Module 11: Energy Balance and Sheet Flow

Learning Objectives

At the end of this module, you will be able to:

- Discuss the Energy Balance concept, equation, and application.
- Evaluate peak runoff rate and runoff volume for compliance with the Energy Balance equation.
- Evaluate sheet flow for compliance with regulatory requirements.

11a. The Energy Balance Method

The Energy Balance method is the required channel protection criteria when runoff is released to a natural conveyance system, and an option for channel protection compliance when runoff is released to manmade or restored conveyance systems (**9VAC25-875-600.B.3)**.

In accordance with the Energy Balance method, the allowable peak discharge flow rate for runoff released to a channel from the **one-year 24-hour storm** is calculated as follows:

$$Q_{1\text{-yr-Developed}} \leq I.F.*(Q_{1\text{-yr-Pre-developed}} * RV_{1\text{-yr-Pre-Developed}})/RV_{1\text{-yr-Developed}}$$

Under no condition shall:

$$Q_{1\text{-yr-Developed}} > Q_{1\text{-yr-Pre-Developed}}$$

$$Q_{1\text{-yr-Developed}} < (Q_{1\text{-yr-Forest}} * RV_{1\text{-yr-Forest}})/RV_{1\text{-yr-Developed}}$$

I.F. (Improvement Factor) = 0.8 for sites > 1 acre or 0.9 for sites ≤ 1 acre

$Q_{1\text{-yr-Developed}}$ = the allowable peak flow rate of runoff from the developed site

$RV_{1\text{-yr-Developed}}$ = the volume of runoff from the site in the developed condition

$Q_{1\text{-yr-Pre-Developed}}$ = the peak flow rate of runoff from the site in the pre-developed condition

$RV_{1\text{-yr-Pre-Developed}}$ = the volume of runoff from the site in pre-developed condition

$Q_{1\text{-yr-Forest}}$ = the peak flow rate of runoff from the site in a forested condition

$RV_{1\text{-yr-Forest}}$ = the volume of runoff from the site in a forested condition

$RV_{1\text{-yr}}$

Runoff Volume (RV) for pre- and post-development drainage areas must be in volumetric units (e.g., acre-feet or cubic feet) when using the Energy Balance Equation. Runoff depth measured in inches can only be used in the Energy Balance Equation when the pre- and post-development drainage areas are equal. Otherwise, runoff depth must be converted to runoff volume by multiplying by the drainage area and applying the appropriate conversion factors to obtain the desired volumetric units.

The Energy Balance Method is intended to achieve a balance between the "energy" exerted on the stream by the pre- and post-developed peak discharge. The formula provided does not actually represent stream energy, but rather a simplification of an effort to balance the hydrologic response characteristics of a developing watershed: impervious cover, channelization, and other impacts associated with the developed landscape result in an increase in the volume and peak rate of runoff. The Energy Balance utilizes the inverse relationship between pre- and post-developed condition runoff volume to reduce the allowable peak discharge:

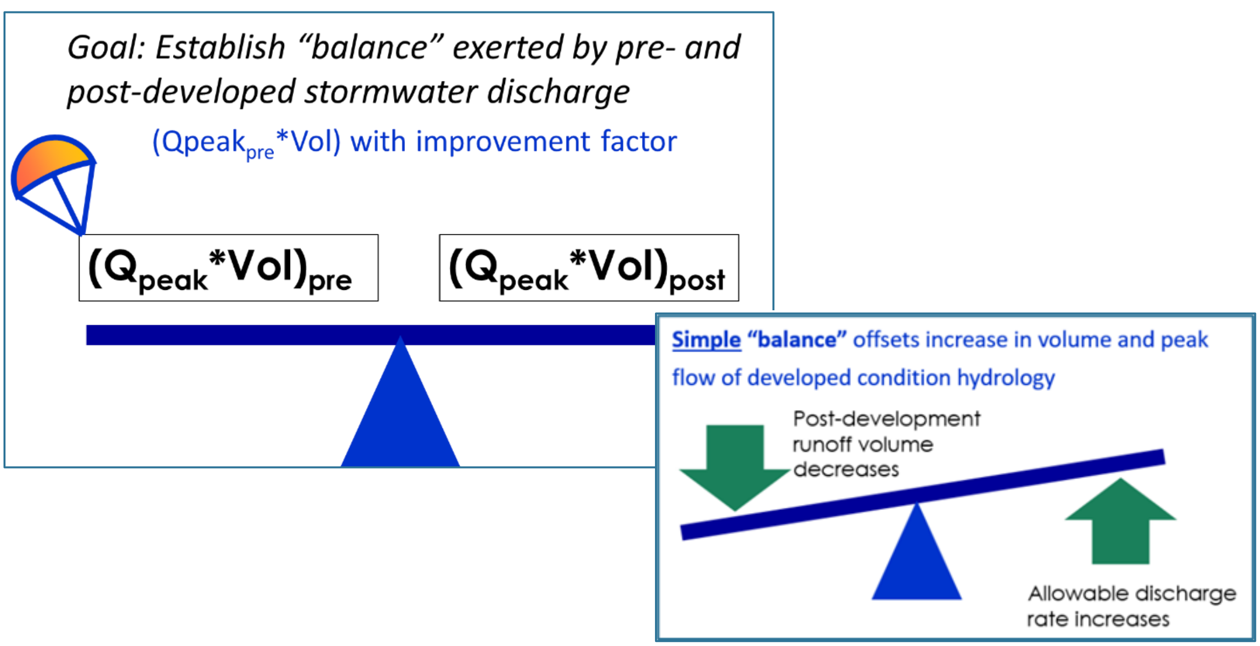
$$Q_{1post} \leq Q_{1pre}\left(\frac{Pre\ Vol_1}{Post\ Vol_1}\right)(IF)$$

