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RESEARCH ARTICLE

Spatial fit between water quality policies and hydrologic ecosystem services in an urbanizing agricultural landscape

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Abstract

Context Sustaining hydrologic ecosystem services is critical for human wellbeing but challenged by land use for agriculture and urban development. Water policy and management strive to safeguard hydrologic services, yet implementation is often fragmented. Understanding the spatial fit between water polices and hydrologic services is needed to assess the spatial targeting of policy portfolios at landscape scales.

Objectives We investigated spatial fit between 30 different public water policies and four hydrologic services (surface and groundwater quality, freshwater supply, and flood regulation) in the Yahara Watershed (Wisconsin, USA)—a Midwestern landscape that typifies tensions between agriculture, urban development, and freshwater resources.

Methods Spatial extent of water policy implementation was mapped, and indicators of hydrologic services were quantified for subwatersheds using empirical estimates and validated spatial models.

Results We found a spatial misfit between the overall spatial implementation of water policy and regions of water quality concern, indicating a need for better targeting. Water quality policies can also be leveraged to protect other hydrologic services such as freshwater supply and flood regulation. Individual policy application areas varied substantially in their spatial congruence with each hydrologic service, indicating that not all services are protected by a single policy and highlighting the need for a broad spectrum of policies to sustain hydrologic services in diverse landscapes. We also identified where future policies could be targeted for improving hydrologic services.

Conclusions Joint spatial analysis of policies and ecosystem services is effective for assessing spatial aspects of institutional fit, and provides a foundation for guiding future policy efforts.

Keywords Freshwater · Spatial overlap · Policy targeting · Surface-water quality · Groundwater quality · Groundwater recharge · Flood regulation · Landscape ecology · Yahara Watershed · Wisconsin

Introduction

Hydrologic ecosystem services, defined as freshwater benefits to people generated by terrestrial ecosystems,

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are among the most essential and threatened ecosystem services for supporting human wellbeing (Brauman et al. 2007; Carpenter et al. 2011; Asbjornsen et al. 2015). In recent decades, major drivers of global change such as climate, land use, and human demands have substantially altered ecosystems, and in turn challenged the sustainability of hydrologic services (Millennium Ecosystem Assessment 2005; Gordon et al. 2008; Carpenter et al. 2011). Institutions, which broadly include formal laws, markets, and informal social norms (Ostrom 1990), exist in the United States and internationally to safeguard hydrologic services, but they have been insufficient to achieve national and regional goals (Gilinsky et al. 2009), especially in agricultural and other human-dominated landscapes where hydrologic services are declining (Gillon et al. 2015; Wardropper et al. 2015). Previous research suggests that policy and management efforts to enhance hydrologic services should take a landscape perspective, and that effectiveness of these efforts could be improved through spatial targeting, or directing policy or management actions to those geographic locations that disproportionately contribute to pollution or service degradation (Wu and Hobbs 2002; van der Horst 2007; Wunscher et al. 2008; Piorr et al. 2009; Maes et al. 2012; Allan et al. 2013; Wu 2013). Despite these calls for research, spatially explicit assessments of the relationship between water policies and the provision of hydrologic services at landscape scales are scarce (Allan et al. 2013, 2015).

To address this need, we examined the spatial aspect of institutional fit and potential misfit between a diverse range of public water policies and multiple hydrologic services. Spatial fit, or “the congruence between geographical extent of a biophysical system and the management area of an institution” (Moss 2012), can be situated within the institutional fit literature, which asks how well environmental institutions match the temporal or spatial scales of ecosystems and account for functional ecosystem processes. Institutional fit is a key aspect of environmental governance (Young 2002; Brown 2003; Ekstrom and Young 2009). Most studies on spatial fit focus on spatial extent, for instance, the misfit of large river basins that span multiple jurisdictional boundaries. However, an expanding literature is adding complexity to spatial fit in theory and practice (Biswas 2004; Moss 2012). Here we go beyond spatial extent to examine the patterns of spatial fit across a heterogeneous landscape. In particular, we address the congruence of multi-level policy implementation with the geographic location of ecosystem service provision and pollution sources.

We focus on public institutions: water policies with goals described in laws, rules or program directives. Governments have deployed diverse policy instruments to improve hydrologic services. Existing policy tools among different public agencies often do not prioritize the same locations for implementation. In the United States, major types of public policies for addressing conservation concerns comprise four categories: incentive, regulation, acquisition, and direct management (Doremus 2003; Bengston et al. 2004). Regulations can be applied uniformly across large areas; incentives are voluntarily implemented on privately or publicly held land parcels; acquisitions also generally rely on voluntary sale or donation and tend to target flagship properties; and direct management occurs largely on public land. While the application of multiple policy instruments should ideally increase effectiveness of public water management, in reality, diverse policy tools implemented by different organizations within a diverse landscape are often uncoordinated and leave gaps in the approach to enhance hydrologic ecosystem services (Wardropper et al. 2015).

Prior research has indicated that spatial assessment is needed to enhance effectiveness of policies at landscape scales (Herrmann and Osinski 1999; Jones et al. 2013; Owen 2013; Guerra et al. 2015). Although the literature on spatial targeting for conservation is expanding (Margules and Pressey 2000), most studies have been piecemeal, either focusing on protected areas (e.g., Andelman and Fagan 2000), or emphasizing one or a few specific policies (e.g., Qiu and Dosskey 2012; Marinoni et al. 2013). However, diverse water policies are being deployed simultaneously across the landscape, many of which serve multiple ecological and societal goals. For example, in agricultural landscapes where excess nutrient inputs have impaired water quality, most water policies have focused on surface-water quality concerns; meanwhile, policy language often cites additional goals such as groundwater quality, water supply and flood control. One reason for multiple targets of water policies is the lack of comprehensive policy frameworks for managing certain hydrologic services, such as groundwater quality (Lavoie et al. 2013); so governments often rely on surface-water policies to protect both surface and groundwater resources. Hence, it is necessary to encompass a portfolio of water policy tools for a more holistic assessment of policy implementation, identifying potential gaps and prioritizing future policy and management actions.

