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Methodology for measuring the spatial distribution of low streamflow within watersheds

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Methodology for measuring the spatial distribution of low streamflow within watersheds

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Abstract

Surveys to map the distribution of low streamflow within watersheds are useful for many purposes including groundwater and aquatic habitat studies. This report describes a detailed methodology to plan, conduct and report a low-flow survey. Low-flow surveys are a cost-effective approach to collect spatial data and develop a conceptual understanding of groundwater-surface water interactions within a watershed. Carefully collected and documented surveys also provide baseline datasets of low-flow discharge and chemistry data for future comparison. This report is intended for both the professional who plans and designs the field program and the technician who does the fieldwork. The first recommended step is to conduct a reconnaissance survey in which basic field data are collected in order to plan an efficient and effective survey. Careful planning of a survey using the reconnaissance data will yield better low-flow survey results in a more time- and cost-effective manner. Stream gauging using the current meter and volumetric methods is then described with a particular emphasis on the measurement of flow in small streams under low-flow conditions. The reporting of results includes both the calculation of stream discharge and estimation of measurement errors. The error estimation is described in detail and the various factors contributing to measurement errors are evaluated. In general, measurement error can be reduced most effectively by choosing a cross-section where water velocities exceed 0.1 m/s and by increasing the number of measurement sections (verticals) within a cross-section. Some uses of low-flow survey results are briefly presented.

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1 Introduction

Periods of low flow[1] in streams are particularly important for the management of water resources since demand for water usually increases during dry weather and streamflow may approach the minimum requirements to sustain ecological or water quality functions. Sources of stream low flows are not uniformly distributed in most watersheds. Groundwater discharge is often concentrated in particular areas as a result of topography, geology and the nature of groundwater flow (Tóth, 1963; Freeze and Witherspoon, 1967; Ophori and Tóth, 1990). Similarly, the release of water from various sources of surface storage is spatially and temporally variable. Commonly, little or no flow data are available at a scale that is appropriate to assess the potential impacts of land development on the local tributaries. Such spatial variations in low stream discharge and the lack of data to quantify these variations can make it difficult for water and land use managers to make informed decisions regarding low-flow water management.

The interaction between surface water and groundwater has significant implications for water resources and surface water ecology (e.g. Winter et al., 1998; Hayashi and Rosenberry, 2002). The nature of these interactions depends on numerous factors that vary spatially both within and among watersheds. Similarly, land use practices have significant impacts on groundwater and surface water resources and these impacts also vary spatially. When available, distributed measurements of low stream discharge can be used to better understand groundwater interactions with streams. These data may also be used to develop conceptual models and calibrate numerical models of groundwater flow. Therefore, understanding and quantifying the spatial distribution of surface water-groundwater interaction is a valuable step in assessing the water resources and ecological habitats of an area and provides useful information to help manage water resources and land use.

Analysis of stream low flows is commonly performed using daily records of stream discharge at monitored gauging locations. The number and distribution of continuously monitored sites is generally inadequate to provide quantitative data of the low-flow distribution within a watershed. As a result, in many watersheds there are good quantitative hydrological measurements at gauging locations yet there are few data that quantify the detailed distribution of discharge within a watershed. Spatial distributions are often estimated using regional regression models, regional prediction curves, spatial interpolation or flow simulation models (Smakhtin, 2001). Low-flow regional regression models have been found to produce estimates with unacceptably large errors (see references in Reilly and Kroll, 2003). To quantify low-flow distribution within a watershed or region, the best approach is often to measure stream discharge at many sites concurrently; this approach is the basis of a stream low-flow survey.

[1] For the purpose of this report, periods of low flow are defined as the periods when stormflow has ceased and streamflow consists entirely of delayed sources of flow (i.e. baseflow). However, depending on the purpose of the study, low flow can also be interpreted more narrowly as the flow during a period of prolonged dry weather.

1.1 Purpose and scope

Despite the simplicity, low cost (relative to other hydrogeological methods) and extensive documentation on stream flow measurement and interpretation methods, low-flow surveys have been used infrequently in Canada. Possible reasons for this shortcoming are a lack of documentation that specifically describes a procedure for low-flow surveys and a lack of awareness of the usefulness of the results. Consequently, the primary purpose of this report is to provide detailed methodologies to conduct stream low-flow surveys and report their results; the secondary purpose is to discuss the value and illustrate some of their potential uses. The intent of the report is to encourage the collection of spatially distributed low-flow data to support watershed management. Although the procedure described in this document is based on experience developed through work that focussed on delineating and quantifying groundwater discharge distributions (Hinton, 1995; Hinton et al., 1998), the procedure may be adapted to low-flow surveys for any general purpose.

This report is intended for both the professional who plans and designs the field program and the technician who does the fieldwork. Although stream gauging methods are described in detail in many other documents, the current meter and volumetric methods are included because this document emphasizes the measurements of small streams, the selection of gauging locations and the consideration of errors. The lack of emphasis on recognizing and estimating gauging errors is a major shortcoming of previous descriptions of low-flow surveys. Consideration of errors at all stages of the survey will not only result in more accurate results and improved interpretations but also in more time- and cost-effective surveys.

Low-flow surveys can be designed to be very simple or to be very detailed according to the goals of the study. The methodology described in this document is suitable for both simple and detailed surveys; the main differences relate to the number and density of sites to be studied, the amount of planning required prior to conducting a survey, and the resources available.

2 Background

Despite numerous efforts to estimate low-flow characteristics at ungauged sites based on similarities in topography, geology, climate, vegetation and watershed area with nearby monitored sites, the uncertainties in these estimates are often very large (Smakhtin, 2001). Smakhtin's (2001) low-flow review recognizes that "the understanding of specific low-flow generating mechanisms and relevance of different gain and loss processes to the wide variety of climatic, topographic and geological conditions remains rather limited" and suggests that " methods for low-flow estimation in small ungauged catchments should be in the focus of future research". There is a lack of detailed spatial data necessary to develop an understanding of low-flow generating mechanisms. Therefore, more emphasis on the collection of spatial low-flow data is required.

Studies investigating surface water-groundwater interactions sometimes use flow measurements along a stream to quantify fluxes between the stream and groundwater systems. In the United States these measurements are called seepage runs (Riggs, 1972). The emphasis of seepage runs has predominantly been to estimate losses or gains to groundwater along specific stream reaches of interest (e.g. Randall, 1978) rather than to understand the spatial distribution of groundwater discharge (and recharge) within an entire watershed. Seepage runs commonly focus on the fluxes to and from the main stream (or river) channel and only measure tributaries at their confluence with the main channel (e.g. Lewelling et al., 1998; Simonds and Sinclair, 2002). The methodology presented in this report aims to quantify the spatial distribution of gains and losses to stream low-flow throughout a watershed. These results are particularly useful to hydrogeologists when changes in low flow can be related to groundwater recharge or discharge. Much can be learned about watershed hydrology and hydrogeology from the areas of high groundwater discharge as well as from the areas where discharge is minimal or where recharge occurs.

Low-flow surveys are a very economical and practical approach to provide data and improve the understanding of hydrological processes within a watershed. First, the surveys help develop an awareness of low-flow controls and their distribution within a watershed. This conceptual understanding is particularly important in areas where data are often limited. Second, these surveys provide important historical or background data. Discharge data are frequently lacking within subwatersheds and land use changes frequently proceed without discharge measurements on local tributaries. Consequently, there are often no historical measurements and it is not possible to establish background conditions and to assess any resulting hydrological consequences of land use over time. Third, low-flow surveys can provide concurrent data between ungauged and gauged sites. Low-flow indices such as Q90 (flow equalled or exceeded 90% of the time), 7Q10 (or $Q_{7,10}$, annual minimum 7-consecutive-day low flow that is expected to be exceeded on average 9 out of 10 years), or MAM7 (mean annual minimum 7-consecutive-day low flow) are commonly used for design or regulatory purposes. However, these values are available at sites with long-term discharge records that usually drain a much larger watershed than the area of interest. Therefore, using low-flow surveys to estimate low-flow indices at additional sites would be useful to address localized issues. Low-flow

indices can be estimated at “partial record stations” when concurrent measurements of low flow are made at both the partial record station and the station with a complete record (an “index station” where the low-flow indices are known) (Searcy, 1959; Riggs, 1972). Several concurrent measurements at different discharges are required to establish this relationship with the index station so that, ideally, surveys should be repeated under different low-flow conditions. The nested approach to low-flow surveys (see section 4.4) is well suited to the establishment of partial record stations.

Finally, low-flow surveys also produce additional measured and observational data that serve a variety of intended and unintended uses. For example, surveys can sometimes be used to identify the flowing lengths of streams, unknown water takings, or practices resulting in water temperature or water quality changes. Low-flow surveys are therefore of considerable value to many watershed specialists and managers interested in groundwater and surface water resources, aquatic habitat, water quality and land use issues.

3 Reconnaissance survey

3.1 Purpose

A low-flow survey involves the measurement of low stream discharge at numerous sites over a short time period. Therefore, it is recommended that a preliminary or reconnaissance survey be used to help ensure that the survey is planned and conducted effectively and efficiently. A well-designed reconnaissance survey will: 1) identify suitable locations and methods for stream gauging, 2) permit preliminary identification of high and low discharge areas, 3) provide information on the flowing length of streams and the elevation where streamflow is initiated, 4) identify activities or problems that may influence stream gauging or interpretation of the low-flow survey results, 5) obtain preliminary information about water chemistry, 6) provide an opportunity to obtain permission to access sites on private property, 7) greatly improve the familiarity with the hydrological conditions and controls within the watershed, and 8) allow the development of an early conceptual understanding of low flow in a watershed.

3.2 Office preparation

Advanced planning in the office will provide background information on the watershed and facilitate fieldwork and subsequent interpretation of the survey results.

3.2.1 Low-flow characteristics

If available, historical stream discharge (and precipitation) records within the watershed provide valuable information to assist in the planning of low-flow surveys. They indicate the magnitude and variability of low-flow discharge through calculation of low-flow indices (e.g. Searcy, 1959; Riggs, 1972), the best time of year to conduct surveys and the time required to return to low-flow conditions following precipitation. This knowledge will help determine when reconnaissance and low-flow surveys may proceed. If several historical or current gauging sites exist, they may provide some indication of the locations of high groundwater discharge within a watershed. Real time discharge or stage data (available on-line from the Water Survey of Canada and the USGS) provide extremely useful information for reconnaissance and low-flow surveys since they can indicate whether previous precipitation is influencing present stream flow conditions.

3.2.2 Background information

Topographic, geologic, soils, and vegetation maps, air photos and remotely-sensed images provide information about the watershed characteristics and thus insight into the anticipated distribution of stream low flow within a watershed. Information about water use in the watershed may also be helpful.

3.2.3 Site selection and numbering

Identification of potential sites for stream gauging will depend on the accessibility of the stream network. In watersheds with a sufficiently dense road network, road crossings over streams are well suited for low-flow surveys because they are readily accessed and are generally public lands. Additional sites for consideration include streams within parks

or along trails, active or discontinued hydrometric stations, suspected groundwater discharge zones, sites near the confluence of tributaries, and sites upstream and downstream of water sources or sinks (e.g. outfalls, dams, pumping sites). Criteria for site selection should be reviewed to ensure that possible sites of interest are included in the reconnaissance survey (see Section 4: Planning the low-flow survey).

Sites should be numbered or coded. Short site numbers are preferable and the following format is suggested: a site number that consists of one to three letters designating a watershed, a dash and three numbers designating a site location (e.g. H-030). Sequencing the numbers from the outlet of the watershed (-001) moving upstream along the route most likely used when conducting the reconnaissance survey will prevent sites from being overlooked and will allow sites to be easily located on maps during data analysis. If additional sites are subsequently added, the closest field site number can be used with an additional dash and number at the end (e.g. H-030-2).

3.3 Equipment

Recommended equipment is listed in Table 1. Detailed topographic maps (1:50 000) labelled with field site numbers and up-to-date road maps allow sites to be readily located. Larger scale maps (1:20 000) may be required for very detailed surveys whereas smaller scale maps (1:250 000) may be suitable for larger watersheds or regional surveys. Geological and soil maps can be used to help develop a conceptual understanding of the controls on stream low flow in the field. Site locations should be documented with sufficient accuracy to ensure that others could readily locate the correct tributary and stream location unambiguously. A Global Positioning System (GPS) should also be used and a photograph of the site taken to document the specific site. Pre-printed notebooks of reconnaissance forms ensure that all the required data are collected at each site (Fig. 1). The information to be recorded at each site is suggested in section 3.4 and summarized in Appendix 1. A meter stick (or calibrated pole for streams deeper than 1 m) and measuring tape are used to estimate water depths and stream width. Stream velocity is roughly estimated by measuring the travel time of floats or food dye over a measured distance. Alternatively, a robust current meter (such as those with electromagnetic sensors) can provide a suitable velocity measurement without the set up time required for the vertical axis current meters (described in section 5.2).

Differences in physical and chemical parameters can exist among tributaries or between surface waters and groundwater. Specific electrical conductivity and temperature are easily and inexpensively measured parameters that can help identify water sources, mixing or contaminant sources, and therefore should be recorded during reconnaissance and low-flow surveys. Similarly, other easily measured parameters such as pH, dissolved oxygen or specific ions could be useful in some watersheds.

Table 1. Recommended equipment for the reconnaissance survey.

topographic maps with field site numbers
up-to-date road/street maps
other maps (geology, soils…) (optional)
GPS unit
camera, film or memory cards, (optional)
reconnaissance forms/field book (Fig. 1)
pencils and pens
meter stick or graduated pole
measuring tape (longer than the widest stream)
floats
food dye and plastic syringe
watch and stopwatch
robust current meter (optional)
flashlight
conductivity/temperature meter
pH, dissolved oxygen, or ion selective meters (optional)
spare batteries
appropriate safety equipment (section 3.6)

3.4 Field procedure

3.4.1 Prior to departure at the start of day

1. Bring selected equipment from Table 1.

2. Ensure all equipment is in good working condition. Calibrate instruments according to manufacturers' instructions (e.g. pH meter). Record the instrument serial numbers.

3. Record general weather conditions and note the date and approximate depth of the most recent precipitation if it is known.

3.4.2 At each site

4. Record the following site information on the reconnaissance forms or in the field notebooks:

- Site number
- Date and time
- Field technicians (initials)
- Site coordinates from map or GPS (e.g. UTMs).
- Nearby road or site markings (to help locate the site if there is any difficulty/ambiguity)
- Description of road crossing (type, material, and/or size; e.g. steel bridge, large cement culvert, or small corrugated culvert) (optional)

Figure 1. Sample site reconnaissance form.

Date: - - **Samplers:** _____ **pH meter #:** _____ **Cond. Meter #:** _____ **Page #:** ____
day month year _____ **GPS unit #:** _____ **DO meter #:** _____ **Coord. Sys.:** NAD 83

Site #	Time	Est. Q (l/s)	Temp. (°C)	Cond. (µS/cm)	pH	DO (mg/L)	Instrument (circle, note container)	Evaluation (circle)
	:						AA Pygmy Float Drop _____	Good Fair Poor Unsuitable
UTM:		**E**	**N**	Photo #:	Section location:			
Location:					Notes:			
	:						AA Pygmy Float Drop _____	Good Fair Poor Unsuitable
UTM:		**E**	**N**	Photo #:	Section location:			
Location:					Notes:			
	:						AA Pygmy Float Drop _____	Good Fair Poor Unsuitable
UTM:		**E**	**N**	Photo #:	Section location:			
Location:					Notes:			
	:						AA Pygmy Float Drop _____	Good Fair Poor Unsuitable
UTM:		**E**	**N**	Photo #:	Section location:			
Location:					Notes:			
	:						AA Pygmy Float Drop _____	Good Fair Poor Unsuitable
UTM:		**E**	**N**	Photo #:	Section location:			
Location:					Notes:			
	:						AA Pygmy Float Drop _____	Good Fair Poor Unsuitable
UTM:		**E**	**N**	Photo #:	Section location:			
Location:					Notes:			
	:						AA Pygmy Float Drop _____	Good Fair Poor Unsuitable
UTM:		**E**	**N**	Photo #:	Section location:			
Location:					Notes:			
	:						AA Pygmy Float Drop _____	Good Fair Poor Unsuitable
UTM:		**E**	**N**	Photo #:	Section location:			
Location:					Notes:			
	:						AA Pygmy Float Drop _____	Good Fair Poor Unsuitable
UTM:		**E**	**N**	Photo #:	Section location:			
Location:					Notes:			
	:						AA Pygmy Float Drop _____	Good Fair Poor Unsuitable
UTM:		**E**	**N**	Photo #:	Section location:			
Location:					Notes:			
	:						AA Pygmy Float Drop _____	Good Fair Poor Unsuitable
UTM:		**E**	**N**	Photo #:	Section location:			
Location:					Notes:			

5. Measure and record desired physical and/or chemical parameters such as water temperature, specific conductance, pH, and dissolved oxygen.

