Low impact development (LID) is increasingly being viewed by local governments and developers alike as a viable approach to stormwater management that can effectively protect aquatic habitat and water quality. LID relies on distributed runoff management measures that seek to control stormwater volume at the source by reducing imperviousness and retaining, infiltrating and reusing rainwater at the development site.

Early conventional stormwater management practices tended to focus on stormwater quantity and controlling a few extreme rainfall events, whereas the more frequent storms, which represent the majority of total runoff volume, carry most of the pollutants, and control the geomorphology of streams, were addressed in stormwater quality design practiced during the last decade. These frequent events are most effectively managed with a volume control approach, often described as stormwater source control or Low impact development (LID). Such an approach is described in this paper, demonstrating how water balance modelling can be an effective tool for evaluating and supporting implementation of LID options such as bioretention, pervious paving, numerous types of infiltration systems, rainwater reuse and green roofs. It also discusses recently developed water balance modelling software, including an Internet-based planning tool and a design optimization tool.

Key words: low impact development, hydrologic modelling, stormwater management

Introduction

Overview of Low Impact Development

Low impact development (LID) is increasingly being viewed by local governments and developers alike as a viable approach to older forms of stormwater management that can effectively protect aquatic habitat and water quality. Alternately known as environmentally sensitive stormwater management, sustainable urban drainage systems and stormwater source control, LID seeks to minimize the impact of stormwater runoff from new development and re-development, restore and protect ecosystems, and reduce the cost of construction and maintenance of stormwater management infrastructure. LID encompasses numerous site planning and engineering measures to manage runoff at the source using distributed, decentralized micro-controls. Virtually any site-level control that minimizes, slows down, infiltrates, retains, filters or treats runoff can be considered LID or source control.

Planning techniques include preserving open space, especially natural features that play an important role in the site’s hydrology such as wetlands, riparian forests and groundwater recharge zones. Other planning techniques involve minimizing effective impervious area through site design strategies such as more efficient development site layout, open drainage, reduced surface parking, narrower roadways, impervious area disconnection and increased vertical building density. Engineering techniques include bioretention, bioswales, box planters, infiltration devices, absorbent landscaping, green roofs, rainfall capture and reuse, and permeable paving. In general these techniques promote infiltration, evapotranspiration or reuse of rainwater at the source by disconnecting impervious surfaces from stormwater conveyance systems and by creating absorbent surfaces (Coffman et al. 1998; Prince George’s County Department of Environmental Resources 2000).

Whereas the older forms of conventional stormwater management sought to dispose of stormwater relatively quickly and often detain it in large end-of-pipe facilities, LID fully utilizes the assimilative capacity of a site to retain and infiltrate water through small controls distributed throughout the site. LID can mitigate runoff from buildings, roadways and parking lots by deploying controls as part of streetscapes, parking lot islands, sidewalks, medians, gardens and landscaping, and vegetated roofs. For new development, the LID approach maximizes the application of hydrologically functional land-
scaping, and for re-development, it optimizes the use of available green space and creates additional absorbent surfaces where possible (Coffman et al. 1998; Prince George’s County Department of Environmental Resources 2000).

The primary objective of LID is to reduce the volume and rate of surface runoff from development or re-development sites that are serviced by stormwater conveyance systems which discharge to downstream watercourses. This approach can have numerous benefits including:

- protection (or restoration) of downstream watercourse geomorphology, aquatic habitat and water quality
- potential reduction in infrastructure costs by minimizing construction and operation of stormdrain pipes, end-of-pipe treatment facilities and associated infrastructure, and
- potential avoidance or resolution of stormwater related problems, such as flooding, channel erosion and combined sewer overflows.

Low Impact Development Challenges

Two inter-related challenges need to be overcome to enable more widespread application of LID approaches. The first is the lack of models that are developed specifically to address LID hydrology. The second challenge is the need to shift the earlier emphasis on peak flow control to volume control. There are jurisdictions that recognize the need for volume control and groundwater recharge, but the majority remain fixated on peak flows. The focus of this paper is on the water balance modelling approach and tools that can help to overcome the first of these challenges. However, before addressing modelling directly, it is important to provide an overview of the paradigm shift that is at the heart of the LID approach—that is, the need to control runoff volume in addition to controlling peak flows.

Volume Control Approach to Stormwater Management

The volume control approach can also be described as water balance management. The “water balance” refers to the sum of the pathways by which rainfall can leave a given site. In general, rainfall landing on a site travels along four pathways (Viessman and Lewis 1996):

- soaking into shallow ground and moving slowly through soils to streams as interflow
- percolating vertically into deep groundwater
- back up into the air as evapotranspiration (evaporation from surfaces and transpiration from leaves), and
- flowing over the ground as surface runoff or stormwater.

