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Discretization of predevelopment flow pathways to better achieve predevelopment water quality from stormwater control measures (SCMs)

Discrétisation des cheminements de l'eau avant aménagement pour mieux atteindre la qualité de l'eau avant aménagement à partir de mesures de contrôle des eaux pluviales

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RÉSUMÉ

Dans le cadre du « Low Impact Development » (LID), les mesures de gestion des eaux de pluie sont censées imiter l'hydrologie initiale avant l'aménagement. Ceci implique généralement une comparaison entre les volumes des rejets des dispositifs de gestion des eaux de pluie et un ruissellement cible. Une telle évaluation simpliste néglige de multiples cheminements d'eau qui se produisent dans les bassins versants cibles et, potentiellement, des mesures de contrôle des eaux pluviales, à savoir l'écoulement hypodermique et la montée rapide des eaux souterraines. Cette discussion fournit un moyen plus développé d'évaluer des conditions apparentées aux mesures de contrôle des eaux pluviales en termes d'hydrologie et de la qualité de l'eau des effluents, en discrétisant les rejets de trois voies : le ruissellement, l'écoulement hypodermique et montée de la nappe phréatique. Les données préliminaires utilisant des isotopes de deutérium des rejets de biorétention appuient ce concept.

ABSTRACT

As part of Low Impact Development, stormwater control measures (SCMs) are expected to mimic predevelopment hydrology. This generally results in a comparison between outflow volumes discharged from SCMs and a target condition runoff. Such a simplistic evaluation overlooks multiple pathways of water occurring in target watersheds and, potentially, SCMs, namely shallow interflow and groundwater surge. This discussion provides a more refined means of evaluating cognate conditions for SCMs in terms of hydrology and effluent water quality by discretizing SCM discharge into three pathways: runoff, shallow interflow, and groundwater surge. Preliminary evidence using deuterium isotopes from bioretention outflow supports this concept.

KEYWORDS

Low impact development, Predevelopment hydrology, Stormwater control measure

1 INTRODUCTION

Stormwater pollution is a primary non-point pollution source of concern, and is linked to ecosystem degradation (Horner et al., 2003; Klein, 1979; Walsh et al., 2004), economic loss (Ajuzie and Altobello, 1997) and public health issues (Curriero et al., 2001; Gaffield et al., 2003). Although water quality and stream health improvements are observed in conjunction with the implementation of stormwater control measures (SCMs, a.k.a. stormwater best management practices, or BMPs), stormwater pollution is still a leading cause of water body impairment (US EPA, 2011).

A recent paradigm in stormwater management includes designing SCMs to mimic predevelopment hydrology, as defined by undeveloped conditions. Conventional SCMs, such as wet ponds or dry detention basins, aim to dampen peak flows. Although these structures effectively regulate large flows of runoff and achieve some degree of treatment (GeoSyntec and WWE, 2008), they offer little improvement to, and may actually worsen, larger watershed-scale flooding (NRC, 2009). A Low Impact Development (LID) approach to stormwater management focuses on designs which reduce/eliminate flow during small events and the first flush of moderate-sized events, where highest pollutant loading occurs, by promoting infiltration and evapotranspiration (ET) (Walsh et al., 2005; Liu et al. 2012). Achieving LID would result in a similar hydrograph to that observed under undeveloped conditions (Davis, 2005; Chang, 2010). To be consistent with LID terminology, this paper uses the term *predevelopment hydrology* to describe hydrology observed under *undeveloped* conditions. Although decreased pollutant loading has been observed in conjunction with the achievement of predevelopment hydrology, very little research examines using the predevelopment hydrograph as a surrogate for achieving predevelopment water quality.

