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RATIONALE FOR A "THRESHOLD OF CONCERN" IN STORMWATER RELEASE RATES

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1. INTRODUCTION--WHY DO WE NEED A THRESHOLD?

Because urbanization typically increases the total volume of stormwater runoff, some or all of the discharges that leave a site must increase following development. If the increased discharges can transport sediment from the channel bed and banks, greater erosion and subsequent downstream deposition will occur as a result. If, however, those increased discharges are still too small to transport sediment, then the increase should be without significant consequence to either the physical condition of the channel or the aquatic resources that depend upon that physical condition. To know whether a projected discharge increase warrants concern, therefore, the discharge at which channel sediment begins to move must be known.

This criterion is *conservative* from the perspective of channel stability but *liberal* from the perspective of the full range of channel functions, particularly those that are biological in nature. An urbanized channel with a modest increase in sediment-transporting ability may still maintain a stable form, if that form is largely determined by nearly immovable obstructions (*e.g.*, large boulders or logs in a step-pool channel as described by Montgomery and Buffington, 1993) and the banks are resistant to erosion. Under such conditions, requiring no sediment-transport increases might be unnecessarily restrictive. However, the function of other elements of the channel may be poorly characterized by aggregate sediment transport (which typically is evaluated on an annual basis only). For example, an urban channel that sees no net annual change in sediment transport but a much higher proportion of sediment-transporting flows in the summertime may become a much less hospitable environment for aquatic insects whose life cycles make them far more susceptible to disruption during their adult (summertime) phase. Under such conditions, requiring no sediment-transport increases would give the illusion of protection while allowing serious degradation to occur.

On a case-by-case basis, these issues can (in theory at least) be addressed. The effort and data required to accomplish such an analysis, however, are substantial and beyond the means or time frame of many development projects. Such an approach would also provide no predictability prior to conducting such an analysis, and the outcome would depend heavily on the quality of the initial work and the sophistication of any subsequent review. For these reasons, a uniform criterion with a clear physical basis may be judged most practical and defensible by permitting jurisdictions. The balance of this discussion accepts the proposed criterion for development mitigation, ***no increase in the net duration of sediment-transporting flows,*** and seeks a simple yet robust method to characterize the discharge threshold at which this limitation should take effect.

2. DETERMINING THE THRESHOLD OF SEDIMENT MOTION--GENERAL CONSIDERATIONS

There is no single discharge value, expressed in either absolute terms (*e.g.* "24 cfs") or proportional terms (*e.g.* "50% of the 2-year flood") that can accurately predict the threshold of sediment motion. Every channel is different from every other; even individual reaches along a single channel differ from one another. Logically, therefore, the threshold discharge should be calculated individually for every channel or concern. In principle, this procedure is quite straightforward:

1. A suite of representative reaches along the channel of interest is identified.
2. The median size of surface and subsurface sediment is measured by point counts, bulk sampling, and sieving.
3. The minimum size of surface clast that is judged significant for bed stability, or is abundant and readily available for transport, is determined.
4. The dimensionless, and then dimensional, critical shear stresses for sediment transport are calculated (see below).
5. Based on the hydraulics of the measured reach(es), the discharge that just achieves the critical shear stress is calculated. This is the "threshold discharge" for sediment transport.

However, such a procedure is impractical to administer in all but a few, carefully selected cases. It can be quite time-consuming and requires significant judgment to apply (especially steps 1 and 3).

Alternatively, the long-recognized similarities in channel form and behavior has invited many studies into the general uniformity between many different channels. Most common has been the association of the 1.5-year discharge (annual flood series) with the "bankfull" flow (*e.g.*, Leopold and others, 1964).

This relationship is not invariant, however; Williams (1978), for example, demonstrated that a significant minority of channels do not follow this relationship terribly well.

Faced with (1) a site-specific method that is somewhat ambiguous and cumbersome to use and (2) a rapid, universally applicable method that likely generates incorrect results in a fraction of circumstances, the choice of method may not appear obvious. However, public regulations are replete with examples of uniform (and so predictable) standards that may be inappropriate in a minority of cases, because the benefits of such a uniform approach are normally judged to outweigh the disadvantages. That approach is recommended for this issue as well.