Since the total volume of rainfall equals the sum of the four components, this relationship is known as the “water balance.” It is a familiar hydrologic concept that until recently has had very little bearing on the planning and design of stormwater management systems (British Columbia Ministry of Water, Land and Air Protection 2002).

The primary objective of the volume control approach to LID is to approximate the natural water balance as closely as possible during development through the use of stormwater source control measures. On an annual basis, surface runoff from a forested or naturally vegetated watershed typically comprises a small fraction of the water balance, except where infiltration capacity is severely limited by factors such as shallow bedrock. Before development, the flow observed in streams tends to be mostly interflow, and surface runoff typically occurs only during large rainfall events. When natural vegetation and soils are replaced with paved surfaces and buildings, less rainfall infiltrates into the ground, less gets taken up by vegetation, and more becomes surface runoff. Piped drainage systems are typically installed to convey this additional runoff away from developed areas as quickly as possible, and as a result, almost every rainfall event results in surface runoff being discharged to downstream watercourses. This alteration of the natural water balance is the root cause of watercourse erosion, flooding, loss of aquatic habitat and water quality degradation (Leopold 1968; Hammer 1972; Booth 1990; Schueler 1994).

End-of-pipe stormwater detention facilities are typically designed to control peak flow rates from a particular design storm, such as a 10-year storm event, and do not substantially reduce the total volume of runoff discharged to watercourses. It is increasingly evident that these types of facilities do not adequately protect stream health (Prince George’s County Department of Environmental Resources 2000), and that source control measures that reduce total runoff volume are a critical element of sustainable stormwater management systems.

Stormwater infiltration is a particularly important volume control strategy because it not only reduces runoff volume but also recharges groundwater and stream baseflows. A number of factors may limit the effectiveness of stormwater infiltration, including low permeability soils (e.g., clays), groundwater table or bedrock near the ground surface, or lack of space in existing urban areas. Other volume reduction strategies include rainwater harvesting, green roofs and absorbent landscaping.

Managing the Complete Spectrum of Rainfall Events

The concept of capturing a large portion of the annual rainfall volume was introduced years ago (Roesner et al.
1991), however, most jurisdictions still need to shift their focus from management of large peak flows to an approach that manages the complete spectrum of rainfall events, from the very small to the large or extreme events. Figure 1 illustrates this approach. A volume-based approach usually still requires provisions for adequate conveyance of runoff from large or extreme storms to prevent flooding damage. In some cases, peak flow control facilities (e.g., detention ponds) may be an appropriate strategy, for example, where peak flow rates from large storms need to be lowered to effectively manage flood risk for a stormwater conveyance system.

The operative words for managing the complete spectrum of rainfall events are retain, detain and convey:

- Retain – the small rainfall events (e.g., less than 6-month return period), which account for the bulk of the total rainfall volume, are to be captured and infiltrated (or reused) at the source.
- Detain – the intermediate events (e.g., between 6-month and 2-year return period) are to be detained and released to watercourses or drainage systems at a controlled rate that approximates natural conditions.
- Convey – the large or extreme events (e.g., greater than the 2-year return period) are to be safely conveyed to downstream watercourses without causing damage to property.

Retention of the frequent small rainfall events is the most critical element for volume control. It is also the element that is missing from conventional stormwater management practices, and the element that is addressed by stormwater source control or LID. There are many hydraulic models available to evaluate conveyance capacity for large storms, but water balance modelling (as discussed in this paper) is more appropriate for evaluating site level strategies for managing the frequent small storms.

Figure 1. Integrated stormwater management approach. LID strategies should be designed to mimic the natural water balance to the extent possible.

Performance Targets for Volume Control

Volume-based performance targets provide a starting point for implementing appropriate stormwater source control measures at the site level. For example, the document “Stormwater Planning: A Guidebook for British Columbia” (British Columbia Ministry of Water, Land and Air Protection 2002), recommends that the total annual volume of surface runoff from a development site should not exceed 10 percent of the total annual rainfall volume on that site. The “10 percent target” is based on the work of May and others in Washington State in the late 1990s, which demonstrated that 10% imperviousness is a threshold for stream health impairment (May et al. 1997). This is an example of a target that was selected for areas without much snowfall, and may not be appropriate for areas where snowmelt runoff contributes a large portion of the total flow in watercourses.

