.
- Field measurements (channel cross-sections, bed grain size, stream velocity at multiple stages) used to calculate bankfull channel characteristics (width, depth, area, velocity, discharge, gradient) and shear stresses to mobilize bed sediment.
- Rating curves (stage-velocity and stage-discharge) constructed to calculate discharge.
- Streamgages installed in 3 tributaries above (N1, N5, N6) the Burnt Mills knickpoint and 4 below (S1, S6, S7, S8) to continuously monitor gage height and create a discharge record for hydrographs, runoff totals and analysis of the annual range of flows.
- Seismic refraction surveys to characterize the regolith/bedrock interface and study potential catchment hydrologic storage capacity.
- Annual/monthly catchment water balances constructed to compare runoff, storage, and ET trends.

Water Balance:

ΔStorage = PPT – (Runoff + Transpiration + Interception + Evaporation from Impervious surface

Bankfull Discharge

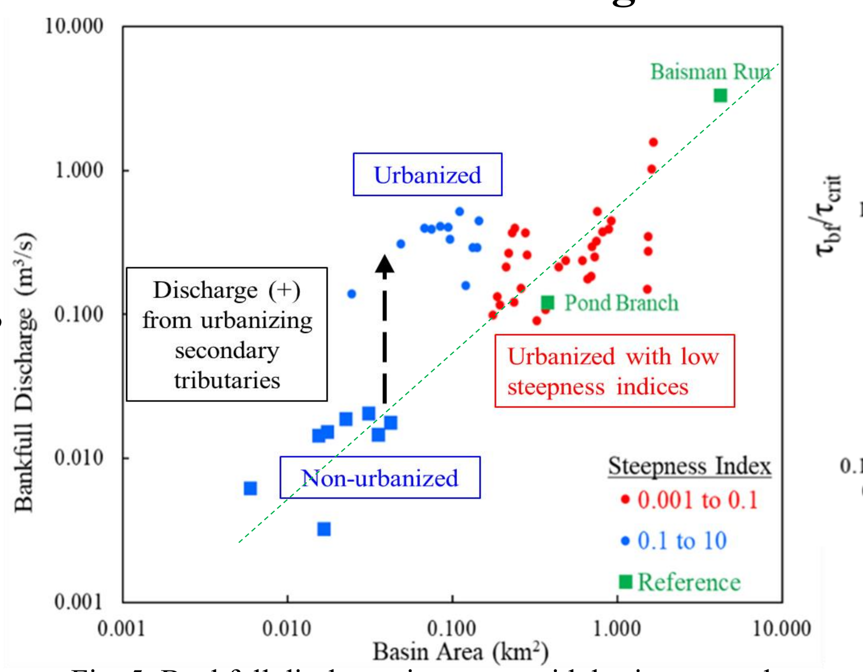
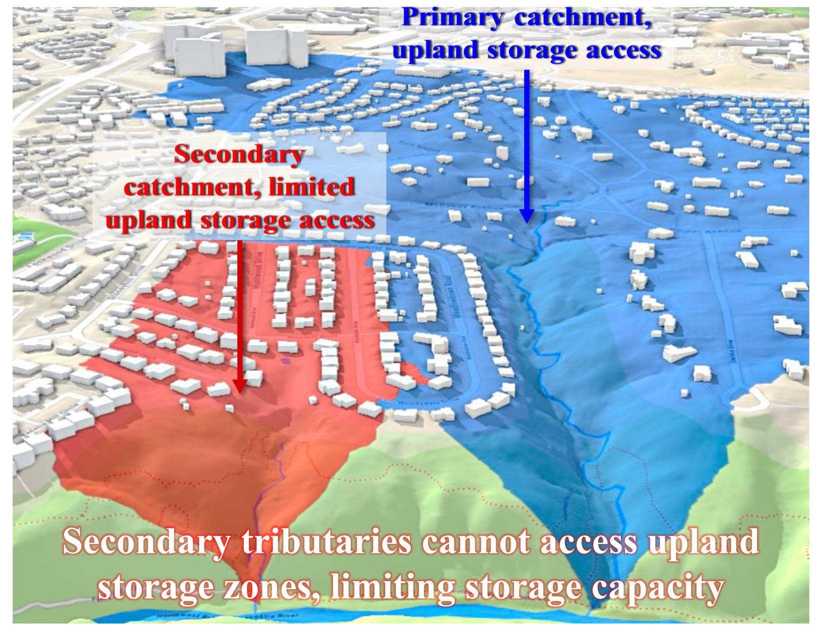


Fig. 5: Bankfull discharge increases with basin area and urbanization. Tributary streams with low steepness indices plot with the non-urbanized stream trend. Urbanized tributaries with high steepness indices have the largest increase in bankfull discharge when urbanized.



