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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 China⁴ and over one third of rivers in the United States⁵ 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 km² 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 km² 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

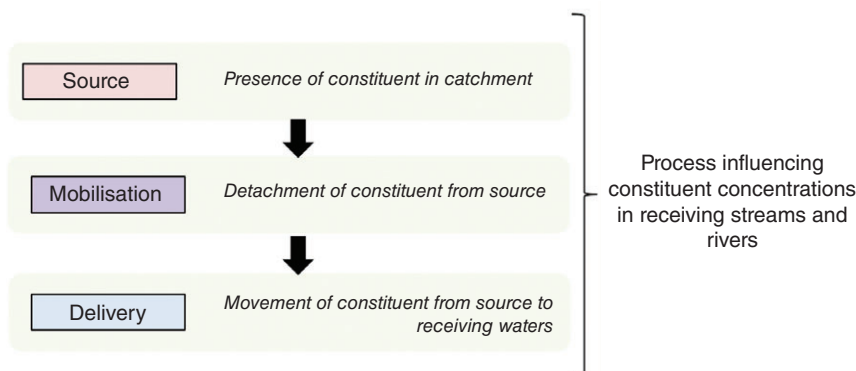


FIGURE 1 | Conceptual framework proposed by Granger et al.²⁷ that explains constituent concentrations in receiving rivers and streams.

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 sediments³¹ (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