6. Estimate the discharge. Discharge is estimated by considering the channel cross-sectional area and multiplying by an estimated average water velocity. Here is a suggested procedure to obtain a rapid estimate of discharge:
- Locate a shallower, more rapid section of the stream (the flow is often easier to estimate than in deep, slow sections).
- Visualize the channel cross-section to be rectangular (average depth times width) and exclude slow water at the edges of the channel.
    - Estimate water velocity by timing the movement of a float or food dye over a measured distance. Alternately, a rugged current meter can be used to rapidly measure the water velocity.

This procedure is not intended to provide an accurate estimate of discharge at any one site but rather is intended to allow comparison with sites immediately upstream and downstream. It is useful to indicate where there is a significant perceived increase or decrease in flow along a stream.

If there is no discharge, be specific about the observation leading to that conclusion. For example, a "dry" site would have no standing water, 'disconnected pools" would have pools of standing water disconnected by dry segments, and "stagnant water" would have a continuous pool of water with no observable flow (using dye or a float).

7. Evaluate the feasibility of gauging the site. Section 5.3 describes the desired conditions of a gauging site. A simple scale (Unsuitable, Poor, OK, Good) describing the accuracy of the potential measurements is sufficient and will greatly assist the planning of the gauging survey. An "unsuitable" site cannot be gauged. A "poor" site could be measured but would likely have sizeable errors caused by conditions such as turbulent flow around obstacles, unmeasurable flow through vegetation along the edges, or water velocities that are too low to measure accurately. An "OK" site can be measured with reasonable accuracy but may require more depth and velocity measurements to capture significant variations across the section. A "good" site can be measured accurately since the depth and velocity changes across the stream are generally gradual and are readily measured. If several nearby sites are rated "good" or "OK", suggest the best site.

8. Determine the most appropriate field method and record the instrument required. For the current meter method, recommend either the AA or pygmy current meter (see section 5.2). For the volumetric method, note that there is a "drop" and record the appropriate container for the measurement (see section 6). Alternate methods (see section 7) can also be listed.

9. Describe the suggested location of the gauging cross-section (e.g. approximate distance upstream or downstream of road crossing).

10. Site photographs, if desired, should be taken. Photographs should include distinctive site features. For sites with no flow, the photograph should show a dry stream segment, if present.

11. Record additional notes as appropriate. These may include: the reason a site is unsuitable or poor, additional equipment required and purpose (e.g. shovels, to block flow through vegetation), a sketch map or additional directions to locate a site, corrections to maps, site observations (seepage, pollution, pumping, suspended sediment, etc.), or permission needed/granted/denied to access a site on private property.

12. Sites that are not visited should be noted and the reason given (e.g. lack of access, hazards, already found a suitable gauging location, etc.).

13. When groundwater springs or seepage areas are observed along a stream, it is recommended that a new reconnaissance site be established (with a different site number). Even if their contribution to stream discharge is minor, these sites can be useful to document groundwater temperature and chemistry.

3.4.3 At the end of the day

14. Photocopy completed reconnaissance forms.

3.4.4 Follow-up reconnaissance

14. A preliminary analysis of reconnaissance survey results can reveal interesting observations such as sudden changes in estimated discharge or water chemistry. It is often worthwhile to further investigate these changes by walking the length of the streams in these reaches. They can reveal very localized areas of groundwater discharge, springs, flowing wells, unknown outfalls, or pumping. Becoming aware and improving knowledge of these areas can be important to the hydrological understanding of the watershed and help better plan the low-flow survey. Similarly, the headwater reaches of selected streams can be walked during dry conditions to map the flowing length of streams and estimate the elevation where the water table intersects the ground surface.

3.5 Weather and flow considerations

Although collection of site information and assessment of sites for gauging can proceed during most flow conditions, flow estimates and measurement of stream parameters are more useful when conducted during low-flow conditions. For practical purposes, it is sometimes necessary to conduct portions of reconnaissance surveys when flow conditions haven't fully returned to low flow following a storm. When working on such days, it is often preferable to work in downstream portions of a watershed where it is more difficult to perceive smaller relatives changes in discharge. It is better to assess the headwater areas during low-flow conditions to allow the identification of dry stream segments. Ideally, field assessments should be avoided on rainy days when other tasks can be performed such as field data entry and obtaining permission to access sites on private property.

3.6 Safety, time and resource considerations

For safety considerations, crews of two field technicians are needed. Field technicians should always be conscious of safety during reconnaissance and stream gauging. Most important is general water safety, particularly for deeper or faster streams or streams with very soft bottoms. Protection from the weather and water (e.g. sun, temperature, and viruses, bacteria or wildlife in the water) should also be used where appropriate. Appropriate safety equipment includes items such as life jackets, chest waders, sunscreen and a first aid kit. Based on experience in areas where field sites are generally 0.5 – 2 km apart, a crew of two can visit approximately 30-50 roadside sites per day where permission to access property is not required.

4 Planning the low-flow survey

Planning the low-flow survey using the results and insight gained from the reconnaissance survey (or a previous low-flow survey) will produce a more efficient and effective low-flow survey and yield better results.

4.1 Assessing reconnaissance survey results

The reconnaissance survey results are generally suitable to make preliminary interpretations of the distribution of groundwater discharge within a watershed by simply plotting the estimated flows on a map and noting the estimated changes in discharge. Water temperature sometimes provides insight into the proximity of discharge areas. It is worthwhile at this stage to re-examine topographic and geologic maps to consider possible conceptual models that explain the observed patterns of low flow and that can guide the selection of sites for the low-flow survey. Careful site selection may allow for hypotheses to be tested or for particular areas of the watershed to be highlighted. An important consideration at this time is whether the original goals of the survey can be met or if they should be altered.

4.2 Site selection

The selection of sites will depend on the purpose and the spatial resolution of the low-flow survey, the time and resources available, the observed flow conditions, their suitability for gauging and access. In general, sites are selected to determine changes in flow along particular reaches (segments) of streams. Stream reaches are often chosen on the basis of increases in estimated low flow from the reconnaissance survey. However, sites (and reaches) may also be chosen according to different criteria such as geology, topography, or even land use.

It is best to select sites immediately upstream and downstream of important discharge areas so that increases in low flow are attributed to particular stream reaches. In areas where the flow is particularly low, fewer upstream sites are required since downstream locations are often suitable to document small flows over larger areas. In areas of unchanging flow, sites are selected near the top and bottom of these reaches.

Important sites to include in a low-flow survey are locations with continuous records of stream discharge, either historical or current. Concurrent discharge measurements at these index sites and other low-flow survey locations may allow some low-flow statistics to be estimated for survey locations if the survey is repeated several times (Riggs, 1972, see section 9.1).

4.2.1 Measurement error considerations

There may be little value in measuring discharge at numerous sites along a stream reach where changes in discharge are expected to be smaller than measurement errors. Using the reconnaissance survey results and an estimate of gauging errors, it is possible to choose an appropriate density of sites. For planning purposes, it is reasonable to assume

gauging errors of approximately 5-7% for current meter gauging of streams (see section 8.3). Therefore, it is often not possible to accurately quantify changes in low flow that are less than 5-10% of the flow along a stream reach. Since the relative changes in low flow are generally much larger where discharges are small (i.e. headwaters) and much smaller where discharges are large (i.e. downstream), low-flow surveys are less effective at demonstrating localized gains or losses from larger streams. For example, a 10 L/s increase in discharge is more readily measured in a 50 L/s stream than in a 250 L/s stream and is not measurable in a 1000 L/s stream. As a result, the spacing of sites along reaches of larger streams is usually increased.

Sites may also be chosen for data verification purposes. For example, where the flow is measured near the mouths of two tributaries, a site downstream of their confluence could be used for comparison.

4.2.2 Time and resource considerations

The number of sites selected should consider the time and the number of field technicians available for the low-flow survey. For planning purposes, a two-person crew typically requires between 30-45 minutes per site for small streams and 1-1.5 hours per site for larger streams using the current meter method. In contrast, the volumetric method generally requires 15-30 minutes per site. Reconnaissance survey data can be used to estimate the travel time between sites.

4.2.3 Activities/problems that may influence gauging strategy

Several features and activities can alter the patterns of stream low flow from those expected from groundwater discharge alone. These include water storage, water removal, and water addition. These influences are often identified during the reconnaissance survey. Ponds, wetlands, dams, reservoirs and lakes often store water during periods of high flow that is subsequently released during low-flow conditions. Where possible, the effects of water storage can be considered by measuring the flow immediately upstream and downstream of such features. By using this approach, contributions from areas with stored water can be identified in the analysis although it would not be possible to distinguish between water storage changes and groundwater discharge (or loss) within these areas.

Water removal from streams is most likely during dry weather conditions when low flow is measured. Typical water users include golf courses, agriculture, nurseries, and water trucks (dust control, lawn care). Similarly, there are several possible sources of stream low flow in addition to groundwater discharge. Typical examples include outflow from wastewater treatment plants, storm sewers, tile drains, and flowing wells. Direct measurement of water removal or addition is preferred, but often not possible. In such situations, gauging immediately above and below the source or sink of water may allow it to be quantified.

4.3 Nested approach

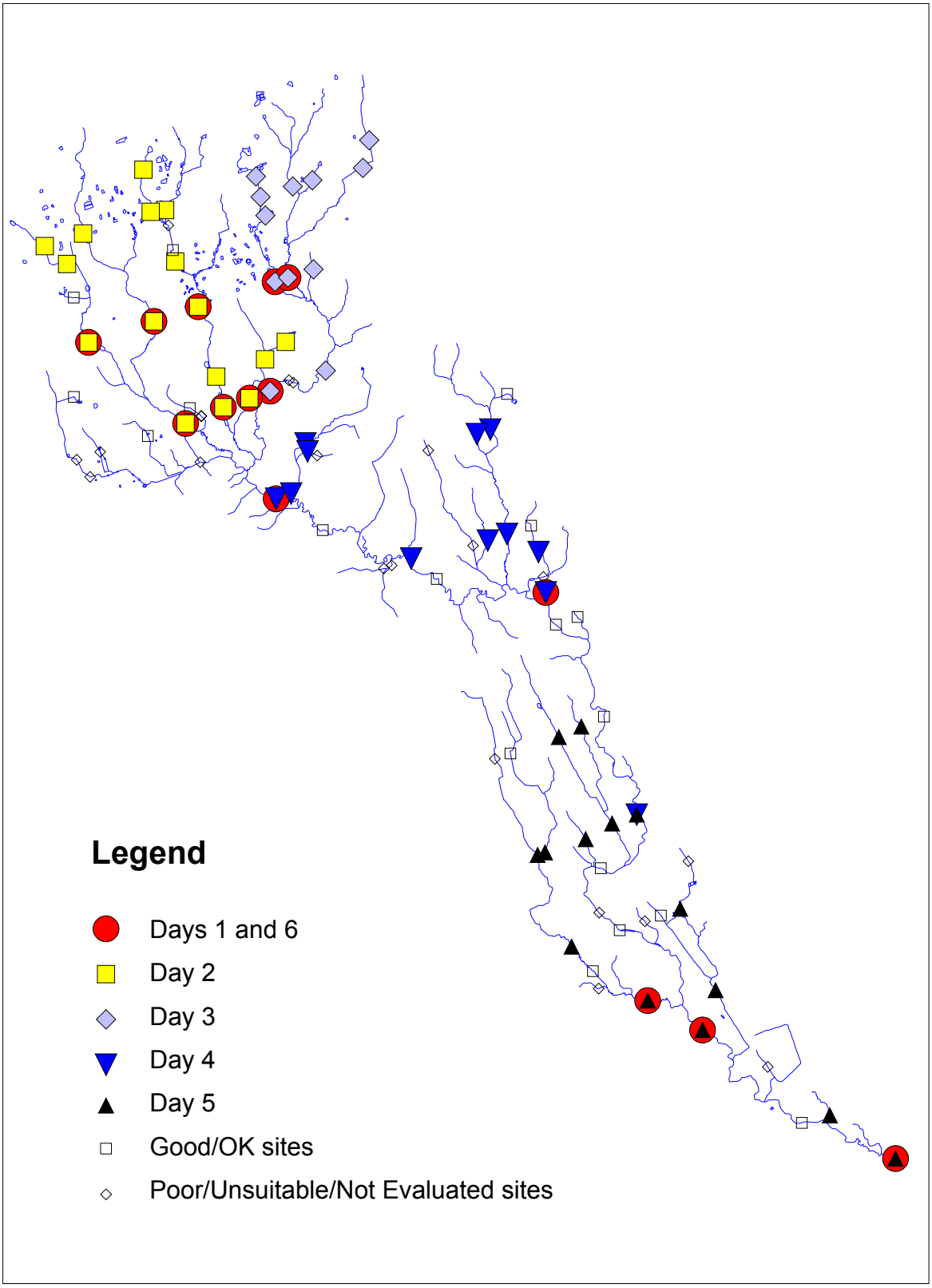
A nested approach involves overlapping surveys. This approach to low-flow surveys is recommended since a survey can require several days to complete and can be interrupted by rain at any time. A watershed scale survey is conducted on the first day to provide the overall low-flow distribution; subwatershed scale surveys are conducted on subsequent days to provide detailed low-flow distributions within each subwatershed. If possible, the watershed scale survey is repeated on the last day to observe any changes in low-flow distribution during the survey. For the watershed scale survey, discharge is measured near the mouth of the main tributaries, at important locations along the main channels and at continuously monitored index stations. Each subwatershed scale survey measures the discharge at the selected sites within that subwatershed including the site measured during the watershed scale survey. For subwatersheds that require more than one day of gauging, a similar nested approach within a subwatershed is used (i.e. with repeated measurement of key sites). As low flow may decrease during the survey, subwatershed results can be scaled to those measured during the watershed scale survey on the first or last day (see the section 9.2).

Every day of the survey is planned in advance for each crew. An attempt is made to ensure that all sites on any single stream reach are measured on the same day. The number of crews and the time estimated to gauge each site determines the number of sites to plan for each day. The survey should also include repeated measurement of selected sites on the same day by different crews for quality control. If the survey is to include measurements of water quality, these sites should also be selected in advance.

Figure 2 illustrates a sample plan for a low-flow survey in which a nested approach is used. In this example, there is more emphasis on the headwater portions of the watershed where most of the stream discharge originates. Day 1 represents the watershed scale survey that would again be repeated on Day 6 should good weather conditions persist. Days 2 to 5 sample the detailed distribution of low flow within different subwatersheds or segments along the main channel. Although the distribution of site locations is not ideal throughout the watershed, these sites were readily accessible by roads. More detailed surveys could be planned in selected areas, if warranted.

A nested approach will also be useful if the low-flow survey is to be repeated in different seasons or different years. Only the watershed scale survey needs to be repeated to determine whether the overall spatial pattern of low flow has changed. If so, specific subwatersheds with disproportionate changes can be resurveyed to identify the areas where low-flow characteristics differ. Repeating the watershed scale survey in different seasons and years will also help establish partial record stations at these sites provided an index site is also gauged concurrently for each survey.