To achieve the 10 percent performance target, 90 percent of the total rainfall volume must be captured on a given development site through the adoption of various source control measures. This requires capturing all of the small storms (up to about 75% of annual rainfall volume) plus a portion of the intermediate events (up to about 15% on an annual basis). At the watershed scale, achieving this target on all development sites should result in cumulative benefits as the natural water balance is preserved or restored. The 90 percent volume capture target is intended for use as a rule-of-thumb only, especially in areas where biophysical thresholds for stream health impairment have not been established through research. In essence the target is preservation or restoration of the pre-development hydrologic condition.

Water Balance Modelling Overview

Just as older conventional stormwater management practices are peak-flow based, so are conventional hydrologic modelling applications. The conventional hydrologic modelling approach is to assign lumped parameters to relatively large catchment areas (e.g., runoff coefficients, infiltration rates, initial depression storage, etc.). This approach is adequate for simulating flow rates to size conveyance systems or detention facilities, but it does not easily allow variations in site design practices, such as the application of source control measures, to be modelled. The remainder of this paper discusses water balance modelling, an alternative approach to conventional hydrologic modelling that treats watersheds as fully integrated systems, where creek headwaters in developed areas originate at the rooftops and roads.

Water balance modelling is a simulation approach with the following key characteristics:

- Object-oriented – the various components of the urban landscape (objects) and the hydraulic connections between them are explicitly defined at the site
level. Each object or connection represents a part of the hydrologic process being modelled, such as a parking lot that produces runoff or a bioretention facility that treats it.

- Physically based – each object has a set of parameters associated with it that describes its physical behaviour in response to rainfall. For example, a bioretention facility will have parameters describing its dimensions and soil properties, and equations that describe the process of receiving and retaining runoff, infiltrating and evapotranspiring it, and releasing overflows, if any.

- Continuous simulation – the behaviour of a site needs to be understood as it responds to a site-specific, long-term rainfall record as opposed to synthetic design storms. Continuous simulation allows for statistical performance evaluation and analysis of individual components of the stormwater management strategy.

The objects and the connections between them can be adjusted to create a series of scenarios that represent various LID options for a development or re-development site. Water balance modelling for these scenarios provides a continuous simulation showing how much water travels the various hydrologic pathways, and how much surface runoff is generated from the site, as well as its temporal distribution. Modelling results can thereby be used to estimate the effectiveness of various source controls at reducing runoff volumes and rates.

The object parameters and the connections between them relate directly to specific design assumptions, such as the dimensions of an infiltration facility, the properties of an amended soil, or how much pavement drains to a certain bioswale. This information provides the user with a clear picture of what each scenario represents at the site level, allowing realistic cost estimates to be developed. By comparing scenario costs and benefits, the feasibility of various LID options can be evaluated, and the most cost-effective solutions for achieving specific performance targets or objectives can be identified.

There are several physically based continuous simulation hydrologic models that have been used for decades, including SWMM, MOUSE and HSPF. However, none of these models are object-oriented, and they are not well suited to the precision modelling required to evaluate small source controls distributed over a site, which is characteristic of LID. They use watershed-level hydrologic parameters as inputs rather than specific object properties (e.g., depth of drain rock under a pervious paving strip). In some cases, it may be possible to use these models for site-level water balance modelling, but it is cumbersome and difficult to properly define the design parameters of source controls and the precise placement of those controls where they are needed. Object-oriented models are more appropriate for evaluating and optimizing LID practices at the site level, as discussed later in this paper.

Climate Data Requirements

As with any continuous simulation hydrologic model, a water balance model requires continuous rainfall data input for specific time periods and time steps. Since water balance modelling must account for all hydrologic pathways, a continuous evapotranspiration (ET) record is also required for the simulation time period. Rainfall data should be obtained from the nearest rainfall gauge to the project site. ET data can either be estimated directly based on pan evaporation data (if available), or calculated from daily minimum and maximum temperature data, for example, using a modified Penman-Monteith equation (Viessman and Lewis 1996).

Representing the Physical Landscape

The objects that represent various components of the physical landscape, including stormwater source control facilities, are the basic building blocks of a water balance model. The various types of physical objects include the following.

Impervious surfaces. Impervious surface objects represent non-infiltrating surfaces (e.g., rooftops, driveways, roads, sidewalks). A surface area must be specified for these objects, and other parameters, such as initial depression storage, may also be defined as appropriate. For LID scenarios, runoff output from an impervious surface object would typically be connected as inflow to a pervious surface object (see below), for example, to simulate capture of roadway runoff by a bioretention swale or dispersion of rooftop runoff over part of an adjacent lawn area.

