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LITERATURE REVIEW: FOREST COVER & WATER QUALITY – IMPLICATIONS FOR LAND CONSERVATION

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KEY FINDINGS

- A host of landscape-scale factors influence water quality. Conservation organizations have the ability to influence only a handful of these—forest cover, and land use more generally—foremost among them.

- Forest cover has clearly-established benefits to water quality at many scales and across many geographies. Watersheds with more land in forest tend to have better water quality. Our review suggests that water quality begins to deteriorate when forest cover falls below 60-90% of catchment area, depending on context. We also suggest that in primarily forested catchments, water quality may deteriorate if agricultural land use falls above 18-50% and/or if impervious area falls above 2-10%.

- The relationship between forest cover and water quality is non-linear and complex. Factors such as location in the watershed, the mix of land uses in the watershed, past land use history, and climate change can all impact the amount of forest cover needed to sustain healthy waters.

- Research that characterizes forest cover and water quality relationships tends to be very site-specific. Results from one location are difficult to translate to another. Combined monitoring and modeling approaches may offer a useful means to identify desirable land use ranges to inform conservation goals at a regional scale.

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INTRODUCTION

The benefits of forest cover to water quality are well established (1, 2), with studies across a range of scales and geographies broadly indicating that forest cover between 60% and 90% is often needed to maintain good water quality. However, conservation efforts built around this relationship must also consider a range of complex factors (*3*) which can modify the ideal amount of forest cover in a given landscape. Spatial relationships between land use types in a watershed (*4*), interactions between forest cover and climate (*5*), and past land use history (*6*) all complicate the pathway from forest conservation to assuring good water quality. In this report, we detail the key findings of a mixed-method[1] literature review that employed traditional 'bottom-up' approaches alongside novel 'top-down' data science methods to identify relevant literature with the goal of informing the design for a multi-year assessment of the water quality impacts of a land protection program in the Delaware River Basin. Ultimately, this work aims to provide conservation best practices for protecting forestland to the benefit of water quality.

In this study, we cast a wide net with respects to the relationship between forest cover and water quality, to identify the land use factors that contribute to abundant, drinkable, biologically healthy watersheds[2]. In the strictest sense, good water quality might be defined in terms of what is chemically safe for human consumption. Yet, biological and even hydrological parameters also define how people commonly think of 'good' water quality. Healthy communities of fish and invertebrates not only reflect the chemical properties of the streams they inhabit, but also provide ecosystem services above and beyond drinkable water (*7*). Likewise, the ability of forested watersheds to supply sufficient water yield might also be considered an aspect of their overall ability to support good water quality (*8*), and at the same time can impact other elements of water quality through mechanism like increased erosion (*3*). Building on this broader understanding, we defined good water quality as the chemical and ecological conditions associated with un-developed forested watersheds in our review.

The goal of this study is to bridge the gap between the excellent academic reviews of land use and water quality that already exist (*3*, *4*, *6*, *9–14*), and the needs of the land conservation community. No reviews to date provide both comprehensive treatment of the range of factors at play in the relationship between land use and water quality and concrete and actionable guidelines for conservation organization interested in strategically focusing their land protection efforts to achieve water quality goals. Building on the work of Lintern et al. (*3*), we aim to characterize the complexity of interactions between land use and water quality for consideration by conservation organizations. And, following on the work of Schueler et al. (*12*) and Sweeney and Newbold (*14*), we aim to generate land use targets that conservation organizations can draw from to shape their protection and restoration efforts. To our knowledge, this review is the first of its kind to bring both of these goals together across the full suite of common land uses in North America's working landscape.

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[1] For a more detailed discussion of the methods we employed, see Appendix C: Review Methods, and also the supplementary methods report on our top-down approaches.

[2] To this end, we survey literature that uses chemical measures of water quality, alongside work that uses biological indexes and broad hydrological measures. Recognizing that different response variables may lead to very different outcomes in terms of a watershed's sensitivity to land use change, we categorize our findings by water quality parameter in Figure 1 and Appendix A.

1.0 RELATING FOREST COVER TO WATER QUALITY

A wide range of factors drive the relationship between forest cover and water quality. Three particularly important factors emerged from our literature review, which we detail at length below: the extent of forest cover in a given watershed, the location of forest cover in a given watershed, and the history of forest cover in a given watershed.

1.1 Extent of Forest Cover

Total forest cover in a catchment is a major—if imperfect—determinant of water quality (*15*). In landscapes where forest is the baseline condition, it is widely recognized that predominantly forested watersheds provide the highest water quality (*9*). Forest cover thresholds ranging from 60% (*16*) to upwards of 90% (*17*) have been put forward as necessary to assure high water quality in site-specific studies. Early work examining the relationship between forest cover and water quality assumed a linear approach, with a given amount forest cover corresponding to a given water quality condition. However, assumptions of linearity have been increasingly called into question (*18*).

1.2 Location of Forest Cover

The spatial relationship between forest cover and other land uses, geological context, and topographical features in a watershed is also an important factor impacting water quality (*19*). Forested buffers (*15*, *16*, *20*) are particularly influential, even in the context of largely forested watersheds (B. Sweeney, personal communication 2018). Forests on slopes and other areas of high potential for erosion are also influential (*19*). These relationships are further developed in section 2.1 - 2.3.