Focusing efforts primarily on the infiltration of stormwater runoff to meet water quality goals can prove difficult when soils have very low infiltration rates. Soils on developed sites show significantly lower infiltration rates than those on undeveloped soils (Pitt et al., 2002; Gregory, 2006). Regions, such as the Triassic Basin in North Carolina and gumbo soils of East Texas, have underlying clay soils with naturally low infiltration rates. The predevelopment hydrograph, in such cases, will include overall larger volumetric contributions of surface runoff than an area with high infiltration rates. However, predeveloped conditions in clay underlying soils preserve a higher degree of water quality than that observed under developed conditions (NC DENR, 2007). Predevelopment conditions, therefore, offer additional pollutant reduction mechanisms not considered when solely focusing on volume reduction.

Upon hitting the ground, rainwater will 1) run along the surface as run off, 2) be evapotranspired, 3) enter the top soil horizons and flow towards a stream as shallow interflow, or 4) infiltrate to long term storage within the groundwater. Evidence suggests that surface runoff accounts for a small fraction of the contributing stream flow during a rainfall event. Williams and Pinder (1990) used stream flow data and ^3H hydrograph separation to identify the pathways contributing to increased stream flow during and after a rain event. Analysis showed that contribution from surface waters ended within 24 hours of the rainfall event, and yet streamflow was elevated above base flow for an additional 24 hours. The source of this additional streamflow is attributed to subsurface contributions, namely a groundwater surge and shallow interflow. Therefore, streamflow during a storm event, beyond baseflow, is actually comprised of water from three sources: 1) surface runoff, 2) shallow interflow, and 3) groundwater surge, with surface runoff comprising a small fraction (25% to 30%) (Brown et al., 1999; Kendell et al., 2001). This is contrary to the popular notion driving stormwater regulations that all water entering a stream above that of baseflow is surface runoff.

This discussion aims to better define predevelopment hydrology to achieve predevelopment water quality through stormwater control measures (SCMs). Presented is a short literature review of 1) forested watershed (a predevelopment hydrologic condition) stream hydrograph fractions during storm events and 2) treatment mechanisms for nutrients along flow pathways in riparian zones. The objectives of such a review are three-fold:

- i. determine the hydrograph fraction associated with each flow pathway to discretize the predevelopment hydrograph
- ii. predict treatment mechanisms for each pathway contributing to predevelopment water quality
- iii. derive implications of flow pathways and associated treatment to stormwater management, specifically in terms of SCM function

Although this research is predominantly theoretical, it is based on scientific literature and preliminary data collection conducted by the authors, and will serve as a stepping stone for future research into SCM hydrograph separation. In this way, predevelopment hydrology and associated water quality can

truly be mimicked by engineered SCMs.

2 DEFINING PREDEVELOPMENT HYDROLOGY

2.1 Hydrograph Pathways

Hydrologic studies conducted in forested watersheds reveal three distinct pathways through which water enters a stream during a storm event: 1) surface runoff, 2) shallow interflow, and 3) groundwater surge. Within these pathways, hydrologists have identified event and pre-event water. Event water is from the rainfall event associated with the examined hydrograph. Pre-event water is associated with a previous rainfall event stored subsurface until discharged during a later event. Event water which enters the stream via overland flow during a rainfall event is aptly named surface runoff. Shallow interflow is composed of event water that has traveled through the upper soil horizons (Brown et al., 1999; Haria and Shand, 2004; Kendell et al., 2001). The groundwater surge is pre-event water forced into a stream during a rainfall event, beyond baseflow.

Hydrologic studies have reported a surge of groundwater (pre-event water) contribution to the hydrograph at the onset of a rain event (Haria and Shand, 2006; Soulsby, 1995; Wenninger et al., 2004). The mechanisms of this surge are described by a pressure wave effect, where increased pressure gradients associated with the rainfall depth on the hillslopes induce a rapid reaction of groundwater levels near the stream (Beven, 1989; Haria and Shand, 2006; Wenninger et al., 2004). Due to topographic convergence, the hydraulic pressure upslope of the stream would need only increase a few millimeters to result in a relatively large discharge (Bergmann et al., 1996, as written in Wenninger et al., 2004).