In this study, we quantified indicators of four hydrologic services (surface and groundwater quality, freshwater supply and flood regulation), and mapped spatial patterns of 30 available public policies (Appendix S1) that all have the stated goal of improving surface-water quality. Because most of these policies also had additional stated goals to enhance the provision of one or more of three other hydrologic services (Table 1), hereafter we refer to all studied policies as "water policies". We focused on surface-water quality policies because they are the most common water policies in this region, where the most publicized freshwater concern is eutrophication and algal blooms (Gillon et al. 2015). Fewer discrete policies address other services such as groundwater recharge and quantity. We also intended to understand the extent to which policies primarily aimed at improving surface water quality were leveraged to enhance other hydrologic services. Our objective was to assess whether water policies spatially aligned with surface-water quality provision areas, and also the degree to which these policies achieved additional stated goals through aligning with the other three hydrologic services.

Our study area is the Yahara Watershed, Wisconsin (Fig. 1), a mixed urban and agricultural landscape in the Midwestern US. This watershed typifies social-ecological stresses (e.g., climate change, urbanization, agricultural intensification, population growth) on the sustainable provision of hydrologic ecosystem services (Carpenter et al. 2007). We focused our analysis at the subwatershed scale to address four research questions: (1) How well do water policies spatially align with the provision of surface-water quality, and other hydrologic services: groundwater quality, freshwater supply and flood regulation? (2) How does the spatial overlap of policy implementation with hydrologic services vary across different categories of policy tools? (3) In what ways are urban and rural areas distinguished in the patterns of different water policies implemented? (4) What locations in the landscape should be prioritized for future policy implementation to enhance hydrologic services?

Methods

Study region

The Yahara Watershed of southern Wisconsin is home to 372,000 people, drains 1345 km^2 and contains five major lakes (Mendota, Monona, Wingra, Waubesa and Kegonsa; Fig. 1). Typical of many Midwestern landscapes, this watershed is largely human-dominated, with most land in agriculture (primarily corn, soy and dairy). However, the region also includes densely populated urban (containing the state capital, Madison, Wisconsin) and suburban areas. Freshwater is central to the Yahara's cultural identity (Stedman et al. 2007), and the chain of five lakes includes most studied lakes in the world (Lathrop 2007). However, freshwater conditions in the Yahara Watershed have deteriorated over the past century (Carpenter et al. 2006). Sustainable management of freshwater has been challenging in the face of eutrophication, flooding, groundwater extraction and contamination. Eutrophication is the most prominent water quality

Table 1 Biophysical indicators, median and range for four hydrologic ecosystem services quantified and mapped at the subwatershed scale for the Yahara Watershed (Wisconsin, USA), as well as the total number of policies with a stated goal to enhance each service

Hydrologic ecosystem service	Biophysical indicator	Estimated values for 2006	No. of policies
Surface-water quality	Annual phosphorus loading	0.11 (0.02–0.22 kg ha^{-1})	30
Groundwater quality	Probability of groundwater nitrate concentration <3.0 mg L^{-1}	0.50 (0.04–0.98; unitless)	25
Freshwater supply	Annual groundwater recharge	37.9 (4.3–46.3 cm year^{-1})	15
Flood regulation	Flood regulation capacity	64.1 (5.8–85.4; unitless)	21

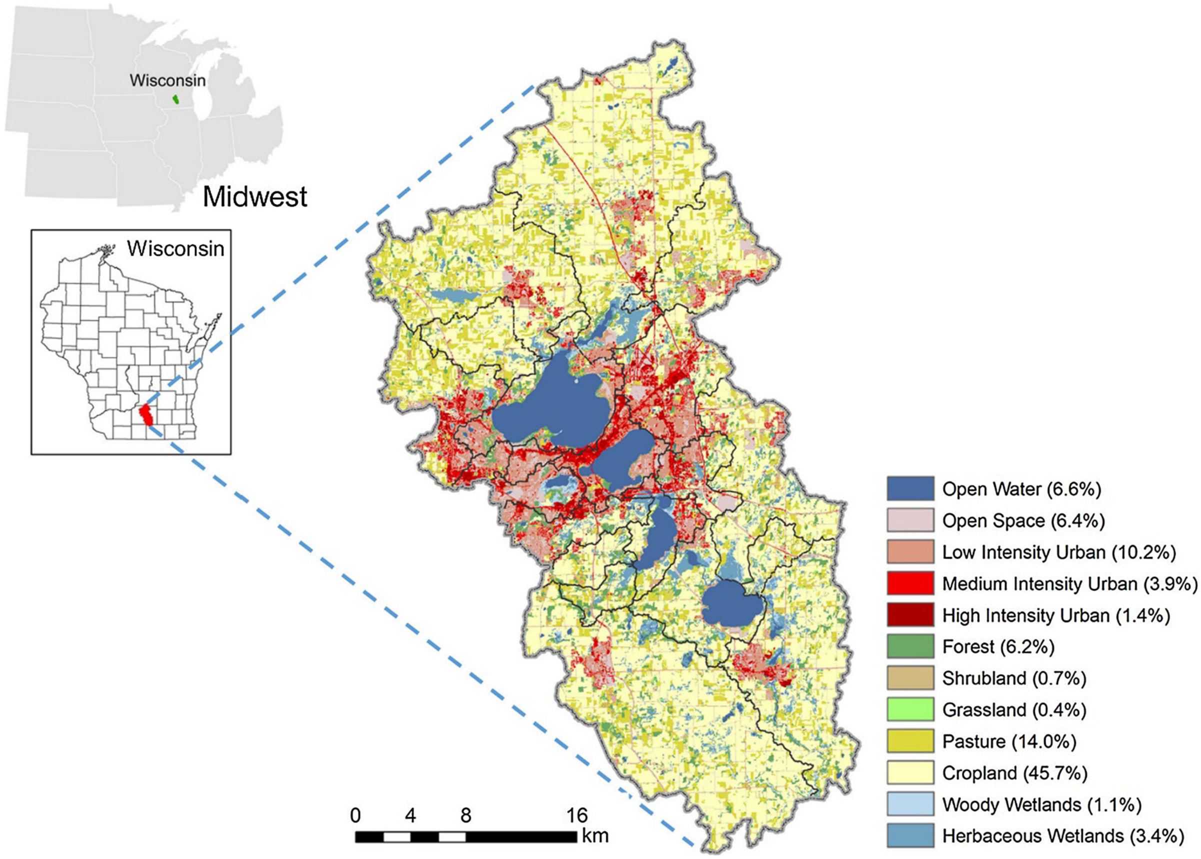


Fig. 1 Map of the Yahara River Watershed (Wisconsin, USA) and the land use/land cover pattern (with percent cover) for 2006, derived from National Land Cover Data (NLCD)

concern, mostly due to excessive nutrient inputs from fertilizer and manure application, and agricultural and urban runoff (Carpenter et al. 2006; Lathrop 2007).

