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Network Structure, and Landscape Characteristics**

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**Tributary Effects in Rivers: Interactions of Spatial Scale, Network Structure,
and Landscape Characteristics**

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Abstract

Landscape characteristics in combination with the physical structure of branched stream networks define the environmental conditions available for lotic biota. From simple stream network “laws” can emerge a spatially explicit understanding of habitat heterogeneity. Based on geographic information system analyses, we explore how stream networks integrate spatial heterogeneity of the landscape and form new characteristics as stream segments accumulate into progressively larger drainages, and how these changes in landscape characteristics relate to confluence symmetry ratio and drainage size. Simple expectations for stream networks include: (i) abrupt changes in longitudinal patterns are more probable among the numerous small and diverse headwater streams than in large, rare, and characteristically similar tributaries, (ii) the many small tributaries flowing into large main stem channels cause individually small, yet collectively gradual changes in longitudinal patterns. Such a spatial understanding of where change is likely to occur helps to reconcile gradual river continuum and abrupt discontinuum views of patterns in rivers and predict the locations of significant confluences, ecological transitions, longitudinal gradients, and patterns of biodiversity in stream networks.

49 Introduction

50 Within a stream and its valley there are changes in physical and chemical properties from
51 small headwater streams to large lowland rivers (e.g., flow volume, degree of shading, sediment
52 size, organic matter). The River Continuum Concept (RCC; Vannote et al. 1980) describes a
53 continuous *gradual* gradient in geomorphological changes and corresponding adjustments of
54 organic matter and biota over long distances. Ward and Stanford (1983) proposed the Serial
55 Discontinuity Concept (SDC) recognizing that most rivers experienced *abrupt* breaks or
56 discontinuities in the continuum from impoundments. Others noted the potential influence of
57 tributaries on a continuous gradient (Bruns et al. 1984). Years later, Fisher (1997) challenged
58 fellow scientists to think of streams in terms of branching systems, or using today's terminology,
59 networks. Since then, the growth of computing power and remote sensing technology has
60 enabled network analysis to rapidly become a topic of much discussion and shifted the paradigm
61 in stream ecology. The linear view of the RCC and SDC has led to the understanding of
62 tributary influences (e.g., Rice et al., 2001) lakes (Jones 2010), and major geological changes
63 (Neff and Jackson 2012) that incorporate network thinking (Poole, 2002; Benda et al., 2004a).
64 Within stream networks each confluence, wetland, lake or impoundment has the potential to
65 punctuate the continuum, resulting in abrupt changes in downstream characteristics (Poole 2002;
66 Jones 2010). This hierarchical patch dynamics view emphasizes variation in pattern, which can
67 reset longitudinal trends forward or backward along the stream (Poole 2002).

68 Research on the influence of tributaries has largely focused on localized small-scale (10^1 -
69 10^3 m) changes in main stem river characteristics at the point where tributaries join main stem
70 rivers (Bruns et al. 1984; Perry and Schaeffer 1987; Kiffney et al. 2006; Milesi and Melo 2014;
71 Hellmann et al. 2015). Much of this research has focused on geomorphological changes in an

effort to identify significant tributaries (e.g., Rice 1998; Benda et al. 2004b). Intuitively, the probability of “significant” confluence effect is a function of tributary size relative to the main stem river (confluence symmetry ratio, CSR, Rice 1998; Benda et al. 2004a). Larger tributaries, relative to main stem size, are more likely to show significant confluence effects compared to relatively small tributaries (Rhoads 1987; Rice 1998). Local geomorphic effects include abrupt changes in sediment quantity and size distribution, wood debris, and flow-related changes including channel width, water depth and velocity. In mountainous streams, local confluence effects can be pronounced (e.g., western USA, sediment rich and high energy systems; see Rice et al. 2001; Benda et al. 2004a,b), whereas, in many other stream types around the world tributaries show little geomorphic influence at confluences. Instead, biophysical characteristics of drainages such as land use, vegetation, and geology drive changes in water quantity quality, and thermal regimes that shape the abiotic and biotic characteristics of rivers (Hynes 1975, Rice et al. 2001, Benda et al. 2004).