Figure 2. Example of a nested approach to a low-flow survey (assumes two field crews).



4.4 Selection of low-flow conditions

The hydrologic conditions during which the survey is to be conducted should be selected according to the purpose of the study. For example, a groundwater study may be interested in an average baseflow condition whereas a study of stream habitats may be interested in a period of minimum annual streamflow. In either case, the survey is intended to represent stream conditions where stormflow is negligible in comparison with baseflow discharge. Where historic stream discharge and precipitation records are available, it is possible to examine recessions of stream discharge to consider how long it takes a particular stream to return to baseflow conditions following an isolated precipitation event. Although this time will vary at a site and within a watershed according to many factors, it is a useful indication of the period required after a storm before the survey is started.

If an operational hydrometric station exists within the watershed, then it is possible to monitor flow conditions and choose to sample when flow conditions approach a desired low-flow index. If there are none, establishment of continuous stage measurements is an effective way of monitoring flow conditions to determine when a survey may begin and whether precipitation or human activities have significantly altered flow conditions. Frequent manual recordings on a staff gauge or on a fixed structure may also be suitable to demonstrate stable flow conditions.

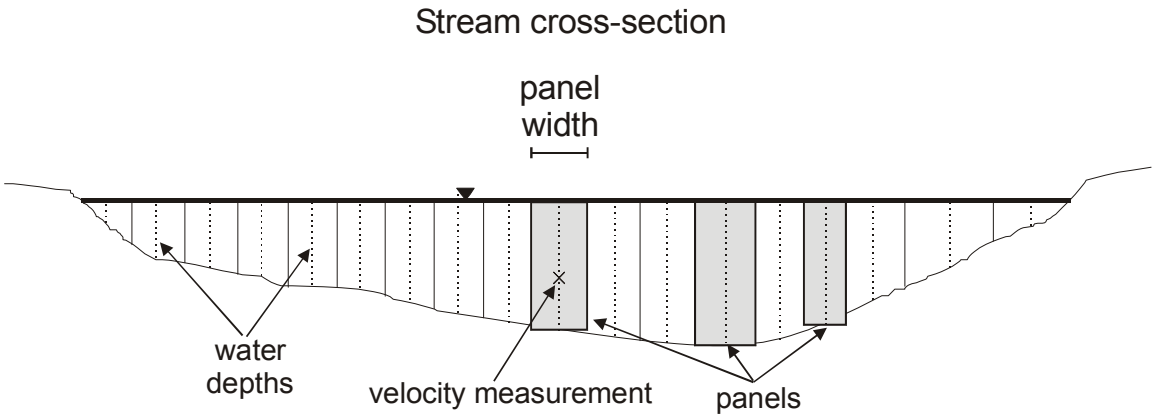
Access to weather forecasts and RADAR images are valuable to plan the timing of the survey. They can be used to judge whether there is sufficient time to conduct the survey prior to the next anticipated rainfall. Precipitation gauges are useful to indicate when the last rainfall occurred and its magnitude. However, since precipitation is often spatially variable within a watershed, the best indication of whether any significant rainfall has occurred is from continuous measurements of stream stage or discharge.

5 Stream gauging – current meter (or velocity-area) method by wading

5.1 Introduction

The measurement of stream discharge using the conventional current meter method is a well-established procedure that is extensively used and documented (Carter and Davidian, 1968; Terzi, 1981; Rantz, 1982; Herschy, 1985; International Organization for Standardization, 1997). This method consists of dividing a stream cross-section into several panels in which panel width, water depth and velocity are measured (Fig. 3). The panel discharge is the product of width, depth and velocity measurements. Panel discharges are added to provide the discharge for the stream cross-section. Widths and depths are measured directly; velocities are measured with a current meter, which is an instrument with a rotor (bucket-wheel) that rotates in proportion to the water velocity.

Figure 3. Streamflow measurement using the current meter method.



This section describes the equipment required, the site selection criteria, and step-by-step methods for gauging streams by the current meter method. Although several designs and models of current meter exist, this report specifically describes the use of Price AA and Price pygmy vertical axis flow meters since these meters have a long history of extensive use throughout North America and are used by the Water Survey of Canada (Environment Canada) and the U.S. Geological Survey. Other current meters can be used provided they are suitably calibrated and used according to their instructions. The method is described for ice-free streams that can be waded since these conditions are most appropriate for low-flow surveys. Measurements made during ice conditions or from boats or bridges are described by Rantz (1982) and Terzi (1981).

The method described in this section is nearly identical to those described by standard references, however, it emphasizes the measurement of discharge for the purpose of stream low-flow surveys. Consequently, there is greater consideration for smaller streams, streams at very low stages, and site selection criteria.

5.2 Equipment

A recommended list of equipment for the measurement of discharge by the current meter method is provided in Table 2. The Price type AA current meter has a rotor 13 cm (5”) in diameter and 5 cm (2”) high with six cone-shaped cups mounted on a vertical stainless steel shaft (Fig. 4a). The Price pygmy (or mini) current meter is of very similar design but is scaled two-fifths the size of the AA (Fig. 4b). The need for both AA and pygmy current meters is warranted because of the wide range of water depths that are likely to be encountered in a low-flow survey. Many streams will be too shallow for the AA meter, whereas the AA is preferred where the water depth is sufficient. Regardless of design or model, current meters should be calibrated so that the rotor’s revolution velocities are accurately related to the water velocities. In Canada, current meters can be calibrated by the National Calibration Service at Environment Canada located at the Canadian Centre for Inland Waters in Burlington, Ontario. Calibration and maintenance of vertical axis current meters are described by Smoot and Novak (1968). Lubricating oil, screwdrivers and a clean, dry cloth are needed for the maintenance of the current meters. Protective cases or padding prevent damage to the current meters during transport.

Wading rods are used both to support the current meter at the correct depth in the water column and to measure the water depth at each measurement site. A top-setting wading rod is recommended since it allows the current meter height to be easily and rapidly adjusted (Fig. 5a). It consists of two joined rods: one fixed rod which rests on the streambed and is graduated every 2 cm to measure water depth (Fig. 5b), and another sliding rod which supports the current meter and is graduated in such a way that the current meter is set at 0.6 of the water depth when the rod is adjusted to indicate the total water depth (Fig. 5c). Wading rods have base plates to minimize sinking into the streambed sediment.

An electrical contact in the current meters allows the use of a beeper (or headphones) that sounds every revolution when the circuit is closed. The AA meter also has a gear reduction (pentagear) that produces one contact every five revolutions so that the number of revolutions is more easily counted in rapid currents. The stopwatch (preferably waterproof) should be easily operated with one hand. Price current meters are also available in digital versions where optical or magnetic contacts are counted and recorded directly on an indicator. Pre-printed forms for stream gauging are useful to ensure all relevant field measurements are recorded (Fig. 6).

Table 2. Recommended field equipment for stream gauging using the current meter method by wading.

calibrated current meters: both AA and pygmy (Fig. 4)
lubricating oil for current meters
screwdriver(s) for current meters
protective cases/padding for current meters
top-setting wading rod (Fig. 5)
beeper
counter or indicator (optional)
watch and stopwatch
notebook or stream gauging forms (Fig. 6)
pens and pencils
measuring tape (20-30 m or more if appropriate)
large tent pegs or stakes (with S hooks) (Fig. 7)
clamp (spring loaded with rubber edges) (Fig. 7)
hammer (to drive in tent pegs or stakes)
duct tape
rulers (30 cm and 1m)
lawn edging
shovel
food colouring
flashlight
20L plastic bucket with handle (to carry field equipment)
conductivity/temperature meter (suggested)
pH meter, dissolved oxygen meter (optional)
chest waders (if appropriate)
clean, dry cloths/rags
maps
list of sites
reconnaissance survey results
GPS
camera, film or memory cards (optional)
spare batteries
appropriate safety equipment (section 3.6)

Figure 4. a) Price Type AA current meter with tailpiece. b) Price Pygmy current meter.

Figure 5. a) Top setting wading rod. b) Markings every 2 cm along wading rod, double markings every 10 cm and triple markings every 50 cm. c) Markings for 0.6 depth setting, shown for 46 cm water depth.

Figure 6. Sample stream gauging form for low-flow surveys.

Site #: _____ **Date:** _ _ **Start Time:** _____ **:** ____

Gen. Site Location: _____

Gauging Location: _____

Gauged by: _____ **Recorded by:** _____

Instrument: AA Pygmy Floats Dye Serial #: _____

Photo #: _____ **Coords.:** _____ **E** _____ **N** **NAD 83**

Weather: _____

Comments: _____

#	Dist.	Depth	Rev's	Time	Code	Notes
	.	.		_.E.W.		
1	.	.		.		
2	.	.		.		
3	.	.		.		
4	.	.		.		
5	.	.		.		
6	.	.		.		
7	.	.		.		
8	.	.		.		
9	.	.		.		
10	.	.		.		
11	.	.		.		
12	.	.		.		
13	.	.		.		
14	.	.		.		
15	.	.		.		
16	.	.		.		
17	.	.		.		
18	.	.		.		
19	.	.		.		
20	.	.		.		
21	.	.		.		
22	.	.		.		
23	.	.		.		
24	.	.		.		
25	.	.		.		
26	.	.		.		
27	.	.		.		
28	.	.		.		
29	.	.		.		
30	.	.		.		
	.	.		_.E.W.		

Water Surface: _____

Stream Bed: _____

Chem. sampled by: _____ **pH**: . (meter #)

Cond: _____ µS/cm (meter #) **Temp**: . ºC (meter #)

Dissolved Oxygen: ____ mg/L (meter #) **Other:**

Stop Time: : **Continued on next page** ☐

Figure 7. Tent pegs, S-hooks and spring-loaded clamp to fasten both ends of measuring tape.

A measuring tape is needed to determine the position of the depth and velocity measurements across the stream. It should be long enough to cross the widest stream and strong enough to be pulled nearly taut across the stream. Metallic tapes provide consistent measurements but need to be kept dry to prevent rusting. Measuring tapes are preferred to beaded cables (called tag lines) for small streams. Two large sturdy tent pegs (metal is better than plastic) with S shaped hooks and a clamp attached to one of the hooks hold the measuring tape tightly in place (Fig. 7). Duct tape can be used to hold one end of the measuring tape when gauging beneath bridges or inside large culverts. Rulers are used to measure distances across very small streams or water depths in shallow or rapid currents. Flexible lawn edging can be inserted into the sediment to prevent flow through vegetated stream edges or reduce the width of flowing water in small streams. Similarly, a shovel can be used to add sediment and reduce the width of flow or to remove obstacles (such as rocks) affecting flow in the cross-section. Food colouring is used for determining whether there is significant flow through vegetated stream edges. A flashlight is needed if fieldwork continues after sunset or if the gauging site is located beneath a bridge or inside a culvert. A large (approximately 20L) bucket with a handle is useful to carry the field equipment and small tools. If the reconnaissance survey indicates a use for temperature, conductivity, pH, dissolved oxygen or other chemical data, such measurements should be considered for the survey.

Safety equipment related to potential water hazards or contaminated water should be provided according to conditions in the survey streams (section 3.6). The need for the remaining equipment in Table 2 is self-evident.

5.3 Selection of cross-section locations for current meter gauging

Whereas the reconnaissance survey was used to assess stream gauging sites, the exact location of the measurement cross-section is determined at the time of gauging. Careful selection of the location is important because it will affect the accuracy and precision of the measurement. The overriding goal for cross-section selection is to identify a section where water velocities change gradually across the stream and are relatively constant in time. Another important consideration is whether water depths and velocities are sufficient for the accurate use of current meters. Specific site conditions that contribute to these goals include (adapted from Rantz, 1982):

1. the cross-section lies within a straight reach, and the flow streamlines are parallel to each other and perpendicular to the cross-section (if possible, the straight reach is 5 times the width of the stream in the upstream direction and 2 times the width in the downstream direction),
2. the streambed is relatively uniform in depth and free of obstacles such as boulders and heavy aquatic growth,
3. flow is relatively uniform and free of eddies, slack water, excessive turbulence, and converging or diverging flow,
4. velocities are greater than 0.1 m/s and depths are greater than 0.1 m.

Given the large range of stream and site conditions likely to be encountered in a low-flow survey, it is likely that these criteria will not always be met. Where they are not met, first consider whether minor modifications may correct the problem, such as removing an upstream rock or blocking flow in an area of aquatic growth. Second, consider whether the variations in velocity can be sampled effectively with an increased sampling density or whether the flow associated with that portion of the cross-section is small. For example, large velocity variations (and shallow depths) near the stream edges are common, yet quantifying these with great accuracy is of minor importance if the proportion of flow in these panels is small relative to the total discharge. Although it is tempting to judge cross-sections on the conditions near the stream edges, the assessment should place greater emphasis on the ability to measure flow effectively in the faster flowing (often central) portions of the stream. Two types of cross-sections to be avoided are those where numerous and/or large obstacles in the stream produce eddies and turbulence that result in variable flow directions and velocities, and those where the water moves so slowly that the current meter rotor does not turn freely.

Where discharge is less than approximately 5 L/s, it is difficult to impossible to meet the fourth criterion listed above. In such conditions, a volumetric measurement of discharge is preferred if possible; otherwise, the best available section is chosen and it is recognized that the gauging errors may be a larger proportion of the measurement. However, a larger error often does not seriously influence the ability to identify important groundwater discharge zones since the downstream increase in discharge between sites is often significantly larger than the measurement error (e.g. for an upstream discharge of 2 ± 1 L/s (50% error) and a downstream discharge of 10 ± 1 L/s).

5.4 Field procedure

5.4.1 Prior to departure at the start of day

1. Bring selected equipment from Table 2 and ensure it is in good working condition.

2. Lubricate and verify the operation of current meters (Smoot and Novak, 1968).

3. Bring the stream gauging plan (section 4), maps, and reconnaissance survey results.

5.4.2 At each site

4. Select the cross-section location most suitable for gauging (see section 5.3).

5. Drive in the tent pegs ensuring that the cross-section is perpendicular to flow. Clamp the measuring tape so that it remains taut across the stream.

6. If necessary, remove obstacles or modify flow to improve flow conditions in the cross-section. Ensure that flow has stabilized in the cross-section before any flow measurements are taken.

7. Record the following site information: date, site number, general site location (e.g. stream name and cross road(s)), specific cross-section location with respect to an identifiable feature, coordinates (e.g. UTMs), any site conditions of relevance (e.g. observed or suspected pumping from stream, comments from residents, precipitation, etc.), field technician names (or initials), weather conditions, and gauge height if the site also has a gauging station. If desired, take a photograph that includes the cross-section location and any distinctive features at the site, and then record the photograph number.

8. Choose the appropriate current meter. In general, the AA model is generally not recommended for water depths less than 0.38 m and the pygmy current meter for water depths less than 0.09 m (Rantz, 1982). In practice, only one flow meter is commonly used for an entire cross-section even if portions of the section are below the recommended depth. Record the serial number of the current meter.

9. Screw the current meter to the wading rod and ensure the rotor's axis aligns with the rod. For the AA current meter, remove the brake completely by unscrewing the raising nut. Since there is no brake on the pygmy current meter, a separate brass plug is used during travel and is replaced with the pivot prior to the measurement. Ensure that the current meter turns freely and that the beeper is connected. Any observed damage to a current meter should be promptly recorded.

10. Record the start time.

11. Record the stream edge (L.E.W. or R.E.W.—Left edge of water or Right edge of water, facing **downstream**) where the measurements will begin. It is also useful to note the general orientation of the stream cross-section (e.g. NW-SE).