Management of eutrophication began as early as the 1930s, and substantial efforts across different government levels have been expended to restrict urban and rural sources of pollution, including stormwater management, erosion control, nutrient management, environmental corridor establishment, and wetland restoration (Appendix S1). Like most watersheds in the United States, few policies are implemented at the watershed scale. Instead, policies are written and implemented at a municipal, county, statewide, or federal scale so that watershed conservation is an intersection of rules and practices from all of these governments. While many collective policy and practice efforts have attempted to reduce nutrient inputs to freshwater, success remains elusive because of long-term legacies and continued intensive nutrient and manure use in the watershed (Nowak et al. 2006; Lathrop 2007; Gillon et al. 2015).

Quantifying hydrologic ecosystem services

Four hydrologic services (Table 1) were quantified for the Yahara Watershed using empirical estimates and validated spatial models. We used biophysical indicators as proxies because these indicators capture key ecohydrological processes that underlie the production or conditions of each hydrologic service (Harrison-Atlas et al. 2016). All services were mapped at 30-m spatial resolution for 2006—the most recent year for which data exist. Please refer to Qiu and Turner (2013) for full details on data sources, methods and accuracy assessment for each service. Below we briefly summarize the approach used for quantifying each hydrologic service.

Surface-water quality (annual phosphorus loading, kg ha^{-1})

In this region, nonpoint source phosphorus is the major threat to surface-water quality and the primary cause for eutrophication (Carpenter et al. 1998). Thus, we quantified annual phosphorus loading as the proxy for surface-water quality using the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) model (Tallis and Polasky 2009). This approach simulated the discharge of nonpoint source phosphorus to downstream water through the ability of vegetation and soils to avoid nutrient loss and to assimilate nutrients received from upslope areas, and accounted for different critical biophysical processes such as interception, runoff, infiltration, and nutrient retention (Kareiva et al. 2011). We ran the model for 2006, and assessed our estimates by comparing with USGS gauge monitored phosphorus loading data for two sub-basins of this watershed; our estimates agreed well with the gauge data (Qiu and Turner 2013; see Supporting Information (SI) text).

Groundwater quality (probability of groundwater nitrate concentration <3.0 mg L^{-1}, unitless 0–1)

Nitrate concentration is a widely used indicator for groundwater quality, because nitrate is the most pervasive groundwater contaminant detrimental for human health (Spalding and Exner 1993). We calculated the probability of groundwater nitrate concentration <3.0 mg L^{-1} (this threshold is an important contamination level likely caused by anthropogenic activities) as the proxy for groundwater quality. Probability kriging analysis was performed to spatially interpolate groundwater nitrate data from 528 wells obtained from Groundwater Retrieve Network (GRN) and Wisconsin Department of Natural Resources (WDNR). The interpolated results were mapped to 30-m spatial resolution using Geostatistical Analyst in ArcGIS 10.0. We performed cross-validation to assess the accuracy of our interpolation; the kriged map predicted nitrate concentration across the watershed well (Qiu and Turner 2013; see SI text).

Freshwater supply (annual groundwater recharge, cm year^{-1})

We used groundwater recharge as the indicator for freshwater supply because this region relies on groundwater for industrial and municipal uses (Buchwald 2011). Hence, sufficient recharge to replenish aquifers is critical to sustain current and future human demands for freshwater in this region. The modified Thornthwaite-Mather Soil–Water-Balance (SWB) model (Dripps and Bradbury 2007) validated for this watershed was used to estimate groundwater recharge. SWB is a physically-based, quasi 3-dimensional model taking into account key ecohydrologic processes (e.g., precipitation, interception, evapotranspiration, surface runoff, snowmelt, etc.). The model was run for a 3-year period from 2004 to 2006 at 30-m resolution, with the first 2 years as “spin-up” to establish antecedent conditions that could affect recharge for the focal year of 2006. Our recharge estimates agreed reasonably well with a recent 10-year average estimate (1998–2007) for Dane County at the sub-basin level (Qiu and Turner 2013; see SI text).

Flood regulation (flood regulation capacity, unitless 0–100)

We adopted Nedkov and Burkhard (2012) capacity-assessment approach to quantify the flood regulation service. This approach considers preventative and mitigation functions of vegetation and soils to regulate water flows by using four hydrologic parameters: interception, infiltration, surface runoff and peak flow. We first applied the Kinematic Runoff and Erosion (KINEROS) model to calculate estimates of three parameters (infiltration, surface runoff and peak flow) for each land cover type. KINEROS is an event-oriented, physically-based distribution model, and we performed the simulation using a defined storm event with 10-year return interval and 24-h duration (Hershfield 1963). The parameter of interception was obtained from Dripps and Bradbury (2007). We then standardized each parameter to 0–10 scale, and summed them to calculate overall flood regulation capacity (FRC). To simplify interpretation, we rescaled original FRC values to a range of 0–100, with 0 representing the lowest regulation capacity and 100 the highest. We compared our FRC maps with the 2008 flooding in southern Wisconsin, one of the most severe and widespread flooding events in the Midwest. Our estimates of low FRC values corresponded well with the 2008 flooding extent (Qiu and Turner 2013; see SI text).

Mapping and coding of water policies

We inventoried available water policies by public agencies in the Yahara Watershed whose primary target was surface-water quality improvement because it is the major freshwater concern in the region that has garnered considerable policy attention. Thirty policies for which spatial data were available were mapped (Appendix Table S1 and Fig. 2), a comprehensive list that represents most major water-quality policies implemented in the watershed. Policies were included if they were (1) publicly funded and implemented, (2) terrestrial-based, (3) implemented between 2007 and 2012, (4) aimed to reduce nutrient and sediment runoff to surface waters in the goal statement of the policy document, and (5) were variable in their implementation across the watershed. We did not include policies implemented by non-profit organizations and for-profit companies due to limited data access. For our study purposes, the selection criteria excluded policies implemented directly in the water bodies (e.g., lakes, streams), because in our study region and many other human-dominated watersheds land use exerts the greatest influence on freshwaters (Allen 2004). Because of the last criterion, we did not include a Total Maximum Daily Load (a designation and improvement plan for impaired waters under the U.S. Clean Water Act) that applies to the entire Yahara Watershed. The most significant unmapped policy was the location of farms that have completed nutrient management plans, for which spatial data are not publicly available. All policies were categorized into four general types: acquisition (land conserved through fee simple acquisition or conservation easement; 4 policies), direction management (public management actions and engineered practices; 3 policies), incentive (grant and cost-share programs; 6 policies), and regulation or standard (17 policies).