The location of forestland in the overall context of the watershed may also have consequences for water quality. Land conservation in the headwaters of a drainage—which can account for as much as 85% of a drainage's total stream length, and can collect much of the drainage's runoff and associated pollutants (*21*)—may be particularly effective in safeguarding whole-system water quality (*22*). Perhaps reflecting this potential, 20 of the 69 papers we reviewed dealt explicitly with first-order streams, or streams otherwise considered "headwaters" by the authors. Ashton et al. (*23*) exemplify this focus in the literature, recommending increased headwater forest cover alongside best management practices at point source pollution risks to benefit water quality.

1.3 History of Forest Cover

Land use history may also impact the value of forest cover to water quality. Reforestation efforts have clear benefits to water quality, reducing present day nutrient loading to streams from other land uses like agriculture (*24*). However, the effects of past land use—or land use legacy—can continue to influence water quality even after a beneficial land use change such as reforestation (*10*). Land use legacy effects are increasingly discussed in the literature, but not well studied; the concept is best covered in review pieces and theory pieces, rather than empirical work.

2.0 INTERACTIONS BETWEEN FOREST COVER AND OTHER FACTORS

In our literature review, five factors emerged as particularly important to the interplay between forest cover and water quality: the presence of agricultural land in a given watershed; the presence of urban and impervious cover in a given watershed; the condition of the buffer zone; geology; and current and projected climate impacts.

2.1 Agricultural Land Interactions

The extend of forest cover needed to sustain healthy water quality varies depending on the cover type of non-forest lands. Sheeder and Barry. (*25*) report 18% agriculture is typically associated with healthy water quality, in predominantly forested (78% forest cover) watersheds. Yet, other authors report that up to 50% agriculture can be tolerated by stream invertebrates, indicating acceptable water quality (*6*). Accepting a degree of impairment as a necessary outcome of agricultural development, still other authors report that up to 60% agriculture is compatible with only moderately degraded invertebrate communities (*26*). The range of values reported suggests to us that in addition to extent and location of agricultural land, intensity of agricultural practices and use of water quality protection best management practices (*27*) may also influence the impact of agriculture on water quality.

2.1 Urban and Impervious Interactions

The presence of urban land use with high amounts of impervious cover in a watershed has a particularly high impact on water quality, even in the context of abundant forest cover. However, reports of the amount of urban and impervious cover needed to significantly impact water quality vary. Kändler et al. (*28*) report that even in a heavily forested catchment, 20% urban cover results in significant shifts away from the chemical conditions of unimpaired watersheds. In contrast, Sheeder & Barry (*25*) report that only 1.4% developed area is typical of healthy watersheds. As with agricultural land, the intensity of urban development (generally indicated by degree of impervious cover) can also be consequential (*29*). This nuance is further discussed in section 3.3

2.3 Buffer Interactions

Even in predominantly forested landscapes, forest cover is particularly important in the immediate riparian area (B. Sweeney, personal communication), commonly referred to as the buffer zone and defined as the 30m area extending parallel to the stream. Streamside disturbance and poor riparian vegetation cover are among the predominant stressors to U.S. rivers (*14*), and forested buffers' benefits to water quality have been thoroughly reviewed by Sweeney and Newbold (*14*). But, relating buffer condition to overall catchment condition remains an emerging area of study. Although there is not broad consensus about whether buffer land use or whole catchment land use is a better predictor of water quality (*15*, *20*, *30*), several studies report on the importance of forested buffers as a complement to overall land use approaches to water quality protection. Pond et al. (*16*) call for at least 70% of stream edges to be in forested buffer in addition to 60% of overall catchment in forest cover to assure good water quality, a figure also identified by King et al. (*19*). However, the relationship between buffer area and whole catchment land cover in forested catchments is close enough (*31*) that pinpointing the relative influences of buffer areas remains challenging.

Considerable research has also focused on the benefits of grass buffers to water quality, particularly in agricultural or pasture systems, with often-conflicting results. Schilling et al. (*32*) find that forest, pasture, and grass buffers are variously associated with both improvements and declines in stream nutrient concentrations, and with no clear land use emerging as 'best' for water quality. Wang et al. (*33*) find that pasture buffers remove slightly more NO_3 derived nitrogen than forest buffers, but note that the difference is negligible. Beyond their water quality benefits, an advantage of grass buffers is that they can permit for limited agricultural use such as mowing (*33*) or livestock grazing (*32*). However, the broader water quality benefits of forest buffers extend beyond strict chemical measures – DeSouza et al. (*34*) and Laceby et al. (*35*) describe the thermal and physical habitat benefits of forest buffers for fish and invertebrate species which furnish ecosystem services that go hand in hand with those of clean water. Ultimately, Sweeney and Newbold (*14*) conclude that although grass buffers can adequately perform many of the functions that forested buffers do, "effective performance across all functions requires a buffer covered with forest."