12. Describe and record the flow conditions and depth at the edge. This information will be useful to estimate the velocity profile between the stream edge and the first measurement point. Although the edges are generally not a significant proportion of the total flow, they become slightly more important for small streams where edge areas may account for a larger proportion. Where the stream edge has a zero depth, it is assumed that the edge also has a zero velocity. Where the edge has a finite depth (e.g. adjacent to a rock or a bridge), the depth should be measured with a meter stick and the velocity estimated either quantitatively using relationships determined experimentally (e.g. Table 3, Rantz, 1982) or qualitatively as a percentage of the velocity at the first measurable section.

Table 3. Velocity near a smooth sidewall of a rectangular channel (from Rantz, 1982)

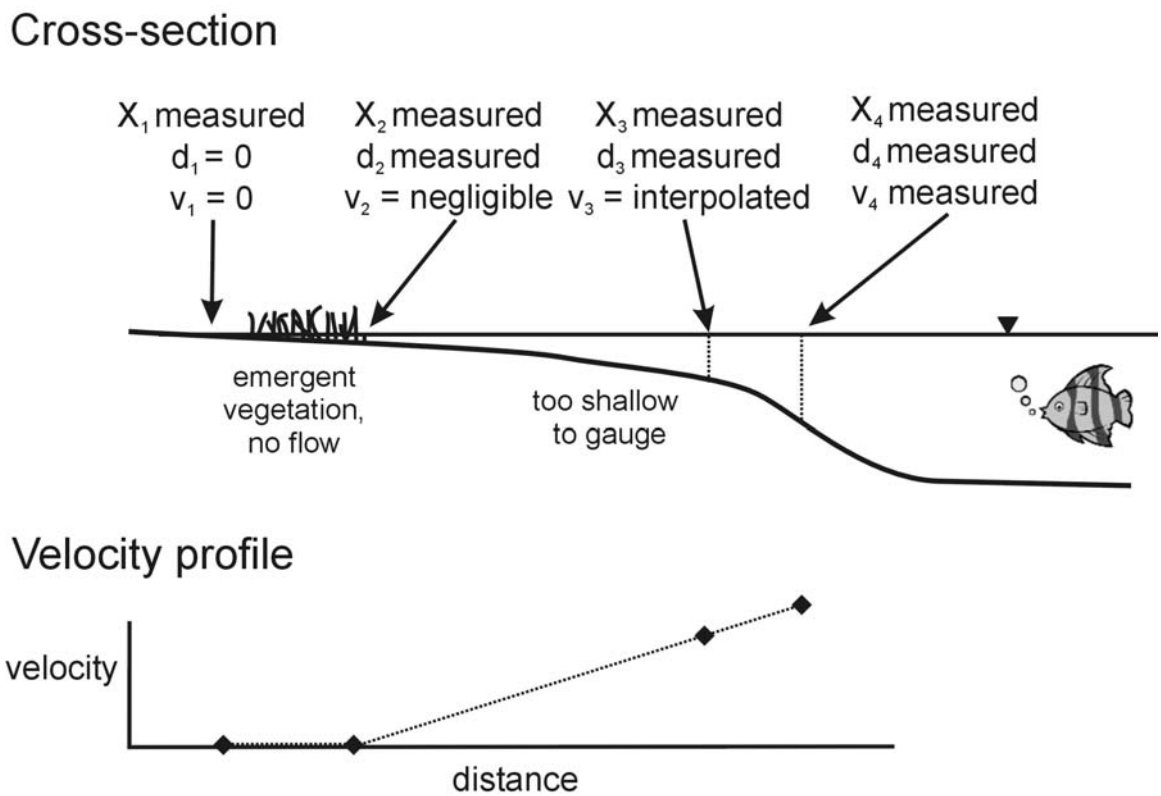
Distance from wall as a ratio of the depth	**Mean velocity, as related to V_D**
0.00	0.65 V_D
0.25	0.90 V_D
0.50	0.95 V_D
1.00	1.00 V_D

V_D is the mean velocity at a distance from the vertical wall equal to the water depth.

13. Sometimes the velocity cannot be measured accurately near the stream edge due to shallow water, obstacles or rapid lateral changes in water velocity (resulting in different water velocities on each side of the current meter rotor). It is recommended to estimate the velocity profile to the first measurable vertical (Fig. 8). The estimated velocity is considered to be either 1) negligible (code N), 2) the same as the first measurable section (code S), 3) a proportion of a measured section (code %) as described in Step 12 above, or 4) a linear interpolation between two known velocities (code I).

14. The number of velocity measurements across the stream (i.e. number of verticals and panels) has the most important influence on the accuracy of the flow measurement. Therefore, the number of verticals is chosen for the desired accuracy (see section 8.3.4). The number of verticals also determines the time required to gauge the stream. In general, the flow should be measured in 20-30 verticals or more. The verticals need not be evenly spaced; but it is preferable that the proportion of flow within each panel is approximately equal. In practice, the spacing is determined by dividing the width of the stream into approximately 20 panels and then reducing the spacing in the deeper and/or faster portions of the stream or where water velocities change considerably in adjacent verticals.

Figure 8. Estimated velocity profile near a stream edge. X_i = lateral distance to vertical i, d = depth, v = velocity.



15. At each vertical, measure and record the distance and water depth. Ensure that the wading rod is positioned on the stream bottom and held vertical. The water depth is measured using the markings on the side of the wading rod. Where flow is rapid, the water will rise on the upstream side and decrease on the downstream side of the wading rod such that depths should be measured on the side of the rod or using a narrow ruler. Where the stream bottom is soft, the meter should be held to prevent it from sinking into the sediment.

16. At each vertical, determine the number of velocity measurements required. Although more measurements better define a vertical velocity profile, each additional measurement adds to the time required to gauge the site. It is generally recommended that one measurement, at 6/10 (0.6) of the water depth from the water surface, be used for water depths less than 0.75 m, and that two measurements, at 2/10 (0.2) and 8/10 (0.8) of the water depth, be used where water depth exceeds 0.75 m (Rantz, 1982). However, it is shown in section 8.3.4 that using additional verticals (each with one measurement depth) reduces gauging error more efficiently than using additional measurement depths in each vertical.

17. Adjust the current meter height to the appropriate depth of measurement. For measurements at 0.6 depth using a top-setting wading rod, the rod is simply adjusted to the recorded water depth (Fig. 5c). For measurements at 0.8 and 0.2 depths, the top-setting rod is adjusted to one-half and twice the measured water depth respectively. Once the depth setting is adjusted, grasp the sliding portion of the rod to ensure that the depth adjustment does not change during the measurement.

18. When the current meter height is adjusted and positioned at the measurement location, stand at least 0.4 m beside and downstream of the current meter to minimize any disturbance to the flow. Ensure that the meter is vertical (both side to side and front to back), and then allow the rotation of the current meter to stabilize.

19. The duration of each measurement depends on the water velocity and the desired accuracy of the measurement. For most surveys, a 60-second measurement is used for velocities between approximately 0.1 and 0.3 m/s (8-26 revolutions per minute for a AA current meter). Measurements of 45 seconds duration are used in faster currents and of 90 seconds duration in slower currents.

20. The stopwatch is started at the beginning of the beep with a rotation count of zero. Each rotation is counted (mentally, manually with the counter, or automatically with the indicator) for the duration of measurement, and the stopwatch is stopped at the beginning of a beep to ensure a whole number of rotations. The number of rotations and the elapsed time is recorded along with any observations of obstacles affecting flow (with position and distance from section, e.g. “submerged rock 1 m upstream at 3.2 m distance”), or variability in the speed of rotation (describe degree of variability or note any stoppages, e.g. “very variable, pulsating”).

After the measurement, check the depth setting on the wading rod to ensure the meter’s depth did not shift. If for any reason there is concern that the measurement may not be accurate (e.g. unsure of rotation count, depth setting etc.), the measurement for that depth must be repeated and the original measurement discarded.

Where water velocity is so slow that the meter does not complete a full turn (often due to friction in the electrical contact), the observation is noted as “DNT” (did not turn).

21. Steps 15-20 are repeated for each vertical across the stream. Additional comments relevant to the time (e.g. the start/stop of precipitation) or location of gauging (e.g. soft sediment) can be recorded as an observation to any given measurement.

22. When reaching the far edge of the stream, flow and edge conditions are reported as in steps 13, 12 and 11.

23. From the field results, check if there are a sufficient number of verticals and that the flow is well distributed among the panels. Examine the velocity profile for sudden changes in velocity between adjacent verticals. If needed, additional verticals should be added between existing measurements.

24. Record the end time. Comment on the evenness of the water surface and the stream bed (e.g. “water surface flat, stream bottom 5 cm cobbles from 1.2 to 3.5 m distance”). Double check to ensure that all required information has been recorded on the stream gauging forms or field notebooks.

25. Engage the current meter raising nut (AA) or replace the pivot with the brass plug (pygmy) to ensure that the current meter pivot is not damaged during transport. Protect the current meters for transport to the following site.

26. Measure stream water temperature and electrical conductivity and record these values along with the time of measurement. These measurements can be made at any time during the visit to the site. Similarly, other measurements such as pH and dissolved oxygen can be made, if desired.

27. Remove all equipment from the site. Dry steel equipment if it gets wets to prevent rusting. Always do a final check when leaving the site to ensure all equipment is removed and the site is left clean.

28. To gauge a wide site more rapidly, it is possible to measure flow concurrently with two flow meters provided that the field technicians do not interfere with each other’s measurements. In such cases, it is particularly important to ensure that each technician’s results (and current meter serial numbers) are recorded on separate pages/forms in the same notebook. The results should be reviewed together to ensure that all required information has been recorded.

5.4.3 At the end of the day

29. Field notes should be photocopied and stored separately if possible. Current meters should be disassembled (remove pivot), cleaned, and allowed to dry overnight. Other field equipment should be maintained and dried if necessary.

6 Stream gauging – volumetric method

6.1 Introduction

The volumetric method is a simple, efficient and accurate way to measure stream discharge for small streams where streamflow can be captured in a container. The method consists of measuring the time required to fill a container of known volume or to partially fill a container with subsequent measurement of the water volume in a graduated container.

This section describes the suitability of sites, equipment required, and field methods for gauging streams by the volumetric method.

6.2 Suitability of sites

An ideal site for the volumetric method has a vertical drop greater than the container height, flow that is narrower than the container, no leakage around the water drop, a level area beneath the drop to support the container and a discharge that will require more than 10 seconds to fill the container. Therefore, the suitability of sites depends not only on the site characteristics but also on the containers available to measure flow. In practice, there is often little control on the site conditions or even the container that can be used for the given height and width configuration.

A key requirement for volumetric measurements is a sudden drop in stream elevation such that flow can be collected in a container. A common type of drop encountered in built up areas is a road culvert (Fig. 9). Where drops are too low to allow a container to be filled, partial filling of a calibrated container can be considered provided it does not back up the flow. Although little can usually be done to modify the height of the drop, it is possible to change the width of the flow either by constricting the edges of flow or by separating the flow into several segments that are gauged individually. For very small streams, it is sometimes possible to build a small drop (Fig. 10).

Culverts and dams often do not fully contain the flow and leakage is evident. Occasionally, leaks can be blocked or can be measured separately. More commonly, they cannot and it is important to assess the significance of the leak. If the leak is smaller than the measurement error of the alternate gauging method (e.g. current meter method), then volumetric measurement is still the most suitable method.

The error using the volumetric method increases as the filling time decreases. When the discharge fills the container in less than one second, measurement error is typically greater than 20%.

Figure 9. Streamflow measurement using the volumetric method.

Figure 10. Constructed drop for a very small stream.

6.3 Equipment

In its simplest form, the only equipment required for volumetric measurements of discharge is a container of known volume and a stopwatch. However, for low-flow surveys it is recommended that a selection of containers be used to accommodate different stream widths, drop heights and discharges. Furthermore, various accessories can be used to improve some sites for these measurements. Suggested equipment is shown in Table 4.

Many everyday household items make suitable containers. Plastic storage containers are generally the most useful because they are available in a wide variety of sizes, they are strong, have handles, are flexible (mould to seal the underside of the drop) and are deep enough to prevent water from splashing out of the container (Fig. 9). Plastic flower boxes are also useful because they accommodate wider flows and smaller drops but can be problematic for higher flow rates because water may splash over the inside lip of the box. Plastic bags or wide mouth food containers (e.g. ice cream containers) are practical to measure very small discharges since they are flexible and can be used for small drop heights. Plastic graduated cylinders are used to measure partially filled containers. Although plastic garbage cans (or barrels) have greater capacity than most storage containers, they are usually too tall, too heavy when full and their round shape is less practical. Plastic buckets are often less practical than storage containers for small streams since buckets are more narrow and taller.

Containers need to be carefully calibrated to prevent systematic errors in volume. A good way to calibrate medium and large containers is by weighing the full container, subtracting the weight of the empty container and dividing the difference by the density of water (0.999 kg/L at 15°C). For small containers, the volume is determined directly by filling it with water measured in a large graduated cylinder.

A waterproof stopwatch that can be operated easily with one hand is most practical. Inexpensive sport wristwatches are frequently suitable. A shovel is a useful accessory to help reduce leaks around culverts, reduce the width of flow or help build drops for very small streams. Similarly, storage containers filled with water can be used to reduce the width of flow or divide the stream into several, more readily measured, segments. Pieces of soft foam (e.g. foam mattresses) effectively seal leaks beneath containers used to constrict or divide flow.

Table 4. Recommended field equipment for stream gauging using the volumetric method.

watch and waterproof stopwatch with good start/stop buttons (e.g. sport wristwatch)
notebook, stream gauging forms
pens and pencils
plastic storage containers (available in various volumes, depths and widths)
plastic flower boxes
plastic food containers (approx. 500 mL – 2L)
watertight plastic bags
plastic graduated cylinders (1L, 2L)
shovel
soft foam (such as used for foam bed mattresses)
lawn edging (optional)
camera, film or memory cards, spare batteries (optional)
appropriate safety equipment (section 3.6)

6.4 Field procedure

6.4.1 Prior to departure at the start of day

1. Bring selected equipment from Table 4 and ensure the stopwatch is in good working condition.

2. Bring the stream gauging plan (section 4), maps, and reconnaissance survey results.

6.4.2 At each site

3. Record the following site information: site number, general site location (e.g. stream name and cross road(s)), specific gauging location (drop location with respect to an identifiable feature), coordinates (e.g. UTMs), type of drop (culvert, dam, weir, built), any site conditions of relevance (e.g. observed or suspected pumping from stream, comments from residents, precipitation, etc.), field technicians, and gauge height if the site also has a gauging station.

4. Prepare the site. If possible, stop or reduce leakage. If necessary, constrict or divide the flow using foam held in place by containers weighted with water or rocks. The foam prevents leakage beneath the containers.

5. Perform one or several trial measurements to ensure that the container fits well beneath the drop and captures all the flow with minimal spillage and splashing out. Determine whether the container can be kept level if it is to be filled completely. Make any adjustments to the site, if required.

6. If the site has been modified, wait until discharge has stabilized by monitoring the water level or wetted perimeter upstream of the drop.

7. Record the start time.

8. To start the measurement, the container is thrust under the water with a rapid, horizontal movement and the stopwatch is started synchronously (Fig. 9). The container is then adjusted to a level position. If the container is to be filled, the stopwatch is stopped when the water level reaches the lip of the container rather than when it overflows. Observe whether the water reaches the lip of the container at the same time on all sides. If the container is to be partially filled, remove the container rapidly and stop the stopwatch synchronously.

9. *Before the time is observed on the stopwatch*, it is important to decide whether or not the measurement was taken correctly and will be retained. If there is any concern that the stopwatch was not started or stopped at the correct time, that the container was not moved rapidly enough, that spillage may have been significant or that the container was not sufficiently level, then the measurement should be discarded and not recorded. If the measurement is accepted, the time is observed and recorded. This procedure prevents measurement bias and ensures that the result will have the correct variance.

10. Record the measurement volume. If the container was only partially filled, ensure that the measurement container is level.

11. The number of measurements required depends on the desired precision. A minimum of five measurements is generally recommended where conditions are good although more are required if the measurement times are short.