As the post-developed volume ***increases***:

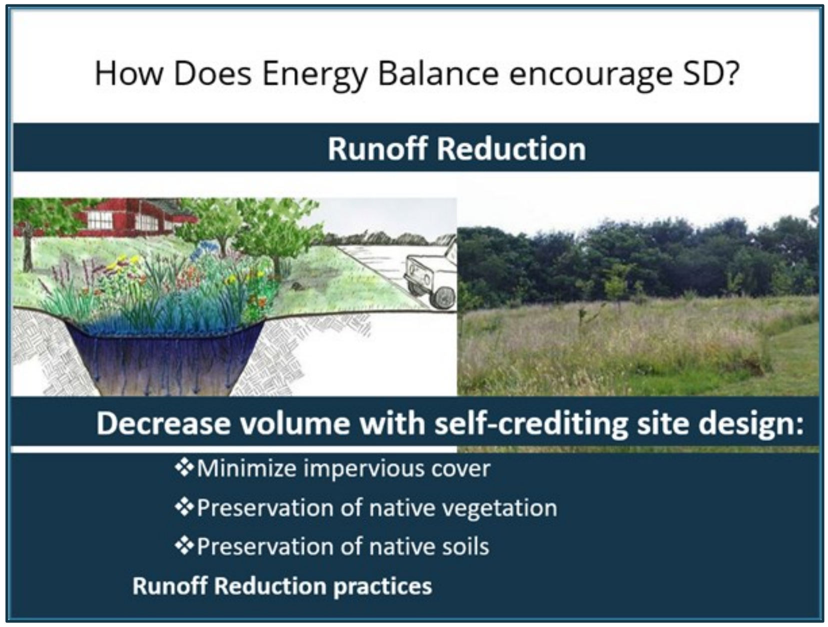
- the ratio of the Pre to Post volume ***decreases***; and
- the allowable 1-year discharge (Q_{1post}) ***decreases***; and
- the storage volume required to meet the reduced Q_{1post} ***increases***

Rephrasing the above information – as the post-developed volume ***decreases***:

- the ratio of the Pre to Post volume ***increases***; and
- the allowable 1-year discharge (Q_{1post}) ***increases***; and
- the storage volume required to meet the reduced Q_{1post} ***decreases***



The designer may elect to reduce impervious cover, which is a self-crediting strategy: less impervious cover means a lower developed condition Runoff Curve Number (CN). Additional strategies such as minimizing impacts to soils and existing mature vegetation, preserving open space, and implementing non-structural stormwater site design BMPs are specifically credited within the water quality compliance method, the Virginia Runoff Reduction Method (VRRM), and result in less stormwater runoff.



In addition to reducing the post-developed condition volume of runoff (*Post* Vol_1), decreasing impervious cover also reduces the curve number. This results in a VRRM ***Curve Number Adjustment*** ***double credit*** as an incentive to implement Stormwater Site Design (SD) strategies. The Curve Number Adjustment is discussed in the DEQ Plan Reviewer for Stormwater Management participant guide.

Therefore, SD is incentivized because these strategies can achieve water quality compliance without large land intensive stormwater practices and the use of the VRRM and the Energy Balance Method can decrease (or in some cases even eliminate) the storage volume required for meeting the channel protection criteria.

WHAT IS THE IMPROVEMENT FACTOR?