2.4 Geology Interactions

The influence of geology on both forest composition and water quality has been well-studied; geology plays a large role in determining site suitability for vegetative communities, and also in dictating the underlying chemistry of area watersheds (*36*). However, the interaction between these factors is less thoroughly understood. Young et al. (*37*) report that bedrock geology impacts certain water quality variables (e.g. pH, dissolved oxygen) alongside land use change. Boggs et al. (*8*) report on the influence of different soil types on water yield and sediment levels in two forested catchments, finding little difference in long-term impact on water quantity or quality. Dow et al. (*36*) find that after the effects of geology are controlled for, land use becomes the more significant variable for predicting water quality in Hudson River area watersheds. Several other authors similarly attempt to either control for the effects of geology in assessing land use impacts on water quality, or combine the two factors to estimate the cumulative impact of both geology and land use (*30, 38*). However, most studies that we reviewed limit their analysis of geology to broad regional descriptions, excluding it from their statistical analyses on the grounds of complexity (e.g. Death and Collier (*26*)). In our assessment relationships between forest cover, geology, and water quality exemplify the site-specific nature of much work in this field and mostly defy easy generalization, although the impacts of certain geologies (e.g. limestone) are sufficiently understood to merit consideration in relevant conservation contexts.

2.5 Climate Interactions

Current and projected impacts of climate change to the benefits of forest cover for water quality are an emerging area of interest with relatively scarce literature (*11*). Although climate change was one of the most frequently-occurring terms in our top-down search, bottom up methods suggest that this frequency may be more associated with acknowledgements of its emerging salience in tangentially related studies, rather than substantive experimental treatment in its own right. However, several papers from our review addressed climate change in detail. Fan et al. (*39*) found that forest land protection will be a priority to compensate for increased expected water yields and sedimentation levels under climate change and land use change scenarios. Relatedly, Martin et al. (*5*) report that anticipated effects of climate change and urbanization could have significant consequences for increased water yield and degraded water quality. Coffey et al. (*32*) provide perhaps the most useful perspective, noting that as climate impacts to water quality are to an extent unavoidable, controlling land use change impacts to water quality (in this case, increased rates of microbial transport) through conservation and best management practices will be especially important.

3.0 TRANSITION BANDS FOR FOREST COVER & OTHER LAND USES

The language of ‘thresholds’ can be a problematic way to describe the transition between states in a complex system like a small watershed. For many, the word ‘threshold’ evokes the idea of a single and concrete tipping point, on either side of which exist two discrete conditions. Ecological research broadly is moving away from this language due to the nuanced responses of ecological variables like stream invertebrate communities to anthropogenic stressors like land use change (*41*). Yet, its utility to managers and policymakers remains; the concept of thresholds provide clear targets for decision-makers to work towards, even if it fails to fully describe the reality of complex ecological systems (*42*).

In the context of stream health, Schueler et al. (*12*) propose a useful alternative to thresholds. In their review of 65 papers dealing with the impact of impervious surfaces on urban stream health, they propose “transition bands” that capture the inherent fluidity of complex systems to reflect allowable degrees of impervious cover. For example, their findings support the idea that depending on a host of other factors, streams transition from ‘sensitive’ to ‘impacted’ conditions between 5-10% impervious cover. We identify potential transition bands for forest cover and other land cover types based on the range of literature values we recorded (figure 1), and thresholds within these bands when the literature supports such extrapolation. See **Appendix A** for a detailed breakdown of citations and recommended land use thresholds and ranges. Broad ranges from the literature are reported below:

3.1 Forestland

Four of five studies that report a forest cover threshold, or band of thresholds, unambiguously call for forest cover **above 70%** to assure healthy water quality. Suggested values range from 60-90%, with nine separate values[3] reported in the five studies. The low outlier represents a highly qualified case; Pond et al. (*16*) report that at least 60% catchment forest cover is needed to assure healthy water quality, but alongside at least 70% forest cover in the upstream riparian area. Based on these findings, we propose a **transition band between 60% and 90%** marking the amount of forest cover below which water quality impacts are detectable.

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[3] For studies like Death and Collier (*26*) which report a range of values (e.g. 80-90%) instead of a single threshold, we use the maximum and minimum of the reported range as single data points in our analysis.

3.2 Agricultural Land

Three of four studies that report an agricultural land use threshold call for catchment agriculture **below 40%,** with values ranging from 18-50%. The high outlier reports a band of values from 30-50% around which water quality begins to suffer (*6*). Based on these figures, we propose a **transition band between 18% and 50%** marking the amount of agriculture above which water quality impacts are detectable.

Although two of the three empirical studies we reviewed did not report on the type of agriculture in their study areas (Quinn and Hickey 1990, who studied improved pasture agriculture, being the exception), we suspect the wide range of values observed corresponds to the intensity of agricultural practices in a given watershed. Allan et al. (*6*) support this supposition, reporting that intensive agricultural practices like row crop cultivation have strong impacts on stream health, but that the effects of less intensive practices such as pasture agriculture may be less pronounced.