There has been little effort to understand how tributaries influence abiotic and biotic characteristics further downstream from confluences and across entire drainages, beyond the mixing zone (Gaudet and Roy 1995) and the immediate geomorphic influence of the tributary (but see Stevens et al. 1997; Rice et al. 2001; Benda et al. 2004a; Torgersen et al. 2008). Aside from sudden fine-scale changes in physical and biological characteristics at confluence “hot spots” (*sensu* Benda et al. 2004a), tributary streams can have persistent and far reaching downstream impacts on water quality, thermal and flow regimes, and biotic communities, imparting change many kilometers downstream (Rice et al. 2001; Benda et al. 2004a). This type of understanding is required to identify breaks in networks that aid in the classification of ecologically meaningful homogeneous stream segments (10^2 - 10^5 m in length) for use in

monitoring programs (Seelbach et al. 2006; Brenden, et al. 2008; Melles et al. 2014) and species distribution modelling (Zorn et al. 2011; McKenna et al. 2014). Such classifications use remotely sensed or thematically mapped information (e.g., surficial geology) in combination with stream network information (e.g. upstream drainage area) to make inferences about the ecological character of streams, particularly over large areas (e.g., states and provinces) where every stream reach cannot be visited in the field to gather fine-scale data. The premise of stream segmentation is to delineate spatial units using statistical methods where environmental variation within the resulting segments is less than the environmental variation between segments (Bizzi and Lerner 2012; Wang et al. 2012; Alber and Piégay 2011). In a hierarchical framework this generalizes finer scale variability within segments such as sedimentary links, pools, riffles, and lateral sediment sources to answer questions at appropriate scales (Frissell et al. 1986; Rice and Church 1998). Recently, stream network segmentation schemas have been tested to assess the homogeneity within segments and whether assigned classes are actually different (Warner et al. 2010). For these types of assessments, researchers avoid sampling near confluences because they are not representative of stream reaches and segments as a whole because of complex fluvial dynamics and flow mixing.

Streams are an integration of the landscape they drain which ultimately defines habitat for aquatic biota in streams (Hynes 1975; Zorn et al. 2002; Allan 2004). Landscape characteristics in combination with the physical structure of branched stream networks define the environmental conditions and habitat heterogeneity available for lotic biota and relates to patterns of ecological diversity (Finn et al. 2011). From simple stream networks “laws” can emerge an understanding of habitat heterogeneity. These laws include:

1. “The valley rules the stream” emphasizing the importance that geology and vegetation has on a stream’s flow, temperature, and availability of ions and organic matter that form the basis of the nutrient cycle for the biota (Hynes 1975). During the last two decades, numerous multi-scale studies in streams have shown the importance of landscape conditions and scale in driving fish and invertebrate communities (Richards et al. 1996; Allan and Johnson 1997; Hughes et al. 2006). Differences in landscape characteristics lead to differences in stream typology.
2. Large tributaries, relative to the main stem, will have a large confluence symmetry ratio (CSR) and are more likely to cause abrupt changes in abiotic and biotic characteristics than small tributaries. In contrast to other studies (e.g., Benda et al. 2004a) that focus on effects immediately at a confluence we are interested in the effects that persist downstream at the segment scale. For example, a large tributary will add significantly more flow than a small one, which changes stream hydraulics and stream width, which opens the riparian canopy and reduces shading, likely causing abrupt and persistent changes in thermal regime and for the purposes of typology creates a new class of stream segment.
3. In every stream network there are many more headwater streams than larger higher order streams and this relationship is approximated by a geometric progression according to the law of stream numbers (Horton 1945). For instance, headwater streams ($<10 \text{ km}^2$) account for 60 percent of stream channel length in the United States (Wang et al. 2011).
4. Smaller streams also drain smaller areas than large streams (Schumm 1956) and, in turn, their characteristics can be very homogeneous because their drainage encompasses only a single type of landscape (e.g., 100% forested or 100% sandy till) which is in contrast to

large rivers that usually integrate from a heterogeneous landscape composed of many types (Wiens 1989; Fig.1).