The Improvement Factor (*IF*) is a statutory hold over from § 62.1-44.15:28 that requires the regulations to improve upon the existing runoff characteristics and site hydrology if stream channel erosion or localized flooding is an existing predevelopment condition. The Channel Protection criterion for discharges to a Natural Stormwater Conveyance System assumes that the natural channel is not adequate and therefore applies Energy Balance. As post-development volume is ***reduced*** with runoff reduction and SD strategies, the ratio of Pre Vol_1 to Post Vol_1

increases to 1. The *IF* then becomes the basis for "improving upon the existing condition" by a factor of 10% or 20% (equivalent to *IF* of 0.9 or 0.8, respectively).

WHY ENERGY BALANCE?

The Energy Balance method was derived from two places. The first was the "safe harbor" provision that includes the proportional reduction in the allowable peak discharge from a range of design storms.

The second is the mandate from [§ 62.1-44.15:28] of the Code to establish regulations that encourage Low Impact Development (LID). The use of the post-development runoff volume (*Post* Vol_1) in the peak discharge formula allows the designer to take credit for the various LID or SD strategies that ultimately decrease the post-developed condition ***volume of runoff.***

ENERGY BALANCE TERMINOLOGY

Both the designer and plan reviewer should become familiar with the terminology of the Energy Balance method as it is documented in the regulations, as well as how various hydrologic methods use the same values with different definitions.

For example, the most common symbol in stormwater management documentation is that of runoff peak discharge, **Q**, measured in cubic feet per second. However, the NRCS TR-55 method, the foundation for computing urban runoff using NRCS methods, designates the same runoff peak discharge (also in cubic feet per second) with a lower-case **q**. TR-55 also designates the depth of runoff (in watershed-inches) as upper-case **Q**.

Another important value that can be the cause of possible confusion is the use of **RV** as the symbol for Runoff Volume in the Energy Balance equation as published in the regulations and noted above. Notice that the rearranged Energy Balance equation version substitutes these values with **Pre** $\mathbf{Vol_1}$ and **Post** $\mathbf{Vol_1}$. The VRRM Compliance spreadsheet uses the term **RV** to refer to runoff depth in inches, which can be used in the Energy Balance equation in place of the runoff volume in those situations when the pre-developed and post-developed drainage areas are the same. In other words, if the drainage area to a given discharge point from the site does not change in size due to grading changes, then the runoff depth ratio and runoff volume ratio ($\mathbf{PreVol_1}$ / $\mathbf{PostVol_1}$) will be exactly the same.

Table 11-1 provides a summary of the different terms used by the different published sources, along with the corresponding units. There is no absolute right or wrong version of the units, as long as they are used consistently within the design.

Table 11-1: Hydrology Terminology

Description	**Units**	**Term**
NRCS TR-55		
Runoff Depth	inches (in)	***Q***
Runoff Volume	cubic feet (ft^3) or acre feet (ac.ft.)	***Vr***
Storage Volume	cubic feet (ft^3) or acre feet (ac.ft.)	***Vs***
Peak Discharge	cubic feet per second (cfs)	q_p
VRRM Treatment Volume Runoff Coefficients		
Unit-less Volumetric Runoff Coefficients		***Rv***
VRRM Curve Number Adjustment		
Runoff Depth*	inches	***RV****
VESM Regulation Channel Protection Criteria (9VAC25-875-600.B)		
Peak Discharge	cubic feet per second (cfs)	***Q***
Runoff Volume*	cubic feet (ft^3) or acre feet (ac.ft.)	***RV****

*RV in VRRM (version 4.1) represents runoff depth. $RV_{Pre\text{-}Developed}$ and $RV_{Developed}$ used in the energy balance method in 9VAC25-875-600.B represents runoff volume. VRRM 4.1 user guide states: The Runoff Volume (RV) provided in watershed inches is a depth measurement and not volume. When comparing forested, pre-, and post- development drainage area volumes for energy balance calculations, the volume units must be in acre-feet or cubic feet unless the drainage areas are the same.

The equation used to convert runoff depth to runoff volume is as follows:

$$Runoff\ Depth\ (inches) \times Drainage\ Area\ (acres) \times \frac{1\ foot}{12\ inches}$$
$$= Runoff\ Volume\ (acre - feet)$$

Considering the nomenclature distinction provided in Table 11-1, the Energy Balance Equation:

$$Q_{1post} \leq Q_{1pre} \left(\frac{RV_{pre1}}{RV_{post1}}\right)(IF) \qquad \textit{(regulation)}$$

Can be re-written as:

$$q_{1post} \leq q_{1pre} \left(\frac{Vr_{pre1}}{Vr_{post1}}\right)(IF) \qquad \textit{(NRCS TR-55)}$$

11b. Evaluating Sheet Flow

This section provides some useful tips for the plan reviewer in how to evaluate sheet flow and verify compliance. This information is pulled together from the regulation (**9VAC25-875-600.D**), federal guidance, and other technical resources.