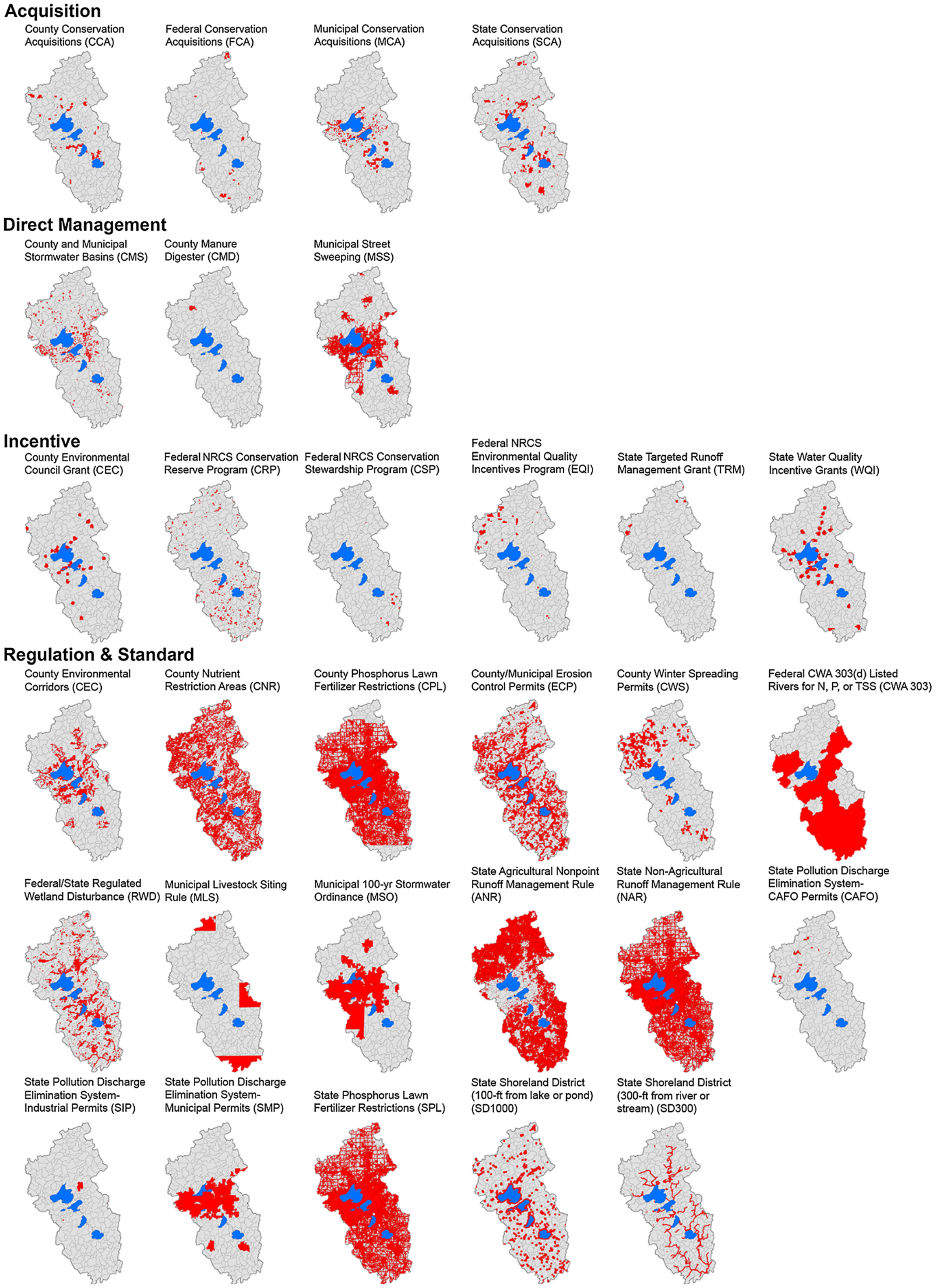
Besides improving surface-water quality, many of these policies had additional goals. To determine whether the other three hydrologic services were designated as additional goals in each policy, we conducted content analysis of the policy documents (e.g., statutes enabling public actions). A policy was categorized as targeting a particular hydrologic service if it had an explicit goal statement to protect or improve that service. We developed a series of keyword terms (Appendix Table S2) to code each hydrologic service, and searched for these terms in the policy documents. Common examples for the keyword terms include freshwater supply (“drinking water supply”, “groundwater recharge”); groundwater quality (“reduce nitrates in groundwater”, “drinking water quality”); surface-water quality (“lake/river/stream water quality”, “prevent nutrient/sediment runoff”, “prevent algae in lakes”); and flood regulation (“reduce floods/peak flow”, “stormwater retention/detention”). We found that, in addition to surface-water quality, policies also explicitly stated other goals including protecting groundwater quality (25 out of 30 policies), freshwater supply (21), and flood regulation (15) (Table 1).

Fig. 2 Spatial patterns of 30 public water policies included in the analysis. Policies fall into four categories: acquisition, direction management, incentive, regulation and standard. *Red* indicates where policies were implemented and *blue* indicates water bodies. (Color figure online) ▶

All 30 policies were mapped in ArcGIS 10.0. Publicly acquired conservation lands and incentive programs were mapped by parcel boundary. For federal Farm Bill conservation programs, parcels owned or managed by the cost-share recipients were mapped with publicly available spatial data from USDA or by matching recipient names with parcel ownership records. Regulatory programs were mapped according to the statute’s application rules. For example, Wisconsin’s shoreland zoning ordinances were mapped as areas within a 300-ft ($\sim$91-m) buffer of rivers or streams, and 1000-ft ($\sim$305-m) buffer of lakes or ponds. When locations of permit data were available, policies were mapped within the specific permit area, such as farm fields with county winter manure spreading permits. Please refer to Wardropper et al. (2015) for greater detail on mapping of all 30 policies.