Seismic Profiles of Upland Storage Zones

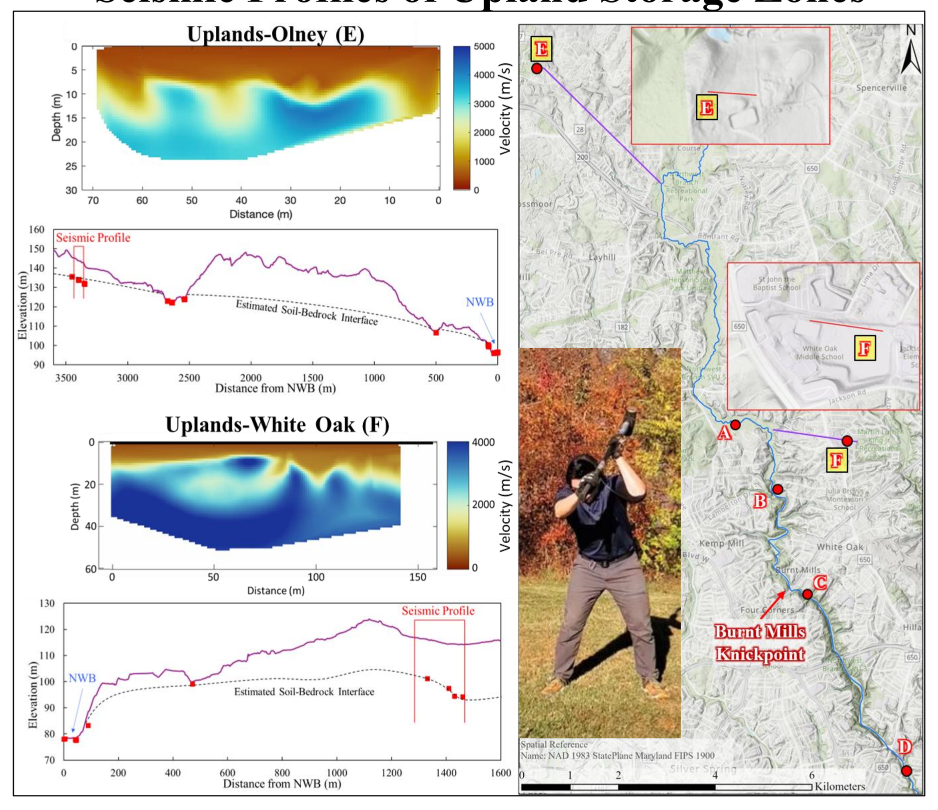


Fig. 7: Seismic profiles showing the bedrock/regolith interface under urbanized uplands. Elevation profiles are oriented perpendicular to the mainstem and extend from the channel to uplands. Estimation of the bedrock/regolith interface depth is shown. Known bedrock depths are indicated with red boxes. Seismic surveys of the uplands are shown for sites E and F. Site E: Bedrock at 10-17 m. Regolith for potential storage is relatively thin in the hillslopes along the mainstem and thickens with distance into the uplands. Site F: Bedrock at 10-24 m. Regolith is thin under mainstem hillslopes, but thickness with distance into the uplands.