Soil and vegetation surfaces. Soil and vegetation surface objects represent all surfaces within a modelled area that are covered by soil or some other growing media, including various types of pervious surfaces (e.g., lawns, landscaped areas, forest) and many types of stormwater source control facilities (e.g., bioretention facilities, bioswales, green roofs, planter boxes). A surface area and a series of hydrologic properties must be specified for each pervious surface object. Some key hydrologic properties include:

- Saturated hydraulic conductivity – controls the movement of water through the soil matrix under saturated conditions. A saturated hydraulic conductivity value must be specified for surface and sub-surface soil layers. In some situations, high conductivity elements, such as underdrains, are added to infiltration facilities and green roofs. Under unsaturated
conditions, the saturated hydraulic conductivity controls the downward movement of a wetting front.

- **Maximum water content** – the water content (fraction of the total volume of the soil matrix) of a completely saturated soil.
- **Field capacity** – the water content above which water starts to drain out of the soil under the force of gravity.
- **Wiltting point** – the water content below which plants are generally unable to extract water from the soil.
- **Crop coefficient** – the multiplication factor that is applied to the continuous ET data to determine evapotranspiration losses during each simulation time step.
- **Surface soil depth** – the assumed thickness of the surface soil reservoir. For bioretention facilities or amended soils on landscaped areas, soil depth is a design parameter. For other pervious surfaces, soil depth can be assumed to be equivalent to vegetation rooting depth.
- **Maximum ponding depth** – the average depth of water that can be retained on the soil surface. Surface runoff occurs when this ponding depth is exceeded, or at soil saturation (if ponding depth is set at zero).

**Other pervious objects.** Other pervious objects are needed to represent infiltration facilities that retain stormwater in a reservoir-type media, such as gravel or open cell chambers, rather than soil pore space. Examples include gravel infiltration trenches, pervious paving underlain by a reservoir base course layer, infiltration chambers and bioretention underdrain layers. There may or may not be rainfall input and ET losses from these objects. A surface area must be defined for each of these objects along with hydrologic properties, including:

- **Media retention depth and maximum ponding depth** – the depth of water that can be retained in the media, and possibly on the ground surface, before overflowing.

**Void space ratio** – the fraction of the total media volume available for water storage (e.g., typically between 0.3 and 0.4 for gravel).
- **Saturated hydraulic conductivity** – must be specified for the storage media and the underlying sub-surface soil.
- **Rainfall multiplier and crop coefficient** – the multiplication factors applied to the continuous rainfall and ET data to determine rainfall input and ET losses during each simulation time step. These values may be zero for underground facilities.

**Water Balance Simulations for Soil and Vegetation Objects**

A key element of water balance modelling is simulation of the movement of water through soil and vegetation objects (Fig. 2). This process is described in more detail below.

Soil depth is assumed to equal the size of the soil “reservoir.” Water flows into the soil from direct rainfall and as inflow from other objects (e.g., impervious surface runoff). The rate that water can infiltrate into the soil and the resulting excess runoff can be simulated using accepted methods, such as the Horton or Green-Ampt infiltration models (for example the LIFE model, discussed below). Alternatively, it may be acceptable, particularly for planning purposes, to simply assume that if the rate of input exceeds the saturated hydraulic conductivity of the surface soil, then the excess becomes surface runoff (for example, the Water Balance Model for British Columbia, discussed below). For infiltration facilities that allow surface ponding, there would not be surface runoff until the facility becomes completely saturated and the ponding depth is exceeded.

Continuous soil moisture accounting is a critical part of water balance modelling because it governs how water is distributed among the various hydrologic pathways. When soil moisture is between the wilting point and the field capacity, water loss from the surface soil occurs through ET only. When soil moisture is between the field capacity and the maximum water content (i.e., soil saturation), water will exfiltrate out of the soil layer

![Fig. 2. Conceptual representation of a bioretention facility object.](https://iwaponline.com/wqrj/article-pdf/39/4/331/228810/wqrj0390331.pdf)
into the underlying sub-surface soil, in addition to the ongoing ET losses.

Flow Simulations

Water balance modelling produces volume outputs—that is, for each simulation time step, a certain volume of water becomes runoff, a certain volume infiltrates into the ground, and a certain volume is lost to ET or reused within a development site. For many planning level applications, these volume outputs may be all that is required. For design applications, flow simulations must account for the following additional elements:

- Overland routing – for example using the kinematic wave method.
- Groundwater contributions to total flow – depending on the application and the significance of groundwater flow, this factor can be simulated by simply assuming that a fraction of the infiltrated water emerges as interflow, and the rest is “lost” to deep groundwater. In some cases, subsurface flow routing using a groundwater model may be appropriate.