Ultimately, hydrograph separation studies tell a similar narrative: 1) rainfall occurs and event water infiltrates into the upper soil horizons, generally a relatively permeable layer; 2) event water accumulates at the border of a less hydraulically conductive soil layer and creates a pressure wave which amplifies the pressure gradient and increases discharge of pre-event water into the stream; and 3) surface runoff and shallow interflow flow relatively quickly downslope and into the stream.

2.2 Pathway Fractions with Hydrograph

Many studies on hydrograph separation during rainfall events performed in hilly or mountainous terrain found large fractions of pre-event water within the storm hydrograph (Brown et al., 1999; Soulsby, 1995; Wenninger et al., 2004). However, in areas of flat topography, such as the coastal plain of South Carolina, Williams and Pinder (1990) also found a large fraction of pre-event water (>90%) associated with the stream hydrograph, possibly as a result of the highly permeable soil reducing the fractions of surface runoff and shallow interflow. Variability in the pre-event water fraction has been linked to scale, with higher event water fractions observed in smaller watersheds (Brown et al., 1999). Despite variability among the literature, pre-event water composes the greatest fraction (at least 2/3) of the stream hydrograph (Table 1). Brown et al. (1999) measured the event and shallow interflow fraction at different points throughout the hydrograph. Significantly smaller fractions of event water were observed prior to the peak flow, supporting the theory of an initial groundwater surge. Shallow interflow composed the highest fraction of event water beyond the peak of the hydrograph, and was the dominant source of water at the tail end of the hydrograph (Figure 1). Ultimately, under predeveloped conditions surface water composes a small fraction (25% to 30%) of the contributing storm hydrograph, with the largest fraction occurring prior to and during peak flow (Brown et al., 1999). In this way, the majority of the water entering receiving waters is subsurface contributions, having undergone a higher level of treatment.

3 TREATMENT MECHANISMS ALONG PATHWAYS

As water travels along each pathway, it undergoes some level of treatment. Each pathway offers a unique set of conditions allowing for a specific mechanism of pollutant removal. Treatment mechanisms observed along each pathway, in terms of nutrient (N and P) removal are described. Ultimately, nutrient reduction is possible to a very high degree, but removal is very specific to underlying soil (Table 2).

Table 1. References investigating hydrograph separation fractions within stream hydrographs.

Reference	Location	Geological Region	Hydrograph Fraction		
			Surface Runoff	Shallow Interflow	Groundwater
Brown et al. (1999)	New York	Catskill Mountains	25% ^a	10% ^a	65% ^a
Kendell et al. (2001)	China	Prairie, artificial watershed	30%	15% ^b 55% ^c	15% ^b 55% ^c
Soulsby (1995)	Wales	--	25%		75%
Wenninger et al. (2004)	Germany	Black Forest Mountains	20%		80%
Williams and Pinder (1990)	South Carolina	Coastal Plain	10%		90%

^a Average of the maximum event water and shallow interflow contributions over the course of all storms sampled