3. DETERMINING THE THRESHOLD OF SEDIMENT MOTION--SPECIFIC STUDIES

Approach

Determining the threshold of sediment motion requires that we locate those studies that have actually measured the movement of sediment in natural channels and correlated that movement with the discharge as a fraction of flood (or bankfull) flow. Based on extensive reviews of the scientific literature (see, for example, Buffington, 1995; Buffington and Montgomery, 1997) three basic criteria have been used to characterize threshold discharges:

I. A specified fraction of the "bankfull discharge," *i.e.* the discharge that just fills the channel form.

II. The discharge associated with a particular flow duration, *i.e.* the discharge that is equaled or exceeded some specified fraction of the year.

III. A specified fraction of the discharge associated with the flood of a particular recurrence, such as the 1.5-year flood (notated as $Q_{1.5\text{-yr}}$).

Criterion III is the one most conveniently used by jurisdictions in review of development proposals, with historic use in King County and by the Washington State Department of Fish and Wildlife as "one half of the two-year flow" ($0.5 \cdot Q_2$). However, most scientific studies have presented their findings in other terms—using either one of the first two criteria, or as a specified fraction of a flood of a *different* recurrence. Thus a simple description of those studies is not sufficient, and we must be prepared to translate their results into a common framework.

Specific Studies

1. Pickup, G., and Warner, R. F., 1976, Effects of hydrologic regime on magnitude and frequency of dominant discharge: Journal of Hydrology, v. 29, p. 51-75.

Study Plan: Study of the discharges that moved the greatest amount of sediment, over time, in humid (30" rain/year) drainage basins 2-66 square miles in size.

Bankfull Discharge: Between 4-year and 7-year flood.

Discharge Moving Most Bedload Sediment: 1.15- to 1.45-year (annual series), or 0.2-0.4-year (partial duration series); *i.e.* most effective discharge exceeded 3-5 times per year.

Threshold of Motion: Not determined; must occur more than 3-5 times per year.

2. Andrews, E. D., 1984, Bed-material entrainment and hydraulic geometry of gravel-bed rivers in Colorado: Geological Society of America Bulletin, v. 95, p. 371-378.

Study Plan: Measurements on 24 rivers (drainage areas 1-3000 square miles) of discharge, sediment motion, and channel geometry.

Bankfull Discharge: Exceeded average 8.1 days/year (range 0.4-22 days/year); not calculated by recurrence interval.

Threshold of Motion: Exceeded by flows "slightly less than bankfull;" *i.e.* must occur more frequently than 8.1 days per year.

3. Leopold, L. B., 1988, The sediment size that determines channel morphology: unpublished manuscript, 18 p.

Study Plan: Summary of three years of sediment and flow data from the East Fork River, Wyoming, emphasizing the threshold of transport for different sediment sizes.

Bankfull Discharge: 20 m^3/sec

1.5-Year Discharge: Equal to bankfull discharge

Threshold of Motion: Sediment trapped at discharges as low as 5 m^3/sec; 9 percent of total bedload moved at discharges at or below 10 m^3/sec (*i.e.* 50% of bankfull, or 50% of 1.5-year discharge).

4. Carling, P., 1988, The concept of dominant discharge applied to two gravel-bed streams in relation to channel stability thresholds: Earth Surface Processes and Landforms, v. 13, p. 355-367.

Study Plan: Correlation of bedload sediment, flood discharge, and channel dimensions; 6 years of data on British stream; drainage area 4.6 mi^2.

Bankfull Discharge: Occurs at 0.9-year (partial duration) discharge of 5-6 m^3/sec.