Water balance model output can be used as input to hydraulic routing models, enabling LID analysis to be integrated with conveyance system analysis.

Water Balance Modelling Applications

Two examples of how water balance modelling has been applied to support implementation of LID practices are provided. One example deals with development of local government standards for LID, and the other deals with design optimization of natural drainage systems (a LID approach) at the site level.

Planning Example: Developing Source Control Standards for Developers

The City of Chilliwack, British Columbia, has adopted an approach to stormwater management that addresses the complete spectrum of rainfall events (see Fig. 1), and a citywide performance target that requires new development to capture and infiltrate (or evapotranspire) up to 30 mm of rainfall per storm event. This corresponds to over 90 percent of the total annual rainfall volume in Chilliwack, as illustrated in Fig. 3 (as determined using long-term rainfall data from a local gauging station). The next 30 mm of rainfall are to be detained and released at a very slow rate that approximates natural conditions, and rainfall events above 60 mm (approximately the 2-year storm) must be safely conveyed to minimize flood risk during these large or extreme events.

Chilliwack has developed a “Policy and Design Criteria Manual for Surface Water Management” that describes the volume control approach and performance targets, and also includes design criteria required to achieve the targets (CH2M HILL 2002). Water balance modelling was used to develop the City’s design criteria for source control. Typical residential development sites with on-site infiltration facilities were modelled using a simple spreadsheet-based water balance model. A wide range of scenarios were modelled to represent the various soil conditions within the City, which range from silty clay loam to sandy gravel, and a range of infiltration facility retention depths. For each scenario (i.e., combination of soil type and facility depth), a series of water balance model simulations was run using all of the available rainfall data from one of the City’s gauges, and the infiltration facility area was adjusted until the runoff volume performance target was achieved (i.e., less than 10 percent of total rainfall volume). In this manner, design tables were developed that show developers how much space they must provide for stormwater infiltration in order to meet the City’s rainfall capture target, given the results of on-site percolation testing and the average retention depth of infiltration facilities to be used. For example, a developer building on silt loam (the most prominent soil type in the City) decides to use gravel infiltration galleries with an average retention depth of 0.5 m (total gravel depth about 1.5 m), which would keep the galleries an acceptable distance above the groundwater table. Percolation testing at the locations and depths of the proposed galleries indicate saturated hydraulic conductivities of about 10 mm/h. The City’s design tables show that 900 m² of infiltration area (e.g., a 30 m x 30 m infiltration gallery) must be provided for each hectare of impervious area. For sites with low permeability soils (hydraulic conductivity less than about 5 mm/h) or other factors that substantially limit infiltration capacity, such as high groundwater table or bedrock, developers may not be required to achieve the City’s performance target for rainfall capture. However,
alternative volume control measures (e.g., rainwater reuse, green roofs) are encouraged in these cases.

The design tables for stormwater infiltration are part of the City’s Design Guidelines for Stormwater Systems, which provides step-by-step procedures for designing infiltration, detention, and conveyance systems that meet the City’s design criteria for rainfall capture, runoff control, and flood risk management. The infiltration and detention guidelines were added to the stormwater component of the City’s subdivision control bylaw, which previously only provided criteria for conveyance of large or extreme storms.

Design Example: Optimization for Natural Drainage Systems

Water balance modelling was used to evaluate the feasibility and cost-effectiveness of various options for retrofitting an existing urban area in Seattle, Washington, with natural drainage systems (a LID approach described in this section) in order to remedy a major downstream ravine erosion and habitat degradation problem (CH2M HILL 2004). Venema Creek is a sensitive watercourse with highly erodible soils, draining a 30-hectare area of mostly single-family residential land use along with some limited commercial development, as shown in Fig. 4. Venema Creek is a tributary to Pipers Creek, which has a watershed plan that defines objectives for aquatic habitat protection. The objective of this urban retrofit project is to design and build natural drainage systems (NDS) for stormwater control in the Venema Creek catchment area.

The City of Seattle was interested in evaluating the effectiveness of narrowing streets and replacing disturbed soils and hard surfaces in the road right-of-ways with amended soils and bioretention swales. The NDS had to be designed to control erosion, water quantity and water quality. Also important was the neighbourhood’s aesthetics to preserve and enhance property values, pedestrian and vehicle safety standards and public health objectives. To avoid private property issues, the NDS had to be contained within road right-of-way, but still capture and treat runoff from adjacent lots.