^b As measured using ¹⁸O isotope separation

^c As measured using SiO₂ concentrations

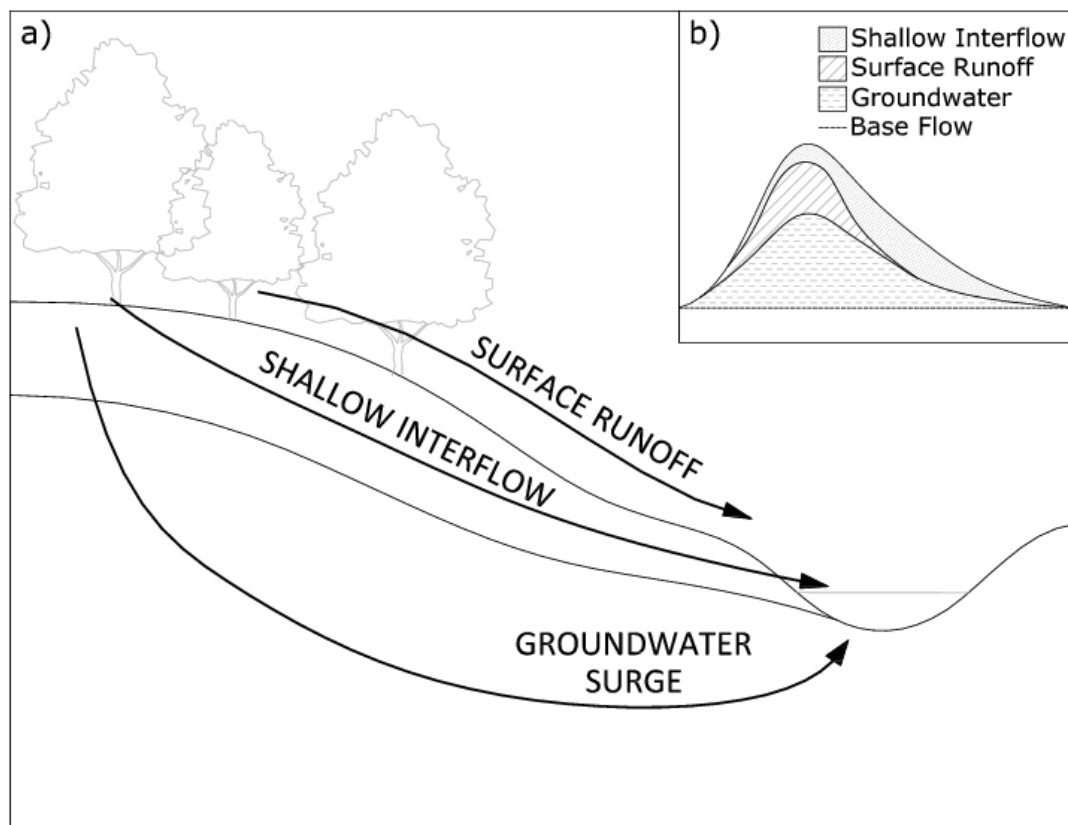


Figure 1. a) depiction of flow pathways experienced under predeveloped, or undeveloped, conditions, and b) example of stream hydrograph with contributing pathway fractions, based on data from Brown et al. (1999).

3.1 Surface Runoff

Surface runoff reduces nutrients by deposition of sediment-bound nutrients (sedimentation) and exchange of dissolved nutrients with soil and leaf litter surfaces (adsorption) (Vought et al., 1994). Due to vegetation type and cover, nitrogen (N) and phosphorus (P) removals vary throughout the research. As based upon grassed filter strip research, grassed watersheds may slightly reduce concentrations of sediment bound P or particulate TN, but generally do very little in terms of nutrient transformation (Lowrance and Sheridan, 2005; Winston et al., 2012). Removal rates from a wooded buffer saw efficiencies as high as 86% and 84% for particulate bound organic-N and total particulate P, as well as removal of nitrate (79%) and ammonium (73%) (Peterjohn and Correll, 1984). Of the

literature examined, most saw little change in dissolved P concentrations within the surface runoff fraction (Peterjohn and Correll, 1984; Lowrance and Sheridan, 2005).

Table 2. Potential nutrient removal associated with different treatment mechanisms within a riparian zone.

