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Overview

Key factors influencing differences in stream water quality across space

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Globally, many rivers are experiencing declining water quality, for example, with altered levels of sediments, salts, and nutrients. Effective water quality management requires a sound understanding of how and why water quality differs across space, both within and between river catchments. Land cover, land use, land management, atmospheric deposition, geology and soil type, climate, topography, and catchment hydrology are the key features of a catchment that affect: (1) the amount of suspended sediment, nutrient, and salt concentrations in catchments (i.e., the source), (2) the mobilization ,and (3) the delivery of these constituents to receiving waters. There are, however, complexities in the relationship between landscape characteristics and stream water quality. The strength of this relationship can be influenced by the distance and spatial arrangement of constituent sources within the catchment, cross correlations between landscape characteristics, and seasonality. A knowledge gap that should be addressed in future studies is that of interactions and cross correlations between landscape characteristics. There is currently limited understanding of how the relationships between landscape characteristics and water quality responses can shift based on the other characteristics of the catchment. Understanding the many forces driving stream water quality and the complexities and interactions in these forces is necessary for the development of successful water quality management strategies. This knowledge could be used to develop predictive models, which would aid in forecasting of riverine water quality. © 2017 The Authors. *WIREs Water* published by Wiley Periodicals, Inc.

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INTRODUCTION

Many rivers across the globe are experiencing declining water quality.[1–3] Over 45% of rivers in China[4] and over one third of rivers in the United States[5] have been classified as polluted. Additionally, most rivers, lakes, and estuaries in Australia are experiencing higher sediment and nutrient loads compared to European settlement approximately 250 years ago.[6] High pollution levels not only threaten the use of rivers as a source of potable water for humans,[7] but can also contribute to the degradation of rivers.[4,8] As such, there is an urgent need for

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water quality management strategies that can help reverse this trend of degrading water quality.

Riverine water quality can vary significantly both within and between river catchments.[9–12] For example, total suspended solids (TSS) concentrations range from 10 to 1700 mg/L globally.[13] At finer scales, total phosphorus (TP) and total nitrogen (TN) concentrations ranged from 0.016 to 0.18 mg/L and 0.34 to 3.55 mg/L, respectively, across 32 stream catchments in Finland.[14] The spatial variability in water quality has also been observed within individual river catchments. Amongst 12 monitoring sites in the 730 km^2 Jinshui River catchment (China), median TN, and total dissolved phosphorus (TDP) concentrations measured between 2006 and 2008 ranged from 0.01 to 4.38 mg/L and 0.022 to 4.16 mg/L, respectively.[15] In a larger catchment of 26,219 km^2 in Korea (Han River basin) the time-averaged concentrations (2000–2002) varied from below detection up to 36 mg/L (TSS), 1.6 mg/L (TP), and 35 mg/L (TN).[9] Observed variability both between and within river catchments has been largely attributed to the influence of landscape characteristics such as land cover, land management, climate, atmospheric deposition, and topography.

This review aims to summarize the current understanding of the key landscape characteristics that influence spatial variability in riverine water quality and to highlight the remaining major knowledge gaps. The link between the anthropogenic impacts of changes in land use/land cover on water quality has been previously studied extensively,[16–19] but the effect of other naturally-occurring landscape characteristics such as geology, soil type, and topography have been relatively less studied.[20,21] This review focuses on suspended sediments, nutrients (particulate and dissolved phosphorus and nitrogen species), and salts. These constituents have been selected because they have been widely studied, and because they can have deleterious impacts on receiving rivers. High-suspended sediment concentrations can result in turbid waters, the smothering and scouring of habitats and biota and decreased light penetration. In addition, heavy metals, persistent organic pollutants (POPs), nutrients, and microorganisms (e.g., pathogens) can be bound to these sediments, thus providing a pollutant source.[22–25] Nitrogen and phosphorus exist in both the particulate and the dissolved forms, and high concentrations of dissolved nutrients can lead to eutrophication in river systems.[26] High salt concentrations in water are of concern because salts can be toxic to flora and fauna. [24] We intend this review to be of use to researchers and practitioners aiming to develop catchment water quality management solutions and infrastructure, and water quality models. First, we provide a summary of the important factors underlying the spatial differences in particulate and dissolved constituent concentrations in rivers and streams. We then discuss the limitations in the existing literature: namely the lack of understanding of the effect of interactions between landscape characteristics on water quality.

LANDSCAPE CHARACTERISTICS THAT INFLUENCE STREAM WATER QUALITY RESPONSES

Based on the conceptual framework by Granger et al.[27], riverine water quality is driven by three key processes: (1) the application or presence of constituent sources within the catchment (source), (2) the mobilization of these constituents from their sources (mobilization), and (3) their delivery to receiving streams and rivers (delivery) (Figure 1). First, constituents such as nutrients and salts may be applied to

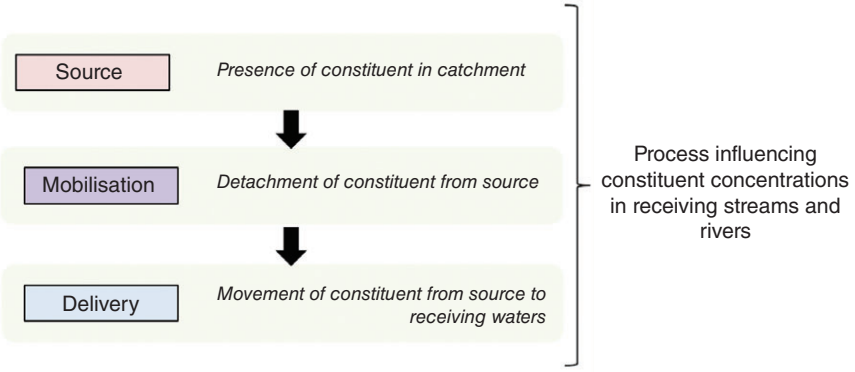

FIGURE 1 | Conceptual framework proposed by Granger et al.[27] that explains constituent concentrations in receiving rivers and streams.

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catchments from external sources (e.g., fertilizers) or they may be present in the catchment or in the stream itself as a result of natural processes (e.g., in the soils or by atmospheric deposition).

Constituents can be mobilized from the catchment by low-energy processes (e.g., desorption, mineralization) or high-energy processes (e.g., erosion, landslide or failure, freeze–thaw). The instream mobilization of constituents can also occur by streambank erosion, organic matter decay, or nutrient cycling. As demonstrated in Figure 2, suspended solids (both organic and inorganic particulates) are mobilized by processes of weathering or displacement by wind, water, or anthropogenic activities.[28,29] Phosphorus and nitrogen can exist in both the particulate and dissolved forms, and the form of the nutrient affects the mobilization processes.[30] The particulate species of these nutrients undergo similar mobilization processes to sediments[31] (Figure 2). Dissolved nutrients can also be mobilized by displacement by runoff or anthropogenic activities.[30] However, in addition, the dissolved nutrient species can be mobilized by the mineralization of organic matter or desorption from particulates.[32] Salts are generally in the dissolved form, and as such are mobilized by weathering and dissolution from soils and parent rock as well as dryland and irrigation salinity processes.

Finally, the delivery of constituents may occur by surface flow, subsurface flows, or artificial drainage systems. Not all constituents in the catchment are necessarily mobilized and delivered to streams. The proportion of mobilized sediments transported from the catchment to receiving waters is sometimes called the 'delivery ratio,' and this concept is also valid for other constituents.[33–35] Suspended sediments are generally transported by overland flow pathways into receiving rivers, with finer sediments sometimes transported by subsurface flows.[36,37] Whilst sediments can be removed from the delivery pathway by sedimentation or filtration, these are relatively inert compounds that do not transform. Similarly, nutrients in the particulate phase are largely transported by overland flow pathways, with dissolved nutrients transported by both overland and subsurface flows. Indeed, previous studies have identified that particulate phases of phosphorus are more readily transported by surface flows and dissolved phases by subsurface flows.[38] The proportion of dissolved nutrients in the subsurface flow pathway depends on landscape characteristics.[39,40] Nitrogen was largely transported by subsurface flows in catchments with permeable soils in three UK catchments.[40] Similar to sediments, particulate species of nitrogen and phosphorus can be taken out of the delivery flow path by sedimentation. The dissolved phosphorus and nitrogen species in these flow paths can undergo biogeochemical transformations and be removed from both surface and subsurface flows by processes such as adsorption (phosphorus) and denitrification (nitrogen). Similarly, mobilized salts can be transported to receiving waters by surface and subsurface flows, the proportioning of which depend on specific landscape features.

Constituent delivery is often conceptualized in terms of connectivity.[41–45] Constituents are only delivered to streams if water is delivered to the stream (either through surface or subsurface flow paths) and if the constituent remains in the water that is being delivered to the stream. This connectivity can vary significantly over both space and time.[46] In particular, sedimentation and transformation of constituents can occur during the delivery process, and hence catchment conditions that increase sedimentation and transformation can decrease the connectivity.[46] As such, the delivery of constituents to streams is dependent on the time it takes for constituent sedimentation and transformation to occur, relative to the time it takes for the constituent to be transported from the catchment to receiving streams.[46]

The source, mobilization, and delivery of sediments, nutrients, and salts (Figure 2) vary temporally and spatially.[47] Although temporal variability in riverine water quality is not a focus of this review, we discuss this briefly in Box 1. Spatial variability in riverine water quality occurs as a result of landscape characteristics including land cover, land use, land management, atmospheric deposition, geology and soil properties, climate, and topography. Catchment hydrology, which is strongly influenced by climate, geology, and soil type, can also play a significant role in the delivery of constituents from the catchment to receiving waters (Figure 3). Each of these landscape characteristics is a collection of different factors that can lead to specific stream water quality responses (Table 1). For example, climatic factors such as rainfall, temperature, and evapotranspiration rates can affect the source, mobilization, and delivery of constituents (Table 1).

The following discussion addresses the impact of each of the landscape characteristics and factors listed in Table 1 on (1) constituent sources in the catchment, (2) mobilization, and (3) delivery to rivers and streams. Several complexities in the relationship between landscape characteristics and receiving water quality are discussed at the end of this

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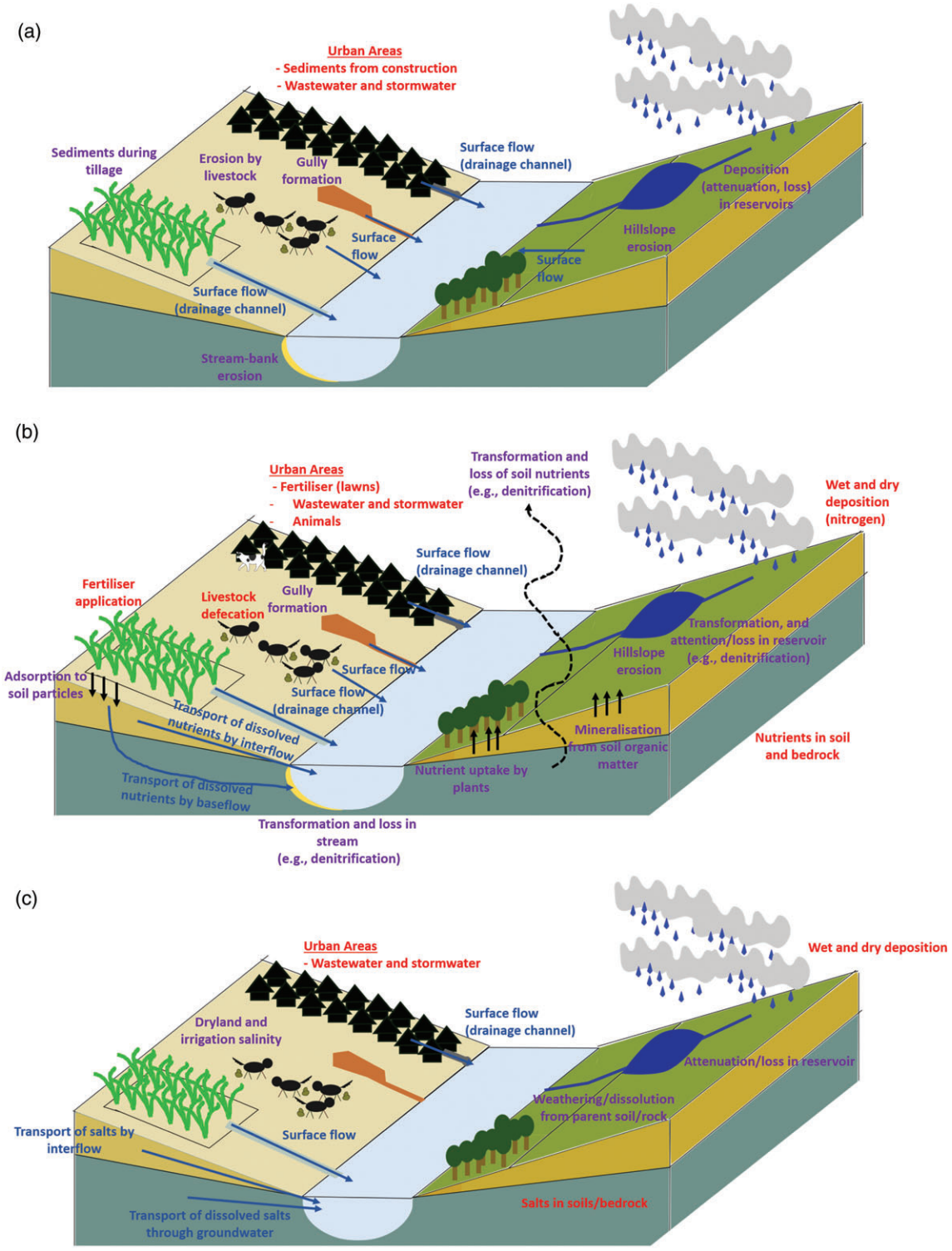

FIGURE 2 | Sources, mobilization, and delivery of sediments (a), nutrients (b), and salts (c) to catchment outlet. Red text represents sources, purple text represents mobilization, and blue text and arrows represent delivery processes.

section. These complexities include the effect of distance between the constituent source and receiving waters on receiving water quality, the cross correlations between landscape characteristics, and the seasonal shift in the importance of different landscape characteristics.

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BOX 1

SEASONAL CHANGES IN WATER QUALITY AT A SITE

The sediments,[139,143] nutrient species,[74,116,144–146] and salts[70] concentrations in receiving streams shift seasonally. This is due to the seasonal changes in source, mobilization, and transport processes. Sources can vary temporally as a result of seasonality in land use patterns (e.g., seasonality in fertilizer application). In addition, climatic conditions can be important. The length of the dry weather period preceding the runoff event impacts the amount of constituents accumulated in the catchment prior to being washed off by surface or subsurface flows.[74,143,145] Temperature and soil moisture conditions (governed by rainfall and evapotranspiration) can influence the connectivity of different flow paths[147], efficiency of biogeochemical processes, and denitrification in catchment soils.[143,145,148–150] The mobilization of constituents can also vary over time as a result of seasonal shifts in vegetation growth and climate (temperature, total rainfall, and rainfall intensity). Season and temperature can affect ground cover and the presence of snow, which in turn affects mobilization and delivery processes. For example, 'rain-on-snow' events, or runoff over frozen soils has been found to contribute significant amounts of nitrate to receiving waters (up to 40% of annual nitrate export in Southern Ontario, Canada).[151] It has been proposed that this is due to impact of snow cover and frozen ground on hydrological flow paths (i.e., the lack of contact between nitrates and soils), and also due to the decrease in biological activity (and denitrification) in winter.[152,153]

The delivery of constituents from the catchment to receiving streams is largely driven by surface and subsurface flow, and the flow paths that transport the constituent depends significantly on its speciation. As a result, the amount of mobilized constituents delivered to the stream can vary with seasonal shifts in flow.[139,150,154–158] Due to the importance of overland runoff in transporting sediments, particulate nutrients and salts (in urban catchments only) to receiving streams, it is often assumed that these constituents have a positive relationship to river discharge.[114,136,139,159] On the other hand, in rural catchments, salts and dissolved nutrients are typically transported by subsurface flows, and as such they are assumed to have a negative relationship to river discharge, when this discharge is entering the river largely through overland runoff. [158,160] There can also be more complex relationships between concentration and flow.[146] Nitrate (which is often in the dissolved form) often first increases with flow as nitrate rich soil water reservoirs connect to the stream but then decrease with further flow increases due to dilution.[46]

Land Cover, Land Use, and Land Management

The links between land cover, land use and land management, and riverine water quality have been explored extensively in previous reviews[16,18,24,47,57,73,161], and therefore are discussed only briefly here. Despite this past work, there is still little understanding of how land cover, land use, and land management interact with other catchment characteristics to yield specific water quality responses.