Shear Stress Ratio vs Steepness Index

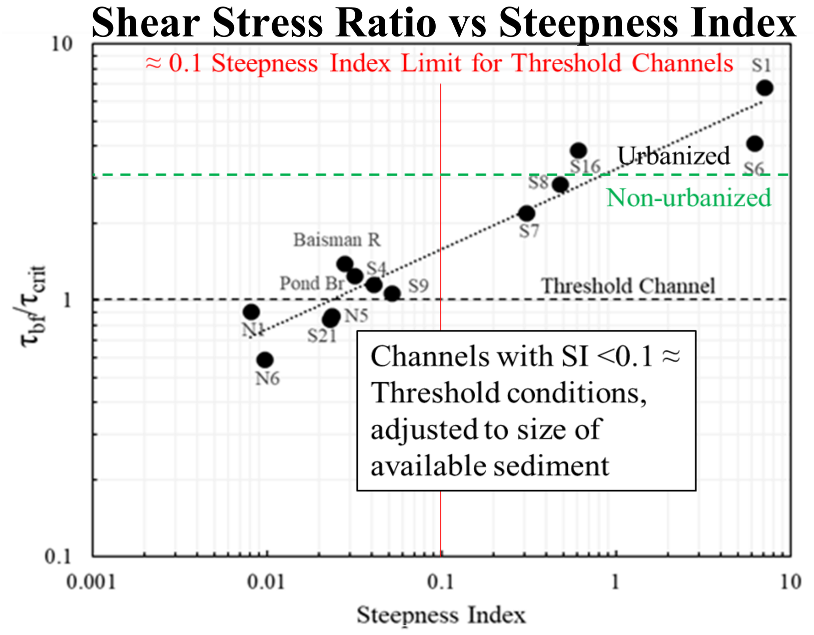


Fig. 6: Shear stress ratios increase with channel steepness index. Shear stress ratio was calculated from bankfull shear stress (τ_{bf}) generated by bankfull discharge. Critical shear stress (τ_{crit}) to move bed sediment was determined from bed grain size, using t*crit values of 0.045. Threshold channels are defined as: $\tau_{bf} = \tau_{crit}$.