Statistical analyses

Our scale of analysis was the subwatershed, which is commonly used for conservation planning and ecological assessment and also the scale at which human activities are likely exerting the most profound effects on freshwater flows and functions (Uriarte et al. 2011; Mubako et al. 2013). We divided the watershed into 296 subwatersheds based on recent modeling that delineated the upper Yahara Watershed into 196 subwatersheds (Montgomery Associates 2011), plus


Acquisition
County Conservation Acquisitions (CCA)
Federal Conservation Acquisitions (FCA)
Municipal Conservation Acquisitions (MCA)
State Conservation Acquisitions (SCA)
Direct Management
County and Municipal Stormwater Basins (CMS)
County Manure Digester (CMD)
Municipal Street Sweeping (MSS)
Incentive
County Environmental Council Grant (CEC)
Federal NRCS Conservation Reserve Program (CRP)
Federal NRCS Conservation Stewardship Program (CSP)
Federal NRCS Environmental Quality Incentives Program (EQI)
State Targeted Runoff Management Grant (TRM)
State Water Quality Incentive Grants (WQI)
Regulation & Standard
County Environmental Corridors (CEC)
County Nutrient Restriction Areas (CNR)
County Phosphorus Lawn Fertilizer Restrictions (CPL)
County/Municipal Erosion Control Permits (ECP)
County Winter Spreading Permits (CWS)
Federal CWA 303(d) Listed Rivers for N, P, or TSS (CWA 303)
Federal/State Regulated Wetland Disturbance (RWD)
Municipal Livestock Siting Rule (MLS)
Municipal 100-yr Stormwater Ordinance (MSO)
State Agricultural Nonpoint Runoff Management Rule (ANR)
State Non-Agricultural Runoff Management Rule (NAR)
State Pollution Discharge Elimination System-CAFO Permits (CAFO)
State Pollution Discharge Elimination System-Industrial Permits (SIP)
State Pollution Discharge Elimination System-Municipal Permits (SMP)
State Phosphorus Lawn Fertilizer Restrictions (SPL)
State Shoreland District (100-ft from lake or pond) (SD1000)
State Shoreland District (300-ft from river or stream) (SD300)

our delineation of the lower Yahara Watershed into 100 subwatersheds based on the light detection and ranging (LiDAR) elevation and stream network following the same criteria. All subwatersheds were further categorized into urban or rural based on the developed land covers from the 2006 National Land Cover Database (NLCD; Fry et al. 2011). Subwatersheds with 50 % or more developed land cover were considered urban, and those with less than 50 % developed land cover were considered rural (Wardropper et al. 2015).

The estimates of indicators of all four hydrologic services were standardized to a 0–1 scale, based on the minimum and maximum values of each indicator. Because surface-water quality was quantified using an inverse indicator (i.e., high service provision was associated with low phosphorus loading), we further used one minus the standardized values for this service so that higher values corresponded to greater supply of service and the maximum value of each service was set at one, following Qiu and Turner (2015). We then averaged estimates of hydrologic services for each subwatershed. In addition, we calculated percent land area covered by each policy at the subwatershed scale, and summed across all policies relevant for each hydrologic service based on the content analysis (Table 1) to obtain the subwatershed-scale cumulative policy coverage for each hydrologic service.

To address our first and second questions on how water policies spatially align with the four hydrologic services, we computed Kendall rank correlations between policy coverage and hydrologic services. We chose Kendall nonparametric correlation because it is robust to non-normal distributions and capable of accounting for ties in the dataset. A negative correlation indicates that policies have targeted areas of concern for a particular hydrologic service (i.e., spatial fit of policy implementation); a positive correlation might suggest that policies have targeted locales with outstanding provision of hydrologic services (i.e., spatial misfit of policy implementations). However, it is also possible that a positive correlation can result from past management that enhanced hydrologic services. But because of temporal limitations in data, we could not test for such causality, and instead interpret positive correlations with caution. To address our third question, we performed principal component analysis (PCA) on the coverage of individual policies, and used the biplot (the first two components of PCA) to visually examine and compare differences in policy implementation between urban and rural subwatersheds in the reduced two-dimensional space. Finally, multi-criteria analysis was used to identify priorities for future policy implementation. Specifically, subwatersheds with policy coverage and hydrologic services both in the lowest 20th percentile (derived from their cumulative frequency distribution) were identified. We restricted this analysis only to services that showed positive correlations with policy coverage (i.e., potential spatial misfit). All statistical analyses were performed in the R statistical software 3.2 (R Development Core Team 2009).

Results

Spatial patterns of hydrologic services and water policies

Production of all four hydrologic services varied geographically among subwatersheds (Fig. 3a), and services were spatially aggregated rather than randomly distributed on the landscape (all Moran's $I > 0.31$, $P < 0.001$). Estimates for surface-water quality, indicated by annual phosphorus loading, varied from 0.02 to 0.22 kg ha^{-1} among subwatersheds (Table 1). Groundwater quality, estimated by the probability of nitrate concentration <3.0 mg L^{-1}, ranged from 0.04 to 0.98 among subwatersheds. Annual groundwater recharge, the proxy for freshwater supply, varied from 4.3 to 46.3 cm year^{-1} among subwatersheds; and finally the estimated capacity for flood regulation service ranged from 5.8 to 85.4 among subwatersheds.

Policy application areas varied substantially in their location, total extent and spatial configuration (Fig. 2). Some policy tools (e.g., Clean Water Act impaired waterway subwatersheds, and State Agricultural Nonpoint Runoff Management Rule) covered large areas that were spatially continuous, whereas others (e.g., County Environmental Corridors, County Conservation Acquisitions, State Shoreland District) were applied to small but ecologically important locations scattered across the watershed. Summing across all the policies relevant to each service, we found more policies in urban areas around the Madison lakes and in the lower part of the watershed (Fig. 3b).