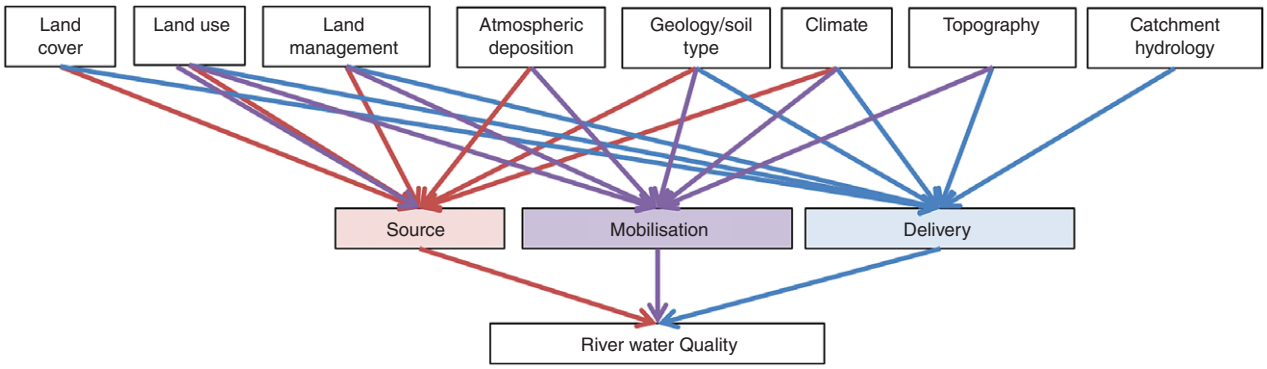

FIGURE 3 | Influence of landscape characteristics on source, mobilization, and delivery of constituents.

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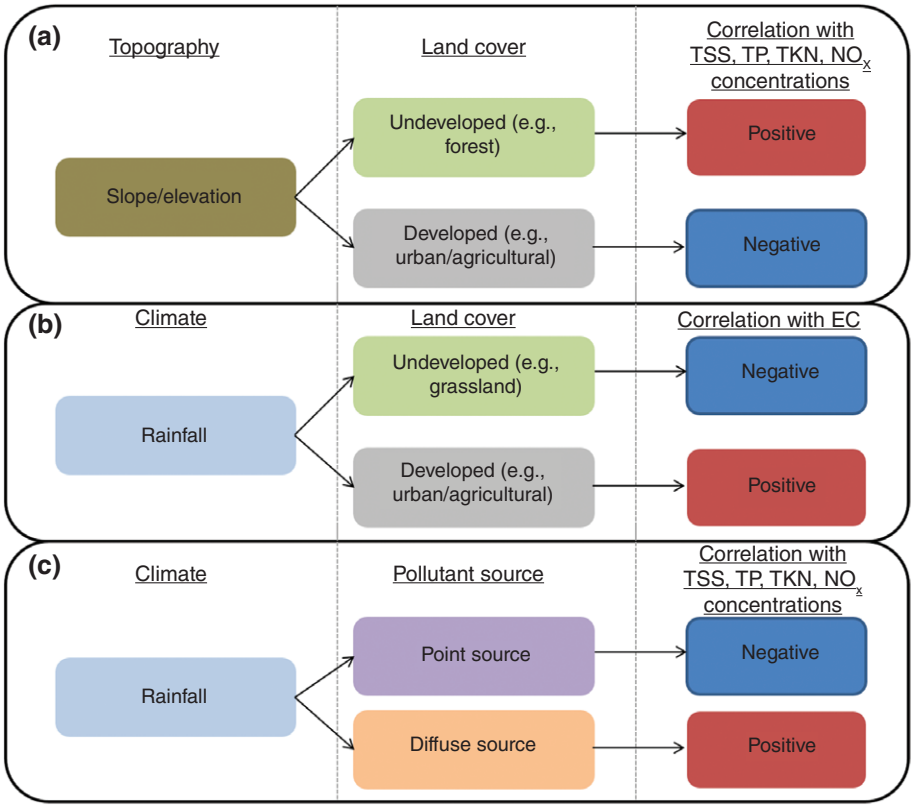

FIGURE 4 | Interactions between landscape characteristics (left column) and concentrations (right column) identified in literature. The middle column is the factor modulating the sign of the correlation. (a) Refs [10,74,126,137,178,234,235,237,278,293,294], (b) Refs [101,134,135,139,227], and (c) Ref [269].

Sources: Influence of Land Cover, Land Use, and Land Management

Land Cover

Land cover, defined here as the amount and type of vegetation present in a catchment, can affect the amount of nutrients present the catchment. Soil nutrient levels within catchments can decrease due to the uptake of bioavailable phosphorus and nitrogen by terrestrial vegetation.[48,49,52,162] The uptake of bioavailable nutrients can also occur within the stream or river itself, by aquatic plants.[48] Nutrient assimilation rates can vary according to both vegetation type[163,164] and age.[165] For example, forests are more effective in removing nitrogen from catchment soils, compared to grasslands and shrubs.[51,54] The greatest nutrient uptake rates often occur at the peak growing period of the vegetation.[48] In addition, nitrogen can be lost from vegetated catchment soils by microbially-mediated transformations.[51,54,60] In the Taizi River basin (China), there were negative correlations between vegetation cover and particulate and dissolved nitrogen (NH_3 and NO_2^-) and both particulate and dissolved phosphorus (TP and PO_4) concentrations in rivers.[166]

Land Use

The extent and type of human activities in the catchment (i.e., the land use) can influence the magnitude of sediments, nutrients, and salts sources. First, the presence of vegetation, which in itself affects nutrient levels in catchments, can be greatly influenced by the land use, with less dense vegetation in urban and agricultural regions. Urban, industrial, and agricultural land uses also produce high levels of sediment, nutrients (both particulate and dissolved), and salts (Table 1). A study of North-West USA rivers found a positive correlation between TP concentrations at 14 river locations and the proportion of the catchment urbanized.[126] Sediments can be present in industrial and domestic wastewater in urban areas.[64,167] Urban and agricultural areas generate both particulate and dissolved nutrients through: (1) the discharge of wastewater,[64,65] (2) construction debris, [66,71] (3) the application of manure and fertilizers on lawns and parks (in urban areas) and on crop and grazing lands,[19,168], (4) waste from livestock,[25,74,75] and (5) atmospheric deposition, often from urban and industrial regions.[169] Similar to nutrients, salts can also be contained in industrial and domestic wastewater[68], and fertilizers.[80,170] In

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TABLE 1 | Summary of Key Factors That Can Influence Spatial Variability in the Source, Mobilization, and Delivery of Suspended Solids, Salts, and Nutrient Concentrations in Catchments, Identified from a Review of Existing Literature

			Constituent Source Availability				Constituent Mobilization				Constituent Delivery			
	Characteristic		Sed	P	N	Salts	Sed	P	N	Salts	Sed	P	N	Salts
Land cover	Vegetation amount		(0)	(–) [24,48–51]	(–) [24,49–54]	(0)	(–)[24,55–57]	(–)[58,59]	_()[54,58–60]	(–)[61–63]	(–)[57]	(–)[57]	(–)[57]	(0)
Land use	Urban	Wastewater	(+)[64]	(+) [64–66]	(+)[64–67]	(+)[68]	(0)	(0)	(0)	(0)	(0)	(0)	(0)	(0)
		Fertilizer application	(0)	(+)[66,69]	(+)[69]	(0)	(0)	(0)	(0)	(0)	(0)	(0)	(0)	(0)
		Deicing	(0)	(0)	(0)	(+)[70]	(0)	(0)	(0)	(0)	(0)	(0)	(0)	(0)
		Construction	(+) [66,71]	(0)	(0)	(0)	(+) [66,71]	(+) [66,71]	(+) [66,71]	(0)	(0)	(0)	(0)	(0)
		Increase in impervious surfaces	(0)	(0)	(0)	(0)	(0)	(0)	(0)	(0)	(+)[57,72,73]	(+)[57,72,73]	(+)[57,72,73]	(+)[57,72,73]
		Stormwater discharge	(0)	(0)	(0)	(0)	(0)	(0)	(0)	(0)	(+)[72]	(+)[72]	(+)[72]	(+)[72]
	Agriculture	Livestock presence	(0)	(+)[25]	(+)[25,74,75]	(0)	(+)[76]	(+)[76]	(+)[76]	(0)	(0)	(0)	(0)	(0)
		Irrigation	(0)	(0)	(0)	(0)	(0)	(0)	(0)	(+)[24,25,77]	(0)	(0)	(0)	(0)
		Fertilizer application	(0)	(+)[19,78]	(+)[19,74,78,79]	(+)[79,80]	(0)	(0)	(0)	(0)	(0)	(0)	(0)	(0)
		Tillage	(0)	(0)	(0)	(0)	(+)[81]	(+)[81,82]	(+)[81,82]	(0)	(0)	(0)	(0)	(0)
		Gully formation and erosion	(0)	(0)	(0)	(0)	(+)[55,83]	(+)[55,83]	(+)[55,83]	(0)	(0)	(0)	(0)	(0)
		Drainage and channels	(0)	(0)	(0)	(0)	(×)	(0)	(0)	(0)	(+)[25,84]	(+)[25,84]	(+)[25,84]	(+)[25,84]
Land management	Extent of best management practices		(0)	(–)[75,76,85–89]	(–)[75,76,85–91]	(–)[85,86]	(–)[75,76,85–88,91]	(–)[75,76,85–89]	(–)[75,76,85–91]	(–)[85,86,92–94]	(–)[95,96]	(–)[95,96]	(–)[95,96]	(–)[95,96]
Geology and soil	Susceptibility of soil/bedrock to erosion/weathering		(0)	(0)	(0)	(0)	(+)[97]	(+)[58,98–100]	(+)[58,75]	(+)[68,101]	(0)	(0)	(0)	(0)
	Nutrient (or salt) content of soil/bedrock		(0)	(+)[19,102–104]	(+)[103–105]	(+)[49,67,101,106]	(0)	(0)	(0)	(0)	(0)	(0)	(0)	(0)
	Soil/aquifer conductivity		(0)	(0)	(0)	(0)	(0)	(0)	(0)	(0)	(0)	(+)[14]	(+)[74,107]	(+)[108]
	Soil sorption capacity		(0)	(0)	(0)	(0)	(0)	(+)[14,79]	(+)[14,21,79]	(0)	(0)	(0)	(0)	(0)
Climate	Average rainfall intensity and duration		(0)	(0)	(0)	(0)	(+)[109,110]	(+)[111,112]	(+)[74,111]	(0)	(+)[113]	(+)[112]	(+)[113]	(0)
	Temperature		(0)	(–)[114,115]	(–)[115–117]	(0)	(+)[118] (–)[118]	(+)[74]	(+)[74,119]	(0)	(0)	(0)	(0)	(0)
	Mean annual rainfall		(0)	(0)	(+)[120]	(+)[121] (–)[49,61,101]	(0)	(–)[122]	(+)[116,120]	(0)	(+)[33,113,123,124]	(+)[33,111,113]	(+)[33,74,111]	(0)
	Mean annual potential evapotranspiration		(0)	(0)	(0)	(0)	(–)[118]	(0)	(0)	(+)[49,101]	(0)	(0)	(0)	(0)
	Atmospheric deposition		(0)	(0)	(+)[145]	(0)	(0)	(0)	(0)	(0)	(0)	(0)	(0)	(0)
Topography	Elevation/Slope		(0)	(0)	(0)	(0)	(+)[21,113,125–127]	(+)[21,125,127]	(+)[21,125,128,129]	(0)	(0)	(–)	(–)	(0)
	Catchment size		(0)	(0)	(0)	(0)	(0)	(0)	(0)	(0)	(–)[33,55]	(–)[130,131]	(–)[74,120,132]	(0)
	Stream density		(0)	(0)	(0)	(0)	(+)[55,133]	(+)[55]	(+)[55]	(0)	(0)	(0)	(0)	(0)

(*continued overleaf*)

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TABLE 1 | Continued

		Constituent Source Availability					Constituent Mobilization			Constituent Delivery			
Catchment Hydrology	Density of dams, lakes and wetlands	(0)	(0)	(0)	(0)	(0)	(0)	(0)	$(-)^{134,135}$	$(-)^{74}$	$(-)^{116,136-138}$	(0)	
	Baseflow contribution	(0)	(0)	(0)	(0)	(0)	(0)	(0)	$(-)^{65,139}$	$(-)^{65,140}$	$(+)^{141,142}$ $(-)^{141}$	$(+)^{101}$	

Notes: Red cells represent positive effect (factor leading to increase in constituent), blue cells represent negative effect (factor leading to decrease in constituent), purple cells report both positive and negative results, and empty cells represent no positive or negative effect. Numbers in the table cells are those references upon which the result is based (see reference list). See following discussion of how specific factors affect constituent generation and transport. 'Sed' represents total suspended solids, 'P' represents phosphorus (and its species), 'N' represents nitrogen (and its species), and 'Salts' represents salts. (+), positive correlation; (−), negative correlation; (+)(−), both positive and negative correlation; (0), neither positive nor negative correlation.

addition, in urban catchments with snow, salt is applied in winter for deicing.[70] These salts can remain in soils and can be transported to surface waters in other seasons (e.g., summer) or years after application.[171] However, deicing as a source of salts is generally not an important factor in catchments in warmer climates.

Land Management

The size and number of constituent sources in catchments can also be influenced by land management practices. Methods implemented for reducing constituent sources in urban and agricultural (Table 2) catchments are mostly 'non-structural,' at-source pollution reduction techniques which include street sweeping (to reduce constituents carried by stormwater into receiving streams), and reduction in the use of salts and fertilizers within the catchment using public education, regulation, or incentives.[85,86,183] For example, ceasing nutrient application to land was found to result in a decrease in dissolved phosphorus concentrations in overland runoff from over 4 to 0.22 mg/L over a period of 6 years in Oklahoma, USA.[184]

Mobilization: Influence of Land Cover, Land Use, and Land Management

Land Cover

Vegetation cover (both amount and type) in the catchment can influence the mobilization of sediments. Less soil erosion occurs in vegetated catchments, because vegetation protects the soil from wind, rain, and overland runoff.[24] Consequently, there tends to be less gully formation, hillslope erosion, and streambank erosion in vegetated catchments.[55,76,185,186] Comparison of forested and deforested sites in Ecuador indicated that TSS concentrations ranged from 3.7–14.1 mg/L (canopy cover >50%) in forested sites and had a higher range of 3.0–19.2 mg/L in deforested sites (canopy cover <50%). Similarly, catchments with more than 90% forest cover were found to have TSS concentrations of 68–149 mg/L in streams, compared to catchments with 70–80% forest cover, which had higher concentrations of 829–456 mg/L.[187] Nutrients (phosphorus and nitrogen) can be adsorbed onto these particulate sediments,[58,59] thereby resulting in a concurrent increase in nutrient yields. This affects phosphorus more so than nitrogen, as P is more prone to adsorption onto particulates.[188,189] Nutrients in the dissolved form are less affected by these mobilization processes and are generally mobilized from soils and transported through subsurface flows and

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groundwater.[38,190] Once deposited in streams, these sediments can act as nutrient sources. However, it is important to note that dense, managed forests can still provide sediments and particulate nutrients to receiving waters under certain climatic and topographic conditions.