Pollutant	Removal Mechanism	Potential Removal	Sources
<i>Surface Runoff</i>			
NO ₃ ⁻	Adsorption/ Sedimentation	10% to 80%	Lowrance and Sheridan, 2005; Peterjohn and Correll, 1984; Verchot et al., 1997
TKN	Adsorption/ Sedimentation	35% to 60%	Daniels and Gilliam, 1996
PON	Sedimentation	85%	Peterjohn and Correll, 1984
TN	Adsorption/ Sedimentation	20%	Lowrance and Sheridan, 2005;
TP	Adsorption/ Sedimentation	10% to 75%	Daniels and Gilliam, 1996; Parsons et al., 1994
Sed-P	Sedimentation	75%	Lowrance and Sheridan, 2005;
<i>Shallow Interflow</i>			
NO ₃ ⁻	Denitrification	60% to 95%	Cooper, 1990; Cooper et al., 1995; McDowell et al., 1992; Jordan et al., 1993, Lowrance et al., 2000
NO ₃ ⁻	Plant Uptake	60%	Cooper, 1990
DON	Mineralization	70%	McDowell et al., 1992
NH ₄ ⁺	Ammoniazation	Increase	Peterjohn and Correll, 1984
TP	Filtration	33%	Peterjohn and Correll, 1984
DOP	Mobilization	Increase	Peterjohn and Correll, 1984
<i>Groundwater</i>			
NO ₃ ⁻	Denitrification	70% to 100%	Bohlke and Denver, 1995; Cooper, 1990; Jacobs and Gilliam, 1985; Lowrance et al., 2000; Puckett and Hughes, 2005; Weil et al., 1990
NO ₃ ⁻	Dilution	85% to 100%	Cey et al., 1999; Komor and Magner, 1996
NO ₃ ⁻	Plant Uptake	55%	Lowrance, 1992
TP	Mobilization	Increase	Osborne and Kovacic, 1993
DOP	Mobilization	Increase	Carlyle and Hill, 2001; Osborne and Kovacic, 1993; Vanek, 1991

3.2 Shallow Interflow

As shallow interflow travels laterally through the soil horizon, it undergoes media filtration. Nutrients in water pass through root zones and are available for plant uptake (McDowell et al., 1992; Verchot et al., 1997). In most cases, the flow pathway is short and will not allow time for denitrification (Lindsey et al., 1998, Verchot et al., 1997). However, several studies have observed evidence of denitrification in shallow interflow when organic matter is present (Cooper, 1990; Cooper et al., 1995; Craig et al., 2008). When denitrification does not occur, the primary removal mechanism is plant uptake, but only during warm seasons (Verchot et al., 1997). Ultimately, 60% to 90% of nitrate and 33% TP was removed under optimal conditions. Unfortunately, conditions which are best for denitrification often see a release of previously bound P (Stevenson and Cole, 1999).

3.3 Groundwater

Nutrient concentrations in groundwater are extremely variable, depending on factors such as input concentration, soils, and depth of the aquifer. Removal mechanisms in groundwater primarily include denitrification and plant uptake in shallow groundwater (Bohlke and Denver, 1995; Lowrance, 1992;

Lowrance et al., 2000, Weil et al., 1990), and dilution by deep groundwater (Cey et al., 1999; Komor and Magner, 1996). Denitrification in shallow groundwater requires organic matter and low dissolved oxygen concentrations (Craig et al., 2008). Without these conditions, plant uptake becomes the primary mechanism, accounting for nitrate reductions up to 50% depending on root depth and vegetation type (Bohlke and Denver, 1995; Lowrance, 1992). Several studies have reported upwelling of nitrate-poor deep groundwater. Cey et al. (1999) reported a sharp decline in nitrate concentration upon entering the riparian zone where water and associated pollutants were able to quickly infiltrate downward (as opposed to laterally), and be replaced by deep nitrogen-poor groundwater.

3.4 Summary of Treatment Potential

The highest potential for P removal is in surface runoff and the aerobic zones of shallow interflow (Table 2). In contrast, N is removed best under anaerobic and reduced conditions within the subsurface pathways (Table 2). Ultimately, each pathway serves an important role in reducing nutrients, and thus must be present for removing both nitrogen and phosphorus. Since these mechanisms are present in undeveloped watersheds, they should also be present in SCMs intending to achieve predevelopment conditions.

4 IMPLICATIONS FOR SCM DESIGN IN THE PIEDMONT, NORTH CAROLINA

The importance of hydrograph separation in the context of striving for predevelopment hydrology in stormwater applications is two-fold. First, under predevelopment conditions, surface runoff is not the main fraction of flow contribution to streams. Rather, subsurface flow contributions typically contribute a substantially larger fraction of additional stream flow. Second, each fraction of water undergoes different mechanisms of treatment important in removing a variety of pollutants. Therefore, under predeveloped conditions, the majority of the flow contribution to streams has undergone a high level of treatment, which in turn buffers receiving waters from pollutant contributions in the stormwater runoff.