Water balance modelling was used to analyze the performance of various NDS scenarios, based on how well they achieved the following objectives:

- Runoff volume reduction – the objective was to reduce total runoff volume from existing conditions, ideally to less than 10% of existing runoff volume. Total runoff volumes for the entire simulation time period (13 years) were summarized for each scenario.
- Flow control – the objective was to reduce peak runoff rates from 6-month and 2-year storm events to levels as close to natural forested conditions as possible. For each scenario, hydrographs were plotted for typical storm events with these return periods, and compared with modelled hydrographs representing forested conditions.
- Limit standing water – Seattle specified that standing water should not persist longer than 72 hours following a 10-year storm event. This criterion is intended to prevent mosquito breeding in urban areas. Water balance plots for individual bioretention swales were used to determine whether this objective was met (e.g., see Fig. 5).

The scenario modelling process occurred in parallel with the conceptual design for the NDS options considered. Cost estimates were developed for the most promising NDS scenarios. A key metric for comparing various NDS scenarios was cost per cubic metre reduction in annual runoff volume ($/m^3$).

**Water balance modelling process.** The following process was followed to develop a series of block-by-block water balance models for the Venema Creek catchment area (20 blocks) using the LIFE model (discussed later in this paper):

- Initially, a model of the catchment area was developed for existing conditions and calibrated using measured flow data at the catchment outlet to Venema Creek.
- A model was then developed for the catchment area under natural forested conditions.
- Next, a series of NDS scenarios was developed for a single prototype block.
- Finally, a series of NDS scenarios was developed for the entire Venema Creek catchment area.

![Stormwater runoff from urban catchment discharges to a highly erodible ravine](https://iwaponline.com/wqrj/article-pdf/39/4/331/228810/wqrj0390331.pdf)

**Fig. 4.** Upper Venema Creek watershed area to be retrofitted with natural drainage systems.
NDS scenarios were developed by adjusting one or more of the following design parameters:

- **Location and extent of NDS application** – the City wanted to avoid retrofitting the arterial roads within the catchment area due to the level of disruption it would cause. Water balance modelling results indicated that it would be most cost effective to apply NDS on select local roads on the east side (downstream side) of the catchment only, and to divert unmitigated flows from the upper catchment down these NDS roads.

- **Type of natural drainage system** – two general categories of bioretention swale design were tested (see Fig. 4):
  - A swale that retains stormwater in a single layer of vegetated absorbent soil and by ponding on the ground surface. Amended soil is placed directly on the underlying native soil.
  - A two-layer system consisting of a surface swale (as described above) underlain by a gravel-filled trench with perforated overflow pipe. Flow out of this type of system consists of both surface runoff and underdrain flow.

The single-layer bioretention swale was found to be the most cost-effective option for a single prototype block. However, two-layer swales would be required for those NDS that are designed to capture additional runoff from the unmitigated upper catchment area. In these cases modelling results indicated that single-layer swales would result in unacceptable durations of standing water and potential problems with mosquito breeding. Figure 5 illustrates temporal variation of water content in one of the modelled bioretention swales.

Other NDS options were also tested. For example, additional subsurface infiltration galleries under driveways (see Fig. 4) were found to significantly improve performance, especially when applied on NDS that capture additional upper catchment runoff. Strategically located groundwater recharge wells were also found to be very beneficial.

- **Distribution of available road right-of-way surface area** – the best modelled performance was achieved using road right-of-way layouts that maximized infiltration area on the side of the road that captures runoff from adjacent lots, for example, by locating the sidewalk on the opposite side of the street and by shifting the road centerline. Note that over half of the right-of-way area was not available for NDS due to driveways, off-street parking areas, buffer zones at intersections, etc.

- **Bioretention swale design details** – the catchment area is underlain by very dense, relatively impermeable till beneath the moderately compact silty loam surface soil. These conditions limited the overall excavation depth for the bioretention swales to about 1.5 m or less. Practical design considerations limited the maximum ponding depth to about 300 mm (see Fig. 4). Additional check dams would be required to achieve the same level of surface ponding on streets running east-west, which have much steeper grades (5 to 8 percent) than the north-south streets (less than 2 percent). For most two-layer swale options, a 450-mm amended soil layer with a 450-mm gravel underdrain layer was found to be the most effective combination, without resulting in excessive excavation depth. For single-layer swales, a greater depth of
amended soil (typically 750 to 900 mm) could be used to improve performance.