Land cover has also affected the mobilization of salts in catchments. The clearing of land for agriculture led to the replacement of vegetation that kept the water table low with shallow rooted (and less transpiring) vegetation, contributing to rising saline groundwater tables (dryland salinity).[62,63] Deforestation has had a particularly severe effect on salinization in subhumid and semiarid areas.[61]

Land Use

Activities within the catchment that can mobilize sediments include: (1) erosion from construction activities[66,71]; (2) erosion due to livestock presence;[76] (3) preparation of the land for cropping;[81] or (4) the creation of gullies due to agricultural practices.[83] These human activities can also contribute to the increased mobilization of some nutrient species in the particulate form, specifically phosphorus because this nutrient tends to bind to particulates.[188,189] Indeed, sediment, TP, and TN event mean concentrations in Australian streams with catchments used for dryland cropping were 32, 4, and 3 times greater than concentrations in streams with forested catchments.[191] It should be noted that the mobilization of dissolved and colloidal nitrogen and phosphorus is less impacted by land use. This is because mobilization and delivery largely occurs via groundwater and subsurface flows rather than surface flows.[38,190]

Agricultural activities can also mobilize salts stored within catchment soils. The rise in the water table due to high levels of irrigation in agricultural areas can mobilize naturally deposited salts within the soil strata and bring them to the surface (irrigation salinity).[24] It is estimated that soil salinity affects approximately 7% of irrigated land globally.[25,77]

Land Management

Due to the impact of construction activities, cropping, and livestock trampling on sediment mobilization within the catchment, management strategies such as increasing vegetation cover, reducing stocking rates, and fencing off riparian zones[76] (Table 2) can reduce the mobilization of sediments and their associated nutrients from the catchment and stream banks. For example, in a field study in North-East Australia, revegetation of slopes from 35 to 75% coincides with a decrease in annual sediment yields of up to 70%.[192] In addition, strategies such as reducing rates of irrigation and planting vegetation with high transpiration rates have been implemented in agricultural areas to reduce salt mobilization.[93,94]

Delivery: Influence of Land Cover, Land Use, and Land Management

Land Cover and Land Use

Land cover and land use also influence the delivery of suspended sediments, nutrients, and salts from the catchment to rivers and streams. A decrease in vegetation cover increases constituent delivery due to the resulting decrease in channel and surface roughness.[57] Decreased surface roughness leads to greater overland runoff velocity and a lower likelihood that sediments and nutrients within this surface flow will be lost by sedimentation (for particulates) or biogeochemical transformations (for dissolved species) before reaching the receiving river or stream. A laboratory study of vegetated filter strips found that the presence of vegetation can increase the trapping efficiency of sediment from approximately 26 to 86% under Canadian rainfall conditions.[193]

Increasing urban and agricultural areas can also lead to greater delivery of suspended solids, nutrients, and salts to rivers. This is a result of the greater connectivity between the catchment and receiving waters via drainage networks.[47] Contaminants in stormwater, wastewater, and agricultural runoff are discharged quickly into rivers by pipes, drains, and channels with minimal loss of contaminants by infiltration or evaporation.[25,72,84] The imperviousness of drainage channels results in greater runoff velocity, and hence: (1) a decrease in residence time, which limits sedimentation of particulates and/or loss of both particulate and dissolved nutrients by transformation (e.g., loss of nitrogen by denitrification) and (2) greater energy of the runoff to transport contaminants over longer distances.[47] In addition, the impervious surfaces in urban areas result in a greater frequency in overland runoff events because of reduced infiltration. This also increases the frequency with which constituents are delivered to receiving rivers and streams.[57] The frequency of overland runoff events (stormwater runoff) and the delivery of this surface flow to receiving rivers impacts phosphorus and nitrogen in the particulate forms. This is particularly true for phosphorus, which is more commonly found in its particulate state.

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TABLE 2 | Land Management Strategies in Agricultural and Urban Areas Used for Limiting the Sources and Mobilization of Constituents

Process	Target Constituent	Management Strategy	Effect of Management Strategy on Constituent Generation
Source	Sediments, particulate and dissolved nutrients, and salts	Street sweeping	Street sweeping can reduce the amount of pollution on urban surfaces that can be mobilized and delivered by overland runoff to receiving waters. This is generally effective in removing large particles.[172]
	Particulate and dissolved nutrients	Reduce stock access to waterways	Livestock can directly deposit nutrients into waterways by urinating and defecating.[75]
		Reduce fertilizer application rates and manage fertilizer application method and timing	Reduction in fertilizer application (optimizing to the crop requirements) and timing (apply during plant growth periods) and method of application (surface vs subsurface, liquid vs solid forms) can reduce the leaching of excess nutrients.[173,174]
		Implement crop rotations using nitrogen fixing crops	Implementing crop rotation systems (e.g., planting legumes, which can fix nitrogen) can improve soil quality, reducing the need for fertilizer application.[89,90,175]
Mobilization	Sediments and nutrients (particulate)	Increase vegetation cover (including the use of winter cover crops, crop residue retention)	Presence of vegetation reduces impact of rainfall on soil and soil erosion.[90] In addition, vegetation on gully walls and streambanks reduces erosion.[91]
		Reduce soil disturbance during tillage (e.g., use conservation tillage approaches)	Mixing and disturbance of soil can lead to greater losses of both sediments and nutrients from the catchment.[87,88]
		Reduce stocking rates in grazing lands and fencing off gullies and river banks	Livestock can trample vegetation, destabilize streambanks, and gully slopes by soil compaction.[75,76]
	Salts	Reduce irrigation and manage timing and method	Altering the timing and method of irrigation can reduce the amount of excess water percolating through the soil (not used by vegetation) that can contribute to the rise in the water table.[176]
		Increase amount of vegetation that has high evapotranspiration rates in cleared areas.	Increasing the amount of vegetation that keeps the water table low through evapotranspiration ensures that the salts remain deep in the soil.[94]
Delivery	Sediments, particulate and dissolved nutrients, and salts	Vegetate and preserve riparian zones	Vegetated riparian buffer zones can remove particulate compounds from overland runoff, and dissolved compounds from subsurface flows.[177,178]
		Implement water sensitive urban design (WSUD) or low-impact design (LID) technologies	The implementation of WSUD or LID technologies such as permeable pavements, infiltration systems, biofilters, constructed wetlands, and rainwater tanks both decrease overall runoff volumes and can lead to reduced constituent concentrations in surface and subsurface runoff.[96,179–182]

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Land Management

Land management practices influence the delivery of constituents from the catchment to receiving waters. In both nonurban and urban areas, vegetated buffer strips and the preservation of riparian zones can obstruct the delivery of suspended sediments, particulate nutrients, and dissolved nutrients into receiving streams.[95] In urban areas, water sensitive urban design (WSUD) or low impact development (LID) technologies such as stormwater biofilters, infiltration systems, and rainwater tanks treat and reduce overland runoff, and therefore reduces the transport of sediments from the catchment to receiving streams.[96,179–182] For example, a global meta-analysis of the effectiveness of WSUD technologies such as riparian buffer strips showed that they have a 91% median removal rate of dissolved nitrite–nitrate from subsurface and surface flows. This is hypothesized to result from the uptake of dissolved nutrients by vegetation.[178]

Atmospheric Deposition

Sources: Influence of Atmospheric Deposition

Wet and dry deposition can act as a source of nitrogen in a catchment or in the stream itself, [24,49,164,194] and atmospheric deposition of nitrogen varies significantly on a global scale .[195] The amount of atmospheric deposition of nitrogen can vary between catchments due to land use. In particular, fossil fuel combustion contributes to spatial variability in atmospheric nitrogen deposition.[25,196] Emissions from agriculture (fertilizers and livestock) can contribute to atmospheric nitrogen,[197] with approximately 70% of atmospheric nitrogen emissions, globally, originating from food production processes.[198] Previous studies identified the important contribution of atmospheric deposition to nitrogen levels in rivers and streams (e.g., up to 40% in the Chesapeake Bay basin, USA).[199] This can be greater in pristine environments, where the largest source of nitrogen can be atmospheric deposition.[200] Furthermore, nitrogen deposition was found to parallel stream NO_x concentrations (sum of nitrogen species: nitrate and nitrite) in the Northeastern United States.[201]

Mobilization: Influence of Atmospheric Deposition

The chemicals contained within both wet and dry deposition can affect the mobilization of nutrients from soils and rocks in the catchment. For example, nutrients (specifically nitrogen) can be mobilized from soils due to increased acidity by acid rain.[202]

Geology and Soil Type

Sources: Influence of Geology and Soil Type

The chemical characteristics of soils and rocks in the catchment influence the magnitudes of nutrient[19,102,103,105] and salt sources in catchments.[49,67,101] Phosphorus, nitrogen, and salts are contained within sedimentary deposits; approximately 20% of the world's nitrogen is contained within sedimentary deposits.[105] Statistically significantly higher phosphorus exports from catchments containing sedimentary geological deposits were identified in Southern Ontario, Canada.[102] Similarly, when underlain with marine bedrock or sediments, greater salt levels in the catchment can be transported to receiving waters.[67,68,101] The chemical composition of these rocks and soils can be affected by the age of the material, with nutrient and salt levels being lower in ancient soils.[203] The chemical composition of these rocks and soils can also be affected by previous atmospheric deposition of contaminants (specifically, nitrogen).[204] The nutrients and salts contained within the bedrock and soils of a catchment can be mobilized by weathering, erosion (for particulate constituents) dissolution, and desorption (for dissolved constituents).

Mobilization: Influence of Geology and Soil Type

Soil and rock erodibility as well as soil sorption capacity can have an influence on constituent mobilization in catchments. First, the mobilization of sediments is positively correlated to the susceptibility of the geological deposit and the soil within the catchment to erosion and weathering[24,25] (Table 1). For example, sediment erodibility explained 19% of the variability in the annual sediment yield in the Chesapeake Bay watershed, USA.[97] Similarly, laboratory studies using plots of 81 m^2 found that an increase in soil stability of over 17% led to a decrease in soil loss by over 25%.[205] Due to the association of phosphorus and nitrogen with sediments,[25,74,206] greater amounts of phosphorus and nitrogen (specifically, particulate phosphorus and Total Kjeldahl Nitrogen; TKN) have been detected in streams that have erodible rock and soils in the catchment.[58,75,207–209] It has also been identified that there are greater salt levels in catchments with easily weathered bedrock such as limestone or marble.[101,210] The link between rock and soil erodibility and weathering rates and climatic factors is addressed below.

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Soil sorption capacity can also have an impact on nutrient mobilization in the catchment. For nutrients delivered to receiving waters primarily via overland runoff (i.e., nutrients in the particulate form), sorption capacity has a positive correlation to constituent concentrations in receiving waters. There was a positive correlation between ammonium concentrations in Southern Ontario rivers and the amount of silt and clay in catchment soils.[21] There were also positive correlations between TN and TP concentrations in rivers in Finland and the silt and clay content of catchment soils.[14] Both of these instances were hypothesized to be a result of the greater adsorption capacity of clays and silts for nutrients.

Delivery: Influence of Geology and Soil Type

The delivery of dissolved phosphorus and nitrogen and salts from the catchment to receiving waters via subsurface flow pathways is strongly affected by soil hydrological properties. When aquifers and catchment soils have lower hydraulic conductivities, there is an increase in the residence time of dissolved constituents entrained in the subsurface flow in the catchment. This allows more opportunity for the constituent to be lost from the flow path by vegetative uptake or biogeochemical processing (e.g., denitrification). There have been several case studies where higher nutrient concentrations have been detected in rivers with well-drained soils in their catchments. For example, greater reactive phosphorus concentrations (by 1.5 times) were found in rivers in the United States where well-draining soils made up more than 3% of the catchment area, compared with catchments where less than 3% of the area had well-draining soils.[211] Similarly, there was a positive correlation between inorganic nitrogen concentrations in rivers in southern Sweden and the drainage capacity of the soils.[74] Finally, a negative correlation has also been observed between the proportion of the catchment comprised of poorly-draining soils and salt concentrations in receiving waters in Iranian rivers.[108] It is likely that the longer residence time resulted in the sorption of salts to particulate matter within the soil strata or aquifer.

Climate

Sources: Influence of Climate

Higher temperatures can correlate with lower nitrogen and phosphorus stores in the catchment. This is largely due to the greater terrestrial and aquatic vegetation growth, and hence nutrient uptake, that occurs at higher temperatures.[114,115] For nitrogen, higher temperatures can also enhance the activity of denitrifying bacteria. As a result, there can be more NO_x converted to N_2 in warmer climates.[115–117] A negative correlation between mean catchment temperature and stream TN concentration was identified in North America.[117] This may have been a result of increased denitrification rates in warmer locations. Denitrification is also enhanced in wet climates, due to the fact that the denitrifying bacteria prefer anaerobic conditions.[120]

Sources of terrestrial salts (cyclic salts, connate salts in marine sediments, weathering of rock minerals) are inherently linked to both the current climate and the historic climatic trends of the region. Salt spray from oceans and salts concentrated in rainfall can supply salts to catchments and river systems, and as such, in some catchments, higher historic rainfall rates correlate with higher atmospheric deposits of salts.[121] However, many studies have found that there is a negative correlation between recent average rainfall levels in the watershed and salt concentrations in rivers.[49,101,212] This is largely because higher rainfall and runoff rates can influence the release of salts that are contained within rock minerals and marine sediments. In areas with recent high rainfall and runoff, the salt that is naturally contained within the soil strata has mostly been flushed out by subsurface flows. For example, one study found that in areas with high rainfall in Western Australia, stream salinity does not increase significantly even after deforestation, whereas there are substantial increases in drier areas.[213]

In addition, climatic characteristics can indirectly affect the amount of pollutants stored in the catchment due to cross correlation between climate and other landscape characteristics such as land use, land cover (vegetation type and extent), topography, and geology. These interactions are discussed in more detail below.

Mobilization: Influence of Climate

Temperature extremes can enhance the mobilization of sediments and particulate nutrients within catchments. High temperatures can accelerate weathering and streambank erosion, because the desiccation of sediments makes them more prone to erosion by wind, rain, flow, and trampling by animals.[118] Freezing and thawing can also increase the mobilization of sediments through increased weathering of soils.[118]

There is another way that higher temperatures can lead to mobilization of nutrients both within the catchment and in the stream. Higher mineralization

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rates of both phosphorus and nitrogen from organic matter within soils and instream organic matter occur at higher temperatures.[74,214] For example, phosphorus mineralization increased by 14% when soil temperatures increased from 15 to 38°C in the laboratory.[215] A field experiment where soil temperatures were increased by 7°C found a 45% increase in net annual nitrogen mineralization.[216]

In addition, both rainfall intensity and volume can increase the mobilization of particulates within the catchment. Soil particles and their associated nutrients can be mobilized by the shear stresses applied by overland sheet flow, which increases with greater rainfall and runoff depths.[27] There is also a positive correlation between rainfall intensity and soil erosion due to the fact that the soil particles can be displaced by the energy applied to the ground by raindrop impact.[25,110] As such, high rainfall intensities have been found to contribute to sediment, phosphorus and nitrogen (in the particulate form) mobilization in the catchment.[57,74,109] For example, precipitation intensity was positively correlated to organic nitrogen concentrations in streams in Sweden[74] and to TP concentrations in surface runoff in an experimental study.[112]

Finally, evaporation rates in the catchment impact the mobilization of salts in the catchment. Salts can accumulate in surface soils in regions where evaporation rates are higher than rainfall rates, due to the evapoconcentration of salts in surface soils.[101,212]

Delivery: Influence of Climate

The delivery of particulate and dissolved constituents to rivers correlates to the total amount of overland runoff.[33,111,126] This is due to the fact that where there are greater overland runoff depths the generated runoff has greater capacity to convey more constituents (in both the particulate and dissolved phase) to rivers.[113] In addition, the greater speed of runoff will decrease the residence time in the catchment (both in the overland and subsurface flow pathways), leading to less sediment being lost from the flow path by sedimentation, and less nutrients being lost by denitrification. As previously discussed, the ability of overland runoff to deliver constituents to receiving waters is also impacted by the presence and roughness of vegetation. For example, organic nitrogen levels in Swedish rivers [74] were found to positively correlate to precipitation. Similarly, suspended solids loss from the catchment positively correlated to total rainfall in an Australian farm.[123] These were both hypothesized to be a result of the positive correlation between rainfall and overland runoff depths, when soil infiltration rates are low and soil is saturated. Additionally, the volume of subsurface runoff can also increase the delivery of fine particulates and dissolved constituents (nutrients and salts) to receiving waters.[217,218] This is a result of the increase in transit time of the subsurface flows from the catchment to rivers.