12. Assess the results. If one of the "accepted" measurements (see step 9 above) appears questionable, it should not be deleted. Rather, additional measurements should be taken to reduce the variance and ensure that the questionable measurement has less influence on the average. If the precision is too low (i.e. the variance is too high), additional measurements can be made, a different container can be used or the flow can be divided into several segments. If the discharge consistently increases or decreases, it is possible that the discharge may not be stable due to site modification or upstream influences. Record the time and wait until conditions again appear to be stable, then repeat steps 7 through 12.

14. Record the end time.

15. Measure stream water temperature and electrical conductivity (and other desired parameters) and record these values along with the time of measurement.

16. If desired, take a photograph that includes the drop and any distinctive features at the site. Record the photograph number.

17. Remove all equipment from the site. Always do a final check when leaving the site to ensure all equipment is removed and the site is left clean.

6.4.3 At the end of the day

18. Field notes should be photocopied and stored separately if possible.

7 Other methods to measure discharge

It is sometimes not possible to measure discharge using either the current meter or volumetric methods. These sites are commonly at locations where the water velocity is too slow, where there is significant aquatic vegetation or obstacles interfering with gauging, where the stream has excessive turbulence, or where the discharge is small and the water is too shallow. Although there is often little that can be done to gauge an inadequate site, there are some additional methods that can be considered.

Water velocities at sites with very shallow depths that cannot be measured with a pygmy current meter can be estimated using the velocity of surface floats or dyes along a measured distance. The measurement is performed as the current meter method except that the number of verticals is reduced (approximately 3-5), and the float/dye velocities are repeated (approximately 5 times) at each vertical. Although this estimate will be imprecise, it may be sufficient to document an increase from a very low discharge to a comparatively larger discharge (see section 5.3).

A portable weir plate or a portable Parshall flume can provide an accurate measurement on small streams (Rantz, 1982). Weir plates with different dimensions can be built to accommodate different size streams and different ranges of discharges (generally < 50 L/s). Weir plates can be used to calculate discharge using the measured water level upstream of the weir or to measure it directly using volumetric measurements on the downstream face of the weir. A 3” portable Parshall flume is rated for flows ranging up to 14 L/s (Rantz, 1982).

Discharge can also be measured by the tracer dilution method in which a known flux or mass of tracer is injected into the stream and the discharge is determined from the downstream concentration of the tracer diluted by the stream. This method is more difficult and less reliable than current meter measurements but has the advantage that it can be used on turbulent streams (Rantz, 1982).

8 Data reporting, discharge calculation and error estimation

Low-flow surveys provide a synoptic view of a watershed at one time. These data have many possible uses and are important baseline information against which future changes can be evaluated. Complete documentation includes reporting collected data, calculating stream discharge and estimating gauging uncertainties.

8.1 Data reporting

All recorded measurements and observations should be recorded digitally in a database or spreadsheet, and the entries verified (Fig. 11). For each site, the fields should include: site number, site coordinates, date, reference to field notebook page(s), start time, end time, instrument(s), field technicians, observations of water surface and stream bed, general gauging location, specific gauging location, site notes or observations, measured discharge (calculated) and total estimated error (calculated). For the current meter method, each vertical should include distance measurement, depth measurement, depth setting, number of revolutions, time, velocity code (N, I, S, %), gauging notes relevant to each vertical (variability of flow, obstructions, stream edges, L.E.W., R.E.W., section orientation), flow meter serial number (if more than one used), and water velocity (calculated). The rating equation for each flow meter should also be provided. For volumetric measurements, each volume and time measurement is noted, as well as any relevant observations or estimates of leakage.

All data from the reconnaissance survey that are to be used in the data analysis (e.g. sites with no observed flow) should be recorded with site number, site coordinates, date, time, field technicians, reference to field notebook page(s) and any relevant notes or observations.

8.2 Calculating stream discharge

Stream discharge using the current meter method can be calculated using either the mid-section or the mean-section methods (Terzi, 1981; Rantz, 1982; Herschy, 1985; International Organization for Standardization, 1997). Since 1950, both the Water Survey of Canada and the USGS use the mid-section method. The mid-section method assumes that the mean velocity in a vertical profile applies for a panel area extending the full depth of the stream and half the lateral distance to the previous and subsequent vertical sections (Fig. 12). The stream discharge for each panel is calculated as:

$$Q_i = \left(\frac{x_{i+1} - x_{i-1}}{2} \right) d_i \bar{v}_i = b_i d_i \bar{v}_i \qquad (1)$$

Figure 11. Sample stream discharge data reporting and calculation.

Site:	D-152
Date:	16-Aug-95
Samplers:	CK, CS
Time start:	10:10
Time end:	10:58
Ref.:	Chris, Book 5, p. 1
Instrument:	Price AA, serial # I-840
Calibration:	vel. (m/s) = 0.6848 * (rev / time) + 0.0059
General location:	Duffins Creek at Highway 2
Specific location:	approx. 20m downstream of bridge
UTM Easting, NAD 83:	655770
UTM Northing, NAD 83:	4857350
Water surface:	flat
Stream bed:	smooth
Site notes:	none

Distance (m)	Panel width (m)	Water Depth (m)	Revol.'s (#)	Time (s)	Depth setting	Code	Gauging Notes	Water Velocity (m/s)	Discharge (Mid Sect.) (L/s)	Explanations
0.30	0.15	0.000	0	0		0	R.E.W., West edge	0.00	0.0	
0.60	0.30	0.146				I		0.006	0.3	I = Interpolated velocities
0.90	0.25	0.272				I		0.012	0.8	from 0.3 to 1.7 m distance
1.10	0.25	0.320				I		0.016	1.3	
1.40	0.30	0.378				I		0.022	2.5	
1.70	0.35	0.435	2	62.68	0.6			0.028	4.2	
2.10	0.40	0.553	6	66.37	0.6			0.07	15.0	
2.50	0.40	0.614	8	60.71	0.6			0.10	23.6	
2.90	0.45	0.630	7	67.06	0.6			0.08	21.9	
3.40	0.50	0.607	9	60.64	0.6			0.11	32.6	
3.90	0.50	0.570	13	60.77	0.6			0.15	43.4	
4.40	0.50	0.547	15	64.61	0.6			0.16	45.1	
4.90	0.50	0.535	16	61.10	0.6			0.19	49.5	
5.40	0.50	0.518	17	61.68	0.6			0.19	50.4	
5.90	0.50	0.490	19	60.79	0.6			0.22	53.9	
6.40	0.50	0.460	17	60.44	0.6			0.20	45.7	
6.90	0.50	0.437	20	59.78	0.6			0.24	51.3	
7.40	0.50	0.418	20	60.01	0.6			0.23	48.9	
7.90	0.50	0.399	23	59.83	0.6			0.27	53.7	
8.40	0.50	0.373	28	70.02	0.6			0.28	52.2	
8.90	0.50	0.372	23	60.46	0.6			0.27	49.6	
9.40	0.50	0.340	26	62.04	0.6			0.29	49.8	
9.90	0.50	0.320	24	61.14	0.6			0.27	44.0	
10.40	0.50	0.294	20	61.08	0.6			0.23	33.8	
10.90	0.50	0.280	19	61.10	0.6			0.22	30.6	
11.40	0.50	0.268	17	59.41	0.6			0.20	27.0	
11.90	0.50	0.270	15	61.89	0.6			0.17	23.2	
12.40	0.67	0.240	9	60.98	0.6			0.11	17.2	
13.24	0.42	0.000	0	0.00		0	L.E.W., East edge	0.00	0.0	
							Discharge (L/s) =		**872**	**± 57**

where

Q_i = discharge in panel i
x_i = lateral distance to vertical i
d_i = water depth at vertical i
$\bar{v}_i$ = mean velocity in vertical i
b_i = width of panel i
i = vertical number or panel corresponding to vertical i

For the first panel, 1, and the last panel, m, the panel discharges are calculated as:

$$Q_1 = \left(\frac{x_2 - x_1}{2}\right) d_1 \bar{v}_1 = b_1 d_1 \bar{v}_1 \qquad (2)$$

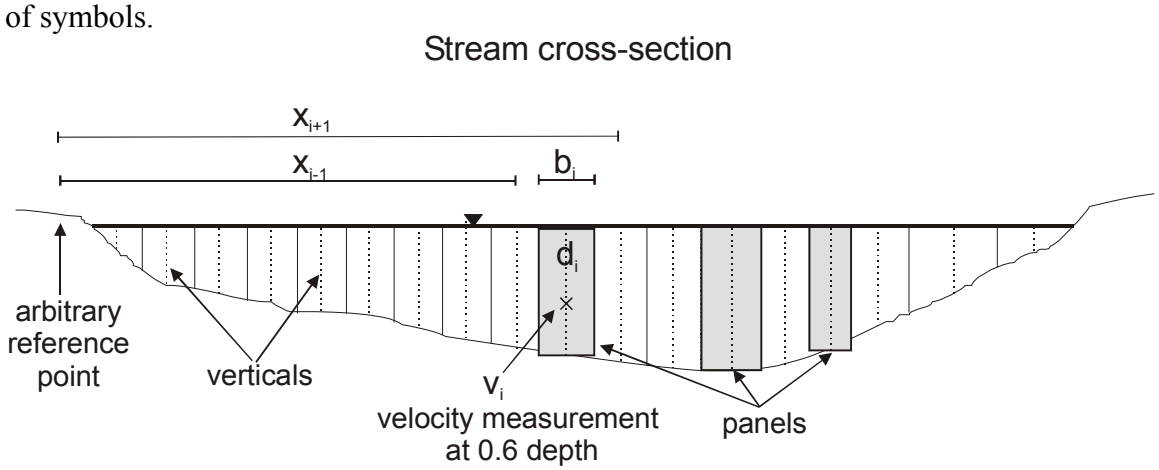
and

$$Q_m = \left(\frac{x_m - x_{m-1}}{2}\right) d_m \bar{v}_m = b_m d_m \bar{v}_m \qquad (3)$$

respectively. The verticals where the velocity has been estimated (e.g. codes N, I, S or %) are treated as true velocity measurements since these velocity and depth profiles are considered more representative of true conditions than if they were omitted. The total discharge, Q, is the summation of discharges from all the panels:

$$Q = \sum_{i}^{m} Q_i \qquad (4)$$

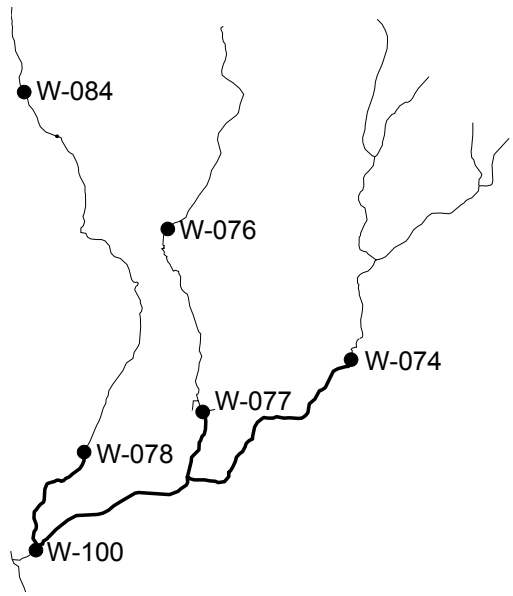
Figure 12. Mid-section method for the calculation of discharge. See text for description of symbols.



For the volumetric method, the average discharge is simply calculated as the average of the individual flow measurements (volume/time). Estimated leakage is added to the average discharge.

The increase or decrease in discharge along a stream reach, the net discharge, equals the stream discharge at the downstream site minus the sum of stream discharge at all the sites immediately upstream (Fig. 13).

Figure 13. Net discharge along the highlighted stream reaches.



$$Q_{NET} = Q_{W-100} - \left(Q_{W-078} + Q_{W-077} + Q_{W-074}\right)$$

8.3 Error estimation

To interpret net discharge along a stream reach it is important to consider the uncertainties in individual discharge measurements so the resulting error estimate in the net discharge can be calculated. This error must be estimated to ensure that the net discharge is not a result of measurement error rather than a true change in discharge. Both random and systematic uncertainties in the discharge measurements should be considered and combined.

8.3.1 Current meter method

The overall random uncertainty of a single discharge measurement using the current meter method is calculated as (Herschy, 1985; International Organization for Standardization, 1997):

$$X'_Q = \pm \sqrt{X'^2_m + \frac{\sum_i^m \left[\left(b_i d_i \bar{v}_i \right)^2 \left(X'^2_{bi} + X'^2_{di} + X'^2_{ei} + X'^2_{pi} + X'^2_{ci} \right) \right]}{\left(\sum_i^m b_i d_i \bar{v}_i \right)^2}} \qquad (5)$$

where

X' = fraction random uncertainty at 95% confidence level
X'_Q = uncertainty in total discharge
X'_m = uncertainty due to number of verticals
X'_{bi} = uncertainty in width for panel i
X'_{di} = uncertainty in depth for vertical i
X'_{ei} = uncertainty in velocity due to time of exposure for vertical i
X'_{pi} = uncertainty in velocity due to number of points in a vertical for vertical i
X'_{ci} = uncertainty in velocity due to current meter calibration for vertical i
b_i = width of panel i
d_i = water depth at vertical i
$\bar{v}_i$ = mean velocity in vertical i
i = vertical number or panel corresponding to vertical i
m = number of verticals

Estimated values of random uncertainties at the 95% confidence level have been provided as a guide (Herschy, 1985; International Organization for Standardization, 1997) as shown in Tables 5 to 8.

Table 5. Random uncertainty due to the number of verticals, X'_m (95% confidence interval), (Herschy, 1985; International Organization for Standardization, 1997).

Number of verticals, m	Percent random uncertainty
5	15
10	9
15	6
20	5
25	4
30	3
35	2
40	2
45	2

Table 6. Percent random uncertainty due to time of exposure, X'_e (95% confidence interval), (Herschy, 1985; International Organization for Standardization, 1997).

Velocity (m/s)	***Fraction of depth in vertical***							
	0.2D, 0.4D or 0.6D				***0.8D or 0.9D***			
	Exposure time (minutes)							
	0.5	***1***	***2***	***3***	***0.5***	***1***	***2***	***3***
0.050	50	40	30	20	80	60	50	40
0.100	27	22	16	13	33	27	20	17
0.200	15	12	9	7	17	14	10	8
0.300	10	7	6	5	10	7	6	5
0.400	8	6	6	5	8	6	6	5
0.500	8	6	6	4	8	6	6	4
1.000	7	6	6	4	7	6	6	4
>1.000	7	6	5	4	7	6	5	4

Table 7. Random uncertainty due to number of points in vertical, X'_p (95% confidence interval), (Herschy, 1985; International Organization for Standardization, 1997).

Method of measurement	***Percent random uncertainty***
Velocity distribution	1
5 points	5
2 points	7
1 point	15

Table 8. Random uncertainty due to current meter rating, X'_c (95% confidence interval) , (Herschy, 1985; International Organization for Standardization, 1997).

Velocity (m/s)	***Percent random uncertainty***	
	Individual rating	***Group or standard rating***
0.03	20	20
0.10	5	10
0.15	2.5	5
0.25	2	4
0.50	1	3
> 0.50	1	2

The uncertainty in width measurements, X'_b, should be estimated based on the measuring device used and stream width. In general, a measuring tape yields reasonably precise measurements with uncertainties of 1% or better for the relatively small streams considered in this document. The uncertainty in depth measurements, X'_d, should be estimated based on the measuring device used, water depth and velocity, and stream substrate. Water depth can be measured with uncertainties of approximately 1-2% with a wading rod in streams with low to moderate velocities and firm, even substrates. In practice, X'_b and X'_d do not need to be determined very accurately for streams that can be waded since they are smaller than X'_e and X'_p, and contribute a very small proportion of the overall uncertainty in equation 5.