We hypothesize that the probability of a persistent abrupt change downstream from a confluence is a function of both CSR and the similarity of drainage landscape characteristics in a logistic functional form (Equation 1; Fig. 2), where p is the probability of an abrupt change downstream of a confluence and is a function of the landscape dissimilarity $a = \{10, 20, 30 \dots 100\}$, the constant $b = 14$, and the confluence symmetry ratio $c = \{0.1, 0.2, 0.3 \dots 1.0\}$.

$$p = \frac{1}{1+e^{-(a+bc)}} \quad [1]$$

Figure 2 represents a reasonable hypothesis. We chose the logistic form for its probabilistic interpretation because we expected the probability of a detectable change to happen abruptly. Estimates of threshold values and true functional form need to be determined in future research. In this hypothesis the probability of a significant change in the ecology downstream from a tributary is high when two streams merge of a similar size ($CSR > 0.8$) and have similar landscape characteristics (Euclidean distance < 10). As the similarity of the two drainages decreases, the inflection point of the logistic function shifts to progressively smaller CSR values (Fig. 2). This recognizes that a small tributary might influence downstream characteristics on the main stem if it is very different in character (i.e., draining a very different landscape). For example, a relatively small, warm and turbid tributary flowing into a cold clear trout stream may cause greater changes in the main stem than a similarly sized tributary that is also cold and clear. These relationships in concert setup simple expectations for the relative importance of confluences in stream networks and provide a physical basis for the likelihood of change downstream of tributaries and network heterogeneity of habitats.

Based on geographic information system (GIS) analyses across southern Ontario, we explore how stream networks integrate spatial heterogeneity of the landscape and form new characteristics as stream segments combine into progressively larger drainages, and how these changes in landscape characteristics relate to confluence symmetry ratio and drainage size. From these analyses we make inferences about how environmental gradients within stream networks may unfold and structure riverine habitats. We emphasize cumulative downstream impacts as a function of scale-dependent landscape heterogeneity that explicitly attempts to recognize the role of tributaries that is broader than aggradation-driven geomorphological impacts. We advance on previous research and provide direction on the likelihood of abrupt and gradual change within stream networks. Such an understanding is useful for the development of system rules and the discretization of stream networks into ecologically meaningful stream classes. Lastly, in the tradition of other concepts and hypotheses in stream ecology we call this the Network Composition Hypothesis (NCH).

Methods

We used GIS to decompose drainage networks into individual interconfluence reaches ($n = 21,473$) and confluence points ($n = 10,705$) in southern Ontario (land area $136,907 \text{ km}^2$). Southern Ontario is represented by a complex physiography with a mixture of geologies, glacial histories and landforms e.g. escarpments, end moraines, glacial lake plains, and drumlins. It also has a mosaic of land covers including wetlands, agriculture, fragmented forest, and urban areas.

To show how landscape variables average over different size drainages, upstream drainage areas were summarized for each reach creating area-weighted average values for base flow index (BFI, Neff et al. 2005; Piggott and Sharpe 2007), percentage of total area wetland,

forested, agriculture, and clay geology. These landscape variables were chosen to illustrate the effect of averaging at different spatial scales using variables of interest to aquatic ecologists. Many other landscape variables could have been chosen to illustrate the averaging effect. Base flow index represents the long-term average rate of base flow relative to the long-term average rate of total stream flow in five classes of quaternary geology including coarse and fine textured sediments, till, shallow bedrock and organic deposits (Piggott and Sharpe 2007). The base flow index is a useful surrogate for actual groundwater delivered to a stream, and therefore, important in stream hydrology and thermal regime characteristics both of which are very important in defining stream habitat.

We assigned a confluence symmetry ratio and similarity value to each confluence in southern Ontario to illustrate that small main stem streams have a wide range of confluence symmetry ratios and landscape similarities and that progressively larger main stem streams have mostly small CSRs. Using the variables described above, similarity in landscape characteristics between the main stem and tributary drainages was calculated using Euclidean distance (*ED*). Other variables could be chosen depending on objectives and region. For the matrix in Figure 2 all Euclidean distance measures were transformed as *landscape similarity* = $(ED/10)-11$. This created drainages and confluence points for which we plot relationships between drainage characteristics in relation to drainage size of the main stem (area km²) and similarity of landscape characteristics.