Topography

Mobilization: Influence of Topography

Catchment slope positively correlates with the level of particulates mobilized in catchments (Table 1). This is because overland runoff has higher velocities on steeper slopes, and therefore has greater erosive and transport power.[21,79,109,128,219,220] Additionally, steep slopes tend to be less stable, leading to a greater chance of mobilization of sediments by mass failure or landslides.[221] Indeed, there were positive correlations between slope and suspended sediment concentrations in rivers and streams in the Northwestern United States, and this was hypothesized to be caused by the increased erosion of suspended sediments from steep slopes.[126] Similarly, using 12 water quality monitoring sites, Sliva and Dudley[21] found a positive correlation between suspended sediment concentrations in receiving waters and the catchment slope in Southern Ontario, Canada. Catchment slope also correlated positively with NO_x concentrations (which is typically delivered to receiving rivers by subsurface flow) in receiving waters and it was suggested that this was due to the faster velocities of subsurface flow,[129] which may leave less time for the transformation and loss of NO_x by denitrification.[126,128,129,222]

In addition, there can be more erosion of particulates and their associated nutrients when there is a denser stream network in the catchment area. This is largely due to the fact that with a higher channel density, there is a greater chance that streambank erosion will occur.[55,133]

Transport: Influence of Topography

Catchment slope influences the delivery of particulate and dissolved constituents (sediments, particulate, and dissolved nutrients and salts). The positive correlation between the standard deviation of catchment slope and total solids concentrations in receiving rivers in Southern Ontario (Canada) identified by Sliva and Dudley[21] could be due to the fact that at shallower slopes (lower catchment slope standard deviations)[223], overland runoff tends to travel more slowly, thereby providing a greater opportunity for particulates to settle out of the overland flow and be deposited in the catchment. In other words, catchment

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topography can impact stream power (with less stream power on shallower slopes) and hence, erosion and deposition processes. The elevation of the river is also important when considering inputs of dissolved compounds. In addition, when dissolved nutrients (e.g., soluble phosphorus or nitrate–nitrite) and salts are traveling over longer distances and/or are traveling more slowly on gentler slopes, there is a higher chance that they will be lost (by microbial degradation (e.g., denitrification), adsorption to particulates and sedimentation, or uptake by vegetation) before they reach the river.[74,120,132]

In lower elevation regions or areas with shallower gradients and slopes, there is likely to be a greater input of groundwater, and hence greater delivery of dissolved compounds (salts, dissolved nitrogen, and phosphorus) into receiving waters.[224] Indeed, Kratz et al.[224] found concentrations of cations (calcium and magnesium) approximately ten times greater in lower elevation lakes in Wisconsin, USA, compared to higher elevation lakes and this was hypothesized to be largely due to the balance between precipitation and groundwater inputs, with greater groundwater inflows in low elevation lakes. It is likely that similar trends would affect riverine environments also.[225]

Catchment Hydrology

Delivery: Influence of Catchment Hydrology

The delivery of sediments, nutrients (particulate and dissolved), and salts to receiving waters can be influenced by the proportion of baseflow contribution compared to total stream discharge.[226] The main transport pathway for particulate matter is overland runoff. As such, when there are high subsurface or baseflow contributions (e.g., in forests), there are generally lower rates of transport of particulates into rivers.[139] Experimental studies have found higher TP losses from plots with greater overland flows compared to those with lower overland flows.[140] However, as subsurface flows can transport dissolved nutrients (e.g., NO_x), fine particles and dissolved solids (salts) through the soil and into rivers, there can be positive correlations between the baseflow contribution and salt and dissolved nutrient concentrations in receiving waters.[65,227–229] For example, there was a positive correlation between the baseflow contribution to stream discharge and stream salinity in the Bremer River catchment in Australia.[101] These dissolved nutrients and salts can be transported through the baseflow to surface waters provided that the residence time and soil properties are such that the nutrients and salts do not adsorb to the soil matrix or that the nutrients are not transformed (e.g., nitrogen through denitrification).[230]

In addition, the presence of impoundments, lakes, and wetlands within a catchment can lead to lower concentrations of sediments, nutrients, and salts in rivers downstream of these features.[134–137,231] Particulate matter can settle in these lentic systems, and dissolved and bioavailable nutrients can be taken up by aquatic plants and microorganisms within the systems.[137] Globally, it is estimated that over 50% of sediments in regulated river catchments are trapped in regulation structures.[232] In a study of rivers in Sweden, it was found that there were lower concentrations of particulate phosphorus in river reaches that had lakes within their catchment.[74] Similarly, wetlands in the United States are estimated to retain 14 to 89% of TN from overland runoff.[137] The retention of nitrogen in wetlands and lakes has been found to be variable; an Australian study found 60% removal of the TP load by a farm dam but minimal removal of TN.[233] It is important to note, however, that in some cases, the presence of these reservoirs and lakes could lead to a reduction in flow and a subsequent increase in concentration of constituents even if the total load (i.e., mass) of the constituent decreases.

Complexities Affecting Links between Landscape Characteristics and Water Quality Responses

The Question of Distance and Spatial Arrangement: Where Does the Source Have to Be to Affect the Stream?

Previous studies have noted that the distance of landscape characteristics from the receiving river or stream can have a large influence on riverine water quality.[79,95,186,234–238] This is largely due to the effect of distance on hydrologic connectivity and constituent transport connectivity between the catchment and streams. Hydrologic connectivity between catchments and streams enables flow from the catchment to contribute to streamflow and generally, this hydrological connectivity is established above a certain soil moisture or rainfall threshold.[147] In addition, under such hydrologically connected conditions, it is necessary to ensure that the constituent is transported to receiving streams through the flow pathway without degradation, sedimentation, or loss.[239] This connectivity is necessary for constituents to be transported from catchments to receiving waters.[226,239]

Contaminants can be lost from surface or subsurface flow during transport. Thus, if the source of the constituent (e.g., land use or geological deposit) is

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closer to receiving rivers, it is more likely that a hydrological connection will be established and the constituent will not be lost from this flow path, thereby entering the river.[79,178,219,240,241] For example, several studies have found that land cover of the riparian zone is better correlated to TSS[9,79] and nutrient concentrations in rivers,[9,14,79,231,242] compared to the land cover of the whole catchment. These findings, in addition to understanding of pollutant (e.g., TSS and nitrate[243]) removal by buffer strips,[244] have led to the management practice of installing buffer strips or preserving riparian zones for the preservation of water quality, with aim of breaking the hydrological and/or constituent transport connection between the catchment and rivers.

In addition, previous studies have found that accounting for the proximity of certain land uses to rivers and streams using distance weighting measures, has improved the relationship between land use and receiving water quality. Distance weighting measures utilized by previous studies include: inverse-distance-weighted metrics (which account for distance)[245,246] and hydrologically active inverse-distance-weighted metrics (which account for the distance and flow contribution).[245,247] Such studies run parallel to a larger body of work that has explored different approaches to distance weighting of catchment land uses and how this can be used to improve statistical relationships between land use and ecological responses.[248–250] These studies have described improved relationships between catchment characteristics and water quality responses in rivers. Specifically, accounting for the hydrological flow paths and flow accumulation through the landscape and coupling these processes with specific landscape features has tightened relationships between landscape features and receiving water quality,[245,247] as well as ecological indicators.[248]

Studies have also identified that it is not merely the distance of landscape characteristics from the rivers, but also the arrangement of these areas within the catchment that can affect connectivity and therefore riverine water quality.[10,235,251–254] In particular, forest fragmentation correlated with high sediment and nutrient concentrations in the Han River catchment (China)[10] and the Upper Du River catchment (China).[234] It is hypothesized that this is due to the fact that small and fragmented forests do not significantly reduce the connectivity between catchments and receiving rivers, and are therefore not as effective at reducing the contaminants contained in runoff from other sources (e.g., urban, agricultural land uses) within the catchment.[10] Similarly, the location of source areas relative to constituent sinks (e.g., depressions, lakes, and wetlands) can also have a significant impact on the concentration of constituents that reach the receiving river.[255,256]

While several studies have identified that (1) the distance of landscape characteristics from rivers and (2) the spatial arrangement of landscape characteristics within the catchment are important factors influencing riverine water quality, other studies[126,257,258] argue that the characteristics of the whole catchment must be considered when explaining the spatial variability in stream water quality. There are two possible explanations for this discrepancy in findings.

First, the spatial resolution of data used to assess the importance of distance and spatial arrangement of landscape characteristics can lead to divergent findings. In particular, coarse resolution spatial data that is unable to clearly differentiate landscape characteristics of the riparian zone from characteristics of the whole watershed may show that whole-of-catchment characteristics have a greater effect on riverine water quality than characteristics of the region more proximal to the stream.[21,125,259]

Second, it is likely that the characteristics of the riparian zone affect its role in buffering the effects of the whole catchment. It has been previously hypothesized that buffer zone slope and hydraulic conductivity were the most important factors determining the amount of particulate matter removed from overland runoff in the buffer zone.[260] Similarly, it was argued that the buffer zone width was the most important factor determining the level of dissolved constituents removed from overland and subsurface flow pathways.[261] This is assuming however that there are no drainage channels or discharge pipes bypassing the riparian buffer and discharging stormwater or wastewater directly into the river.

Cross Correlations between Landscape Characteristics

There can be strong cross correlations between landscape factors (Table 3). Several studies have commented on cross correlations between topography and land cover. For example, theoretically, it is expected that steep slopes would produce greater amounts of sediment from erosion due to higher runoff velocities, but previous studies argued that the supply of both particulate and dissolved contaminants is less in steeply sloping areas because of the cross correlations between catchment topography and land cover.[9,74,132,159,275–277] Shallow slopes are often used for anthropogenic (e.g., agricultural) activities, which act as sources of sediments and nutrients.[14,269,278,279]

Seasonal changes in constituent delivery processes are also possible, leading to temporal changes in the relationship between catchment characteristics

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TABLE 3 | Cross Correlations between Landscape Characteristics

	Land Cover	Land Use	Geology/Soil Type	Climate	Topography
Land use	Where there is more anthropogenic land use such as urban/agricultural land uses, forest cover, or vegetation cover are generally lower.[262]				
Geology/ Soil type	The nutrients and minerals contained in soils as well as the water holding capacity of soil will affect vegetation cover in the catchment, with more dense vegetation in regions with fertile soils with greater water holding capacity.[263,264]	Agricultural land use often occurs where soil has more nutrients and organic matter.[14]			
Climate	More vegetation growth occurs in locations with warmer temperatures and higher rainfall.[265,266]	Agricultural land uses are more common in areas where there is higher rainfall and warmer temperatures.[136]	Soil salinity tends to be lower with higher rainfall. Weathering and erosion is affected by climate (e.g., wind, rain, and temperature changes).[267] Soil nutrient levels (especially nitrogen) can be influenced by temperature and soil moisture, through effects on vegetation growth, carbon and microbial communities in soils, and hence, biogeochemical processing.[32,120,268]		
Topography	There tends to be more forested land cover or vegetation on steeper slopes and at higher elevations in the catchment.[269]	There tends to be less agriculture, grazing, and urban development at higher elevations and steep slopes.[14,137]	Topography can be influenced by the geology (e.g., resistance of bedrock to erosion) of the region.[270] Conversely, topography influences soil removal rates (soil depth is less on steep slopes) and soil water content.[271]	Higher rainfall and lower temperatures occur at elevations high in the catchment.[272]	
Hydrology	In areas with greater vegetation cover, there tends to be lower levels of total runoff.[273] As stated in Mao et al.[273] This can	Greater levels of overland runoff occur in urban and agricultural lands.[16,72] Subsurface drainage can	Geology and soil influences runoff and runoff pathways. It determines how fast water moves via subsurface flow into	Greater levels of runoff occur when there is high rainfall and less evapotranspiration.	Runoff flows more quickly and baseflow travels more quickly down

(*continued overleaf*)

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TABLE 3 | Continued

Land Cover	Land Use	Geology/Soil Type	Climate	Topography
however depend on the type of vegetation (leaf area index, roughness), the soil water holding capacity, and the climatic characteristics of the site.	be more rapid where artificial drainage is installed or less rapid where landscapes have been cleared of forests and replaced with impervious surfaces.[72]	receiving streams.[274] Soil depth influences the amount of groundwater recharge (subsurface flows).	Seasonality and rainfall intensity are also a factor.[147]	steep slopes in the catchment.[228]

and receiving water quality. For example, the strength of the link between land use, land cover, geology, and water quality can vary seasonally due to temporal changes in rainfall levels. This is because seasonality in rainfall can lead to shifts in hydrologic connectivity between constituent sources and receiving rivers and streams.[280,281] There was a weaker relationship between land uses within the catchment and nitrate concentrations in Canadian streams in the dry summer seasons, and it was hypothesized that this was due to a lack of hydrological connectivity in the catchment because of lower rainfall and higher evaporation rates.[138]

In addition, stream constituent concentrations can be more strongly affected by topographic and geologic characteristics of the catchment in drier months and years. In dry months and years, subsurface flows dominate stream discharge. The delivery of these nutrients in subsurface flow is governed by topographic characteristics such as slope and geologic and soil characteristics such as sorption capacity.[79,282] For example, in the driest months in the mid-western United States, while the impact of land use on water quality decreased, the impact of soil type and catchment slope remained unchanged.[79]

Finally, the relationship between water quality and catchment characteristics can shift seasonally due to changes in flow pathways (i.e., subsurface vs surface flows). Flow pathways can shift temporally (both within individual events and seasonally) as a result of changes in soil moisture.[147,283] Whether the constituent travels to receiving rivers via subsurface flows or by surface flows can significantly influence the constituent sources contributing to receiving streams, and the extent of mobilization and loss of the constituent (and the effect of the catchment characteristics on these processes) before it reaches the river.[226] For example, the flow pathway of constituents affects the biogeochemical transformation of nutrients because they impact the residence time of constituents within the catchment, and the matrix through which constituents travel.[226]

MAJOR KNOWLEDGE GAPS: RELATIVE IMPORTANCE OF LANDSCAPE CHARACTERISTICS AND INTERACTION BETWEEN CHARACTERISTICS

While we understand how particular landscape characteristics individually impact riverine water quality, there is still limited understanding of the relative importance of these landscape characteristics.