Catchment Water Balances

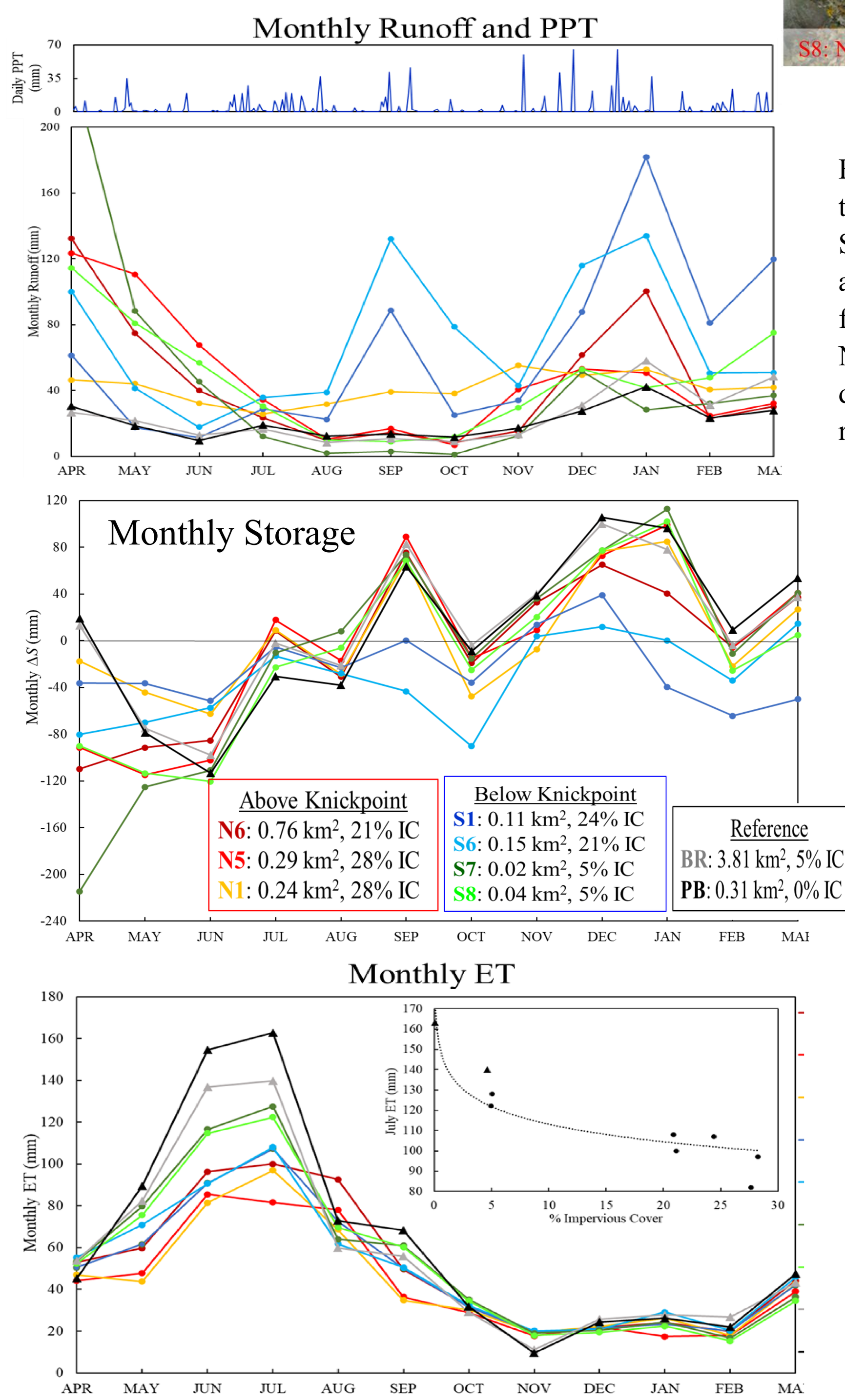


Fig. 8: (Top): S1 & S6 show isolated runoff spikes in SEP from storms following the summer drought. This indicates that their catchments were not able to infiltrate the PPT and recharge their storage like the other catchments, resulting in elevated runoff. S1 and S6 also show elevated runoff during the wetter winter months. (Middle): Changes in storage follow seasonal trends, with storage loss in the spring and summer and recharge in the fall and winter. Notable exceptions are catchments S1 and S6. They do not recharge their storage in the fall and winter with the other catchments. Limited storage capacity in these two catchments likely results in the observed storage loss instead of gain in SEP, and the earlier peak storage timing in the winter.
(Bottom) ET is greatest in the forested catchments during the summer months, and effectively shuts off in all of the studied catchments during the late fall-early spring. (Inset): Peak ET in JUL 2023 vs % impervious cover.