The regulations indicate where sheet flow is expected. This provides reasonable conditions under which sheet flow could occur. For example:

- Pervious areas: from a lawn.
- Disconnected impervious areas: a roof with gutters and downspout that discharges to a flat vegetated area like a lawn
- Level spreaders: Engineered structures where concentrated flow goes in one end and sheet flow comes out the other end.

Any such areas where sheet flow is expected to be discharged from a site must be identified on a plan and must be evaluated for potential impacts. Identification and evaluation of potential impacts may vary depending on the different land cover and land-use conditions where the sheet flow is directed.

Where sheet flow is discharged from a site and stated to comply with the water quantity technical criteria, plan reviewers should expect to see in a plan some kind of statement that the sheet flow is not going to cause erosion, sedimentation, or flooding damage downgradient from the site.

An adequate plan requires information and computations to justify the above statement of compliance. The evaluation of potential impact is where professional judgement is needed by the designer and by the plan reviewer. It is not possible to list everything that should be looked at. The plan preparer needs to provide the evaluation to the plan reviewer, and the plan reviewer deems the evaluation acceptable or not. Some considerations for both designers and plan reviewers for the evaluation of sheet flow are provided here.

Implicit to the sheet flow criteria is the understanding that sheet flow that re-concentrates has the potential to cause impacts (erosion, sedimentation, flooding); therefore, the expectation would be that sheet flow eventually infiltrates, gets absorbed, or deposits in a waterway, reservoir, or stormwater facility without causing impacts on the way. The NRCS National Engineering Handbook and WINTR-55 documentation describe sheet flow as flow over plane surfaces with a maximum 100-foot sheet flow length. Maximum depths are normally in the magnitude of 0.1 feet. The Virginia Stormwater Management Handbook (VSWHB) also provides guidance where the recommended maximum length of sheet flow should be calculated using a specific equation. The VSWHB Chapter 5, section 5.3.2.2 (Sheet Flow) references this equation:

LSF = $(100\sqrt{S})/n$, where:

- LSF – maximum length of sheet flow (ft.)
- S = land slope (ft/ft)
- Manning's Roughness Coefficient (VSWHB Chapter 5, Table 5-2)

The key considerations when evaluating sheet flow are as follows:

- ☑ Is the flow over a plane surface? All concentrated flows discharged directly from a pipe, ditch or swale are not over plane surfaces and are not sheet flow.
- ☑ Is the depth of the sheet flow, analyzing a 10-year, 24-hour storm, less than 0.10 ft.? If not, chances are sheet flow will not be sustained and concentration of the flow will occur. (Use Manning's velocity equation or the weir equation-see note below).
- ☑ Surface condition? Is the flow discharged over a plane surface? Is the flow discharged to a plane surface that is steep? Over 5%? Is it irregular, causing re-concentration? Does it have an established, stabilized vegetated cover or other non-erodible cover?
- ☑ Is the plane surface over which the sheet flow is discharged less than 100 ft. in length? If it is longer, concentration of the flow is likely. Has the maximum length of sheet flow been calculated, or the maximum 100 ft assumed?
- ☑ Has the velocity been calculated? It should be demonstrated to be non-erosive for soils during a 10-year, 24-hour storm. (Erosion)
- ☑ Land use of the discharge area: Can the area pass the sheet flow without disruption of the intended use? Example would be a walkway that is physically acceptable (planar, regular, stable, flat) but will be unusable with an inch of water actively flowing across it.

(Flooding) In addition, is the sheet flow area on-site and fully under the control of the owner to provide maintenance?

- ☑ What happens to the flow after it passes by the sheet flow area? Will erosion, sedimentation, or flooding be an issue there? Will it enter an adequate channel?

> One approach to check if increases in sheet flow will cause erosion issues is to analyze sheet flow, using Manning's Equation for a 10yr, 24hr storm, and compare that calculated velocity with the parameters laid out in Table 5-1 of the VSWHB. When considering the site conditions, including slope, land cover type, and maximum permissible velocity in Table 5-1, if the calculated velocity is greater than the velocity outlined in Table 5-1, then it should be assumed that the sheet flow in that area of the site will cause erosion.

This is not meant to be an exhaustive list of everything that may need to be considered, but it provides some considerations when evaluating sheet flow. For every project submitted to a program authority, the goal of the plan submitter should be to provide the plan reviewer with sufficient information to verify that the project, when complete, is not going to cause damage downstream.

Notes