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TABLE 4 | Previous Studies That Have Aimed to Identify the Most Important Landscape Variables Affecting Spatial Variability in Water Quality (Blank Cells Indicate That the Landscape Characteristic or Constituent Was Not Explored in the Study)

Case Study		Landscape characteristics explored					Landscape Characteristics with Most Significant Influence on Spatial Variability in Water Quality				
Catchment Name	Number of Sites Used	Land Cover/Land Use/Land Management (LU)	Geology and Soil Type (G)	Climate (C)	Topography (T)	Catchment Hydrology (H)	TSS	Phosphorus	Nitrogen	Salts	Citation
Motueka River catchment (New Zealand)	23	x	x				LU	LU	LU	G	106
Han River basin (South Korea)	118	x	x		x		LU	LU	LU		9
Caspian Sea (Iran)	23	x	x							G	108
Highland Creek, Duffins Creek, Rouge River (Southern Ontario, Canada)	12	x	x		x		LU		LU		21
River Paimionjoki (South-West Finland)	34	x			x		LU, T	LU, T	LU		127
North-West England	264–566	x	X	x	x	x	LU	LU	LU	T, LU, G	286
Saginaw Bay catchment (USA)	62	x	x		x				LU	LU	79
Finland	32	x	x	x	x	x		LU	LU		136
Coastal Plain catchments (Chesapeake Bay, USA)	27	x				x			LU		141
Cedar River (USA)	78	x	X		x				LU, G		107
Richmond River (Australia)	79	X	X	X	X			LU	LU		287
Alzette River (Luxembourg)	24	x	X		x	x			G		220
North America (USA)	72	x	x	x	x		G, LU, C				284

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Some previous studies have attempted to identify the most important landscape characteristics affecting spatial variability in water quality using multiple regression[284], geographic weighted regression,[285] and variance partitioning approaches (Table 4).[136] However, most of these studies have only included a subset of possible factors (listed in Table 1) in the analysis, and some have been limited by consideration of a limited number of sites/catchments (Table 4). Varanka and Luoto[136] studied the whole suite of possible factors in their analysis, and found that agricultural land use area in the catchment was the most important factor affecting TP and TN concentrations in Finland. However, it is important to apply these methods to other regions, to identify whether these are global trends, specific to these regions, or can be related to broad characteristics such as climate type or biome. The studies in Table 4 generally use different mixes of multivariate statistical approaches, but machine learning techniques have also been used to identify links between landscape features and water quality responses.[288] These include: boosted regression trees,[288,289] artificial neural networks,[290] fuzzy rule-based models,[291] and self-organizing maps.[292]

Additionally, we must better understand how the importance of certain landscape characteristics can change based on the other characteristics of the catchment. This has been addressed to a small extent in the literature (Figure 4). For example, in catchments with intense agricultural and urban land uses, geological deposits do not have a strong influence on nutrient concentrations in rivers.[106] This is likely because the delivery of anthropogenically-derived nitrogen and phosphorus to rivers is overwhelming any effects caused by the local geology. In addition, previous studies have found that the impact of the landscape characteristics listed in Table 1 on riverine water quality decreases when there are point source discharges from septic tanks systems, wastewater treatment plants, or other wastewater sources.[79,97,259,278,295,296] However, we still lack a systematic understanding of the interactions between the factors listed in Table 1, and how different landscape characteristics may interact with the effect of other landscape characteristics on stream water quality.[282]

CONCLUSIONS

Many landscape characteristics influence spatial variability in sediments, nutrients, and salts concentrations in rivers and streams, and heterogeneity in landscapes can significantly affect spatial differences in stream water quality. Studies have previously addressed the relationship between land use, land cover, and the extent of catchment disturbance on constituent concentrations, showing that human activities (urbanization, agriculture, and deforestation) can lead to higher concentrations of suspended solids, nutrients, and salts. Other landscape characteristics that impact riverine water quality include: atmospheric deposition, climate, topography, geology, soil properties, and catchment hydrology. When attempting to understand the factors affecting spatial variability in constituent concentrations, and how landscape heterogeneity can influence water quality responses, it is important to consider: (1) the cross correlations and interactions between catchment features, (2) the potential effect of the spatial arrangement of landscape characteristics within the catchment (e.g., distance from rivers, fragmentation of constituent source areas in the landscape), and (3) the interannual and interseasonal variability in the relationships between landscape characteristics and water quality responses.

In the current body of literature, there is a large emphasis on the effect of humans on stream water quality, in particular, the relationship between land use, land cover and land management, and constituent concentrations in streams.[16,161] While still limited, there is also a growing understanding of how natural factors (e.g., geology, topography, and climate) are likely to impact sediment, nutrient, and salt concentrations in rivers and streams. Still required, however, is a better understanding of the interactions and relationships between catchment features. Characterizing these interactions is critical in enhancing our insight of the key catchment features that influence spatial variability in riverine water quality. Increasing our knowledge of the interactions between these catchment features will (1) improve our ability to implement targeted and cost-effective management strategies and (2) better equip us to build models and tools that will be able to predict the spatial variability in water quality both between and within river catchments.

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FURTHER READING

Norris V. The use of buffer zones to protect water quality: a review. *Water Resour Manage* 1993, 7:257–272.

Baker A. Land use and water quality. *Hydrol Process* 2003, 17:2499–2501.

Huang J, Li Q, Pontius RG, Klemas V, Hong H. Detecting the dynamic linkage between landscape characteristics and water quality in a subtropical coastal watershed, Southeast China. *Environ Manag* 2013, 51:32–44.

Ball Coelho B, Murray R, Lapen D, Topp E, Bruin A. Phosphorus and sediment loading to surface waters from liquid swine manure application under different drainage and tillage practices. *Agric Water Manag* 2012, 104:51–61.

Gardner KK, McGlynn BL. Seasonality in spatial variability and influence of land use/land cover and watershed characteristics on stream water nitrate concentrations in a developing watershed in the Rocky Mountain West. *Water Resour Res* 2009, 45:W08411.

REFERENCES

1. Nash L. Water quality and health. In: Gleick PH, ed. *Water in Crisis: A Guide to the World's Fresh Water Resources*. New York: Oxford University Press; 1993, 25–39.
2. Schwarzenbach RP, Egli T, Hofstetter TB, von Gunten U, Wehrli B. Global water pollution and human health. *Annu Rev Env Resour* 2010, 35:109–136.
3. Loucks DP, van Beek E, Stedinger JR, Dijkman JPM, Villars MT. *Water Resources Systems Planning and Management: An Introduction to Methods, Models and Applications*. Paris: UNESCO; 2005.
4. Vorosmarty CJ, McIntyre PB, Gessner MO, Dudgeon D, Prusevich A, Green P, Glidden S, Bunn SE, Sullivan CA, Liermann CR, et al. Global threats to human water security and river biodiversity. *Nature* 2010, 467:555–561.
5. Bernhardt ES, Palmer MA, Allan JD, Alexander G, Barnas K, Brooks S, Carr J, Clayton S, Dahm C, Follstad-Shah J, et al. Synthesizing U.S. river restoration efforts. *Science* 2005, 308:636–637.
6. National Water Commission. *Australian Water Resources*. Canberra; 2005.
7. Jiang Y. China's water scarcity. *J Environ Manage* 2009, 90:3185–3196.
8. Smith VH, Tilman GD, Nekola JC. Eutrophication: impacts of excess nutrient inputs on freshwater, marine, and terrestrial ecosystems. *Environ Pollut* 1999, 100:179–196.
9. Chang H. Spatial analysis of water quality trends in the Han River basin, South Korea. *Water Res* 2008, 42:3285–3304.
10. Ai L, Shi ZH, Yin W, Huang X. Spatial and seasonal patterns in stream water contamination across mountainous watersheds: linkage with landscape characteristics. *J Hydrol* 2015, 523:398–408.
11. Vega M, Pardo R, Barrado E, Debán L. Assessment of seasonal and polluting effects on the quality of river water by exploratory data analysis. *Water Res* 1998, 32:3581–3592.
12. Bengräne K, Marhaba TF. Using principal component analysis to monitor spatial and temporal changes in water quality. *J Hazard Mater* 2003, 100:179–195.
13. Meybeck M, Helmer R. The quality of rivers: from pristine stage to global pollution. *Palaeogeogr Palaeoclimatol Palaeoecol* 1989, 75:283–309.
14. Varanka S, Hjort J, Luoto M. Geomorphological factors predict water quality in boreal rivers. *Earth Surf Process Landf* 2015, 40:1989–1999.
15. Bu H, Tan X, Li S, Zhang Q. Temporal and spatial variations of water quality in the Jinshui River of the South Qinling Mts., China. *Ecotoxicol Environ Saf* 2010, 73:907–913.
16. Allan JD. Landscapes and riverscapes: the influence of land use on stream ecosystems. *Annu Rev Ecol Syst* 2004, 35:257–284.
17. Polyakov V, Fares A, Ryder MH. Precision riparian buffers for the control of nonpoint source pollutant loading into surface water: a review. *Environ Rev* 2005, 13:129–144.
18. Carey RO, Migliaccio KW. Contribution of wastewater treatment plant effluents to nutrient dynamics in aquatic systems: a review. *Environ Manag* 2009, 44:205–217.
19. Drewry JJ, Newham LTH, Greene RSB, Jakeman AJ, Croke BFW. A review of nitrogen and phosphorus export to waterways: context for catchment modelling. *Mar Freshw Res* 2006, 57:757–774.

 © 2017 The Authors. *WIREs Water* published by Wiley Periodicals, Inc.

20. Fatehi I, Amiri BJ, Alizadeh A, Adamowski J. Modeling the relationship between catchment attributes and in-stream water quality. *Water Resour Manage* 2015, 29:5055–5072.
21. Sliva L, Dudley Williams D. Buffer zone versus whole catchment approaches to studying land use impact on river water quality. *Water Res* 2001, 35:3462–3472.
22. Taylor K, Owens P. Sediments in urban river basins: a review of sediment–contaminant dynamics in an environmental system conditioned by human activities. *J Soil Sediment* 2009, 9:281–303.
23. Bilotta GS, Brazier RE. Understanding the influence of suspended solids on water quality and aquatic biota. *Water Res* 2008, 42:2849–2861.
24. Meybeck M, Chapman D, Helmer R. *Global Freshwater Quality, a First Assessment*. New York: WHO and UNEP/Blackwell Ltd.; 1989.
25. Perry JA, Vanderklein E. *Water Quality: Management of a Natural Resource*. Cambridge, MA: Blackwell Science; 1996.
26. Bennett EM, Carpenter SR, Caraco NF. Human impact on erodable phosphorus and eutrophication: a global perspective. *Bioscience* 2001, 51:227–234.
27. Granger SJ, Bol R, Anthony S, Owens PN, White SM, Haygarth PM. Chapter 3: Towards a holistic classification of diffuse agricultural water pollution from intensively managed grasslands on heavy soils. *Advances in Agronomy*, vol. 105. San Diego, CA: Academic Press; 2010, 83–115.
28. Rickson RJ. Can control of soil erosion mitigate water pollution by sediments? *Sci Total Environ* 2014, 468–469:1187–1197.
29. Ellis JB, Revitt DM, Lundy L. An impact assessment methodology for urban surface runoff quality following best practice treatment. *Sci Total Environ* 2012, 416:172–179.
30. Miguntanna NP, Liu A, Egodawatta P, Goonetilleke A. Characterising nutrients wash-off for effective urban stormwater treatment design. *J Environ Manage* 2013, 120:61–67.
31. Schoumans OF, Chardon WJ, Bechmann ME, Gascuel-Odoux C, Hofman G, Kronvang B, Rubæk GH, Ulén B, Dorioz J-M. Mitigation options to reduce phosphorus losses from the agricultural sector and improve surface water quality: a review. *Sci Total Environ* 2014, 468:1255–1266. Available at: http://www.sciencedirect.com/science/article/pii/S0048969713009881. (Accessed May 11, 2017).
32. Vidon P, Allan C, Burns D, Duval TP, Gurwick N, Inamdar S, Lowrance R, Okay J, Scott D, Sebestyen S. Hot spots and hot moments in riparian zones: potential for improved water quality management. *J Am Water Resour Assoc* 2010, 46:278–298.
33. Novotny V. Delivery of suspended sediment and pollutants from nonpoint sources during overland flow. *J Am Water Resour Assoc* 1980, 16:1057–1065.
34. Beven K, Heathwaite L, Haygarth P, Walling D, Brazier R, Withers P. On the concept of delivery of sediment and nutrients to stream channels. *Hydrol Process* 2005, 19:551–556.
35. Hoos AB, McMahon G. Spatial analysis of instream nitrogen loads and factors controlling nitrogen delivery to streams in the Southeastern United States using spatially referenced regression on watershed attributes (SPARROW) and regional classification frameworks. *Hydrol Process* 2009, 23:2275–2294.
36. Oeurng C, Sauvage S, Sánchez-Pérez J-M. Dynamics of suspended sediment transport and yield in a large agricultural catchment, southwest France. *Earth Surf Process Landf* 2010, 35:1289–1301.
37. Perks MT, Owen GJ, Benskin CMH, Jonczyk J, Deasy C, Burke S, Reaney SM, Haygarth PM. Dominant mechanisms for the delivery of fine sediment and phosphorus to fluvial networks draining grassland dominated headwater catchments. *Sci Total Environ* 2015, 523:178–190.
38. Rodríguez-Blanco ML, Taboada-Castro MM, Taboada-Castro MT. Phosphorus transport into a stream draining from a mixed land use catchment in Galicia (NW Spain): significance of runoff events. *J Hydrol* 2013, 481:12–21.
39. Mellander P-E, Melland AR, Jordan P, Wall DP, Murphy PNC, Shortle G. Quantifying nutrient transfer pathways in agricultural catchments using high temporal resolution data. *Environ Sci Policy* 2012, 24:44–57.
40. Outram FN, Lloyd CEM, Jonczyk J, Benskin CMH, Grant F, Perks MT, Deasy C, Burke SP, Collins AL, Freer J, et al. High-frequency monitoring of nitrogen and phosphorus response in three rural catchments to the end of the 2011–2012 drought in England. *Hydrol Earth Syst Sci* 2014, 18:3429–3448.
41. Ali G, Oswald CJ, Spence C, Cammeraat ELH, McGuire KJ, Meixner T, Reaney SM. Towards a unified threshold-based hydrological theory: necessary components and recurring challenges. *Hydrol Process* 2013, 27:313–318.
42. Lehmann P, Hinz C, McGrath G, Tromp-Van Meerveld H-J, McDonnell JJ. Rainfall threshold for hillslope outflow: an emergent property of flow pathway connectivity. *Hydrol Earth Syst Sci Discuss* 2006, 3:2923–2961.
43. Detty JM, McGuire KJ. Threshold changes in storm runoff generation at a till-mantled headwater catchment. *Water Resour Res* 2010, 46:W07525.
44. Western AW, Bloschl G, Grayson RB. How well do indicator variograms capture the spatial connectivity of soil moisture? *Hydrol Process* 1998, 12:1851–1868.

 © 2017 The Authors. *WIREs Water* published by Wiley Periodicals, Inc.

45. Western AW, Blöschl G, Grayson RB. Toward capturing hydrologically significant connectivity in spatial patterns. *Water Resour Res* 2001, 37:83–97.

46. Ocampo CJ, Sivapalan M, Oldham C. Hydrological connectivity of upland-riparian zones in agricultural catchments: implications for runoff generation and nitrate transport. *J Hydrol* 2006, 331:643–658.

47. Heathwaite AL. Multiple stressors on water availability at global to catchment scales: understanding human impact on nutrient cycles to protect water quality and water availability in the long term. *Freshw Biol* 2010, 55:241–257.

48. Reddy KR, Kadlec RH, Flaig E, Gale PM. Phosphorus retention in streams and wetlands: a review. *Crit Rev Environ Sci Technol* 1999, 29:83.

49. Boyd CE. *Water Quality: An Introduction*. Cham: Springer; 2015. (Springer English/International eBooks 2015 - Full Set).

50. Houlahan JE, Findlay CS. Estimating the "critical" distance at which adjacent land-use degrades wetland water and sediment quality. *Landsc Ecol* 2004, 19:677–690.

51. Fennessy MS, Cronk JK. The effectiveness and restoration potential of riparian ecotones for the management of nonpoint source pollution, particularly nitrate. *Crit Rev Environ Sci Technol* 1997, 27:285–317.

52. Harris GP. Biogeochemistry of nitrogen and phosphorus in Australian catchments, rivers and estuaries: effects of land use and flow regulation and comparisons with global patterns. *Mar Freshw Res* 2001, 52:139–149.

53. Basnyat P, Teeter LD, Flynn KM, Lockaby BG. Relationships between landscape characteristics and nonpoint source pollution inputs to Coastal Estuaries. *Environ Manag* 1999, 23:539–549.

54. Groffman PM, Williams CO, Pouyat RV, Band LE, Yesilonis ID. Nitrate leaching and nitrous oxide flux in urban forests and grasslands. *J Environ Qual* 2009, 38:1848–1860.

55. Prosser IP, Rutherfurd ID, Olley JM, Young WJ, Wallbrink PJ, Moran CJ. Large-scale patterns of erosion and sediment transport in river networks, with examples from Australia. *Mar Freshw Res* 2001, 52:81–99.

56. Sidorchuk A. Dynamic and static models of gully erosion. *Catena* 1999, 37:401–414.

57. Novotny V. *Water Quality: Diffuse Pollution and Watershed Management*. Hoboken, NJ: Wiley; 2003.

58. Pimentel D, Harvey C, Resosudarmo P, Sinclair K, Kurz D, McNair M, Crist S, Shpritz L, Fitton L, Saffouri R, et al. Environmental and economic costs of soil erosion and conservation benefits. *Science* 1995, 267:1117 LP–1111123.