We also examined more specific patterns in individual drainages to show interrelationships among CSR, the similarity of drainage characteristics, and the probability of an abrupt change. Focusing on the main stem and five of the largest tributaries of the diverse Saugeen River (N 44.50°, W 81.37°, drainage area 3,983 km²), we applied the network

composition hypothesis described in Figure 2 to confluences and plot the expected pattern of continuous and abrupt changes in longitudinal pattern on the main stem and the major tributaries. We also plotted all confluences in the Saugeen drainage with the potential for change by drainage area. Due to binning of the continuous values in Figure 2, the first column ($CRS < 0.1$) contains many ($n=4189$) very small CSRs (mean = 0.03) with very low probability of causing an abrupt change downstream of a confluence.

Results

Among Drainages in Southern Ontario

Small headwater streams are more variable in landscape characteristics and more numerous than larger drainages (Fig. 3). GIS zonal statistics for progressively larger drainages approach the mean value ($BFI = 46\%$) of the entire data set (Fig. 3). Strong decreases in the diversity of BFI values starts at approximately $40\text{--}100\text{ km}^2$ and asymptotes around the mean at approximately $4,000\text{ km}^2$. Similar patterns were found for the other variables percentage wetland, forested, agriculture, and clay geology.

In headwater streams ($< 10\text{ km}^2$) there were many confluences that spanned the full range of confluence symmetry ratios. Headwater streams also spanned a wide range of similarities in landscape characteristics; although there were more headwater streams that were similar than very different (Fig. 4). As drainages grow in size, the number tributaries that are similar in size to their main channel decrease. Differences in landscape characteristics between tributaries and the main stem also decrease, particularly for large CSR values.

The number and frequency of confluences characterised by CSR and landscape similarity in drainage networks shows a pattern (Fig. 5). There are many relatively small tributaries with

similar drainage characteristics (top left). Large tributaries that have contrasting landscape characteristics are very rare (bottom right). Using > 0.9 probability of a significant confluence from Fig. 2 we calculate that there are 1,400 significant confluences causing segment breaks of a possible 10,705 in southern Ontario. That is, 13% of the confluences are likely to show significant physical, chemical and biological effects in the stream segments downstream of the confluences, assuming the underlying principles of this analysis hold true.

Within Drainages- Saugeen River

The Saugeen River has six main tributaries including the main stem. Based on the NCH, we expected a pattern of abrupt changes tending to occur more frequently within headwater areas where there are many small streams and a higher potential for large differences in landscape characteristics (Fig. 6 and 7). This pattern was particularly evident on the larger branches of the Saugeen (e.g., main stem and South Saugeen). Although there were a couple of exceptions in mid-reaches, a more gradual gradient was apparent in larger drainage areas further downstream (Fig. 6 and 7). The North Saugeen River has an elongated drainage shape and few confluences with large CSRs where changes could occur, that is, few of its tributaries are large enough. Across the entire Saugeen River drainage there were 1,470 confluences, 193 (13%) had a probability (>0.9) of being a significant confluence, 267 (18%) were between 0.1 and 0.95, and 1,010 (69%) confluences had a potential for change <0.1 (Fig. 8).

Discussion

The averaging of landscape characteristics in progressively larger drainages means that larger drainages will tend to have similar landscape and environmental characteristics, and thus, ecology (Wiens 1989). This similarity is predicated on the idea that the valley rules the stream

(Hynes 1975). Plots of drainage size (area) in relation to drainage characteristics for most variables will show a trumpet-shaped distribution of data points with high diversity for small drainages and low diversity for larger drainages. Similar trumpet shaped distributions can be found in the relationship between low-flow yield and catchment area in Zorn et al. (2011, Fig 2a). This is a simple mathematical determination. As drainage size increases, a greater proportion of the spatial heterogeneity is contained and averaged. This relationship will not hold true for landscape variables that have little variation over regional or drainage scales (e.g. air temperature). Our analysis occurred in a very patchy, post-glacial landscape. In more homogenous landscapes, where the size of the landscape patches matches or exceeds the size of even the largest drainages, confluence symmetry ratio might be the main driver of change.