Systematic uncertainty in total discharge is generally small compared to random uncertainty and is due to systematic uncertainty in width, depth and current meter velocity calibration.

$$X''_Q = \pm\sqrt{X''^2_{bi} + X''^2_{di} + X''^2_{ci}} \qquad (6)$$

where

X'' = fraction systematic uncertainty at the 95% confidence level

X''_Q = systematic uncertainty in total discharge

X''_b = systematic uncertainty in width

X''_d = systematic uncertainty in depth

X''_c = systematic uncertainty of the current meter

Estimated values of systematic uncertainty have been suggested by Herschy (1985) and are reproduced in Table 9.

Table 9. Systematic uncertainty in width, depth and current meter calibration (95% confidence interval), (Herschy, 1985).

	Percent systematic uncertainty
X''_b (width)	0.5
X''_d (depth)	0.5
X''_c (current meter calibration)	1.0

The overall estimate of uncertainty in the discharge measurement, X_Q, is then obtained by combining the random and systematic uncertainty (International Organization for Standardization, 1997):

$$X_Q = \pm\sqrt{X'^2_Q + X''^2_Q} \qquad (7)$$

Finally, the total error for a discharge measurement, E_Q, is simply calculated by multiplying X_Q by Q.

8.3.2 Volumetric method

Since volumetric measurements are easily repeated, the random uncertainty is easily determined from the standard deviations of repeated measurements. Because the sample size is usually small (<30), critical values from the Student's t-distribution are used to correct for sample size. The random uncertainty at the 95% confidence level, E'_Q, is then:

$$E'_Q = t^{0.025}_{n-1} s_{n-1} \qquad (8)$$

where

$t^{0.025}_{n-1}$ = critical t value for a 0.05 probability (two tailed) and n-1 degrees of freedom
s_{n-1} = sample standard deviation
n = number of measurements

In practice, the random error is small when measurement times exceed 10 seconds and is generally reasonable when times exceed 3 seconds. Random errors increase as measurement times decrease and the uncertainty may become smaller for the current meter method than for the volumetric method for times less than approximately 1-2 seconds.

Where some of the flow is leaking and therefore has been estimated, the error of the leakage, E'_L, should also be estimated and generally should at least equal the estimated leakage. It is assumed that leakage is a small proportion of total discharge.

Systematic errors in the container volume, either through calibration or systematic misinterpretation of when a container is full, results in systematic uncertainty in measured discharges. The systematic error for volumetric measurements is estimated to be less than 1-2%. The overall estimate of uncertainty for volumetric measurements is calculated as follows:

$$E_Q = \pm\sqrt{E'^2_Q + E'^2_L + E''^2_Q} \qquad (9)$$

where

E_Q = total uncertainty in discharge
E'_Q = random uncertainty
E'_L = leakage uncertainty
E''_Q = systematic uncertainty

For example, if five discharge measurements have an average of 20.0±1.0 L/s (1 standard deviation), an estimated 0.5 L/s was leaking (assume a 100% error in estimated leakage), and the container used had an estimated 2% systematic error, the total uncertainty (at the 95% confidence level) would be 2.9 L/s $\left(= \pm\sqrt{(1.0 \times 2.78)^2 + 0.5^2 + (20 \times 0.02)^2}\right)$. In this example, the largest error is attributed to random uncertainty; both the leakage and systematic uncertainty contribute little to the total uncertainty (note that the critical value of t for 4 degrees of freedom and a probability of 0.025 is 2.78).

8.3.3 Net discharge error

The uncertainty in net discharge is calculated as in any other application where errors must be propagated in addition and subtraction. Uncertainties are squared and added, and the combined error is the square root of the sum. For net discharge calculations, the net discharge error is calculated as:

$$E_{NetQ} = \pm\sqrt{E^2_{Q_{downstream}} + \sum E^2_{Q_{upstream}}} \qquad (10)$$

where

E_{NetQ} = total uncertainty of the net discharge
$E_{Q_{downstream}}$ = total uncertainty of the discharge at the downstream site
$E_{Q_{upstream}}$ = total uncertainty of the discharge at each upstream site

For example, if the discharge for two upstream sites were 650 ± 60 and 150 ± 15 L/s and the discharge at a site downstream of their confluence is 900 ± 80 L/s, the net discharge within this stream reach would be 100 ± 101 L/s ($= 900 - (650 + 150) \pm \sqrt{80^2 + 60^2 + 15^2}$, all at the 95% confidence level). Since the error is comparable to the net discharge, there

would still be approximately a 5% chance that the increase in discharge was simply the result of random error in the measurements.

8.3.4 Reducing gauging error efficiently

Examination of Equation 5 and Tables 5 to 8 shows that the largest sources of error are the number of verticals and the water velocity. Their relative influence on uncertainty is demonstrated in Table 10 where approximate errors are estimated using Equation 5 and the values in Tables 5 to 8. This calculation assumes that flow is equally distributed among the panels and that velocity is the same for all verticals. Errors decrease considerably as water velocity increases from 0.05 m/s to 0.1 m/s. It is for this reason that a minimum velocity of 0.1 m/s is recommended for the selection of a cross-section location. Some improvement is observed as water velocities increase to 0.2 m/s but little reduction in error is observed for velocities above 0.3 m/s. The error also decreases rapidly as the number of verticals is increased to 15 and then decreases more gradually until approximately 35 verticals, beyond which there is very little reduction in error. Table 11 repeats the calculations of Table 10 with a value of X'_p (=0.05) that corresponds to measuring the velocity profile at five depths in each vertical instead of one. The decrease in uncertainties is small such that the increased effort to measure velocity profiles is generally not justified. Instead, doubling the number of verticals is much more effective in reducing error than measuring velocity at two (or more) depths in each vertical.

The results in Tables 10 and 11 suggest that the most efficient way to reduce measurement error is 1) to select cross-sections where water velocity is greater than 0.1 m/s, and 2) to increase the number of verticals. Once velocity is measured at a site, Table 10 can be used to estimate the approximate number of verticals needed to obtain the desired accuracy.

It is important to note that the random uncertainties in Tables 5 to 8 and the resulting error estimates in Tables 10 and 11 have been provided as a guide and they are not necessarily applicable to all streams. In particular, they were likely estimated for larger streams and may not be strictly applicable to smaller streams. Despite this stipulation, it is recommended that Table 10 be used as a guide to determine the number of verticals even for small streams. Although the International Organization of Standards (1997) recommends that only 4 or 5 verticals are needed for streams less than 1 m wide and 8 to 10 verticals for streams 3 to 5 m wide, Table 10 suggests that these numbers of verticals would result in uncertainties greater than 17% and 10% respectively. Measuring 15 or more velocities (i.e. verticals) across a small stream may seem excessive but is justified even for small streams on the basis that the increased number of verticals 1) provides a better sampling of velocity across the stream (i.e. reduces X'_m), and 2) reduces the flow associated with each panel ($b_i d_i \bar{v}_i$) such that a random error (in velocity, width or depth) is likely to have a smaller effect on the result and random errors are more likely to cancel out as the number of verticals increases.

Table 10. Estimated random errors in discharge using the current meter method. Assumes discharge and velocity in each panel is equal, time of exposure is one minute, $X'_p = 0.15$ (one measurement per vertical), $X'_b = 0.01$, and $X'_d = 0.02$.

Number of verticals	***Velocity (m/s)***					
	0.05	***0.1***	***0.2***	***0.3***	***0.4***	***0.5***
5	26%	19%	17%	17%	17%	17%
10	17%	12%	11%	10%	10%	10%
15	14%	9%	8%	7%	7%	7%
20	12%	8%	7%	6%	6%	6%
25	10%	7%	6%	5%	5%	5%
30	9%	6%	5%	4%	4%	4%
35	8%	5%	4%	3%	3%	3%
40	8%	5%	4%	3%	3%	3%
45	7%	5%	4%	3%	3%	3%

Table 11. Estimated random errors in discharge using the current meter method. Assumes discharge and velocity in each panel is equal, time of exposure is one minute, $X'_p = 0.05$ (five measurements per vertical), $X'_b = 0.01$, and $X'_d = 0.02$.

Number of verticals	***Velocity (m/s)***					
	0.05	***0.1***	***0.2***	***0.3***	***0.4***	***0.5***
5	25%	18%	16%	16%	15%	15%
10	17%	12%	10%	9%	9%	9%
15	13%	8%	7%	6%	6%	6%
20	11%	7%	6%	5%	5%	5%
25	10%	6%	5%	4%	4%	4%
30	9%	5%	4%	3%	3%	3%
35	8%	4%	3%	3%	2%	2%
40	8%	4%	3%	2%	2%	2%
45	7%	4%	3%	2%	2%	2%

9 Data analysis

Stream discharge data can be used for many purposes, and the data analysis method should be suited to the study goals. The purpose of this section is to illustrate some appropriate uses for low-flow survey data. However, no attempt is made to be comprehensive in scope.

9.1 Estimating low-flow indices

Low-flow indices can be estimated at sites where a quantitative relationship is established with an index station (a station for which low-flow indices have been determined)(Searcy, 1959; Stedinger and Thomas, 1985; Stedinger et al., 1993; Reilly and Kroll, 2003). One approach to estimating low-flow indices uses simple linear regression of concurrent measurements (Searcy, 1959; Stedinger et al., 1993) and is illustrated in Figure 14. Low-flow discharge measured at site D-108 on six different dates is plotted as a function of average daily discharge recorded for these same dates at a downstream Water Survey of Canada gauging station, 02HC049. In this example, the regression is very strong ($r^2 = 0.98$) and low-flow indices for station 02HC049 are used to estimate comparable indices for site D-108 (Fig. 14, Table 12). Site D-108 is located within approximately 250 m of the discontinued Water Survey of Canada gauging station, 02HC026. Within the range of discharges defining the relationship in Figure 14, the low-flow indices determined for station 02HC026 compare well with those indices estimated for site D-108 (Table 12).

Stedinger and Thomas (1985) suggest that a simple linear model like the one demonstrated in the previous example may not be unbiased and propose the use of a logarithmic model assuming a Pearson type 3 distribution of annual minimum 7-day low flows. They also provide a first-order estimate of the variance of the estimated low-flow indicator at the ungauged location. Using this model, Reilly and Kroll (2003) found that the method performed best when correlation coefficients were above 0.8. They also found that model performance improved with the number of concurrent measurements but that performance levelled off with 15 to 20 measurements.

Because it may not be valid to extrapolate the relationship beyond the range of available measurements, it is best either to select indices with values within the range of concurrent measurements or to select days for measurements when the discharge at the index station is approximately equal to the desired low-flow index. In the previous example, the 7Q10 discharge at 02HC049 (510 L/s) is well below the range of concurrent measurements. Additional concurrent measurements would be needed to expand the range of the relationship to estimate the 7Q10 at site D-108.

Figure 14. Estimation of a low-flow index for a site with a partial record.

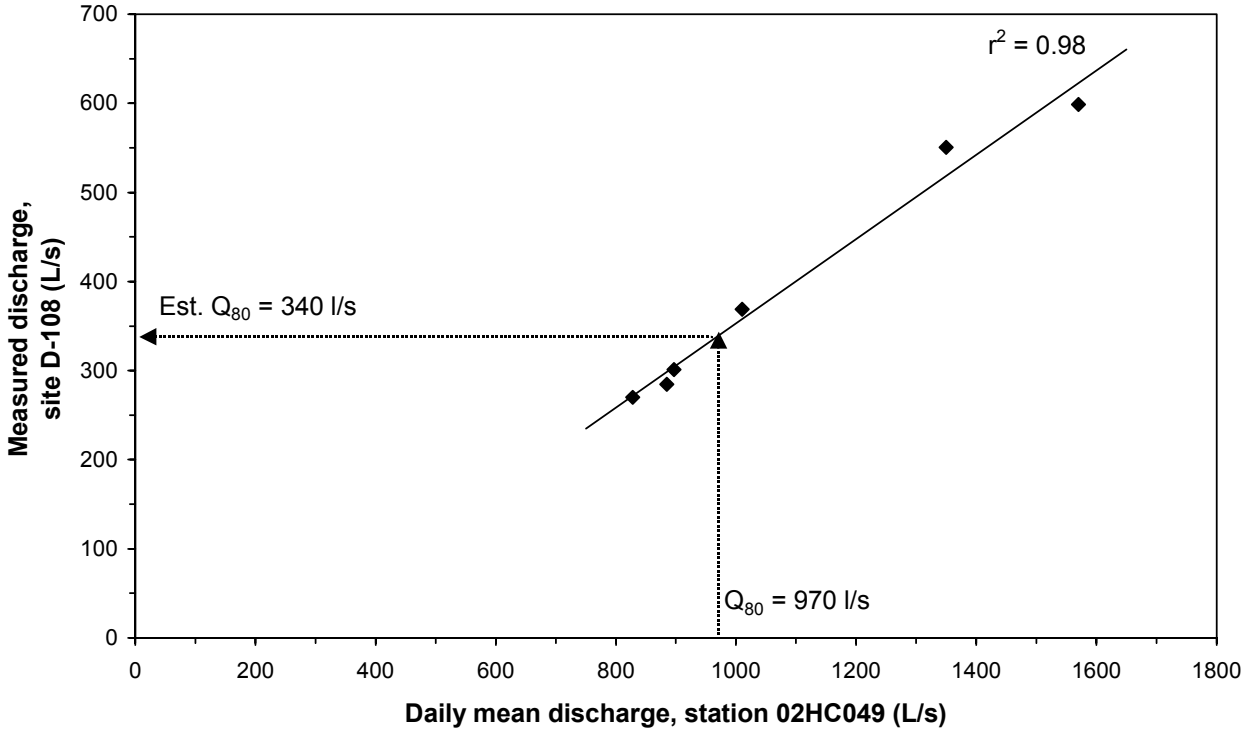


Table 12. Low-flow indices (1961-90). Low-flow indices for site D-108 are estimated from station 02HC049 based on the regression shown in Figure 13. Indices for discontinued station 02HC026, located approximately 250 m upstream of site D-108, are shown for comparison.

Low-flow index	***02HC049[1]***	***D-108***	***02HC026[2]***
	(L/s)	***(L/s)***	***(L/s)***
Q90	800	260	290
Q80	970	340	360
Q70	1100	400	410
Q60	1260	480	490
Q50	1460	570	580

[1] Station 02HC049 replaced station 02HC006 (located < 500 m upstream). Low-flow indices were calculated for station 02HC006 (1961-90) and adjusted for station 02HC049 using a regression based on concurrent daily data.

[2] Complete annual records for station 02HC026 are available for 1964-67 and 1970-1987. The flow duration curve was adjusted to 1961-1990 based on a regression of concurrent flow duration curves with station 02HC006.

The estimation of low-flow indices demonstrates the value of performing multiple surveys or of establishing partial record stations at selected sites. Ideally, manual measurements would also be made concurrently at the index station because discharge measurements based on the measurement of stage (as in the previous example) may not be accurate at very low flows such that the correlation between the site and the index station may not be strong.

Even if there is no intent to establish partial record stations, it is still useful to determine the percentile of flow exceedance (e.g. Q90) at an index station in order to provide a benchmark that defines the state of hydrological conditions during the survey.

9.2 Standardizing low-flow data to a common date or flow condition

When low-flow results are to be used as a variable in a regional analysis (e.g. as one factor influencing the distribution and abundance of fish populations), it may be inappropriate to compare the results from different portions of a watershed or from different watersheds if they correspond to different relative flow conditions. Consequently, it may be desirable to standardize low-flow results to a common date or flow condition (e.g. a common low-flow index).

Ideally, one could establish a relationship between each site and an index station as described in section 9.1 and estimate the discharge for the desired flow condition. However, such an approach may be unrealistic due to cost and time constraints of obtaining sufficient data to estimate low-flow indices at non-recording sites. For many sites, there will only be a single measurement of low-flow discharge. A similar, yet simpler approach to data standardization to a common date is proposed. Low-flow survey results are related to "standardization sites" for which low-flow discharge has been measured on a common date. This approach is possible given three conditions:

1) the assumption that the ratio of low-flow discharge at the survey site to the low-flow discharge at a standardization site is constant for the range of flow conditions being considered.
2) the discharge is measured on the same date at both the survey site and the standardization site,
3) the discharge at each standardization site is measured on the date to which it is to be standardized.