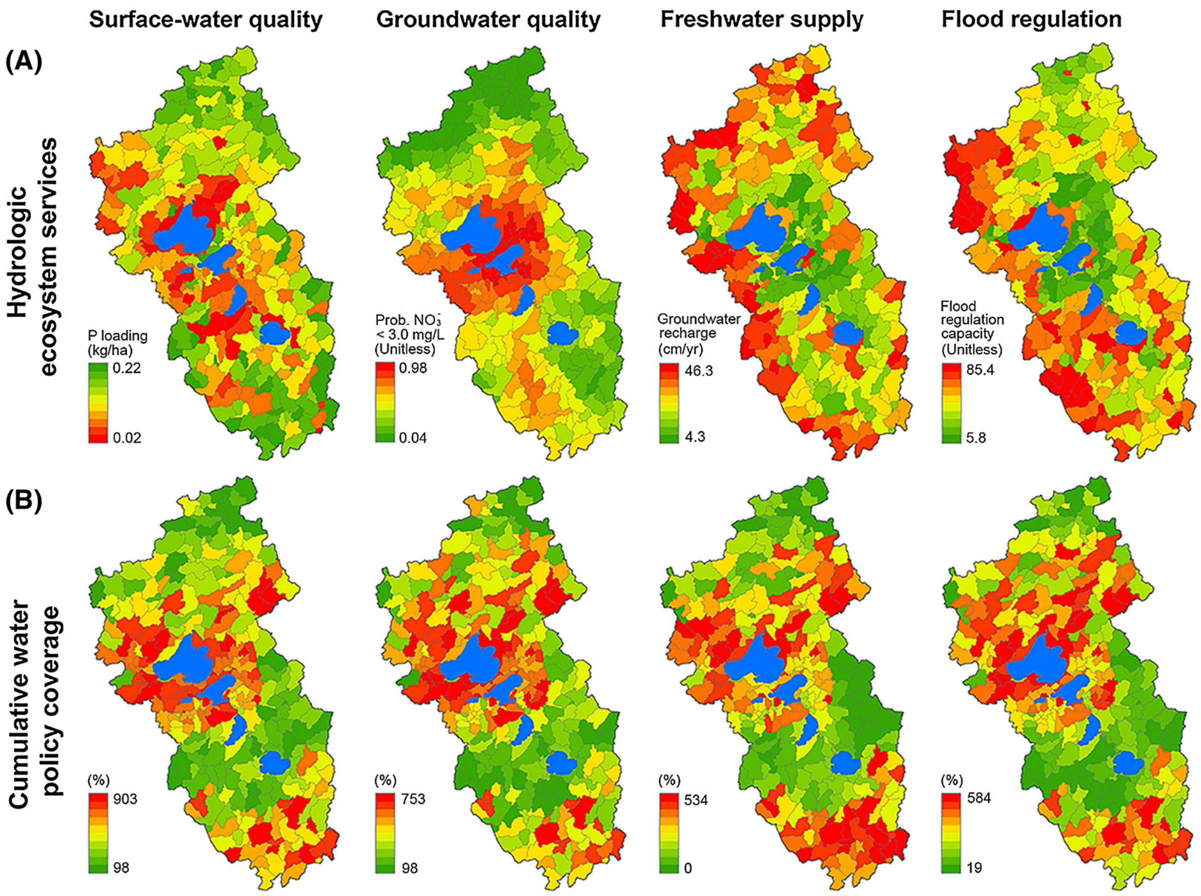


Fig. 3 Spatial patterns of hydrologic ecosystem services (**a**) and cumulative coverage of water policies relevant for each service (**b**). *Green* indicates high supply of service or high policy coverage, and *red* represents low supply of service or low policy coverage. (Color figure online)

Spatial overlap between policy coverage and hydrologic services

Overall cumulative policy coverage was positively correlated with surface and groundwater quality—meaning that higher concentrations of policy implementation occurred where water quality was also high (Fig. 4a, b). However, negative correlations were observed between cumulative policy coverage and freshwater supply and flood regulation, indicating that more policies were implemented where the provision of water supply and flood regulation services was low (Fig. 4c, d).

Despite the overall pattern, relationships between cumulative policy coverage and hydrologic services were generally weak. Individual policies varied widely in both magnitude and direction of their correlations with each hydrologic service (Fig. 5). For example, 9 policies showed negative correlations with surface-water quality (i.e., targeting areas of high phosphorus runoff or water-quality concern), while an equal number of policies had positive correlations. In addition, individual correlations between policy application areas and service provision were relatively weaker for freshwater supply and flood regulation, and often opposite of the correlations with water quality services (Fig. 5). For instance, Federal/State Regulated Wetland Disturbance that prevented filling or degrading wetlands had the strongest negative correlation with freshwater supply (mostly because many wetlands in this area are water sources occupying low topographic positions where groundwater is discharged) (Carter and Novitzki 1987; Winter 1999), but showed positive correlation with surface-water quality (likely because phosphorus runoff tended to be much lower where wetlands were well conserved).

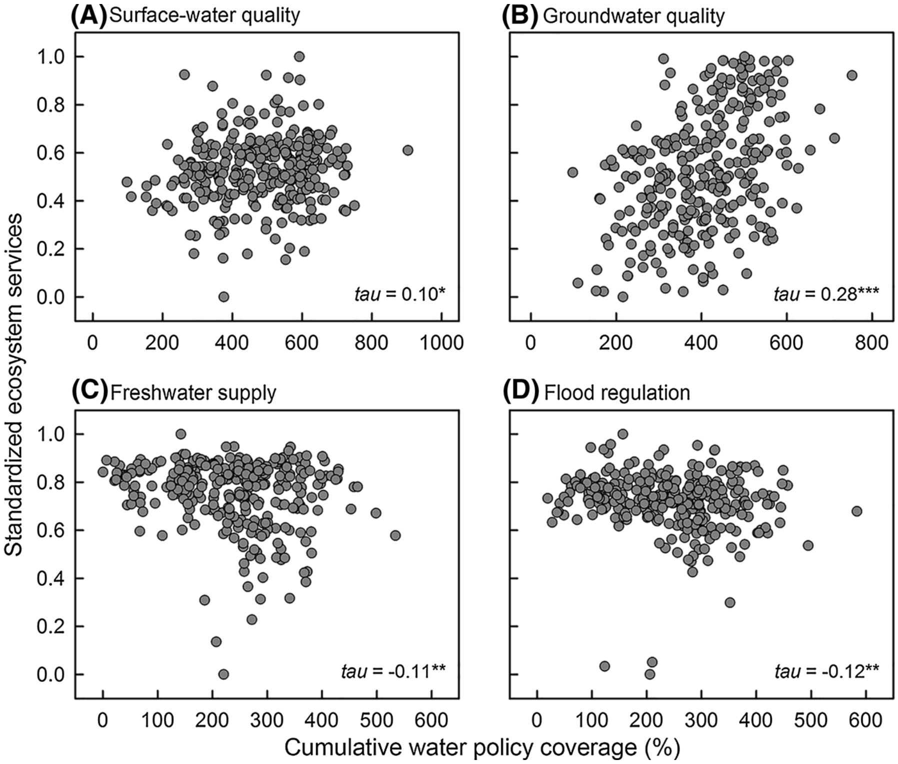


Fig. 4 Kendall rank nonparametric correlation (*tau*) between the provision of hydrologic ecosystem services and cumulative coverage of water policies (%) at the subwatershed scale. Significance level: $*p < 0.05$; $**p < 0.01$; $***p < 0.001$