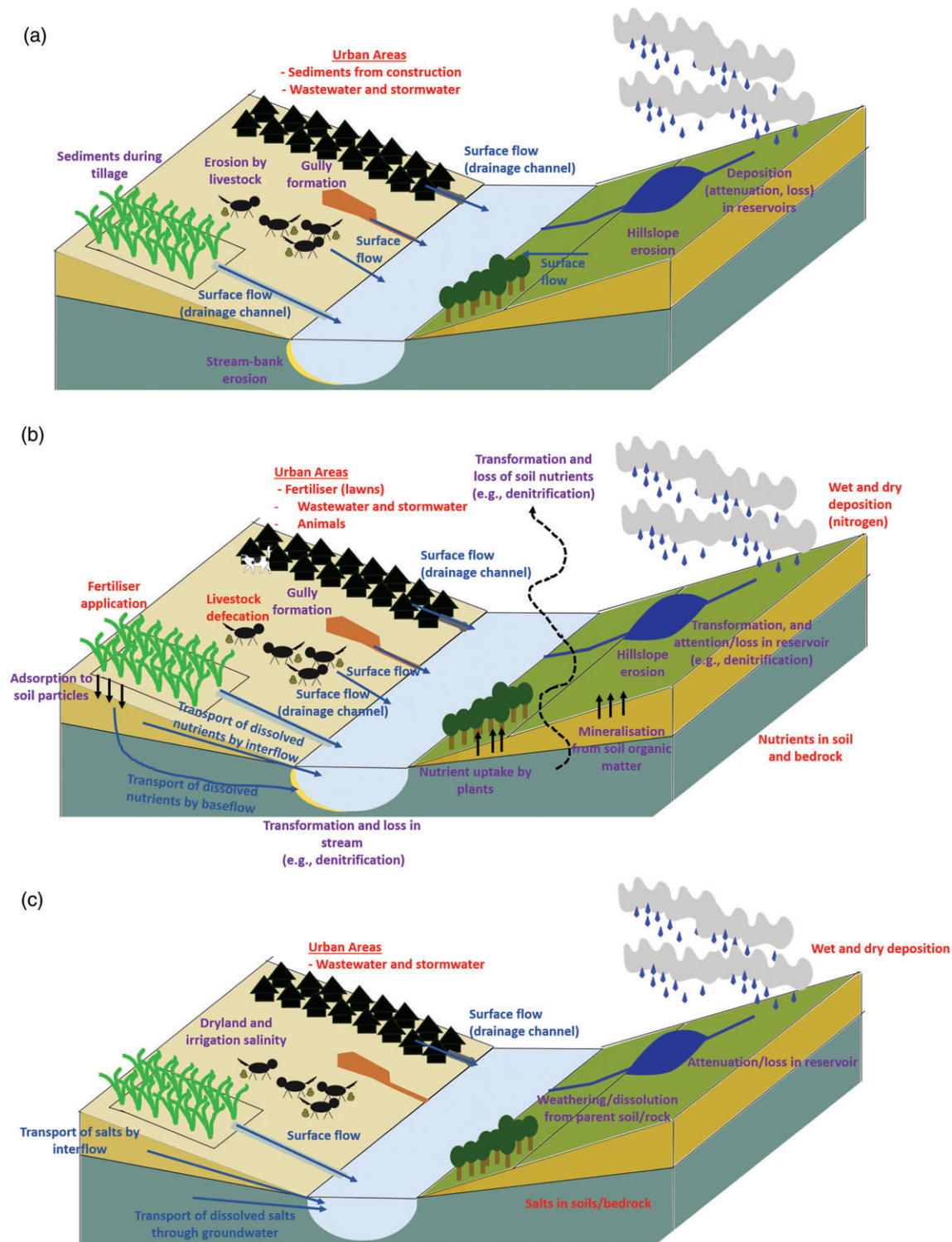


FIGURE 2 | Sources, mobilization, and delivery of sediments (a), nutrients (b), and salts (c) to catchment outlet. Red text represents sources, purple text represents mobilization, and blue text and arrows represent delivery processes.

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.

BOX 1

SEASONAL CHANGES IN WATER QUALITY AT A SITE

The sediments,^{139,143} nutrient species,^{74,116,144–146} and salts⁷⁰ 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 paths¹⁴⁷, 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.

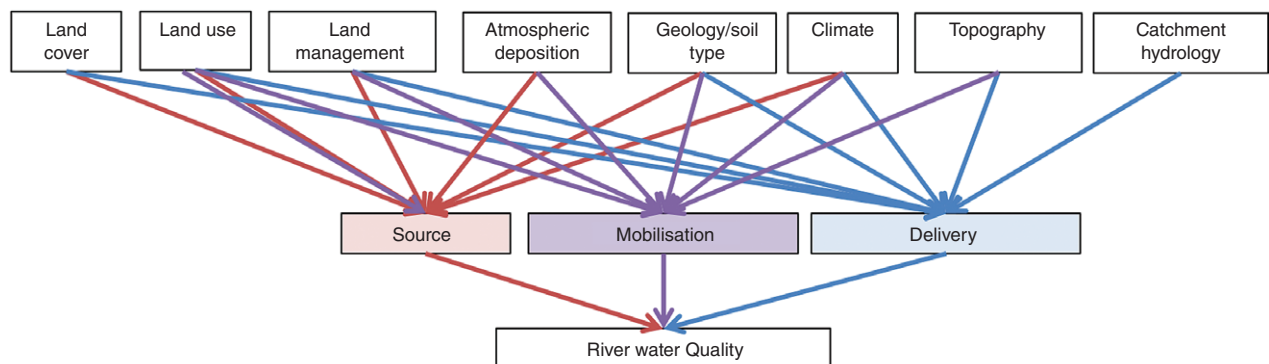


FIGURE 3 | Influence of landscape characteristics on source, mobilization, and delivery of constituents.