We note that the maximum reported range for agricultural cover in our review exceeds the minimum reported range for forest cover. It is possible that some flexibility in the bands we propose may exist due to variations intensity of agricultural land use in the study areas, or based on differences in response variable rigidity. For example, although Death and Collier (*26*) identify an 80-90% native forest and scrub threshold for 'clean' water quality in New Zealand streams, they also report that 80% of the invertebrate community integrity (a less stringent response variable) characteristic of clean forested stream can be achieved with 40-60% catchment forest cover. While this lower range does not reflect the author's standard for 'clean' water quality, it does suggest that some characteristics of an un-impacted stream might be retained at higher rates of forest conversion.

3.3 Urban or Developed Cover and Impervious Cover

We found literature thresholds associated with several measures of human development ranging from <2% to as much as 30%, with very little consensus. We observed that papers which reported on the effects of urban or developed land such as Pond et al. (*16*) often reported higher threshold values than those which made more rigorous assessments of impervious cover, such as Morse et al. (*43*). The methods of determining impervious area are generally more difficult than those for delineating developed or urban land use, contributing to the lack of standard measures in this arena when compared to more easily measured habitat types like forest or agricultural land (*12*). Accordingly, we have identified separate transition bands for urban or developed cover, and impervious cover.

3.3.1 Urban or Developed Cover Transition Band

Seven studies reported figures for the amount of developed land above which water quality suffered, ranging from 1.4% to 30%. The high outlier, Pond et al. (*16*), proposed two figures - 15% developed area for high-intensity development, and 30% developed area for lower density development. Based on these figures, we tentatively report a **transition band from 1.40-30% developed** area above which negative impacts to water can be detected. However, we suggest that impervious area may be a better statistic from which to derive a transition band for high-intensity human use.

3.3.2 Impervious Cover Transition Band

Six studies reported figures for the amount of impervious area above which water quality suffered, ranging from 2-10% impervious area. We propose a **transition band from 2-10% impervious area**, expanding on the 5-10% range proposed by Schueler et al. in their 2008 review (*12*) to include lower figures from works that were not captured by, or were published after, their study (*4*, *44*).

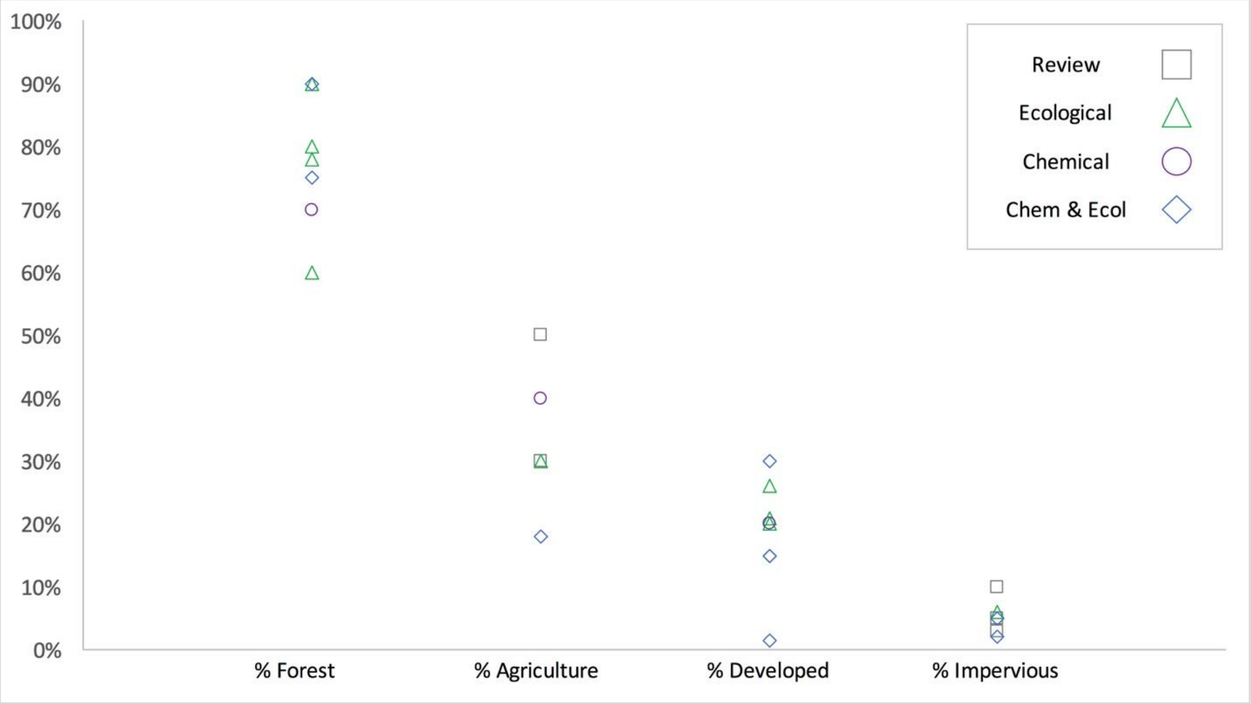

Figure 1: Literature values for thresholds to assure good water quality for each major land cover type in our review. Values represent either individual thresholds, or the high and low ranges of transition bands reported by papers which favored a range over an individual threshold. Values are organized by response variable: ecological (invertebrates, fish), chemical (nutrient concentrations, major ion concentrations, sedimentation, pH, dissolved oxygen, etc); combined response variable studies; and review studies which did undertake original empirical tests of water quality.