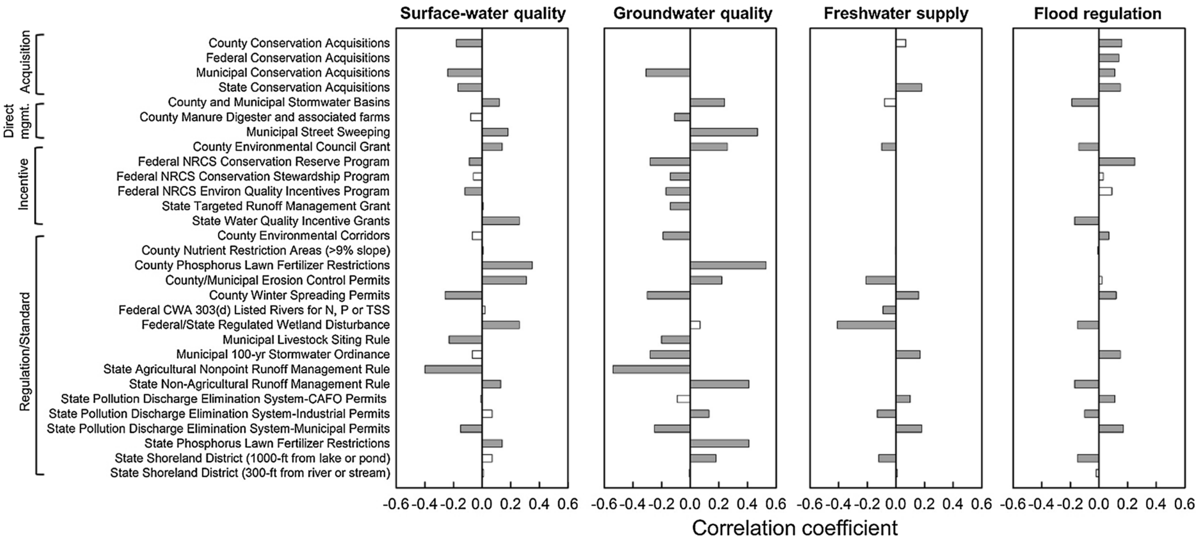


Fig. 5 Kendall rank nonparametric correlation (*tau*) between the provision of hydrologic services and individual policy application area at the subwatershed scale

Relationships differ by policy type

Relationships between cumulative policy coverage and hydrologic services also differed by policy type (Fig. 6). Direct management, incentive, and regulation/standard were positively correlated with surface and groundwater quality services, indicating that they were more likely to target areas of lower phosphorus runoff, while acquisition showed negative correlations. For freshwater supply and flood regulation, the direction of relationships was opposite of the two water quality services, with acquisitions positively correlated with these two water quantity services (Fig. 6).

Distinctions between urban and rural subwatersheds

Urban and rural subwatersheds diverged in their patterns or combinations of water policies implemented. PCA analysis revealed clear distinctions between urban and rural areas in the reduced two-dimensional space of policy coverage (Fig. 7). Policies such as Municipal Street Sweeping (MSS), the State Non-Agricultural Runoff Management Rule (NAR), and County Phosphorus Lawn Fertilizer Restrictions (CPL) were dominant in urban areas. In contrast, policies such as State Agricultural Nonpoint Runoff Management Rule (ANR), Municipal Livestock Siting Rules (MLS), and County Winter Spreading Permits (CWS) were dominant in rural areas. Some policies such as the federal Natural Resources Conservation Service (NRCS) Environmental Quality Incentives Program (EQI) and Conservation Stewardship Program (CSP), did not fall into either the urban or rural cluster (Fig. 7).

Priorities for future policy implementation

Based on the relationships between cumulative policy coverage and hydrologic services, we identified locales where future policy implementation might be needed. We restricted our analysis to surface and groundwater quality services that showed positive correlation with policy coverage, because for these two services more policies were implemented in regions with relatively good water quality. In total, we identified 15 and 21 subwatersheds for surface and ground water quality, respectively, that might be priorities for future policies, mostly situated in the rural northern part of the watershed (Fig. 8). These subwatersheds were dominated by intensively managed agriculture such as corn production and dairy farms that contributed substantially to degradation of surface- and groundwater quality services, but have fewer implemented conservation policies.

Discussion

Our results suggest an overall spatial misfit between water policy implementation and areas of water quality concern in this Midwestern agricultural watershed, where the sustainability of freshwater resources is imperiled. However, water policies were leveraged to protect other hydrologic services, such as freshwater supply and flood regulation. Individual policy application areas varied substantially in their spatial congruence with each hydrologic service. Not surprisingly, no single policy can protect all services, underscoring the importance of a broad portfolio of water policies to sustain multiple hydrologic services at landscape scales. Our analysis also identified where