59. Ensign SH, Mallin MA. Stream water quality changes following timber harvest in a coastal plain swamp forest. *Water Res* 2001, 35:3381–3390.

60. Groffman PM, Butterbach-bahl K, Fulweiler RW, Gold AJ, Morse JL, Stander EK, Tague C, Tonitto C, Vidon P. Challenges to incorporating spatially and temporally explicit phenomena (hotspots and hot moments) in denitrification models. *Biogeochemistry* 2009, 93:49–77.

61. Sivapalan M, Ruprecht JK, Viney NR. Water and salt balance modelling to predict the effects of land-use changes in forested catchments. 1. Small catchment water balance model. *Hydrol Process* 1996, 10:393–411.

62. Jolly ID, Williamson DR, Gilfedder M, Walker GR, Morton R, Robinson G, Jones H, Zhang L, Dowling TI, Dyce P, et al. Historical stream salinity trends and catchment salt balances in the Murray-Darling Basin, Australia. *Mar Freshw Res* 2001, 52:53–63.

63. Runyan CW, D'Odorico P, Lawrence D. Physical and biological feedbacks of deforestation. *Rev Geophys* 2012, 50, 4:RG4006.

64. Suárez J, Puertas J. Determination of COD, BOD, and suspended solids loads during combined sewer overflow (CSO) events in some combined catchments in Spain. *Ecol Eng* 2005, 24:199–217.

65. Edwards AC, Withers PJA. Transport and delivery of suspended solids, nitrogen and phosphorus from various sources to freshwaters in the UK. *J Hydrol* 2008, 350:144–153.

66. Paul MJ, Meyer JL. Streams in the urban landscape. *Annu Rev Ecol Evol Syst* 2001, 32:333.

67. Grayson RB, Gippel CJ, Finlayson BL, Hart BT. Catchment-wide impacts on water quality: the use of "snapshot" sampling during stable flow. *J Hydrol* 1997, 199:121–134.

68. Simons M, Podger G, Cooke R. IQQM—A hydrologic modelling tool for water resource and salinity management. *Environ Software* 1996, 11:185–192.

69. Bedan ES, Clausen JC. Stormwater runoff quality and quantity from traditional and low impact development watersheds. *J Am Water Resour Assoc* 2009, 45:998–1008.

70. Corsi SR, Graczyk DJ, Geis SW, Booth NL, Richards KD. A fresh look at road salt: aquatic toxicity and water-quality impacts on local, regional, and national scales. *Environ Sci Technol* 2010, 44:7376–7382.

71. Nelson EJ, Booth DB. Sediment sources in an urbanizing, mixed land-use watershed. *J Hydrol* 2002, 264:51–68.

72. Walsh CJ, Roy AH, Feminella JW, Cottingham PD, Groffman PM, Morgan RP. The urban stream

 © 2017 The Authors. *WIREs Water* published by Wiley Periodicals, Inc.

syndrome: current knowledge and the search for a cure. *J North Am Benthol Soc* 2005, 24:706–723.

73. Brabec E, Schulte S, Richards PL. Impervious surfaces and water quality: a review of current literature and its implications for watershed planning. *J Plan Lit* 2002, 16:499–514.
74. Arheimer B, Lidén R. Nitrogen and phosphorus concentrations from agricultural catchments—influence of spatial and temporal variables. *J Hydrol* 2000, 227:140–159.
75. McKergow LA, Weaver DM, Prosser IP, Grayson RB, Reed AEG. Before and after riparian management: sediment and nutrient exports from a small agricultural catchment, Western Australia. *J Hydrol* 2003, 270:253–272.
76. Agouridis CT, Workman SR, Warner RC, Jennings GD. Livestock grazing management impacts on stream water quality: a review. *J Am Water Resour Assoc* 2005, 41:591–606.
77. Foley JA, DeFries R, Asner GP, Barford C, Bonan G, Carpenter SR, Chapin FS, Coe MT, Daily GC, Gibbs HK, et al. Global consequences of land use. *Science* 2005, 309:570–574.
78. Zhu Q, Schmidt JP, Bryant RB. Hot moments and hot spots of nutrient losses from a mixed land use watershed. *J Hydrol* 2012, 414–415:393–404.
79. Johnson L, Richards C, Host G, Arthur J. Landscape influences on water chemistry in Midwestern stream ecosystems. *Freshw Biol* 1997, 37:193–208.
80. Scanlon BR, Jolly I, Sophocleous M, Zhang L. Global impacts of conversions from natural to agricultural ecosystems on water resources: quantity versus quality. *Water Resour Res* 2007, 43:W03437.
81. Skaggs RW, Brevé MA, Gilliam JW. Hydrologic and water quality impacts of agricultural drainage*. *Crit Rev Environ Sci Technol* 1994, 24:1–32.
82. Sharpley AN, Daniel TC, Edwards DR. Phosphorus movement in the landscape. *J Prod Agr* 1993, 6:492–500.
83. Newham LTH, Letcher RA, Jakeman AJ, Kobayashi T. A framework for integrated hydrologic, sediment and nutrient export modelling for catchment-scale management. *Environ Model Software* 2004, 19:1029–1038.
84. Needelman BA, Kleinman PJA, Strock JS, Allen AL. Improved management of agricultural drainage ditches for water quality protection: an overview. *J Soil Water Conserv* 2007, 62:171+.
85. Federal Highway Administration. *Stormwater Best Management Practices in an Ultra-urban Setting: Selection and Monitoring*. Washington, DC: Federal Highway Administration; 2000.
86. Barbosa AE, Fernandes JN, David LM. Key issues for sustainable urban stormwater management. *Water Res* 2012, 46:6787–6798.
87. Zhao SL, Gupta SC, Huggins DR, Moncrief JF. Tillage and nutrient source effects on surface and subsurface water quality at corn planting. *J Environ Qual* 2001, 30:998–1008.
88. Munodawafa A. Assessing nutrient losses with soil erosion under different tillage systems and their implications on water quality. *Phys Chem Earth A/B/C* 2007, 32:1135–1140.
89. Vance CP. Symbiotic nitrogen fixation and phosphorus acquisition. Plant nutrition in a world of declining renewable resources. *Plant Physiol* 2001, 127:390–397.
90. Dinnes DL, Karlen DL, Jaynes DB, Kaspar TC, Hatfield JL, Colvin TS, Cambardella CA. Nitrogen management strategies to reduce nitrate leaching in tile-drained Midwestern soils. *Agron J* 2002, 94:153–171.
91. Thorburn PJ, Wilkinson SN. Conceptual frameworks for estimating the water quality benefits of improved agricultural management practices in large catchments. *Agr Ecosyst Environ* 2013, 180:192–209.
92. Walker WR, Skogerboe GV, Evans RG. Developing best management practices for salinity control in Grand Valley, Colorado. *Water Resour Res* 1979, 15:1073–1080.
93. Pannell DJ, Roberts AM. Australia's National Action Plan for Salinity and Water Quality: a retrospective assessment. *Aust J Agric Resour Econ* 2010, 54:437–456.
94. Pannell DJ, Ewing MA. Managing secondary dryland salinity: options and challenges. *Agric Water Manag* 2006, 80:41–56.
95. Peterjohn WT, Correll DL. Nutrient dynamics in an agricultural watershed: observations on the role of a riparian forest. *Ecology* 1984, 65:1466–1475.
96. Roy AH, Wenger SJ, Fletcher TD, Walsh CJ, Ladson AR, Shuster WD, Thurston HW, Brown RR. Impediments and solutions to sustainable, watershed-scale urban stormwater management: lessons from Australia and the United States. *Environ Manag* 2008, 42:344–359.
97. Boomer KB, Weller DE, Jordan TE. Empirical models based on the universal soil loss equation fail to predict sediment discharges from Chesapeake Bay catchments. *J Environ Qual* 2008, 37:79–89.
98. Miller C, Magdalina A, Willows RI, Bowman AW, Scott EM, Lee D, Burgess C, Pope L, Pannullo F, Haggarty R. Spatiotemporal statistical modelling of long-term change in river nutrient concentrations in England and Wales. *Sci Total Environ* 2014, 466–467:914–923.
99. McDowell RW, Biggs BJF, Sharpley AN, Nguyen L. Connecting phosphorus loss from agricultural landscapes to surface water quality. *Chem Ecol* 2004, 20:1–40.

 © 2017 The Authors. *WIREs Water* published by Wiley Periodicals, Inc.

100. Heathwaite AL, Johnes PJ. Contribution of nitrogen species and phosphorus fractions to stream water quality in agricultural catchments. *Hydrol Process* 1996, 10:971–983.

101. Poulsen DL, Simmons CT, Le Galle La Salle C, Cox JW. Assessing catchment-scale spatial and temporal patterns of groundwater and stream salinity. *Hydrgeol J* 2006, 14:1339–1359.

102. Dillon PJ, Kirchner WB. The effects of geology and land use on the export of phosphorus from watersheds. *Water Res* 1975, 9:135–148.

103. Ice G, Binkley D. Forest streamwater concentrations of nitrogen and phosphorus: a comparison with EPA's proposed water quality criteria. *J For* 2003, 101:21–28.

104. Baker JL, Laflen JM. Water quality consequences of conservation tillage: new technology is needed to improve the water quality advantages of conservation tillage. *J Soil Water Conserv* 1983, 38:186–193.

105. Holloway JM, Dahlgren RA, Hansen B, Casey WH. Contribution of bedrock nitrogen to high nitrate concentrations in stream water. *Nature* 1998, 395:785.

106. Young RG, Quarterman AJ, Eyles RF, Smith RA, Bowden WB. Water quality and thermal regime of the Motueka River: influences of land cover, geology and position in the catchment. *N Z J Mar Freshw Res* 2005, 39:803–825.

107. Yang X, Jin W. GIS-based spatial regression and prediction of water quality in river networks: a case study in Iowa. *J Environ Manage* 2010, 91:1943–1951.

108. Hasani Sangani M, Jabbarian Amiri B, Alizadeh Shabani A, Sakieh Y, Ashrafi S. Modeling relationships between catchment attributes and river water quality in southern catchments of the Caspian Sea. *Environ Sci Pollut Res* 2014, 22:4985–5002.

109. Wang G, Gertner G, Singh V, Shinkareva S, Parysow P, Anderson A. Spatial and temporal prediction and uncertainty of soil loss using the revised universal soil loss equation: a case study of the rainfall–runoff erosivity R factor. *Ecol Model* 2002, 153:143–155.

110. Vaze J, Chiew FHS. Comparative evaluation of urban storm water quality models. *Water Resour Res* 2003, 39:1280.

111. Kleinman PJA, Srinivasan MS, Dell CJ, Schmidt JP, Sharpley AN, Bryant RB. Role of rainfall intensity and hydrology in nutrient transport via surface runoff mention of trade names does not imply endorsement by the USDA. *J Environ Qual* 2006, 35:1248–1259.

112. Shigaki F, Sharpley A, Prochnow LI. Rainfall intensity and phosphorus source effects on phosphorus transport in surface runoff from soil trays. *Sci Total Environ* 2007, 373:334–343.

113. Walling DE. The sediment delivery problem. *J Hydrol* 1983, 65:209–237.

114. Hanrahan G, Gledhill M, House WA, Worsfold PJ. Evaluation of phosphorus concentrations in relation to annual and seasonal physico-chemical water quality parameters in a UK chalk stream. *Water Res* 2003, 37:3579–3589.

115. Picard CR, Fraser LH, Steer D. The interacting effects of temperature and plant community type on nutrient removal in wetland microcosms. *Bioresour Technol* 2005, 96:1039–1047.

116. Houser JN, Richardson WB. Nitrogen and phosphorus in the Upper Mississippi River: transport, processing, and effects on the river ecosystem. *Hydrobiologia* 2010, 640:71–88.

117. Smith RA, Schwarz GE, Alexander RB. Regional interpretation of water-quality monitoring data. *Water Resour Res* 1997, 33:2781–2798.

118. Prosser IP, Hughes AO, Rutherfurd ID. Bank erosion of an incised upland channel by subaerial processes: Tasmania, Australia. *Earth Surf Process Landf* 2000, 25:1085–1101.

119. Mattsson T, Finér L, Kortelainen P, Sallantaus T. Brook water quality and background leaching from unmanaged forested catchments in Finland. *Water Air Soil Pollut* 2003, 147:275–298.

120. Creed IF, Beall FD. Distributed topographic indicators for predicting nitrogen export from headwater catchments. *Water Resour Res* 2009, 45:W10407.

121. White I, Macdonald BCT, Somerville PD, Wasson R. Evaluation of salt sources and loads in the upland areas of the Murray–Darling Basin, Australia. *Hydrol Process* 2009, 23:2485–2495.

122. Turner BL, Haygarth PM. Biogeochemistry: phosphorus solubilization in rewetted soils. *Nature* 2001, 411:258.

123. Hollinger E, Cornish PS, Baginska B, Mann R, Kuczera G. Farm-scale stormwater losses of sediment and nutrients from a market garden near Sydney, Australia. *Agric Water Manag* 2001, 47:227–241.

124. Lu H, Moran CJ, Prosser IP. Modelling sediment delivery ratio over the Murray Darling Basin. *Environ Model Software* 2006, 21:1297–1308.

125. Hunsaker CT, Levine DA. Hierarchical approaches to the study of water quality in rivers: spatial scale and terrestrial processes are important in developing models to translate research results to management practices. *Bioscience* 1995, 45:193–203.

126. Pratt B, Chang H. Effects of land cover, topography, and built structure on seasonal water quality at multiple spatial scales. *J Hazard Mater* 2012, 209–210:48–58.

127. Ekholm P, Kallio K, Salo S, Pietiläinen O-P, Rekolainen S, Laine Y, Joukola M. Relationship between catchment characteristics and nutrient

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concentrations in an agricultural river system. *Water Res* 2000, 34:3709–3716.