Aside from being relatively average in characteristics, larger rivers are also rarer on the landscape based on the law of stream numbers (Horton 1945). In turn, this means that finding a confluence of two large rivers with very different landscape characteristics is even rarer. Hence, abrupt changes in longitudinal pattern are more likely to involve confluences of smaller streams. There are, however, great examples of large contrasting rivers joining. For example, the confluence of the turbid Fraser and clear Thompson Rivers at Lytton, British Columbia, or the Colorado and the slightly smaller and silty Green Rivers in Utah, or the turbid Mamoré River and the clear Itenez River in Bolivia or the confluence of the Rhone and muddy Arve Rivers in Switzerland. Many of these large river confluences have contrasting turbidity and cross over major geological/ecological boundaries. We should expect stream segments downstream of significant confluences such as these to have characteristics (e.g., physiochemical, biological) different than adjacent upstream segments of the tributary and the main stem.

We anticipate that it is more common for small streams to merge with contrasting environmental and ecological characteristics such as thermal, sediment, or flow regimes, to become something entirely different supporting different fishes and invertebrates downstream of the confluence. Headwater streams are numerous and because of their small drainages, can be very specific to certain landscape conditions (e.g., geology type, land cover) and as a result even directly neighbouring streams can be different from each other. Such variation and juxtaposition in environmental characteristics is common in headwaters and is likely to cause ecological changes downstream of confluences in these areas and influence biological diversity (Finn et al. 2011).

In contrast, along large main stem rivers hundreds of small tributaries with small confluence symmetries may join without causing noticeable changes individually despite most likely being different from the large main stem that exhibits the average conditions of the drainage. Thus, the distance between significant confluences or different stream typologies becomes greater as rivers increase in size (Benda et al. 2004a,b). At the same time, small incremental changes in flow volume and environmental characteristics lead to continuous gradual changes in pattern and process. Such information is vital to researchers attempting to classify stream valley segments, particularly on large main stem valley segments. In many cases, there will not be a tributary large enough to cause significant changes in stream typology for many kilometers yet the river may have significantly increased in size (e.g., double bankfull width) since the last significant confluence upstream. Measures other than landscape characteristics described above need to be used to elicit a break in the stream segment (e.g., sudden changes in geology, waterfalls, drainage area). Such a spatial understanding of where

change is likely to occur within drainages helps to reconcile river continuum (gradual) and discontinuum (abrupt) views of patterns in rivers.

Basin shape has important implications for longitudinal patterns (Benda et al. 2004a, Rice 2016). Round-shaped drainages have more large tributaries likely capable of causing change compared to elongated drainages. The Saugeen River is a good example of a round drainage where significant changes do occur in the mid-reaches at major tributary confluences. Elongated drainages with narrow valleys, as noted on the North Saugeen River sub-watershed, have many small tributaries that by themselves cannot cause abrupt changes yet flows still accumulate leading to gradual change.

Streams are an integration of the landscape which ultimately define habitat for biota. Contrasting stream types merging at confluences have the potential to create ecotones and these heterogeneous junctures are often hot spots for local scale α biodiversity (Osborne and Wiley 1992; Kiffney et al. 2006; Milesi et al. 2014; Hellmann et al. 2015). Increasing to the basin scale, Finn et al. (2011) documented that among site β biodiversity of benthic invertebrates was much greater among headwater than in mid-order streams at both population-genetic and community levels. Small headwater streams contributed significantly to basin-scale biodiversity through high levels of among-site habitat variation across stream networks (Finn et al. 2011). We similarly found that headwater streams are diverse in characteristics because they often drain specific types of landscape, not the average condition of a larger area (Wiens 1989). The extremes associated with headwater streams have led to difficulties in modelling. Seelbach et al. (2011) noted how regression models predict the central tendency of data well but often fail in predicting extremes. They further note that small catchments are very abundant within river networks and suffer prediction errors as they often have homogeneous landscape characteristics

and are not well-represented by gaged data from long-term monitoring sites (Seelbach et al. 2011).