To achieve true predevelopment hydrology in stormwater control design, an SCM must provide a hydrology that not only represents the predevelopment stream flow event contribution in terms of hydrograph volume, but also the treatment mechanisms associated with each pathway. This concept is especially important in soils with low hydraulic conductivity, where infiltration is small and, therefore, overall volume reduction provided by SCMs is minimal. SCMs which are able to best mimic treatment mechanisms observed in all pathways will offer the best potential at maintaining ecosystem and public health. For example, a wet pond and a bioretention cell may release similar quantities of water from a developed site. However, the water released from the wetpond mostly undergoes sedimentation (GeoSyntec and WWE, 2008), whereas bioretention cells offer many different pollutant removal mechanisms prior to release (Hunt et al., 2012).

4.1 Evidence of Pathways in Bioretention Cells in North Carolina

The Piedmont of North Carolina is an optimal location for considering the pathways associated with predevelopment hydrology. Due to HSG C and D soils, as well as the shallow regolith, the NC Piedmont naturally exhibits three distinct flow pathways contributing to the stream flow hydrograph (Lowrance et al., 1997). Therefore, SCMs which are able to mimic these pathways may offer a tool to meet predevelopment hydrologic and water quality conditions.

Bioretention cells located within the NC Piedmont have shown evidence of flow pathways observed in undeveloped watersheds. Bioretention cells with internal water storage (IWS, Hunt et al., 2012) release water which 1) remains from a previous storm event (similar to predevelopment groundwater), 2) underwent media filtration, but from the current event (similar to predevelopment shallow interflow), and, if a large enough rainfall event, 3) overflowed into a vegetated swale (cognate to surface runoff). DeBusk et al. (2011) compared bioretention cell outflow hydrographs in the Piedmont to corresponding stream flow in pasture-based target watersheds. The results were nearly identical between the two, suggesting that bioretention outflow mimics shallow interflow (the tail end of the stream hydrograph) nearly perfectly.

Thus far, no study examines the age of the water exiting a bioretention cell to determine the cell's ability to mimic the pre-event pathway. A preliminary investigation occurred on a bioretention cell with an IWS located in Knightdale, NC releasing water to Mango Creek (Luell et al., 2011). Samples were taken in the Spring 2012 from the inflow and the outflow of one cell using ISCO 6712 auto samplers over the course of the storm hydrograph. The cumulative inflow sample and samples at selective points within the outflow hydrograph underwent analysis for deuterium concentration at Duke DEVIL Labs in Durham, NC. All four storms measured displayed outflow deuterium concentrations initially

high relative to that of the inflow, but deuterium concentrations gradually decreased to inflow concentrations as more water was released from the cell (Figure 2). Stored water in the bioretention cell will increase in deuterium concentration over time as the water undergoes ET (Barnes and Allison, 1988; Friedman et al., 1964). Therefore, in this case, pre-event water is expected to be enriched in deuterium as compared to the precipitation. These data, although preliminary, suggest that the bioretention cell initially releases pre-event water, and at least partially mimics the pre-event (groundwater surge) pathway observed in predevelopment conditions.

Bioretention cells constructed with internal water storage (IWS), offering all three pre-development hydrology pathways, also exhibit some of the highest degrees of N and P removal within SCMs (Brown and Hunt, 2011; Hurley and Forman, 2011; Passeport et al., 2009). This, therefore, suggests that all predevelopment hydrologic pathways are necessary to truly optimize SCM design, particularly with the goal achieving predevelopment hydrology in an effort to mimic predeveloped conditions within a developed watershed.