- **Amended soil texture** – for two-layer bioretention swales, amended soil texture governs the rate that water drains out of the surface soil layer into the underlying gravel layer. Faster draining soil textures typically reduce the frequency and duration of surface ponding, but may lead to higher levels of underdrain flow. Modelling showed that the optimized design soil for two-layer swales has a saturated hydraulic conductivity of 50 mm per hour.

The design optimization process for NDS in the Venema Creek catchment resulted in NDS design concepts that achieve significant reductions in runoff (runoff volumes reduced to less than less than 4 percent of total annual rainfall volume), while minimizing retrofit costs and levels of disruption within the catchment area. An important part of this project will be post-construction monitoring to validate the water balance modelling predictions.

**Water Balance Modelling Tools**

Most conventional hydrologic modelling software is designed to use lumped parameters at a watershed scale, which is adequate for quantifying peak flows and sizing conveyance systems but is not well-suited to modelling the spatially distributed controls that are typical of LID practices. This section reviews two recent examples of water balance modelling tools developed specifically for the purpose of modelling LID practices.

- **Water Balance Model for British Columbia** – an Internet-based water balance model that is intended to assist British Columbia municipalities with integrating LID considerations with land-use planning. Intended for use as a decision support tool, the model is also well-suited to education and outreach initiatives for promoting LID.

- **LIFE Model** – a water balance modelling application developed using a dynamic simulation platform which simulates water quantity and quality and is suitable for undertaking source control design and optimization.

**Water Balance Model for British Columbia**

A partnership of local and senior government agencies in British Columbia was formed in 2002 to develop an Internet-based decision-support tool designed to enable non-technical users to integrate LID considerations with land-use planning and development decisions. Based on the water balance modelling approach, the Water Balance Model for British Columbia (www.waterbalance.ca) is a public-domain tool that allows users to quantify the benefits of incorporating various source controls for managing stormwater runoff volume. In particular, the model evaluates the effectiveness of infiltration facilities, landscaping practices and green roofs at achieving specific performance targets for runoff volume reduction.

The British Columbia Stormwater Planning Guidebook (British Columbia Ministry of Water, Land and Air Protection 2002) challenges developers and land-use managers to maintain predevelopment hydrology in urbanizing watersheds. The Guidebook lays out a methodology for identifying specific performance targets for managing runoff volume based on the annual rainfall spectrum. The Water Balance Model, designed to be consistent with the provincial Guidebook, demonstrates what is required to meet these targets on individual development sites. The model is intended for use as a planning-level decision support tool to demonstrate the benefits of integrating LID practices into site design. As the model does not include a routing routine, it deliberately does not address issues related to slope of a particular site or depth of the water table. Neither does the model incorporate snowmelt considerations or water quality outputs. Instead, the model was developed to enable users to quickly and easily compare development scenarios and evaluate appropriate stormwater source controls.

The effectiveness of different stormwater source controls will vary with climate, soils and surface conditions, as well as with the design of the source control itself. Water Balance Model users have the option to select climate data from a drop-down menu of British Columbia stations, or to upload their own data as appropriate. Similarly, native soils can be selected from a menu of generic soil types, or defined by the user if site-specific data is available. Additional inputs include information about surface conditions on the development site, which may be set up to correspond to zoning in individual municipalities. With these basic inputs, the model generates a variety of information on the expected stormwater runoff, including the rainfall-runoff relationship, runoff hydrographs and charts describing the water level in each infiltration facility. Users can then begin to generate different scenarios by changing the amount of lot coverage, changing right-of-way widths and surface cover, or by adding, removing or re-sizing source controls.

The user-friendly interface of the Water Balance Model is also well-suited to education and outreach initiatives for promoting LID. A comprehensive outreach program was launched in 2003 with a series of workshops aimed at different target audiences, including local government elected officials, planners, engineers, developers and community stewardship groups. The objective of the workshops was to clearly explain the link between decisions about land use and consequences for stream health, supplemented by hands-on, computer-based training on using the model to generate scenarios. As a diverse range of users become familiar with using the
model to evaluate the impact of different planning and engineering decisions, the expectation is that consideration of the natural water balance will become an integral part of land development practices in British Columbia.