The NCH provides a physical basis for the likelihood of change in the characteristics of stream segments downstream of tributaries and patterns of heterogeneity of habitats across entire drainage networks. Through the inputs of water, sediment, and organic material, each tributary contributes to incremental change within a stream network: many are small changes and a few are large changes. Using simple confluence symmetry ratios and landscape similarity measures, other researchers can generate maps and an understanding of where to expect changes within stream networks. Our approach is not limited to mountain streams and their geomorphically significant confluences but is applicable to all stream types. Such spatially explicit hypotheses can be tested and help guide field sampling campaigns. Synthetic models and field research are required to determine which combinations of CSR and landscape similarity produce significant changes in abiotic conditions and the ecology for stream segments that are meaningful to management. Given the small magnitude of change expected at many confluences, ecological thresholds might be difficult to detect and determine what is significant given the natural spatial and temporal variability of streams and the resolution and extent of traditional sampling methods (Torgersen et al. 2008). Detection will likely be more successful by measuring physical variables such as small changes in discharge, water quality, and temperature than biological measures e.g., benthic invertebrate communities (but see Rice et al. 2001). Geographic information systems, remote sensing, innovative statistical and field methodological approaches and technologies, and new views such as network thinking will provide opportunities to develop testable hypotheses about ecological patterns and processes that will help protect and conserve flowing waters.

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Figures

Figure 1. The relationship between drainage basin size (area) and the heterogeneity of landscape types they contain. A) illustrates the many different landscape types, perhaps surficial geology (coloured polygons), that influence the Saugeen River at its outlet, B) shows a smaller nested subwatershed, which has noticeably fewer landscape types present within, and C) demonstrates that in the context of this scenario a very small headwater catchment can be composed of a single landscape type because its drainage area is smaller than the patch size. Note scale in the top right-hand corner of each panel.

Figure 2. The probability of an abrupt change downstream from a confluence is a function of both confluence symmetry ratio (CSR, the ratio of tributary drainage area to main stem drainage area) and the similarity of drainage characteristics in a logistic functional form (Equation 1). The probability of an abrupt change is high (red shade) when two streams merge of a similar size ($CSR > 0.8$) and drainage characteristics are similar (similarity < 10). As the similarity of the two drainages decreases (i.e., landscape characteristics), the inflection point of the logistic function shifts to progressively lower CSR values.

Figure 3. Area-weighted values of base flow index (BFI, Neff et al. 2005) as a function of drainage area (km^2). The mean base flow index value for all drainages combined is 46% and represented by the dashed line.

Figure 4. Confluence symmetry ratio vs the similarity of landscape characteristics by drainage size (area km^2). The absences of data points on the left side of $< 10 \text{ km}^2$ panel is an artifact of the minimum area (1 km^2) required to form a stream in our spatial base data such that the smallest ratio possible is $1/10 \text{ km}^2$ in the $< 10 \text{ km}^2$ bin.

Figure 5. Counts for confluences with various combinations of confluence symmetry ratio and similarity of drainage characteristics in southern Ontario. Red shade for low counts and green for high counts. The jagged vertical line separates combinations of CRS and landscape similarity that are significant (right side, probability of significant downstream effects ≥ 0.9) with confluences that are not significant (left side, probability of significant downstream effects ≤ 0.9).

Figure 6. Stream network map showing the probability of change *downstream of confluences* in the Saugeen River. The potential for change as a logistic function of confluence symmetry ratio and the (dis)similarity of landscape characteristics calculated as a Euclidean distance (see Fig. 2). North Saugeen (A), Rocky Saugeen (B), main channel Saugeen (C), Beatty Saugeen (D), South Saugeen (E), and Teeswater (F) shown with red water lines. Symbology for confluence symmetry ratio is reflected in size of circles at confluences. Colour ramp indicates probability for change in the stream segment downstream of the confluence. Red shade = high probability; green shade = low probability.

Figure 7. Expected patterns of change in the Saugeen River and its main tributaries based on the logistic function of confluence symmetry ratio and the (dis)similarity of landscape characteristics calculated as a Euclidean distance (see Fig. 2). North Saugeen (A), Rocky Saugeen (B), main channel Saugeen (C), Beatty Saugeen (D), South Saugeen (E), and Teeswater (F) shown with red water lines.