If applied to all stations in a watershed, the first condition assumes that the spatial distribution of low flow remains constant in the watershed for the range of flow conditions being considered. It is effectively equivalent to a relationship between the survey site and the standardization site (analogous to Fig. 14) in which a straight line is drawn between the origin and the single measurement point. The validity of this assumption obviously depends on the hydrologic and hydrogeologic response of the watershed(s). Although this assumption may not strictly be valid for the entire range of flow conditions (e.g. Fig. 14), it may be reasonable for small corrections (i.e. where the low-flow discharges at the standardization site are nearly equal on both dates). Additional

concurrent measurements can be used to test this assumption. The second and third conditions, in contrast, are controlled by project design.

The recommended nested design of the low-flow survey (see section 4.3) is intended to ensure that all three conditions are fulfilled as best as possible. The first condition is likely more reasonable for a nearby site on the same tributary than for a site at the mouth of the entire watershed where many more factors (e.g. pumping, variations in geology, surface water storage) may influence the ratio of discharges. The nested approach includes a watershed scale survey in which discharge is measured at all the main tributaries on the same day. Each site of the watershed scale survey (i.e. each main tributary) is intended to be used as a standardization site. This approach ensures that most survey locations will have a nearby standardization site measured on a common date (condition 3). The subsequent subwatershed surveys provide concurrent measurements at each survey site and a standardization site such that the second condition is also met.

If discharges are to be standardized to a common flow condition (e.g. a common low-flow index), the third condition is replaced by the following:

3) the low-flow index is estimated at each standardization site.

This condition requires either that a relationship is also established (or assumed) between the index site and the standardization site (as described in section 9.1) or that the standardization site is also an index site. For example, when a nested approach has not been used, it may still be possible to standardize discharges to a common date or flow condition using the results of an operational hydrometric station as both a standardization and index site. Since these stations generally measure discharges near the mouths of watersheds, the standardization is likely to be less reliable than using localized standardization sites as described above.

The standardized discharge is then calculated as:

$$Q_s^0 = \frac{Q_s^m}{Q_{std}^m} \times Q_{std}^0 \qquad (11)$$

where

Q_s^0 = Standardized discharge at the survey site, s, on the standardized date, 0, or discharge for the desired low-flow index at the survey site.

Q_s^m = Discharge at the survey site, s, on the measured date, m.

Q_{std}^m = Discharge at the standardization site, std, on the measured date, m.

Q_{std}^0 = Discharge at the standardization site, std, on the standardized date, 0, or discharge for the desired low-flow index at the standardization site.

9.3 Discharge and net discharge

Because stream discharge data are collected over a short time interval, they are essentially a "snapshot" of low flow for one set of hydrological conditions. Maps of stream discharge and net discharge effectively illustrate the magnitude and distribution of discharge within a watershed (Figs. 15 and 16). In addition, discharges and net discharge can be divided by the total discharge at the most downstream site to provide the relative proportion of discharge (or net discharge) within the watershed. Tables and maps of discharge proportions are easily understood and readily demonstrate the relative significance of discharge within different subwatersheds to the entire watershed (Fig. 17).

9.4 Discharge per unit length and area

Because gauging locations are seldom evenly distributed within a watershed, the lengths and contributing areas to each stream reach will be variable. Consequently, the pattern of net discharge does not indicate whether a particular stream reach has a higher net discharge simply because it has a longer reach or a larger contributing area. Therefore, it is useful to normalize the discharge (or net discharge) to either stream reach length or subwatershed area.

If the flowing reaches of streams are established, the net discharge per unit length of stream can be calculated. Maps of net discharge per unit length effectively show where the stream is gaining (or losing) most rapidly (e.g. Fig. 18).

Either net or total discharge per unit area can be calculated at the subwatershed scale (e.g. Fig. 19). When expressed as an equivalent depth per year, the results sometimes demonstrate that the discharge within a subwatershed originates as groundwater flow from outside the subwatershed (e.g. if depth/year > recharge rates). Alternately, if groundwater flow is entirely contained within a subwatershed, total discharge per unit area may constrain estimates of recharge rates.

9.5 Flowing length of streams

The reconnaissance and gauging surveys provide data that can help map the perennially flowing and intermittent reaches of streams (e.g. Figs. 16 and 18). Observations of groundwater seepage and flowing streams also help define the groundwater elevation in the vicinity of headwater streams.

Figure 15. Map of low-flow discharge, Wilmot Creek, Ontario, August 1995.

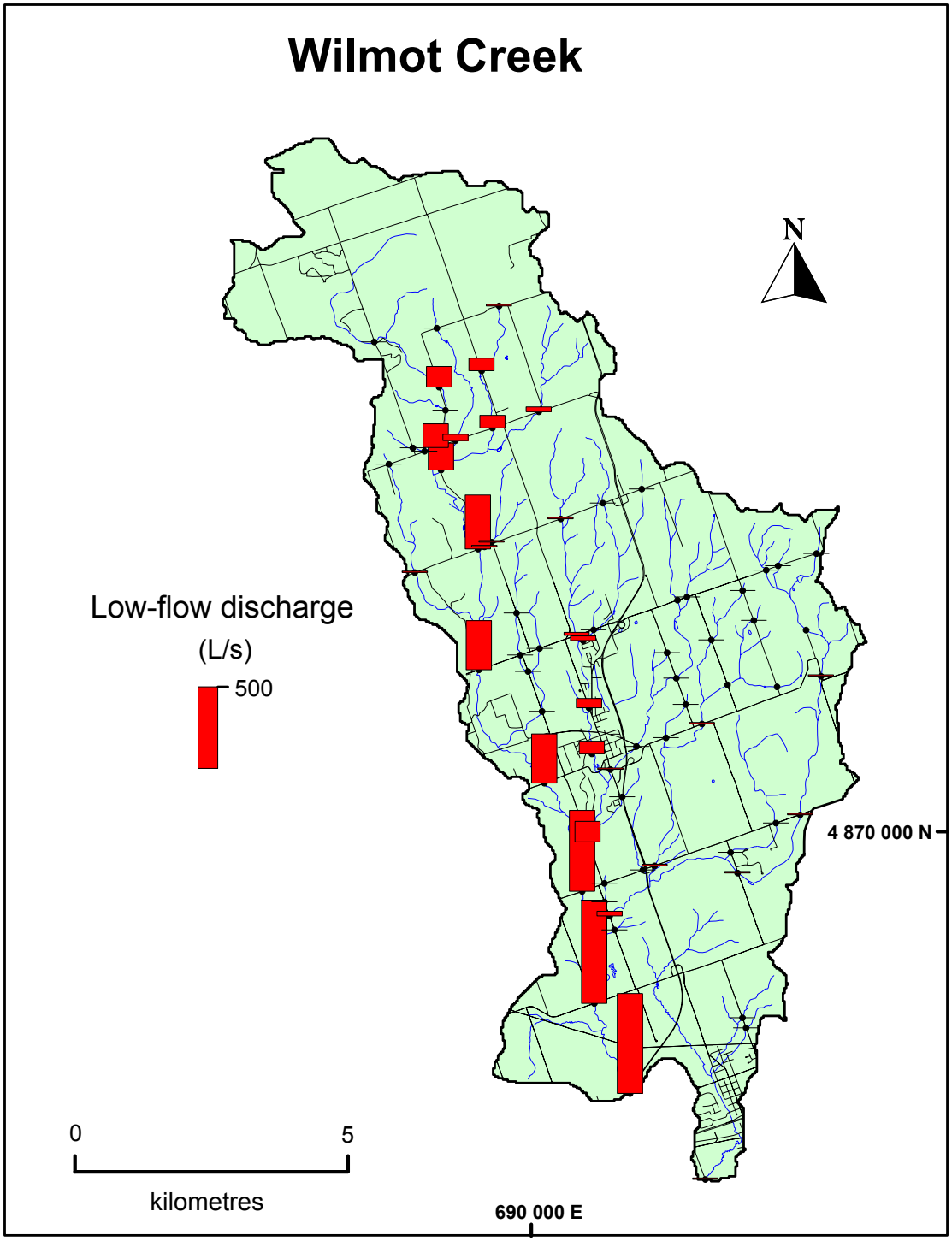


Figure 16. Map of net low-flow discharge, Wilmot Creek, Ontario, August 1995.

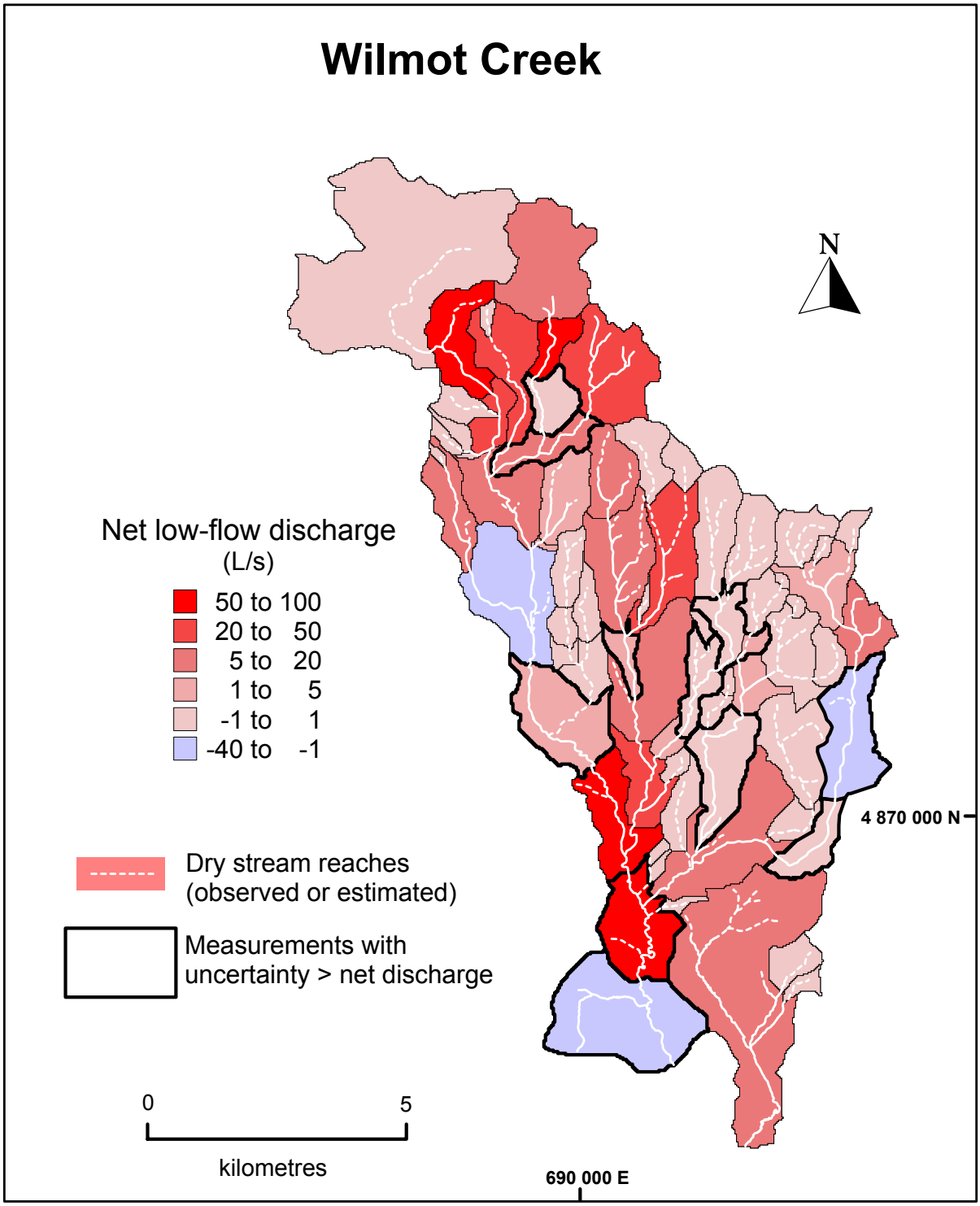


Figure 17. Simplified map showing the proportion of net low-flow discharge contributed by various subwatersheds, Wilmot Creek Ontario, August 1995. Negative value indicates a loss of discharge, likely due to water extraction.

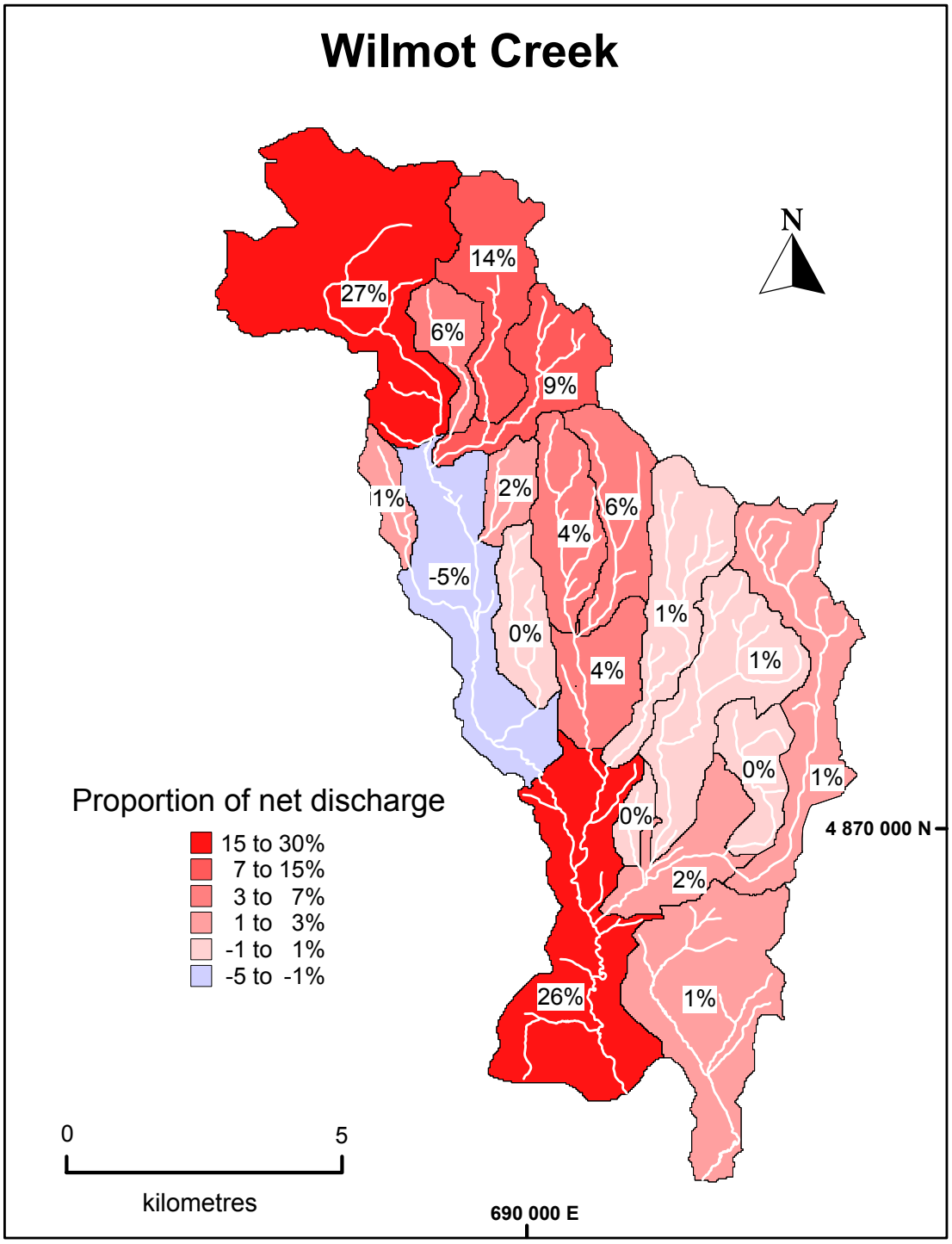


Figure 18. Map of net low-flow discharge per unit length, Wilmot Creek, Ontario, August 1995.