**LIFE Model**

The *LIFE* model is a proprietary water balance simulation application that was developed by CH2M HILL, which represents the processes of water quantity and quality. It is a visually oriented, interactive tool developed on an Extend dynamic simulation platform. The Extend package is used to create dynamic models from basic units called blocks (Krahl 2002). Each block in the *LIFE* model simulates a component of the process being modelled, has a set of parameters associated with it, and contains its own procedural information that describes its behaviour. Each component of the physical landscape, including source control facilities, is represented by a block (analogous to the “objects” described previously). There are also blocks that perform other functions, such as flow routing, storing climate data and soil data to be accessed by other blocks, and generating various outputs. Blocks are grouped into libraries according to their function. *LIFE* is intended to be used as a tool for evaluation, design and optimization of LID techniques at the development-site level. There are more suitable models available for watershed level analyses that focus on stormwater conveyance systems. *LIFE* does not include simulation of snowmelt hydrology.

A *LIFE* model is created by dragging blocks from a library, connecting them, and entering the appropriate parameters in a dialogue box customized for the block. Figure 6 shows an example representation of the runoff generation process for a typical lot using blocks describing a rooftop, a driveway and a lawn. The resulting surface runoff is then routed to a bioretention facility. Infiltration occurs over the lawn area and the bioretention facility.

A major advantage of the Extend platform is the ability to define complex combinations of blocks and “encapsulate” them into hierarchical blocks (H-blocks) for visual clarity and for inclusion as modules in other projects. For example, the arrangement of blocks shown in Fig. 6 could be encapsulated as an H-block block representing a typical single family lot with source control, which could then be stored in a library and reused numerous times within the same model or in a different model. This capability enables complex site configurations to be modelled in a simple organized manner.

The *LIFE* model has numerous other capabilities that complement the basic water balance modelling capabilities described in this paper. The model produces a physically based representation of all of the components of the hydrologic cycle: interception, infiltration (two approaches), interflow, baseflow, runoff, evapotranspiration, routing and storage. In addition, the *LIFE* model provides the option of performing the following functions:

- simulating the generation and transport of sediment and other pollutants, and the effect of runoff on water temperatures
- performing overland flow routing using the kinematic wave approach, and basic channel processes (routing, sediment and pollutant transport) based on a one-dimensional stream channel or reservoir
- simulating groundwater contributions to total flow through one-dimensional routing of interflow and aquifer outflows (baseflow)

**Fig. 6.** Facility water balance for surface amended soil layer of two-layer bioretention swale.
simulating fish growth as a result of changes in water quantity and quality

• simulating dynamic land-use changes to represent the effects of increasing development over time, and

• linkage to GIS to aid in populating land-use information directly into the model.

**Design optimization tool.** The LIFE model includes an optimization routine that assists in the optimization of source control design to minimize costs while meeting watershed protection criteria for volume, flow rates and/or water quality. Once site inputs are defined, the user can specify various constraints within the optimization routine, and then generate the optimum solution that produces the maximum return on investment while meeting the defined set of constraints. The constraints would typically include watershed protection criteria, such as maximum allowable runoff volume or sediment loading from a development site. Any number of other constraints can be defined based on the needs of the watershed and site-specific considerations, for example, maximum amount of space available for source control facilities, number of development units required to be profitable, or the acceptable amount of runoff that can be diverted to adjacent natural treatment areas (e.g., wetland, forest, groundwater recharge zone). Certain cost assumptions would need to be input prior to running the optimization routines, including cost of land, cost of development, including permitting and construction, and costs of stormwater infrastructure, including source control facilities.

**Conclusion**

Water balance modelling is an important tool for stormwater management practitioners, local governments and land developers interested in moving from the early stormwater management approach that only controls peak flows to a more integrated approach adopted in modern stormwater management that controls runoff volume and manages the complete spectrum of rainfall events. This paradigm shift is essential to the widespread implementation of low-impact development practices that seek to minimize surface runoff and protect stream geomorphology, aquatic habitat, water quality, stream baseflows and groundwater recharge.

Water balance modelling enables a quantitative evaluation of the effectiveness of stormwater source control alternatives, given information about land use, soils and subsurface conditions, climate and source control design options. This information will enable local governments and land developers to determine what can realistically be achieved through the application of source controls, as well as to determine which source control options are worth pursuing and where. In addition, this type of modelling may be used to optimize source control design to achieve the best performance at the least cost. Water balance modelling is a useful tool for LID implementation, but should not override a good understanding of hydrology, hydrogeology, geotechnical issues, environmental issues, community acceptance, cost implications, and ongoing operation and maintenance requirements.

Since it may take many years to achieve the potential benefits of stormwater source control, the opportunities for implementing low-impact development techniques must be considered in the context of a long-term vision for watershed protection and restoration that is shared by all stakeholders.

**References**


Prince George’s County Department of Environmental Resources. 2000. Low impact development design strategies: an integrated design approach. Largo, Md.


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