2-Year Discharge: Appx. 6.5 m^3/sec

Threshold of Motion: "Phase I" (winnowing of fines): less than 0.6 x bankfull discharge (recurrence interval = 0.35 year); "Phase II" (movement of gravel on bed): between 0.6 and 1.3 x bankfull discharge, *i.e.* beginning at about 3.3 m^3/sec (= 51% of 2-year discharge) (recurrence interval between 0.6 year and 5-7 year); "Phase III" (wholesale movement of largest clasts and disruption of channel form): discharges above 5- to 7-year flood.

5. Sidle, R. C., 1988, Bed load transport regime of a small forest stream: Water Resources Research, v. 24, p. 207-218.

Study Plan: 33 individual storms monitored over 6 years for sediment movement and water discharge in 0.6-mi^2 Alaskan watershed.

Bankfull Discharge: 1.7-1.8 m^3/sec

2-Year Discharge: Appx. 1.8 m^3/sec

Threshold of Motion: For "bed load transport, 0.25 m^3/sec" (quoted from the abstract; 0.25 m^3/sec = 14% of 2-year discharge). Omitting the smallest transporting events, transport of more than 10% of the sediment moved during a bankfull event occurs at discharges of 0.74 m^3/sec (= 41% of 2-year flow).

6. Other studies:

a) **Helley (1969)—**The threshold of sediment transport occurs at flows at or larger than the “5% duration,” *i.e.* the flows that are equaled or exceeded 5% of the time.

b) **Milhous (1973)—**98 percent of the annual sediment load is moved by flows at or larger than the “3% duration.”

c) **Jackson and Beschta (1982)—**Threshold of sediment motion occurs at 108% of the bankfull discharge.

d) **Andrew and Erman (1986)—**Threshold of sediment motion occurs at 93% of the bankfull discharge.

Analysis

None of these studies have presented their data in a way that can be immediately used for the desired purpose here. In some instances the threshold of sediment motion is presented as a fraction of a flood recurrence (Criteria III) but not specifically the 2-year discharge (studies 1 and 5); others are presented as a percentage of bankfull discharge (Criteria I—studies 3, 4, 6c, and 6d), and others in terms of duration (Criteria II—study 2, 6a, and 6b). To express these sediment-transport thresholds into a fraction of the two-year discharge, therefore, requires some interpretation or conversion for each.

“Criterion I” Studies (bankfull criterion). Bankfull discharge does not have the same flood recurrence for every channel. Williams (1978) presented the most complete compendium of available data; he showed that $Q_{1.5\text{-yr}}$ was the median value of the bankfull discharge for available North American stations, but that a range of recurrence intervals could be found that equal the bankfull discharge for a variety of less typical channels.

These complications notwithstanding, a bankfull discharge equal to $Q_{1.5\text{-yr}}$ is clearly the best single choice. Once this recurrence of the bankfull discharge is determined, our purposes here require that it be converted into a fraction (or multiple) of the 2-year discharge. Hydrologic simulations of the Bear Creek and Hylebos Creek basins (King County, 1989, 1990) show a range in the ratio $Q_{1.5}/Q_2$ of 0.76-0.87 (see Appendix A), suggesting that the 1.5-year discharge may be about 80 percent of the 2-year discharge in typical lowland streams of the eastern Puget Lowland. If the bankfull discharge is equal to $Q_{1.5\text{-yr}}$ (the best assumption that can be made in the absence of more site-specific information), then we have a simple computational method to express a bankfull criterion for sediment transport as a fraction of the 2-year discharge.

Leopold (1988) found an identity of bankfull discharge and $Q_{1.5\text{-yr}}$ exactly; he further determined significant transport at 50% of this bankfull discharge (*i.e.* at $0.5{\cdot}Q_{1.5\text{-yr}}$). Thus transport is likely significant in his channel at about $0.4{\cdot}Q_{2\text{-yr}}$. Carling (1988) found bankfull discharge to occur at 0.9 years on the *partial-duration series*, precisely equivalent to $Q_{1.5\text{-yr}}$ on the annual flood-frequency series being used here (Dunne and Leopold, 1978). Movement of gravel on the bed began at 60 percent of that discharge, which is therefore approximated by $0.5{\cdot}Q_{2\text{-yr}}$. In contrast, Jackson and Beschta (1982) and Andrew and Erman (1986) found somewhat higher flows were needed for transport, presumed equivalent to $0.9{\cdot}Q_{2\text{-yr}}$ and $0.7{\cdot}Q_{2\text{-yr}}$ respectively.