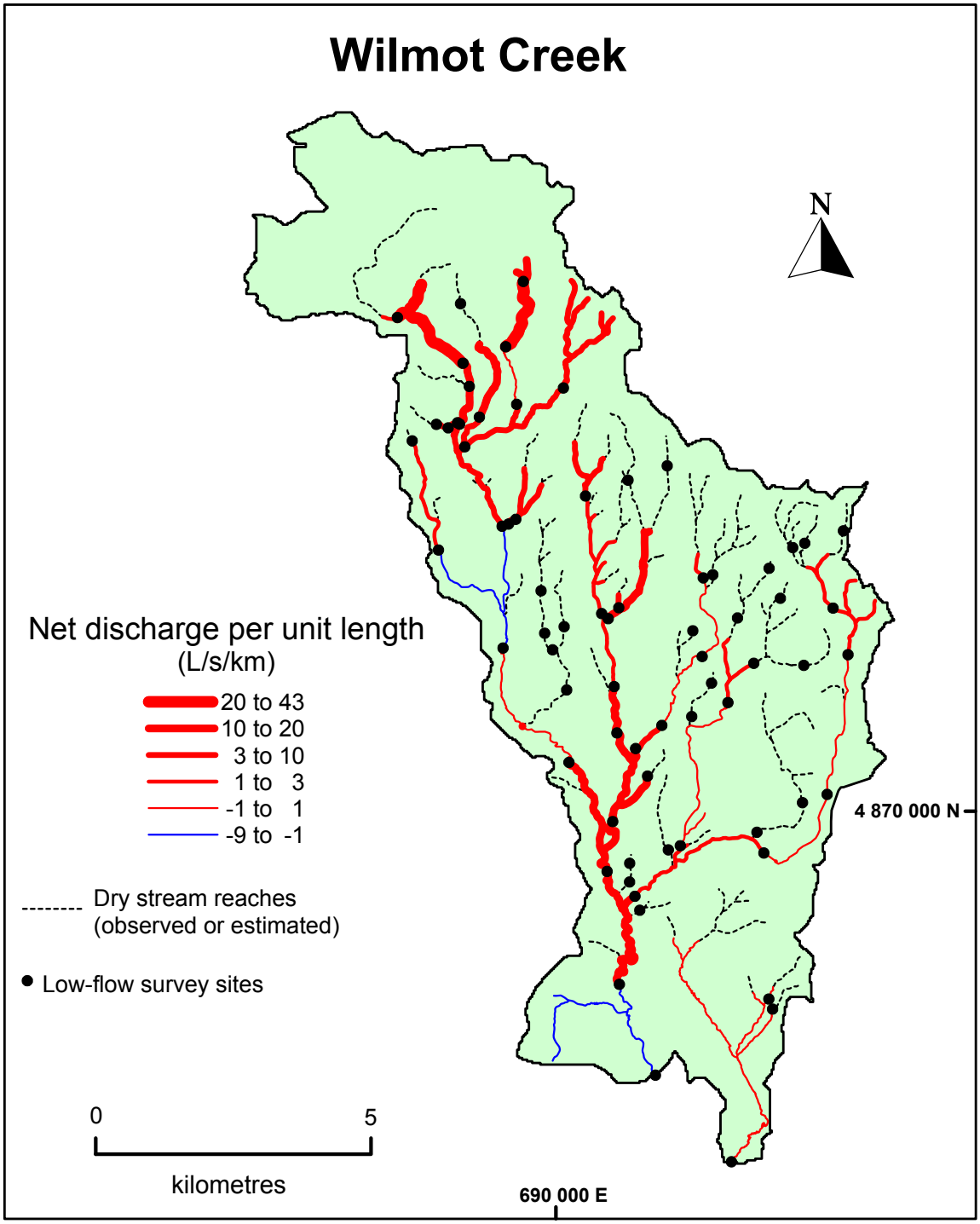
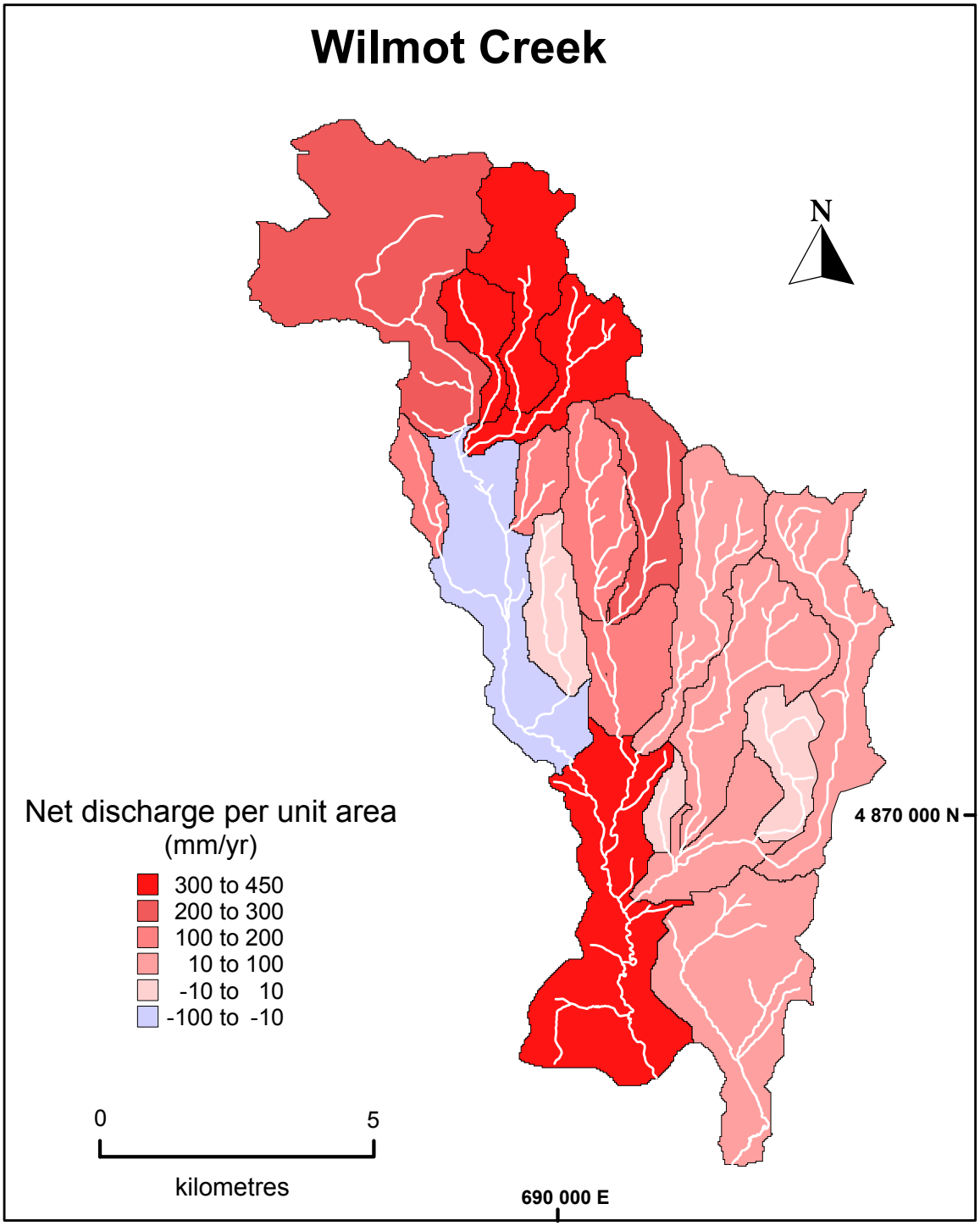


Figure 19. Simplified map showing the net low-flow discharge per unit area, Wilmot Creek Ontario, August 1995. Negative value indicates a loss of discharge, likely due to water extraction.



10 Summary

Periods of low streamflow are a growing concern for watershed managers and regulators who must deal with increasing demands for water use, changes in land use and land practices, and the need to maintain aquatic habitats and stream functions. In most watersheds, streamflow data are only available near the main outlet or along major tributaries; few data are collected along most tributaries. Consequently, it may be difficult to assess the potential local, regional and cumulative impacts of development and make scientifically defensible decisions. Low-flow surveys are a cost-effective approach to collect spatial data within a watershed and improve the conceptual understanding of controls on low flow within a watershed.

This Open File Report describes a methodology to conduct stream low-flow surveys. The procedure explains how to conduct a reconnaissance survey, plan a low-flow survey, measure stream flow using both the current meter and volumetric methods, report results, calculate discharge and estimate errors. This manual is designed for both the professional who plans and designs the field program, and the field technician who does the fieldwork. In general, these surveys are intended for streams that can be gauged by wading. The suitability of this method is determined by the magnitude of measurement errors in relation to the changes in discharge. Two key recommendations to reduce measurement errors include the selection of cross-sections where water velocities exceed 0.1 m/s and increasing the number of measurement sections (verticals) within a cross-section.

A low-flow survey is a simple, low-technology method to collect data that will both help develop an understanding of low-flow hydrology within a watershed and provide useful baseline information to assist scientific assessment and watershed management.

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13 Appendix 1: Reconnaissance survey field checklist

13.1.1 Prior to departure at the start of day

1. Bring selected equipment from Table 1.
2. Check equipment. Calibrate instruments. Record the instrument serial numbers.
3. Record weather conditions and recent precipitation.

13.1.2 At each site

4. Record site information: site number, date and time, field technicians (initials), site coordinates, nearby road or site markings, description of road crossing (type, material, and/or size).
5. Measure and record desired physical and/or chemical parameters such as water temperature, specific conductance, pH, and dissolved oxygen.
6. Estimate the discharge by multiplying the channel cross-sectional area and by an estimated average water velocity. To obtain a rapid estimate of discharge:
    - If possible, locate a shallower, more rapid section of the stream.
    - Visualize the channel cross-section to be rectangular (average depth times width) and exclude slow water at the edges of the channel.
    - Estimate water velocity using floats, food dye or a current meter.

No flow recorded as “dry”, “disconnected pools” or “stagnant water”.

7. Evaluate the feasibility of gauging the site:

Unsuitable = cannot gauge, Poor = problematic to gauge or conditions leading to sizeable uncertainties, OK = can be measured but conditions may lead to moderate uncertainties or require more depth and velocity measurements to capture significant velocity variations across the section, Good = can be measured accurately since the depth and velocity changes across the stream are generally gradual. If several nearby sites are rated “good”, suggest the best site.

8. Determine the most appropriate field method and record the instrument required.
9. Describe the suggested location of the gauging cross-section (e.g. approximate distance upstream or downstream of road crossing).
10. Photograph the site, if desired. Photographs should include distinctive site features.
11. Record additional notes as appropriate. These may include: the reason a site is unsuitable or poor, additional equipment required and purpose, a sketch map and additional directions to locate a site, corrections to maps, site observations (seepage, pollution, pumping, suspended sediment, etc.), or permission needed/granted/denied to access a site on private property.
12. Sites that are not visited should be noted and the reason given.
13. Record observed groundwater springs or seepage areas.

13.1.3 At the end of the day

14. Photocopy completed reconnaissance forms.

14 Appendix 2: Current meter method field checklist

14.1.1 Prior to departure at the start of day

1. Bring selected equipment from Table 2 and ensure it is in good working condition.
2. Lubricate and verify the operation of current meters.
3. Bring the stream gauging plan, maps, and reconnaissance survey results.

14.1.2 At each site

4. Select the cross-section location most suitable for gauging.
5. Set up the measuring tape perpendicular to flow.
6. If necessary, remove obstacles and improve flow conditions. Ensure flow has stabilized.
7. Record all site information. Take a photograph of the section; record its number.
8. Choose the appropriate current meter. AA for water depths > 0.38 m and pygmy for water depths > 0.09 m. Record the serial number of the current meter.
9. Prepare the current meter. Remove the brake (AA) or replace the pivot (pygmy).
10. Record the start time.
11. Record the stream edge (L.E.W. or R.E.W., facing **downstream**) and cross-section orientation (e.g. NW-SE).
12. Describe and record the flow conditions and depth at the stream edge.
13. Where needed, estimate water velocity near the stream edge. N = Negligible, S = Same, % = proportion of first measured section, or I = interpolated. Record distance and water depth at these locations.
14. Determine the number and spacing of verticals across the stream (20-30 or more).
15. At each vertical, measure and record the distance and water depth.
16. At each vertical, determine the number of velocity measurements required. Generally one measurement per vertical is sufficient, at 6/10 of the water depth from the surface.
17. Set the current meter height.
18. Stand at least 0.4 m beside and downstream of the current meter, allow the rotation of the current meter to stabilize.
19. Measurement duration: ~60 second for velocities 0.1 - 0.3 m/s, ~90 seconds for velocities < 0.1 m/s, and ~45 seconds for velocities > 0.3 m/s.
20. Make the velocity measurement. Record the number of rotations, elapsed time and relevant observations. After the measurement, check to see if meter depth is set correctly.
21. Repeat steps 15-20 for each vertical across the stream.
22. At far edge, record flow and edge conditions as in steps 13, 12 and 11.
23. Check the velocity profile across the stream. Add verticals as needed.
24. Record the end time. Ensure all required information has been recorded.
25. Engage current meter brake (AA) or replace the pivot with the brass plug (pygmy).
26. Measure and record stream parameters (e.g. temperature and electrical conductivity).
27. Remove all equipment from the site. Dry steel equipment. Leave the site clean.

14.1.3 At the end of the day

28. Copy field notes. Clean current meters. Maintain equipment as necessary.

15 Appendix 3: Volumetric method field checklist

15.1.1 Prior to departure at the start of day

1. Bring selected equipment from Table 4 and ensure the stopwatch is in good working condition.
2. Bring the stream gauging plan, maps and reconnaissance survey results.

15.1.2 At each site

3. Record the following site information: site number, general site location (e.g. stream name and cross road(s)), specific gauging location (drop location with respect to an identifiable feature), coordinates (e.g. UTMs), type of drop (culvert, dam, weir, built), any site conditions of relevance (e.g. observed or suspected pumping from stream, comments from residents, precipitation, etc.), field technicians, and gauge height if the site also has a gauging station.
4. Prepare the site. Stop or reduce leakage. If necessary, constrict or divide the flow.
5. Perform one or several trial measurements. Make site adjustments, if required.
6. If the site has been modified, monitor the water level or wetted perimeter upstream of the drop until the discharge stabilizes.
7. Record the start time.
8. To start the measurement, the container is thrust under the water with a rapid, horizontal movement and the stopwatch is started synchronously. The container is then adjusted to a level position. If the container is to be filled, the stopwatch is stopped when the water level reaches the lip of the container rather than when it overflows. Observe whether the water reaches the lip of the container at the same time on all sides. If the container is to be partially filled, remove the container rapidly and stop the stopwatch synchronously.
9. *Before the time is observed on the stopwatch*, decide whether or not the measurement was taken correctly and will be retained. If there are any concerns, the measurement should be discarded and not recorded. If the measurement is accepted, the time is observed and recorded.
10. Record the measurement volume. If the container was only partially filled, ensure that the measurement container is level.
11. Repeat the measurements. Generally five or more measurements are recommended; more may be required if measurement times are short (< 10 seconds)
12. Assess the results. Additional measurements should be taken to reduce the variance and ensure that any questionable measurement has less influence on the average.
14. Record the end time.
15. Measure and record stream parameters (e.g. temperature and electrical conductivity).
16. If desired, take a photograph that includes the drop. Record the photograph number.
17. Remove all equipment from the site. Leave the site clean.

15.1.3 At the end of the day

18. Copy field notes.