128. Sueker JK, Clow DW, Ryan JN, Jarrett RD. Effect of basin physical characteristics on solute fluxes in nine alpine/subalpine basins, Colorado, USA. *Hydrol Process* 2001, 15:2749–2769.
129. D'Arcy P, Carignan R. Influence of catchment topography on water chemistry in southeastern Québec Shield lakes. *Can J Fish Aquat Sci* 1997, 54:2215–2227.
130. Prairie YT, Kalff J. Effect of catchment size on phosphorus export. *J Am Water Resour Assoc* 1986, 22:465–470.
131. Vanni MJ, Renwick WH, Headworth JL, Auch JD, Schaus MH. Dissolved and particulate nutrient flux from three adjacent agricultural watersheds: a five-year study. *Biogeochemistry* 2001, 54:85–114.
132. Prasad VK, Ortiz A, Stinner B, Mccartney D, Parker J, Hudgins D, Hoy C, Moore R. Exploring the relationship between hydrologic parameters and nutrient loads using digital elevation model and GIS—a case study from Sugarcreek Headwaters, Ohio, U.S.A. *Environ Monit Assess* 2005, 110:141–169.
133. Collins AL, Anthony SG. Assessing the likelihood of catchments across England and Wales meeting "good ecological status" due to sediment contributions from agricultural sources. *Environ Sci Policy* 2008, 11:163–170.
134. Ahearn DS, Sheibley RW, Dahlgren RA, Anderson M, Johnson J, Tate KW. Land use and land cover influence on water quality in the last free-flowing river draining the western Sierra Nevada, California. *J Hydrol* 2005, 313:234–247.
135. Golladay SW, Battle J. Effects of flooding and drought on water quality in gulf coastal plain streams in Georgia. *J Environ Qual* 2002, 31:1266–1272.
136. Varanka S, Luoto M. Environmental determinants of water quality in boreal rivers based on partitioning methods. *River Res Appl* 2012, 28:1034.
137. Johnston CA. Sediment and nutrient retention by freshwater wetlands: effects on surface water quality. *Crit Rev Environ Contr* 1991, 21:491–565.
138. Hill AR. Factors affecting the export of nitrate-nitrogen from drainage basins in Southern Ontario. *Water Res* 1978, 12:1045–1057.
139. Wood PA. Controls of variation in suspended sediment concentration in the River Rother, West Sussex, England. *Sedimentology* 1977, 24:437–445.
140. Kleinman PJA, Sharpley AN, Veith TL, Maguire RO, Vadas PA. Evaluation of phosphorus transport in surface runoff from packed soil boxes. *J Environ Qual* 2004, 33:1413–1423.
141. Jordan TE, Correll DL, Weller DE. Relating nutrient discharges from watersheds to land use and streamflow variability. *Water Resour Res* 1997, 33:2579–2590.
142. Shrestha S, Kazama F. Assessment of surface water quality using multivariate statistical techniques: a case study of the Fuji river basin, Japan. *Environ Model Software* 2007, 22:464–475.
143. Lecce SA, Pease PP, Gares PA, Wang J. Seasonal controls on sediment delivery in a small coastal plain watershed, North Carolina, USA. *Geomorphology* 2006, 73:246–260.
144. Scanlon TM, Kiely G, Xie Q. A nested catchment approach for defining the hydrological controls on non-point phosphorus transport. *J Hydrol* 2004, 291:218–231.
145. Stutter MI, Langan SJ, Cooper RJ. Spatial and temporal dynamics of stream water particulate and dissolved N, P and C forms along a catchment transect, NE Scotland. *J Hydrol* 2008, 350:187–202.
146. Bende-Michl U, Verburg K, Cresswell HP. High-frequency nutrient monitoring to infer seasonal patterns in catchment source availability, mobilisation and delivery. *Environ Monit Assess* 2013, 185:9191–9219.
147. Saffarpour S, Western AW, Adams R, McDonnell JJ. Multiple runoff processes and multiple thresholds control agricultural runoff generation. *Hydrol Earth Syst Sci* 2016, 20:4525–4545.
148. Robson BJ. State of the art in modelling of phosphorus in aquatic systems: review, criticisms and commentary. *Environ Model Software* 2014, 61:339–359.
149. Lloyd CEM, Freer JE, Johnes PJ, Collins AL. Using hysteresis analysis of high-resolution water quality monitoring data, including uncertainty, to infer controls on nutrient and sediment transfer in catchments. *Sci Total Environ* 2016, 543:388–404.
150. Mellander P-E, Jordan P, Shore M, Melland AR, Shortle G. Flow paths and phosphorus transfer pathways in two agricultural streams with contrasting flow controls. *Hydrol Process* 2015, 29:3504–3518.
151. Eimers MC, Buttle JM, Watmough SA. The contribution of rain-on-snow events to annual NO3-N export from a forested catchment in south-central Ontario, Canada. *Appl Geochem* 2007, 22:1105–1110.
152. Casson NJ, Eimers MC, Buttle JM. The contribution of rain-on-snow events to nitrate export in the forested landscape of south-central Ontario, Canada. *Hydrol Process* 2010, 24:1985–1993.
153. Tetzlaff D, Buttle J, Carey SK, McGuire K, Laudon H, Soulsby C. Tracer-based assessment of flow paths, storage and runoff generation in northern catchments: a review. *Hydrol Process* 2015, 29:3475–3490.
154. Sharpley AN, Kleinman PJA, McDowell RW, Gitau M, Bryant RB. Modeling phosphorus transport

 © 2017 The Authors. *WIREs Water* published by Wiley Periodicals, Inc.

in agricultural watersheds: processes and possibilities. *J Soil Water Conserv* 2002, 57:425–439.

155. Jordan P, Menary W, Daly K, Kiely G, Morgan G, Byrne P, Moles R. Patterns and processes of phosphorus transfer from Irish grassland soils to rivers—integration of laboratory and catchment studies. *J Hydrol* 2005, 304:20–34.

156. Blanco AC, Nadaoka K, Yamamoto T, Kinjo K. Dynamic evolution of nutrient discharge under stormflow and baseflow conditions in a coastal agricultural watershed in Ishigaki Island, Okinawa, Japan. *Hydrol Process* 2010, 24:2601–2616.

157. Warner S, Kiely G, Morgan G, O'Halloran J. Does quantifying antecedent flow conditions improve stream phosphorus export estimation? *J Hydrol* 2009, 378:97–104.

158. Ahearn DS, Sheibley RW, Dahlgren RA, Keller KE. Temporal dynamics of stream water chemistry in the last free-flowing river draining the western Sierra Nevada, California. *J Hydrol* 2004, 295:47–63.

159. Donohue I, Styles D, Coxon C, Irvine K. Importance of spatial and temporal patterns for assessment of risk of diffuse nutrient emissions to surface waters. *J Hydrol* 2005, 304:183–192 (Nutirent Mobility within River Basins: A European Perspective).

160. Vaze J, Barnett P, Beale G, Dawes W, Evans R, Tuteja NK, Murphy B, Geeves G, Miller M. Modelling the effects of land-use change on water and salt delivery from a catchment affected by dryland salinity in South-East Australia. *Hydrol Process* 2004, 18:1613–1637.

161. Giri S, Qiu Z. Understanding the relationship of land uses and water quality in Twenty First Century: a review. *J Environ Manage* 2016, 173:41–48.

162. Attiwill PM, Adams MA. Tansley review No. 50. Nutrient cycling in forests. *New Phytol* 1993, 124:561–582.

163. Christopher SF, Page BD, Campbell JL, Mitchell MJ. Contrasting stream water NO3– and Ca2+ in two nearly adjacent catchments: the role of soil Ca and forest vegetation. *Glob Chang Biol* 2006, 12:364–381.

164. Christopher SF, Mitchell MJ, McHale MR, Boyer EW, Burns DA, Kendall C. Factors controlling nitrogen release from two forested catchments with contrasting hydrochemical responses. *Hydrol Process* 2008, 22:46–62.

165. Vought LB-M, Dahl J, Pedersen CL, Lacoursiere JO. Nutrient retention in riparian ecotones. *Ambio* 1994, 23:342–348.

166. Bu H, Meng W, Zhang Y, Wan J. Relationships between land use patterns and water quality in the Taizi River basin, China. *Ecol Indic* 2014, 41:187–197.

167. Song Z, Williams CJ, Edyvean RGJ. Sedimentation of tannery wastewater. *Water Res* 2000, 34:2171–2176.

168. Law N, Band L, Grove M. Nitrogen input from residential lawn care practices in suburban watersheds in Baltimore county, MD. *J Environ Plan Manage* 2004, 47:737–755.

169. Howarth RW, Sharpley A, Walker D. Sources of nutrient pollution to coastal waters in the United States: implications for achieving coastal water quality goals. *Estuaries* 2002, 25:656–676.

170. Juahir H, Zain SM, Yusoff MK, Hanidza TIT, Armi ASM, Toriman ME, Mokhtar M. Spatial water quality assessment of Langat River Basin (Malaysia) using environmetric techniques. *Environ Monit Assess* 2011, 173:625–641.

171. Findlay SEG, Kelly VR. Emerging indirect and long-term road salt effects on ecosystems. *Ann N Y Acad Sci* 2011, 1223:58–68.

172. Zhao H, Li X, Wang X, Tian D. Grain size distribution of road-deposited sediment and its contribution to heavy metal pollution in urban runoff in Beijing, China. *J Hazard Mater* 2010, 183:203–210.

173. Mahler RL, Koehler FE, Lutcher LK. Nitrogen source, timing of application, and placement: effects on winter wheat production. *Agron J* 1994, 86:637–642.

174. Gehl RJ, Schmidt JP, Maddux LD, Gordon WB. Corn yield response to nitrogen rate and timing in sandy irrigated soils. *Agron J* 2005, 97:1230–1238.

175. Karlen DL, Mausbach MJ, Doran JW, Cline RG, Harris RF, Schuman GE. Soil quality: a concept, definition, and framework for evaluation. *Soil Sci Soc Am J* 1997, 61:4–10.

176. Pereira LS, Oweis T, Zairi A. Irrigation management under water scarcity. *Agric Water Manag* 2002, 57:175–206.

177. Newbold JD, Herbert S, Sweeney BW, Kiry P, Alberts SJ. Water quality functions of a 15-year-old riparian forest buffer system. *J Am Water Resour Assoc* 2010, 46:299–310.

178. Mayer PM, Reynolds SK Jr, McCutchen MD, Canfield TJ. Meta-analysis of nitrogen removal in riparian buffers. *J Environ Qual* 2007, 36:1172–1180.

179. Hamel P, Daly E, Fletcher TD. Source-control stormwater management for mitigating the impacts of urbanisation on baseflow: A review. *J Hydrol* 2013, 485:201–211.

180. Water M. *WSUD Engineering Procedures: Stormwater*. Melbourne Water: Melbourne; 2005.

181. Davis AP. Green engineering principles promote low-impact development. *Environ Sci Technol* 2005, 39:338A–344A.

 © 2017 The Authors. *WIREs Water* published by Wiley Periodicals, Inc.

182. Davis AP, Traver RG, Hunt WF. Improving urban stormwater quality: applying fundamental principles. *J Contemp Water Res Educ* 2010, 146:3–10.

183. Taylor AC, Fletcher TD. Nonstructural urban stormwater quality measures: building a knowledge base to improve their use. *Environ Manag* 2007, 39:663–677.

184. Meals DW, Dressing SA, Davenport TE. Lag time in water quality response to best management practices: a review all rights reserved. No part of this periodical may be reproduced or transmitted in any form or by any means, electronic or mechanical, including photocopying, recording, or any information. *J Environ Qual* 2010, 39:85–96.

185. Zaimes GN, Schultz RC, Isenhart TM. Streambank soil and phosphorus losses under different riparian land-uses in Iowa. *J Am Water Resour Assoc* 2008, 44:935–947.

186. Schlosser IJ, Karr JR. Water quality in agricultural watersheds: impact of riparian vegetation during baseflow. *J Am Water Resour Assoc* 1981, 17:233–240.

187. Price K, Leigh DS. Comparative water quality of lightly- and moderately-impacted streams in the Southern Blue Ridge Mountains, USA. *Environ Monit Assess* 2006, 120:269–300.

188. Petrone KC. Catchment export of carbon, nitrogen, and phosphorus across an agro-urban land use gradient, Swan-Canning River system, southwestern Australia. *J Geophys Res Biogeosci* 2010, 115: G01016.

189. Bowes MJ, Jarvie HP, Halliday SJ, Skeffington RA, Wade AJ, Loewenthal M, Gozzard E, Newman JR, Palmer-Felgate EJ. Characterising phosphorus and nitrate inputs to a rural river using high-frequency concentration–flow relationships. *Sci Total Environ* 2015, 511:608–620.

190. Dupas R, Gascuel-Odoux C, Gilliet N, Grimaldi C, Gruau G. Distinct export dynamics for dissolved and particulate phosphorus reveal independent transport mechanisms in an arable headwater catchment. *Hydrol Process* 2015, 29:3162–3178.

191. Bartley R, Speirs WJ, Ellis TW, Waters DK. A review of sediment and nutrient concentration data from Australia for use in catchment water quality models. *Mar Pollut Bull* 2012, 65:101–116.

192. Bartley R, Corfield JP, Abbott BN, Hawdon AA, Wilkinson SN, Nelson B. Impacts of improved grazing land management on sediment yields, Part 1: hillslope processes. *J Hydrol* 2010, 389:237–248.

193. Abu-Zreig M, Rudra RP, Lalonde MN, Whiteley HR, Kaushik NK. Experimental investigation of runoff reduction and sediment removal by vegetated filter strips. *Hydrol Process* 2004, 18:2029–2037.

194. Kortelainen P, Mattsson T, Finér L, Ahtiainen M, Saukkonen S, Sallantaus T. Controls on the export of C, N, P and Fe from undisturbed boreal catchments, Finland. *Aquat Sci* 2006, 68:453–468.

195. Galloway JN, Townsend AR, Erisman JW, Bekunda M, Cai Z, Freney JR, Martinelli LA, Seitzinger SP, Sutton MA. Transformation of the nitrogen cycle: recent trends, questions, and potential solutions. *Science* 2008, 320:889 LP–889892.

196. Verhoeven JTA, Arheimer B, Yin C, Hefting MM. Regional and global concerns over wetlands and water quality. *Trends Ecol Evol* 2006, 21:96–103.

197. Zhang Y, Dore AJ, Ma L, Liu XJ, Ma WQ, Cape JN, Zhang FS. Agricultural ammonia emissions inventory and spatial distribution in the North China Plain. *Environ Pollut* 2010, 158:490–501.

198. Bouwman AF, Lee DS, Asman WAH, Dentener FJ, Van Der Hoek KW, Olivier JGJ. A global high-resolution emission inventory for ammonia. *Global Biogeochem Cycles* 1997, 11:561–587.

199. Fisher DC, Oppenheimer M. Atmospheric nitrogen deposition and the Chesapeake Bay estuary. *Ambio* 1991, 20:102–108.

200. Driscoll CT, Whitall D, Aber J, Boyer EW, Castro M, Cronan C, Goodale CL, Groffman PM, Hopkinson C, Lambert K, et al. Nitrogen pollution in the Northeastern United States: sources, effects, and management options. *Bioscience* 2003, 53:357–374.

201. Aber JD, Goodale CL, Ollinger SV, Smith M-L, Magill AH, Martin ME, Hallett RA, Stoddard JL. Is nitrogen deposition altering the nitrogen status of Northeastern forests? *Bioscience* 2003, 53:375.

202. Johnson DW, Turner J, Kelly JM. The effects of acid rain on forest nutrient status. *Water Resour Res* 1982, 18:449–461.

203. Lambers H, Raven JA, Shaver GR, Smith SE. Plant nutrient-acquisition strategies change with soil age. *Trends Ecol Evol* 2008, 23:95–103.

204. Rothwell JJ, Evans MG, Daniels SM, Allott TEH. Baseflow and stormflow metal concentrations in streams draining contaminated peat moorlands in the Peak District National Park (UK). *J Hydrol* 2007, 341:90–104.

205. Tejada M, Gonzalez JL. Influence of two organic amendments on the soil physical properties, soil losses, sediments and runoff water quality. *Geoderma* 2008, 145:325.

206. Lewis WM, Melack JM, McDowell WH, McClain M, Richey JE. Nitrogen yields from undisturbed watersheds in the Americas. *Biogeochemistry* 1999, 46:149–162.

207. Lewis C, Rafique R, Foley N, Leahy P, Morgan G, Albertson J, Kumar S, Kiely G. Seasonal exports of phosphorus from intensively fertilised nested grassland catchments. *J Environ Sci* 2013, 25:1847–1857.

 © 2017 The Authors. *WIREs Water* published by Wiley Periodicals, Inc.

208. Edwards AC, Withers PJA. Soil phosphorus management and water quality: a UK perspective. *Soil Use Manage* 1998, 14:124–130.

209. Kleinman PJA, Sharpley AN, McDowell RW, Flaten DN, Buda AR, Tao L, Bergstrom L, Zhu Q. Managing agricultural phosphorus for water quality protection: principles for progress. *Plant and Soil* 2011, 349:169–182.

210. Herczeg AL, Dogramaci SS, Leaney FWJ. Origin of dissolved salts in a large, semi-arid groundwater system: Murray Basin, Australia. *Mar Freshw Res* 2001, 52:41–52.

211. Franklin DH, Steiner JL, Duke SE, Moriasi DN, Starks PJ. Spatial considerations in wet and dry periods for phosphorus in streams of the Fort Cobb Watershed, United States. *J Am Water Resour Assoc* 2013, 49:908–922.

212. Sivapalan M, Viney NR, Ruprecht JK. Water and salt balance modelling to predict the effects of land-use changes in forested catchments. 2. Coupled model of water and salt balances. *Hydrol Process* 1996, 10:413–428.

213. Peck AJ, Hatton T. Salinity and the discharge of salts from catchments in Australia. *J Hydrol* 2003, 272:191–202.

214. Nadelhoffer KJ, Giblin AE, Shaver GR, Laundre JA. Effects of temperature and substrate quality on element mineralization in six arctic soils. *Ecology* 1991, 72:242–253.

215. Grierson PF, Comerford NB, Jokela EJ. Phosphorus mineralization and microbial biomass in a Florida Spodosol: effects of water potential, temperature and fertilizer application. *Biol Fertil Soils* 1999, 28:244–252.