4.0 METHODS FOR RELATING FOREST COVER AND WATER QUALTIY

Our review finds three main approaches to relating forest cover and water quality: monitoring, modeling, and combined approaches. Monitoring studies used naturally occurring or manipulated differences in land use conditions across a sampling area to compare water quality data collected in the field. Modeling studies used pre-existing water quality data to predict water quality response to land use variables under change scenarios, or in areas where pre-existing data is not available. However, the most compelling studies we reviewed used high quality monitoring data in their focus areas to build powerful, site specific predictive models to identify conservation priorities.

4.1 Monitoring

Monitoring approaches have been most useful in determining the strength and direction of relationships between land cover and water quality. Black et al. (*17*) exemplify this approach, collecting macroinvertebrate and chemical water quality data at 45 sites and comparing those parameters to GIS land cover estimates to establish that forest cover is a dominant factor influencing water quality at the local watershed scale.

4.2 Modeling

Modeling approaches have been most useful for predicting water quality response to changing conditions, or identifying likely areas of good water quality based on land use conditions. For example, Martin et al. (*5*) used a range of climate and land use projections to estimate water yield and quality under a four land use and climate change scenarios, to inform their call for land management measures as a response to likely future threats to water quality.

4.3 Combined Approaches

Combined approaches used site-specific monitoring data to populate models that can predict water quality in ecologically similar conditions to those of monitoring sites, but for which no monitoring data is available. The West Virginia EPA and Nature Conservancy partnered to create one such model (*45*), enabling them to identify likely sites of high water quality based on land use data, and prioritize those areas for conservation. Similarly, Merovich et al (*38*) used original invertebrate and chemical water quality data from 84 and 123 sites, respectively, in tandem with land cover data to identify the relationship between land use and water quality, and used these findings to predict spatial relationships between likely high and low quality watersheds to identify priorities for protection and restoration.

5.0 QUALIFICATIONS AND CONSIDERATIONS

Four important caveats to the general findings reported above emerged in our review: the site-specific nature of land use/water quality relationships; the relative benefits of monitoring and modeling efforts; the broad role of protecting forest land for water quality; and the balance between protection and restoration of forest land for water quality.

5.1: Threshold and Transition Band Site-Specificity and Transferability

Land use and water quality results are highly site-specific, and the transferability of threshold or transition band values is tenuous. Factors such as bedrock, local climate, land use history, and broader watershed health all play into the amount of forest cover needed to assure water quality in a given setting. The site-specific nature of these factors may help explain the wide range of threshold reported in the literature we reviewed. Accordingly, no single literature threshold should be transferred to a novel landscape. A site-specific study would be the best approach to identify a forest cover target for a given focus area, with a broad review of literature values across similar geographies being a viable alternative.

5.2 Monitoring vs. Modeling Approaches

Assessing the relative merits of modeling and monitoring approaches is difficult. Monitoring is the only way to know with total certainty the water quality conditions in a given sampling area. Yet, it is impractical to monitor across large areas to identify conservation priorities. While predictive models provide an attractive alternative, determining the appropriate level of model specificity with respects to input data and selection of predictive variables is also a significant undertaking. Different regions will have different access to pre-existing monitoring data at different levels of detail, which may be suited for use as modeling input; determining whether to use such data or to conduct an original monitoring effort will depend on programmatic goals and resources.

5.3 The Role of Forest Protection

Although the link between forest cover and water quality is well established in the literature that we reviewed, very few papers explicitly call for land conservation (restoration and protection) approaches to assure good water quality. For instance, Ashton et al. (*23*) call for increased forest cover in the headwaters and other best management practices to achieve water quality benefits, but are circumspect with regards to what these methods might be. Likewise, Ouyang et al. (*24*) suggest reforestation of agricultural lands as a means to reduce nutrient loading in streams, but do not acknowledge a need to ensure that existing forestlands remain in forest. However, several authors do identify projected land forest loss as a threat to water quality (*5*, *40*).

5.4 Protection and Restoration

This review focused on protecting intact forestland to achieve water quality goals, however, conservation work can also include water quality restoration projects. Merovich et al. (*38*) propose and test a framework for identifying protection and restoration priorities given the quality of a conservation unit (reach, subwatershed, etc) in a larger focus area. They suggest that high protection priority units both exhibit excellent water quality and are in close proximity to degraded units, because the favorable conditions—both biotic and chemical—of the high-quality conservation unit will aid in the restoration of adjacent degraded unit.

APPENDIX A: TABLE OF REPORTED LAND USE THRESHOLDS

This table categorizes papers with explicit references to land use thresholds or bands at which water quality impacts are observed according to three factors. *Study Region* indicates the location of fieldwork or focus of modeling work, when applicable. *Water Quality Response Variable* broadly categorizes the water quality measures into two classes: chemical (e.g., NO_3 derived Nitrogen, pH, specific conductivity), and ecological (e.g., macroinvertebrate diversity or fish species diversity). *Land Use Thresholds* reports on the figure or range of figures at which the study observed water quality impacts.