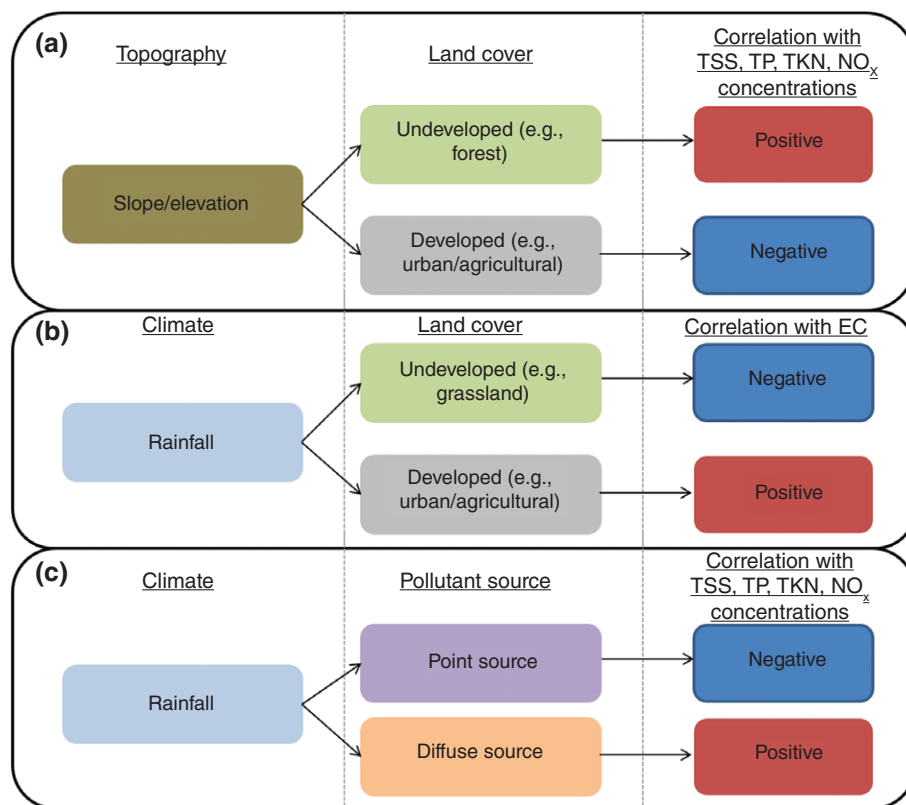


FIGURE 4 | Interactions between landscape characteristics (left column) and concentrations (right column) identified in literature. The middle column is the factor modulating the sign of the correlation. (a) Refs ^{10,74,126,137,178,234,235,237,278,293,294}, (b) Refs ^{101,134,135,139,227}, and (c) Ref 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 (NH₃ and NO₂⁻) and both particulate and dissolved phosphorus (TP and PO₄) 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 wastewater⁶⁸, and fertilizers.^{80,170} In

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

Characteristic	Constituent Source Availability				Constituent Mobilization				Constituent Delivery			
	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	0	(−) 61–63	(−) 57	(−) 57	(−) 57	(0)
Land use												
Urban	(+) 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)
Defining	(0)	(0)	(0)	(+) 70	(0)	(0)	(0)	(0)	(0)	(0)	(0)	(0)
Construction	(+) 66,71	(0)	(0)	(0)	(+) 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
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
Susceptibility of soil/bedrock to erosion/weathering	(0)	(0)	(0)	(0)	(+) 97	(+) 98,99–100	(+) 98,75	(+) 98,101	(0)	(0)	(0)	(0)
Climate												
Nutrient (or salt) content of soil/bedrock	(0)	(+) 19,102–104	(+) 103–105	(+) 99,67,101,106	(0)	(0)	(0)	(0)	(0)	(0)	(0)	(0)
Soil/aquifer conductivity	(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)
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	(+) 74	(+) 74,119	(0)	(0)	(0)	(0)	(0)
Mean annual rainfall	(0)	(0)	(+) 120	(+) 121	(−) 118	(−) 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)
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)

TABLE 1 | Continued

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

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 zones⁷⁶ (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.

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
		Reduce stock access to waterways	Livestock can directly deposit nutrients into waterways by urinating and defecating. ⁷⁵
	Particulate and dissolved nutrients	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}
Mobilization	Sediments and nutrients (particulate)	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}
		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}
	Salts	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}
		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}

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 m² 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.

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 N₂ 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

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 Sweden⁷⁴ 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 rivers⁷⁴ 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 Dudley²¹ 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 Dudley²¹ 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

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

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 nitrate²⁴³) 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

TABLE 3 | Cross Correlations between Landscape Characteristics

Land use	Land Cover	Land Use	Geology/Soil Type	Climate	Topography
	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)

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.

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				
	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
Motueka River catchment (New Zealand)	23	x	x				LU	LU	LU	G
Han River basin (South Korea)	118	x	x		x		LU	LU	LU	9
Caspian Sea (Iran)	23	x	x							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
Saginaw Bay catchment (USA)	62	x	x		x				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

Some previous studies have attempted to identify the most important landscape characteristics affecting spatial variability in water quality using multiple regression²⁸⁴, 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 Luoto¹³⁶ 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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