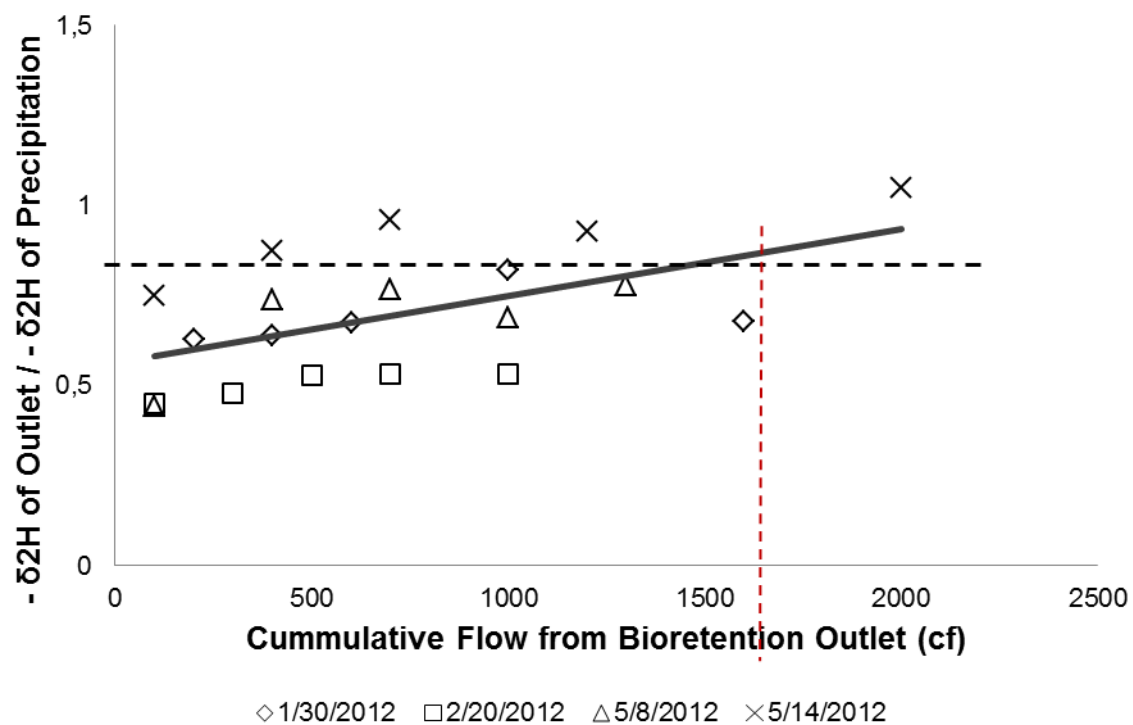


Figure 2. Summary of the deuterium isotope concentration ratio between outflow and inflow as compared to cumulative outflow. A ratio of 1 or higher suggests the water is predominantly event water. IWZ is calculated to hold approximately 1600 cf of water (as indicated by vertical dotted line).

4.2 Implications for SCM Design Beyond NC

Specific design aspects should be incorporated into SCMs based on this understanding of contributing pathways. To mimic groundwater surge, SCMs should collect and temporarily store runoff while providing media filtration and fluctuating redox conditions. Shallow interflow is mimicked by media filtration and exposure of runoff to plant roots. Conventional SCMs, such as swales or wetponds, already mimic treatment processes experienced by surface runoff.

Although bioretention is able to provide potential for each pathway, SCM design is not limited to such systems. For example, regenerative stormwater conveyance (RSC), which includes media underlying step-pool system, may also exhibit opportunities for all three pathways (Flores et al., 2012; Brown et al., 2010). Further research and creative design is necessary to develop and analyze the potential of new SCM approaches which can truly mimic predevelopment hydrology.

5 CONCLUSIONS

Matching predevelopment hydrology on a developed site must include consideration of all flow pathways present in the undeveloped watershed (beyond just runoff, infiltration, and ET). This ensures predevelopment water quality associated with each pathway is included in SCM design.

Sustainable growth requires development which is able to truly mimic predeveloped conditions through specific definition of stormwater goals, as well as sound and creative SCM design.

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