Author (Date)	**Study Region**	**Water Quality Response Variable**	**Land Use Thresholds** **Assumes baseline forested catchment unless otherwise noted*
Allan (2004)	*Lit review*	NA	Reports literature values for macroinvertebrates tolerating **30% to 50% agricultura**l land use with no major impact, and a wide range of thresholds for urban and impervious area.
Black et al. (2004)	Wadeable streams (order not specified), U.S. Washington	Chemical, Ecological	Reports **80-90% forestland** as a threshold for healthy macroinvertebrates
Brabec et al. (2002)	*Lit review*	NA	Reports biotic water quality indexes responding to as little as **3% land use change**; but some abiotic factors resilient to up to 30% land use change.
Death & Collier (2010)	Headwater streams (order not specified), New Zealand	Ecological	Suggests that **80-90% native vegetation** is needed to maintain un-impacted invertebrate communities and indicate ‘clean’ water quality; **40-60%** allows 80% of invertebrate diversity relative to forested conditions to persist.
Kändler et al. (2017)	Catchment areas from 4.2 to 349 km^2 (order not specified), Czech Republic	Chemical	Reports that **70% forested area** is needed for water quality to be chemically “characteristic” of a forested landscape, indicates that more than **20% development** will shift the chemical profile to that of a developed landscape

King et al. (2005)	1st through 3rd order streams, U.S. Maryland	Chemical, Ecological	Reports that **21% to 32% development** in a catchment will result in significant negative impacts to stream invertebrates
King et al. (2011)	1st through 4th order streams, U.S. Maryland	Ecological	Reports that **2% impervious cover** results in negative impacts to invertebrate communities, with variability based on location of impervious cover in the catchment
Kratzer et al. (2006)	Wadeable streams (order not specified), U.S. New York	Chemical, Ecological	Suggests that less than **26% urban development** is needed to avoid negative impacts to invertebrate communities
Kreutzweiser et al. (2005)	1st and 2nd order headwaters, Canada Ontario	Chemical, Ecological	Reports that timber harvest up to **42% of forested buffer strip basal** area can be carried out without negative consequences to water quality
Long & Schorr (2005)	2nd to 5th order streams, U.S. Georgia	Ecological	Greater than **20% urban land use** severely degrades fish communities
Morse et al. (2003)	Wadeable streams, U.S. Maine	Ecological	Reports at **6% impervious area threshold** over which invertebrate community structure begins to simplify
Ourso & Frenzel (2003)	2nd and 4th order streams, U.S. Alaska	Chemical, Ecological	Reports that **<5% impervious** area is needed to avoid water quality impairment
Pond et at. (2017)	1st and 2nd order headwaters, U.S. West Virginia	Chemical, Ecological	"Impairment occurred when **% forest catchment was <60%** (and <70% forest riparian buffer for entire network upstream), **total developed >30%,** developed urban > 15%..."
Quinn & Hickey (1990)	Wadeable streams (order not specified), New Zealand	Ecological	Reports that **>30% agriculture** has serious impacts to fish and invertebrate communities

Roy et al. (2003)	Catchments from 15 to 100 km^2 +/- 25%, U.S. Georgia	Chemical, Ecological	Impaired water quality corresponds to **≥ 15% urban land cover**
Sheeder & Barry (2007)	Headwater streams (order not specified), U.S. Pennsylvania	Chemical, Ecological	Reports that unimpaired catchments average **78% forest cover**, with only **1.8% in development** and the remainder in agriculture.
Schueler et al. (2009)	*Literature review*	NA	Proposes a transition band of **5-10% impervious area** distinguishing sensitive streams from impacted streams

APPENDIX B: REFERENCES

1. F. H. Bormann, G. E. Likens, D. W. Fisher, R. S. Pierce, Nutrient Loss Accelerated by Clear-Cutting of a Forest Ecosystem. *Science*. **159**, 882–884 (1968).

2. E. B. Kratzer *et al.*, Macroinvertebrate distribution in relation to land use and water chemistry in New York City drinking-water-supply watersheds. *Journal of the North American Benthological Society*. **25**, 954–976 (2006).

3. Lintern A. *et al.*, Key factors influencing differences in stream water quality across space. *Wiley Interdisciplinary Reviews: Water*. **5**, e1260 (2017).

4. E. Brabec, S. Schulte, P. L. Richards, Impervious Surfaces and Water Quality: A Review of Current Literature and Its Implications for Watershed Planning. *Journal of Planning Literature*. **16**, 499–514 (2002).

5. K. L. Martin *et al.*, Watershed impacts of climate and land use changes depend on magnitude and land use context. *Ecohydrology*. **30**, 1–17 (2017).

6. J. D. Allan, LANDSCAPES AND RIVERSCAPES: The Influence of Land Use on Stream Ecosystems. *Annual Review of Ecology, Evolution, and Systematics; Palo Alto*. **35**, 257–384 (2004).