Primary and Secondary Tributary Hydrographs

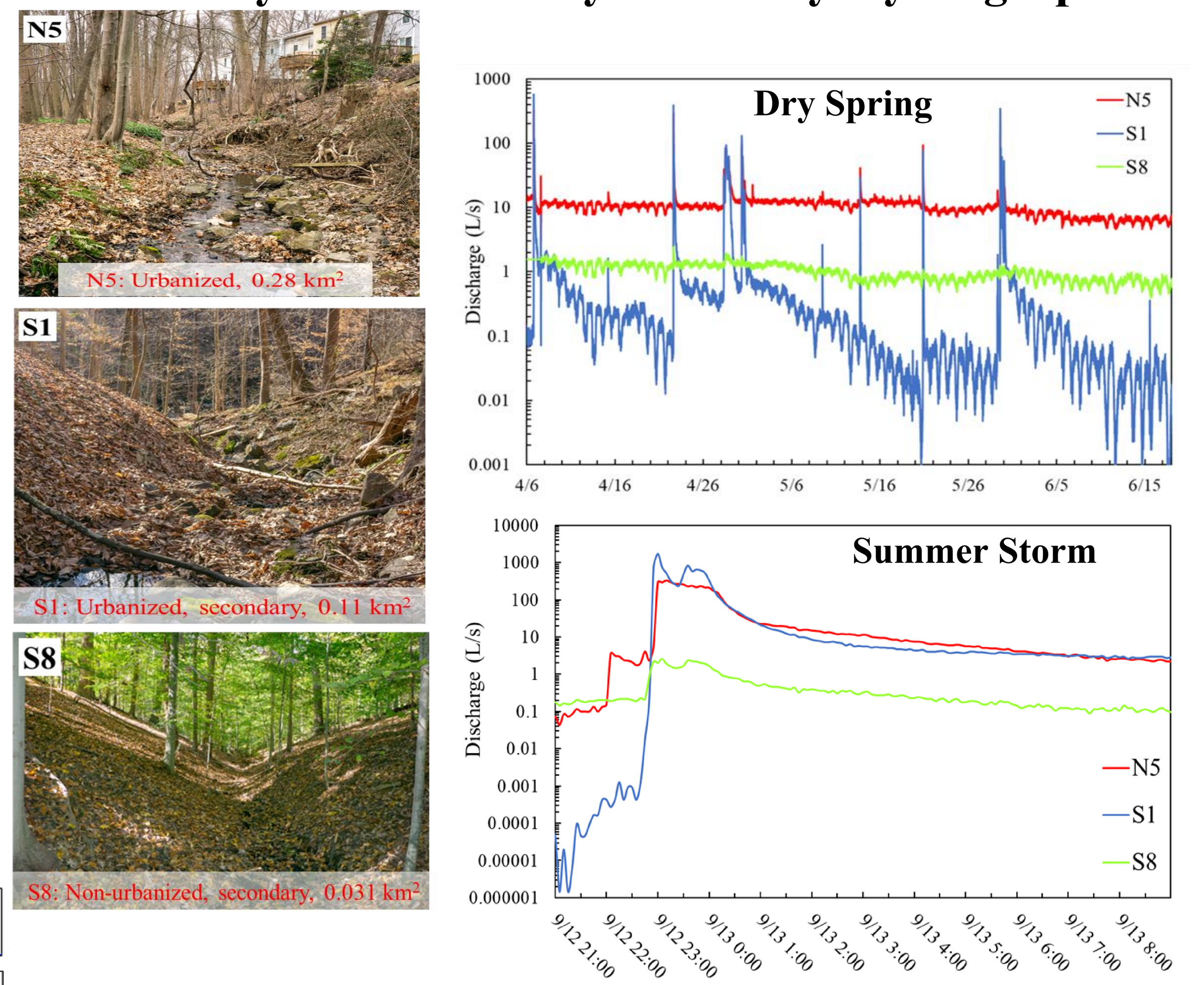


Fig. 8: Response of urbanized (S1) and non-urbanized (S8) secondary tributaries compared to an urbanized primary tributary (N5). (Top): Dry period during the spring of 2023. N5 and S8 maintain constant baseflow. The urbanized secondary tributary, S1, recesses quickly after storm events. (Bottom): A high intensity storm that ended a summer drought. S1 rises from nearly zero baseflow to a peak discharge more than 5 times greater than N5's. S1 and N5 have matching recession curves directly following the storm response, but S1's discharge drops below N5's after 40 hours. The non-urbanized tributary, S8 ,shows a muted response to the storm compared to the two urbanized streams.

Annual Runoff Partitioned into Baseflow and Stormflow

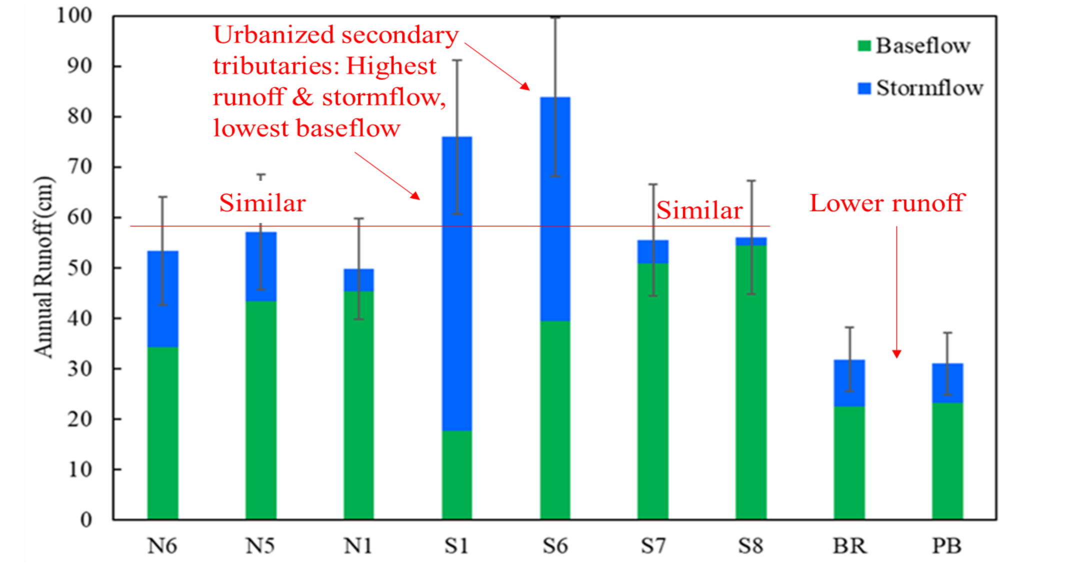


Fig. 9: Annual runoff partitioned between baseflow and stormflow. Urbanized secondary tribs S1 & S6 have the highest total and storm runoff. The non-urbanized secondary tributaries, S7 & S8, have lower total runoff, with mostly baseflow. Forested sites BR and PR located above the Fall Zone have the lowest total runoff. Urbanized primary tribs, S7 & S8, have similar total runoff to the tributaries above the knickpoint. Error bars show the max uncertainty of 20% for discharge measurements.

Conclusions

- Secondary tributaries, initiated due to a drop in mainstem base level have steep, convex profiles, low storage capacity, and transport the highest storm and bankfull discharges per basin area.
- The flat uplands, where development is concentrated, provide storage capacity for tributary channels that extend into this region, which supports stream baseflow.
- Steep channels + low storage capacity + urban overprint = Limited infiltration to moderate storm response and recharge storage.

Acknowledgements

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