“Criterion II” Studies (durational criterion). If duration is used as the basis for expressing sediment-transport thresholds, then the conversion to flood recurrence also requires some preexisting data. Here too, hydrologic simulations are available for certain basins in King County (Hylebos and Lower Puget Sound—King County, 1990) that can show this relationship directly (Appendix A). Two simulations, for Hylebos Creek and Lakota Creek, show a flow-duration exceedence of 3 to 3.5 percent for the discharge equal to one-half of the 2-year flow. This is equal to 11-13 days per year, at the mid-point of the range (and close to the average) of exceedence levels for sediment-transporting flows reported by Andrews (1984). It is identical to the threshold value reported by Milhous (1973) and significantly smaller (*i.e.* representing a rarer and thus larger flow) than the discharge necessary to initiate motion reported by Helley (1969).

“Criterion III” Studies (recurrence criterion). These studies are the most immediately useful for the present purposes, but in general they do not present the threshold of motion in terms of a fraction of the 2-year discharge and so they too require translation. Pickup and Warner (1976) found movement beginning at 1.15- to 1.45-year discharges; these translate into a likely range of about $0.4{\cdot}Q_{2\text{-yr}}$ to $0.8{\cdot}Q_{2\text{-yr}}$. Sidle (1988) reported absolute values for both the sediment-transporting discharges and the 2-year flow; his data show initial motion at only $0.14{\cdot}Q_{2\text{-yr}}$ and quite notable transport at $0.4{\cdot}Q_{2\text{-yr}}$.

4. CONCLUSIONS AND RECOMMENDATIONS

Avoiding flow increases that destabilize the stream channel is one of the main requirements for protecting those channels in the face of urban development. That destabilization is a result of increases in the duration of sediment-transporting flows. Identifying what minimum flow actually transports sediment, the "threshold of sediment transport," is thus a critical task.

Differences between stream channels ensure that no single threshold will work equally well on all channels. Existing studies support this contention, with a range of threshold values identified by different studies (or even by the same study for different streams). Nevertheless, a single criterion has substantial advantages in ease of analysis and implementation, and such a standard appears to have reasonable substantiation in the scientific literature. Based on available studies, the threshold of significant bedload-sediment movement ranges from about 14 to 90 percent of the two-year discharge and is probably best represented by the central value of 50 percent of the 2-year discharge.

Alternative thresholds of sediment transport have been proposed by others. Based on the information assembled here, using 70 percent of the 2-year discharge simply applies an "inverse factor of safety" of 0.7 on the best-estimate target discharge. It may represent a significant savings in detention volume but does not achieve the desired level of protection in the stream channel. Controlling to the "1-year discharge," another past suggestion, is more intriguing but also problematic. This discharge level is not unambiguously defined; in many uses, this value is intended to be equivalent to the 1.01-year discharge on the annual series (*i.e.* the smallest peak annual discharge in a record of 99 years). Based on simulations of the Issaquah Creek basin (King County, 1991), the 1.01-year discharge (annual series) is only 25 to 50 percent of the 2-year discharge. In no subcatchment does the 1.01-year simulated flow exceed 50 percent of the 2-year flow; and so this represents an even *more* conservative threshold and would result in even larger detention volumes to achieve.

The "1-year discharge" is precisely defined only for the partial- duration series and is about equal to the 1.6-year event on the annual series (Dunne and Leopold, 1978). The 1.6-year discharge (annual series), in turn, is about 70 percent of the 2-year discharge for flood-frequency curves of King County streams. Using this (partial-duration) definition of the "1-year discharge" thus results in the same conditions discussed above, namely an increase in sediment transport following development. If the stated level of protection is for unchanging conditions of the physical channel following development, this alternative is unlikely to achieve it.

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