7. B. L. Keeler *et al.*, Linking water quality and well-being for improved assessment and valuation of ecosystem services. *PNAS*. **109**, 18619–18624 (2012).

8. J. Boggs, G. Sun, D. Jones, S. G. McNulty, Effect of Soils on Water Quantity and Quality in Piedmont Forested Headwater Watersheds of North Carolina1. *JAWRA Journal of the American Water Resources Association*. **49**, 132–150 (2012).

9. Edwards Pamela J., Schoonover Jon E., Williard Karl W. J., Guiding Principles for Management of Forested, Agricultural, and Urban Watersheds. *Journal of Contemporary Water Research & Education*. **154**, 60–84 (2015).

10. S. E. Gergel, M. G. Turner, J. R. Miller, J. M. Melack, E. H. Stanley, Landscape indicators of human impacts to riverine systems. *Aquat. Sci.* **64**, 118–128 (2002).

11. J. M. Vose *et al.*, Forest ecohydrological research in the 21st century: what are the critical needs? *Ecohydrol.* **4**, 146–158 (2011).

12. Schueler Thomas R., Fraley-McNeal Lisa, Cappiella Karen, Is Impervious Cover Still Important? Review of Recent Research. *Journal of Hydrologic Engineering*. **14**, 309–315 (2009).

13. D. G. Neary, Long-Term Forest Paired Catchment Studies: What Do They Tell Us That Landscape-Level Monitoring Does Not? *Forests*. **7**, 164 (2016).

14. B. W. Sweeney, J. D. Newbold, Streamside Forest Buffer Width Needed to Protect Stream Water Quality, Habitat, and Organisms: A Literature Review. *J Am Water Resour Assoc*. **50**, 560–584 (2014).

15. L. Sliva, D. Dudley Williams, Buffer Zone versus Whole Catchment Approaches to Studying Land Use Impact on River Water Quality. *Water Research*. **35**, 3462–3472 (2001).

16. G. J. Pond, K. J. G. Krock, J. V. Cruz, L. F. Ettema, Effort-based predictors of headwater stream conditions: comparing the proximity of land use pressures and instream stressors on macroinvertebrate assemblages. *Aquat Sci*. **79**, 765–781 (2017).

17. R. W. Black, M. D. Munn, R. W. Plotnikoff, Using macroinvertebrates to identify biota–land cover optima at multiple scales in the Pacific Northwest, USA. *Journal of the North American Benthological Society*. **23**, 340–362 (2004).

18. I. J. Sutherland, E. M. Bennett, S. E. Gergel, Recovery trends for multiple ecosystem services reveal non-linear responses and long-term tradeoffs from temperate forest harvesting. *Forest Ecology and Management*. **374**, 61–70 (2016).

19. King Ryan S. *et al.*, Spatial considerations for linking watershed land cover to ecological indicators in streams. *Ecological Applications*. **15**, 137–153 (2005).

20. B. J. Amiri, K. Nakane, Entire catchment and buffer zone approaches to modeling linkage between river water quality and land cover—A case study of Yamaguchi Prefecture, Japan. *Chin. Geogr. Sci.* **18**, 85–92 (2008).

21. B. J. Peterson *et al.*, Control of Nitrogen Export from Watersheds by Headwater Streams. *Science*. **292**, 86–90 (2001).

22. C. Ernst, Protecting the Source. *The Trust for Public Land* (2004), (available at https://www.tpl.org/protecting-source).

23. M. J. Ashton, R. P. Morgan, S. Stranko, Relations between macroinvertebrates, nutrients, and water quality criteria in wadeable streams of Maryland, USA. *Environ Monit Assess*. **186**, 1167–1182 (2014).

24. Y. Ouyang, T. D. Leininger, M. Moran, Estimating effects of reforestation on nitrogen and phosphorus load reductions in the Lower Yazoo River Watershed, Mississippi. *Ecological Engineering*. **75**, 449–456 (2015).

25. Sheeder Scott A., Evans Barry M., Estimating nutrient and sediment threshold criteria for biological impairment in pennsylvania watersheds1. *JAWRA Journal of the American Water Resources Association*. **40**, 881–888 (2007).

26. R. G. Death, K. J. Collier, Measuring stream macroinvertebrate responses to gradients of vegetation cover: when is enough enough? *Freshwater Biology*. **55**, 1447–1464 (2010).

27. N. S. Rao *et al.*, Modeling watershed-scale effectiveness of agricultural best management practices to reduce phosphorus loading. *Journal of Environmental Management*. **90**, 1385–1395 (2009).

28. M. Kändler *et al.*, Impact of land use on water quality in the upper Nisa catchment in the Czech Republic and in Germany. *Science of The Total Environment*. **586**, 1316–1325 (2017).

29. D. Ackerman, E. D. Stein, Estimating the Variability and Confidence of Land Use and Imperviousness Relationships at a Regional Scale1. *JAWRA Journal of the American Water Resources Association*. **44**, 996–1008 (2008).