Figure 8. Upstream drainage area (km^2) in relation to the potential for change downstream of confluences in the Saugeen River. The main stem upstream drainage is used for area.

Figure 1. The relationship between drainage basin size (area) and the heterogeneity of landscape types they contain. A) illustrates the many different landscape types, perhaps surficial geology (coloured polygons), that influence the Saugeen River at its outlet, B) shows a smaller nested subwatershed, which has noticeably fewer landscape types present within, and C) demonstrates that in the context of this scenario a very small headwater catchment can be composed of a single landscape type because its drainage area is smaller than the patch size. Note scale in the top right-hand corner of each panel.

184x424mm (600 x 600 DPI)

Figure 2. The probability of an abrupt change downstream from a confluence is a function of both confluence symmetry ratio (CSR, the ratio of tributary drainage area to main stem drainage area) and the similarity of drainage characteristics in a logistic functional form (Equation 1). The probability of an abrupt change is high (red shade) when two streams merge of a similar size (CSR >0.8) and drainage characteristics are similar (similarity < 10). As the similarity of the two drainages decreases (i.e., landscape characteristics), the inflection point of the logistic function shifts to progressively lower CSR values.

95x95mm (600 x 600 DPI)

Figure 3. Area-weighted values of base flow index (BFI, Neff et al. 2005) as a function of drainage area (km^2). The mean base flow index value for all drainages combined is 46 and represented by the dashed line.

82x80mm (600 x 600 DPI)

Figure 4. Confluence symmetry ratio vs the similarity of landscape characteristics by drainage size (area km²). The absences of data points on the left side of <10 km² panel is an artifact of the minimum area (1 km²) required to form a stream in our spatial base data such that the smallest ratio possible is 1/10 km² in the <10 km² bin.

221x579mm (600 x 600 DPI)

		Confluence Symetry Ratio									
		Different					Similar				
		0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
Landscape Characteristics	Similar										
	10	738	415	302	238	222	206	209	166	164	195
	20	904	426	297	254	205	194	176	142	137	142
	30	884	294	190	147	138	102	92	79	79	78
	40	686	163	108	71	58	53	55	45	38	25
	50	441	91	48	35	42	26	18	30	21	19
	60	298	43	26	21	16	15	17	11	7	6
	70	135	22	20	8	8	6	7	4	3	3
Different	80	76	10	5	4	0	2	0	3	2	1
	90	25	1	2	1	1	1	1	2	0	0
	100	2	2	0	0	0	0	0	0	0	0

Figure 5. Counts for confluences with various combinations of confluence symmetry ratio and similarity of drainage characteristics in southern Ontario. Red shade for low counts and green for high counts. The jagged vertical line separates combinations of CRS and landscape similarity that are significant (right side, probability of significant downstream effects ≥ 0.9) with confluences that are not significant (left side, probability of significant downstream effects ≤ 0.9).

95x95mm (300 x 300 DPI)

Figure 6. Stream network map showing the probability of change downstream of confluences in the Saugeen River. The potential for change as a logistic function of confluence symmetry ratio and the (dis)similarity of landscape characteristics calculated as a Euclidean distance (see Fig. 2). North Saugeen (A), Rocky Saugeen (B), main channel Saugeen (C), Beatty Saugeen (D), South Saugeen (E), and Teeswater (F) shown with red water lines. Symbology for confluence symmetry ratio is reflected in size of circles at confluences. Colour ramp indicates probability for change in the stream segment downstream of the confluence. Red shade = high probability; green shade = low probability.

129x96mm (600 x 600 DPI)

Figure 7. Expected patterns of change in the Saugeen River and its main tributaries based on the logistic function of confluence symmetry ratio and the (dis)similarity of landscape characteristics calculated as a Euclidean distance (see Fig. 2). North Saugeen (A), Rocky Saugeen (B), main channel Saugeen (C), Beatty Saugeen (D), South Saugeen (E), and Teeswater (F) shown with red water lines.

89x43mm (300 x 300 DPI)

Figure 8. Upstream drainage area (km2) in relation to the potential for change downstream of confluences in the Saugeen River. The main stem upstream drainage is used for area.

78x72mm (300 x 300 DPI)