216. Butler SM, Melillo JM, Johnson JE, Mohan J, Steudler PA, Lux H, Burrows E, Smith RM, Vario CL, Scott L, et al. Soil warming alters nitrogen cycling in a New England forest: implications for ecosystem function and structure. *Oecologia* 2012, 168:819–828.

217. Eastman M, Gollamudi A, Stämpfli N, Madramootoo CA, Sarangi A. Comparative evaluation of phosphorus losses from subsurface and naturally drained agricultural fields in the Pike River watershed of Quebec, Canada. *Agric Water Manag* 2010, 97:596–604.

218. Gao Y, Zhu B, Wang T, Wang Y. Seasonal change of non-point source pollution-induced bioavailable phosphorus loss: a case study of Southwestern China. *J Hydrol* 2012, 420–421:373–379.

219. Delong MD, Brusven MA. Classification and spatial mapping of riparian habitat with applications toward management of streams impacted by nonpoint source pollution. *Environ Manage* 1991, 15:565–571.

220. Onderka M, Wrede S, Rodný M, Pfister L, Hoffmann L, Krein A. Hydrogeologic and landscape controls of dissolved inorganic nitrogen (DIN) and dissolved silica (DSi) fluxes in heterogeneous catchments. *J Hydrol* 2012, 450–451:36–47.

221. Bednarik M, Magulová B, Matys M, Marschalko M. Landslide susceptibility assessment of the Kra□ovany–Liptovský Mikuláš railway case study. *Phys Chem Earth A/B/C* 2010, 35:162–171.

222. Inamdar SP, Mitchell MJ. Hydrologic and topographic controls on storm-event exports of dissolved organic carbon (DOC) and nitrate across catchment scales. *Water Resour Res* 2006, 42:W03421.

223. Richards C, Johnson LB, Host GE. Landscape-scale influences on stream habitats and biota. *Can J Fish Aquat Sci* 1996, 53:295–311.

224. KRATZ T, WEBSTER K, BOWSER C, MAGUSON J, BENSON B. The influence of landscape position on lakes in northern Wisconsin. *Freshw Biol* 1997, 37:209–217.

225. Thomas SM, Neill C, Deegan LA, Krusche AV, Ballester VM, Victoria RL. Influences of land use and stream size on particulate and dissolved materials in a small Amazonian stream network. *Biogeochemistry* 2004, 68:135–151.

226. Hrachowitz M, Benettin P, van Breukelen BM, Fovet O, Howden NJK, Ruiz L, van der Velde Y, Wade AJ. Transit times—the link between hydrology and water quality at the catchment scale. *Wiley Interdiscip Rev Water* 2016, 3:629–657.

227. Webb JA, Stewardson MJ, Koster WM. Detecting ecological responses to flow variation using Bayesian hierarchical models. *Freshw Biol* 2010, 55:108–126.

228. Schilling KE. Chemical transport from paired agricultural and restored prairie watersheds. *J Environ Qual* 2002, 31:1184–1193.

229. Sudduth EB, Perakis SS, Bernhardt ES. Nitrate in watersheds: straight from soils to streams? *J Geophys Res Biogeo* 2013, 118:291–302.

230. Rasiah V, Armour JD, Cogle AL, Florentine SK. Nitrate import export dynamics in groundwater interacting with surface-water in a wet-tropical environment. *Soil Res* 2010, 48:361–370.

231. Scott D, Harvey J, Alexander R, Schwarz G. Dominance of organic nitrogen from headwater streams to large rivers across the conterminous United States. *Global Biogeochem Cycles* 2007, 21:GB1003.

232. Vörösmarty CJ, Meybeck M, Fekete B, Sharma K, Green P, Syvitski JPM. Anthropogenic sediment retention: major global impact from registered river impoundments. *Global Planet Change* 2003, 39:169–190.

233. Adams R, Arafat Y, Eate V, Grace MR, Saffarpour S, Weatherley AJ, Western AW. A catchment study of sources and sinks of nutrients and sediments in South-East Australia. *J Hydrol* 2014, 515:166–179.

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234. Shi ZH, Ai L, Li X, Huang XD, GL W, Liao W. Partial least-squares regression for linking land-cover patterns to soil erosion and sediment yield in watersheds. *J Hydrol* 2013, 498:165–176.

235. Gergel SE. Spatial and non-spatial factors: When do they affect landscape indicators of watershed loading? *Landsc Ecol* 2005, 20:177–189.

236. Tran CP, Bode RW, Smith AJ, Kleppel GS. Land-use proximity as a basis for assessing stream water quality in New York State (USA). *Ecol Indic* 2010, 10:727–733.

237. Johnes PJ, Heathwaite AL. Modelling the impact of land use change on water quality in agricultural catchments. *Hydrol Process* 1997, 11:269–286.

238. Yates AG, Brua RB, Corriveau J, Culp JM, Chambers PA. Seasonally driven variation in spatial relationships between agricultural land use and in-stream nutrient concentrations. *River Res Appl* 2014, 30:476–493.

239. Oldham CE, Farrow DE, Peiffer S. A generalized Damköhler number for classifying material processing in hydrological systems. *Hydrol Earth Syst Sci* 2013, 17:1133–1148.

240. Anbumozhi V, Radhakrishnan J, Yamaji E. Impact of riparian buffer zones on water quality and associated management considerations. *Ecol Eng* 2005, 24:517–523.

241. Weller DE, Jordan TE, Correll DL. Heuristic models for material discharge from landscapes with riparian buffers. *Ecol Appl* 1998, 8:1156–1169.

242. Uriarte M, Yackulic CB, Lim Y, Arce-Nazario JA. Influence of land use on water quality in a tropical landscape: a multi-scale analysis. *Landsc Ecol* 2011, 26:1151–1164.

243. Sweeney BW, Newbold JD. Streamside forest buffer width needed to protect stream water quality, habitat, and organisms: a literature review. *J Am Water Resour Assoc* 2014, 50:560–584.

244. Gumiere SJ, Le Bissonnais Y, Raclot D, Cheviron B. Vegetated filter effects on sedimentological connectivity of agricultural catchments in erosion modelling: a review. *Earth Surf Process Landf* 2011, 36:3–19.

245. EE PETERSON, SHELDON F, DARNELL R, SE BUNN, BD HARCH. A comparison of spatially explicit landscape representation methods and their relationship to stream condition. *Freshw Biol* 2011, 56:590–610.

246. King RS, Baker ME, Whigham DF, Weller DE, Jordan TE, Kazyak PF, Hurd MK. Spatial considerations for linking watershed land cover to ecological indicators in streams. *Ecol Appl* 2005, 15:137–153.

247. Grabowski ZJ, Watson E, Chang H. Using spatially explicit indicators to investigate watershed characteristics and stream temperature relationships. *Sci Total Environ* 2016, 551–552:376–386.

248. Van Sickle J, Burch Johnson C. Parametric distance weighting of landscape influence on streams. *Landsc Ecol* 2008, 23:427–438.

249. Sheldon F, Peterson EE, Boone EL, Sippel S, Bunn SE, Harch BD. Identifying the spatial scale of land use that most strongly influences overall river ecosystem health score. *Ecol Appl* 2012, 22:2188–2203.

250. Walsh C, Webb J. Spatial weighting of land use and temporal weighting of antecedent discharge improves prediction of stream condition. *Landsc Ecol* 2014, 29:1171–1185.

251. Lee S-W, Hwang S-J, Lee S-B, Hwang H-S, Sung H-C. Landscape ecological approach to the relationships of land use patterns in watersheds to water quality characteristics. *Landsc Urban Plan* 2009, 92:80–89.

252. Guo Q, Ma K, Yang L, He K. Testing a dynamic complex hypothesis in the analysis of land use impact on lake water quality. *Water Resour Manage* 2010, 24:1313–1332.

253. Zhang S, Fan W, Li Y, Yi Y. The influence of changes in land use and landscape patterns on soil erosion in a watershed. *Sci Total Environ* 2017, 574:34–45.

254. Ouyang W, Skidmore AK, Hao F, Wang T. Soil erosion dynamics response to landscape pattern. *Sci Total Environ* 2010, 408:1358–1366.

255. Walsh CJ, Fletcher TD, Ladson AR. Stream restoration in urban catchments through redesigning stormwater systems: looking to the catchment to save the stream. *J North Am Benthol Soc* 2005, 24:690–705.

256. Kadlec RH, Wallace S. *Treatment Wetlands*. Boca Raton, FL: Taylor and Francis Group; 2009.

257. Zhou T, Wu J, Peng S. Assessing the effects of landscape pattern on river water quality at multiple scales: a case study of the Dongjiang River watershed, China. *Ecol Indic* 2012, 23:166–175.

258. Houser JN, Mulholland PJ, Maloney KO. Upland disturbance affects headwater stream nutrients and suspended sediments during baseflow and stormflow. *J Environ Qual* 2006, 35:352–365.

259. Li S, Liu W, Gu S, Cheng X, Xu Z, Zhang Q. Spatio-temporal dynamics of nutrients in the upper Han River basin, China. *J Hazard Mater* 2009, 162:1340–1346.

260. Phillips JD. An evaluation of the factors determining the effectiveness of water quality buffer zones. *J Hydrol* 1989, 107:133–145.

261. Correll DL. Principles of planning and establishment of buffer zones. *Ecol Eng* 2005, 24:433–439.

262. Amiri BJ, Nakane K. Modeling the linkage between river water quality and landscape metrics in the Chugoku district of Japan. *Water Resour Manage* 2009, 23:931–956.

263. Laurance WF, Fearnside PM, Laurance SG, Delamonica P, Lovejoy TE, Rankin-de Merona JM, Chambers JQ, Gascon C. Relationship between soils

 © 2017 The Authors. *WIREs Water* published by Wiley Periodicals, Inc.

and Amazon forest biomass: a landscape-scale study. *For Ecol Manage* 1999, 118:127–138.

264. Goldberg DE. The distribution of evergreen and deciduous trees relative to soil type: an example from the Sierra Madre, Mexico, and a General Model. *Ecology* 1982, 63:942–951.
265. Churkina G, Running SW. Contrasting climatic controls on the estimated productivity of global terrestrial biomes. *Ecosystems* 1998, 1:206–215.
266. Prentice IC, Cramer W, Harrison SP, Leemans R, Monserud RA, Solomon AMA. Global biome model based on plant physiology and dominance, soil properties and climate. *J Biogeogr* 1992, 19:117–134.
267. Price DG. Weathering and weathering processes. *Quart J Eng Geol Hydrogeol* 1995, 28:243–252.
268. Saarnio S, Heimonen K, Kettunen R. Biochar addition indirectly affects N2O emissions via soil moisture and plant N uptake. *Soil Biol Biochem* 2013, 58:99–106.
269. Chen J, Lu J. Effects of land use, topography and socio-economic factors on river water quality in a mountainous watershed with intensive agricultural production in East China. *PLoS ONE* 2014, 9: e102714.
270. Mills HH. Inferring erosional resistance of bedrock units in the east Tennessee mountains from digital elevation data. *Geomorphology* 2003, 55:263–281.
271. Baumann F, Schmidt K, Dörfer C, He J-S, Scholten T, Kühn P. Pedogenesis, permafrost, substrate and topography: plot and landscape scale interrelations of weathering processes on the central-eastern Tibetan Plateau. *Geoderma* 2014, 226–227:300–316.
272. Lettenmaier DP, Gan TY. Hydrologic sensitivities of the Sacramento-San Joaquin River Basin, California, to global warming. *Water Resour Res* 1990, 26:69–86.
273. Mao D, Cherkauer KA. Impacts of land-use change on hydrologic responses in the Great Lakes region. *J Hydrol* 2009, 374:71–82.
274. Jencso KG, McGlynn BL. Hierarchical controls on runoff generation: topographically driven hydrologic connectivity, geology, and vegetation. *Water Resources Research* 2011, 47:W11527.
275. Shi W, Xia J, Zhang X. Influences of anthropogenic activities and topography on water quality in the highly regulated Huai River basin, China. *Environ Sci Pollut Res* 2016, 23:21460–21474.
276. Yoon V, Stein E. Natural catchments as sources of background levels of storm-water metals, nutrients, and solids. *J Environ Eng* 2008, 134:961–973.
277. Rothwell JJ, Dise NB, Taylor KG, Allott TEH, Scholefield P, Davies H, Neal C. A spatial and seasonal assessment of river water chemistry across North West England. *Sci Total Environ* 2010, 408:841–855.
278. Ye L, Cai Q, Liu R, Cao M. The influence of topography and land use on water quality of Xiangxi River in Three Gorges Reservoir region. *Environ Geol* 2009, 58:937–942.
279. Yevenes MA, Arumí JL, Farías L. Unravel biophysical factors on river water quality response in Chilean Central-Southern watersheds. *Environ Monit Assess* 2016, 188:1–17.
280. Bracken LJ, Croke J. The concept of hydrological connectivity and its contribution to understanding runoff-dominated geomorphic systems. *Hydrol Process* 2007, 21:1749–1763.
281. Bracken LJ, Wainwright J, Ali GA, Tetzlaff D, Smith MW, Reaney SM, Roy AG. Concepts of hydrological connectivity: research approaches, pathways and future agendas. *Earth Sci Rev* 2013, 119:17–34.
282. Kaushal SS, Groffman PM, Band LE, Shields CA, Morgan RP, Palmer MA, Belt KT, Swan CM, Findlay SEG, Fisher GT. Interaction between urbanization and climate variability amplifies watershed nitrate export in Maryland. *Environ Sci Technol* 2008, 42:5872–5878.
283. Stieglitz M, Shaman J, McNamara J, Engel V, Shanley J, Kling GW. An approach to understanding hydrologic connectivity on the hillslope and the implications for nutrient transport. *Global Biogeochem Cycles* 2003, 17:1105.
284. Tramblay Y, Ouarda TBMJ, St-Hilaire A, Poulin J. Regional estimation of extreme suspended sediment concentrations using watershed characteristics. *J Hydrol* 2010, 380:305–317.
285. Tu J, Xia Z-G. Examining spatially varying relationships between land use and water quality using geographically weighted regression I: model design and evaluation. *Sci Total Environ* 2008, 407:358–378.
286. Rothwell JJ, Dise NB, Taylor KG, Allott TEH, Scholefield P, Davies H, Neal C. Predicting river water quality across North West England using catchment characteristics. *J Hydrol* 2010, 395:153–162.
287. McKee LJ, Eyre BD, Hossain S, Pepperell PR. Influence of climate, geology and humans on spatial and temporal nutrient geochemistry in the subtropical Richmond River catchment, Australia. *Mar Freshw Res* 2001, 52:235–248.
288. Oehler F, Durand P, Bordenave P, Saadi Z, Salmon-Monviola J. Modelling denitrification at the catchment scale. *Sci Total Environ* 2009, 407:1726–1737.
289. JE CLAPCOTT, KJ COLLIER, RG DEATH, EO GOODWIN, JS HARDING, KELLY D, JR LEATHWICK, RG YOUNG. Quantifying relationships between land-use gradients and structural and functional indicators of stream ecological integrity. *Freshw Biol* 2012, 57:74–90.

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290. Lek S, Guiresse M, Giraudel J-L. Predicting stream nitrogen concentration from watershed features using neural networks. *Water Res* 1999, 33:3469–3478.

291. Shrestha RR, Bárdossy A, Rode M. A hybrid deterministic–fuzzy rule based model for catchment scale nitrate dynamics. *J Hydrol* 2007, 342:143–156.

292. Kalteh AM, Hjorth P, Berndtsson R. Review of the self-organizing map (SOM) approach in water resources: analysis, modelling and application. *Environ Model Software* 2008, 23:835–845.

293. Johnson LB, Host GE. Recent developments in landscape approaches for the study of aquatic ecosystems. *J North Am Benthol Soc* 2010, 29:41–66.

294. Zhang T. Distance-decay patterns of nutrient loading at watershed scale: regression modeling with a special spatial aggregation strategy. *J Hydrol* 2011, 402:239–249.

295. Galbraith LM, Burns CW. Linking land-use, water body type and water quality in Southern New Zealand. *Landsc Ecol* 2006, 22:231–241.

296. Walling DE. Tracing suspended sediment sources in catchments and river systems. *Sci Total Environ* 2005, 344:159–184.

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