30. L. Johnson, C. Richards, G. Host, J. Arthur, Landscape influences on water chemistry in Midwestern stream ecosystems. *Freshwater Biology*. **37**, 193–208 (1997).

31. D. L. Strayer *et al.*, Effects of Land Cover on Stream Ecosystems: Roles of Empirical Models and Scaling Issues. *Ecosystems*. **6**, 407–423 (2003).

32. K. E. Schilling, P. Jacobson, Effectiveness of natural riparian buffers to reduce subsurface nutrient losses to incised streams. *CATENA*. **114**, 140–148 (2014).

33. L. Wang, J. A. Duggin, D. Nie, Nitrate–nitrogen reduction by established tree and pasture buffer strips associated with a cattle feedlot effluent disposal area near Armidale, NSW Australia. *Journal of Environmental Management*. **99**, 1–9 (2012).

34. E. R. DeSouza, T. Pierce, J. C. Zanelli, C. Hutz, Perceived Sexual Intent in the U.s. and Brazil as a Function of Nature of Encounter, Subjects' Nationality, and Gender. *Journal of Sex Research*. **29**, 251–260 (1992).

35. J. P. Laceby *et al.*, The effect of riparian restoration on channel complexity and soil nutrients. *Mar. Freshw. Res.* **68**, 2041–2051 (2017).

36. C. L. Dow, D. B. Arscott, J. D. Newbold, Relating major ions and nutrients to watershed conditions across a mixed-use, water-supply watershed. *Journal of the North American Benthological Society*. **25**, 887–911 (2006).

37. R. G. Young, A. J. Quarterman, R. F. Eyles, R. A. Smith, W. B. Bowden, 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.* **39**, 803–825 (2005).

38. G. T. Merovich, J. T. Petty, M. P. Strager, J. B. Fulton, Hierarchical classification of stream condition: a house–neighborhood framework for establishing conservation priorities in complex riverscapes. *Freshwater Science*. **32**, 874–891 (2013).

39. M. Fan, H. Shibata, Q. Wang, Optimal conservation planning of multiple hydrological ecosystem services under land use and climate changes in Teshio river watershed, northernmost of Japan. *Ecological Indicators*. **62**, 1–13 (2016).

40. R. Coffey, B. Benham, K. Kline, M. L. Wolfe, E. Cummins, Modeling the impacts of climate change and future land use variation on microbial transport. *Journal of Water and Climate Change; London*. **6**, 449–471 (2015).

41. R. S. King, M. E. Baker, Considerations for analyzing ecological community thresholds in response to anthropogenic environmental gradients. *Journal of the North American Benthological Society*. **29**, 998–1008 (2010).

42. P. M. Groffman *et al.*, Ecological Thresholds: The Key to Successful Environmental Management or an Important Concept with No Practical Application? *Ecosystems*. **9**, 1–13 (2006).

43. C. C. Morse, A. D. Huryn, C. Cronan, Impervious Surface Area as a Predictor of the Effects of Urbanization on Stream Insect Communities in Maine, U.S.A. *Environ Monit Assess*. **89**, 95–127 (2003).

44. King Ryan S., Baker Matthew E., Kazyak Paul F., Weller Donald E., How novel is too novel? Stream community thresholds at exceptionally low levels of catchment urbanization. *Ecological Applications*. **21**, 1659–1678 (2011).

45. WVWAPP Watershed Assessment, (available at http://www.watershedmapwv.tnc.org/).

APPENDIX C: REVIEW METHODS

We conducted this mixed-method literature in two stages. By combining traditional search-engine, library, and correspondence-based research with novel data science approaches, we were able to access a more comprehensive body of literature that would otherwise be possible in a selective review, without making an exhaustive systematic study of the corpus.

Traditional Methods

We used a traditional “bottom up” approach for the bulk of our analysis (~ 50 papers), identifying roughly 10 promising initial articles on Web of Science through a broad keyword search and subjective selection of titles and abstracts based on relevance to our study goals. We expanded our analysis to include the papers referenced by these initial articles, as well as more current works which in turn referenced them. We supplemented this review with personal communication to selected authors whose work was particularly relevant to our interests and to solicit further literature recommendations. This expert input informed our analysis of literature gaps or conflicting findings; for example, correspondence with Dr. Bernard Sweeney of Stroud Water Research Center confirmed our observation that the literature on buffer interactions with whole watershed land use is nascent.

Data Science Methods

We supplemented our traditional review with novel “top-down” data science approaches to identify additional papers for review. We used expert input and selective literature review to identify search factors (e.g., “land use”) and specific terms to indicate whether a paper substantively addressed those factors (e.g., “area”, “change”, “conversion”), against which we analyzed the abstracts of over 3,000 articles using original code. After multiple iterations, we identified a subset of 242 articles as promising targets, and systematically selected the most promising 18 for in-depth analysis to complement the 51 articles from our more traditional review.

Review Parameters

We systematically reviewed each paper selected for analysis according to a range of parameters including study location and watershed context, experimental design, choice of water quality indicators, land covers assessed, and explicit land use thresholds recommended. The full range of parameters assessed is available in the spreadsheet accompanying this report.