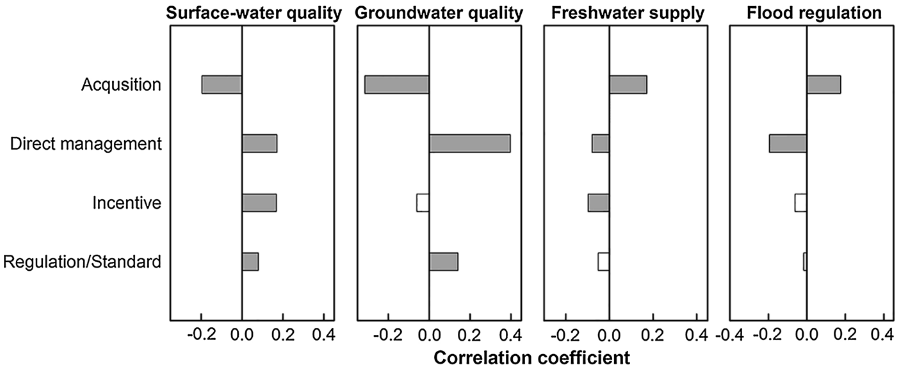
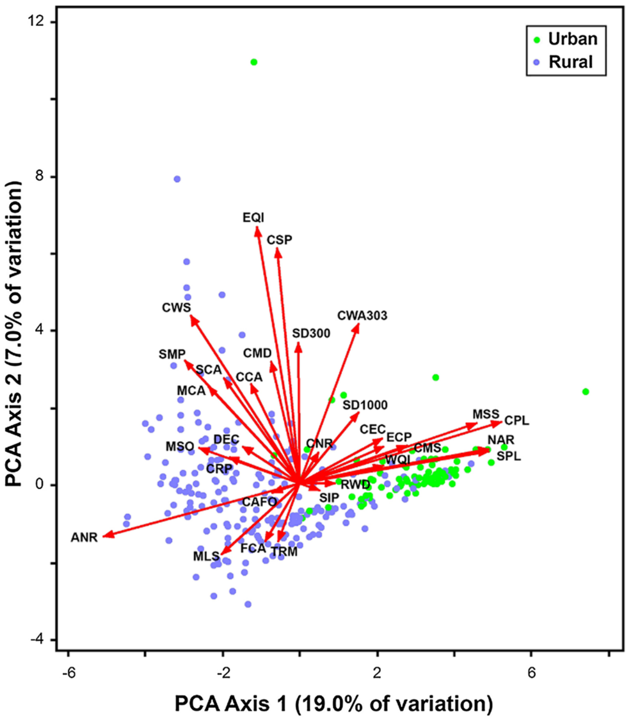


Fig. 6 Kendall rank nonparametric correlation (*tau*) between provision of hydrologic service and cumulative coverage of different policy types: acquisition, direct management, incentive and regulation/standard, at the subwatershed scale



Water Policy Abbreviations:

ACQUISITION

CCA: County Conservation Acquisitions
FCA: Federal Conservation Acquisitions
MCA: Municipal Conservation Acquisitions
SCA: State Conservation Acquisitions

DIRECT MANAGEMENT

CMS: County and Municipal Stormwater Basins
CMD: County Manure Digester and associated farms
MSS: Municipal Street Sweeping

INCENTIVE

CEG: County Environmental Council Grant
CRP: Federal NRCS Conservation Reserve Program
CSP: Federal NRCS Conservation Stewardship Program
EQI: Federal NRCS Environmental Quality Incentives Program
TRM: State Targeted Runoff Management Grant
WQI: State Water Quality Incentive Grants

REGULATION/STANDARD

CEC: County Environmental Corridors
CNR: County Nutrient Restriction Areas (>9% slope)
CPL: County Phosphorus Lawn Fertilizer Restrictions
ECP: County/Municipal Erosion Control Permits
CWS: County Winter Spreading Permits
CWA303: Federal CWA 303 (d) Listed Rivers for P, N or TSS
RWD: Federal/State Regulated Wetland Disturbance
MLS: Municipal Livestock Siting Rule
MSO: Municipal 100-yr Stormwater Ordinance
ANR: State Agricultural Nonpoint Runoff Management Rule
NAR: State Non-Agricultural Runoff Management Rule
CAFO: State Pollution Discharge Elimination System-CAFO Permits
SIP: State Pollution Discharge Elimination System-Industrial Permits
SMP: State Pollution Discharge Elimination System-Municipal Permits
SPL: State Phosphorus Lawn Fertilizer Restrictions
SD1000: State Shoreland District (1000-ft from lake or pond)
SD300: State Shoreland District (300-ft from river or stream)

Fig. 7 Principal component analysis (PCA) biplot shows factor loadings of water policies as *arrows* and subwatersheds as *points* ($N = 296$)

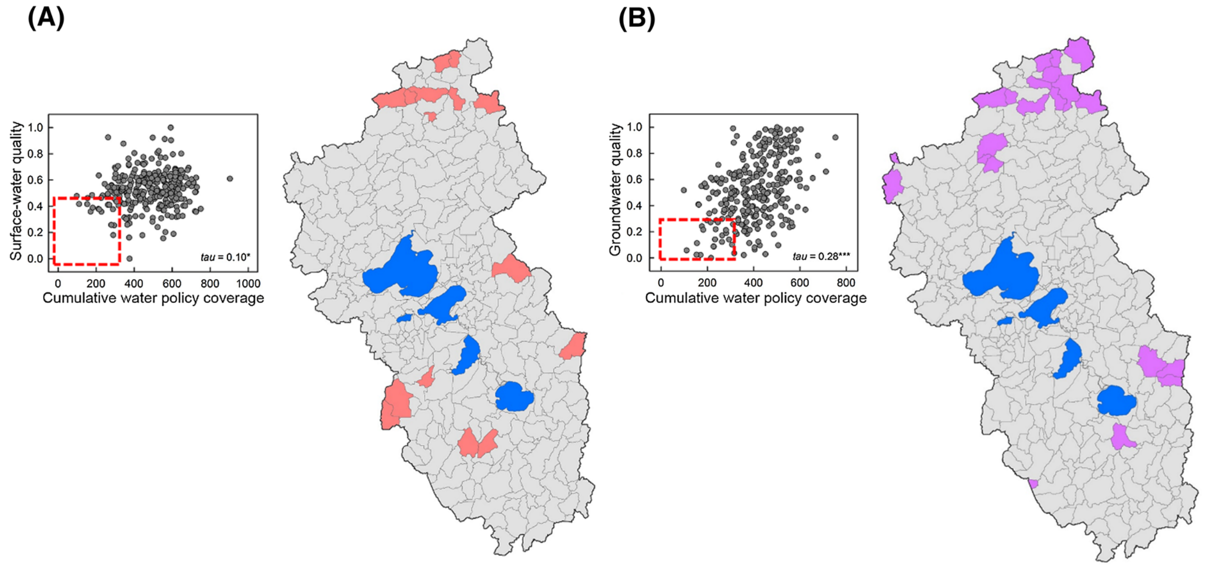


Fig. 8 Subwatersheds identified as priorities for future policy implementation: **a** surface-water quality (highlighted in *red*); **b** groundwater quality (highlighted in *purple*). In the scatterplot of each panel, *red dashline box* represents the lowest 20th percentile in the service provision and the cumulative policy coverage. (Color figure online)

future policies might be targeted. Our study demonstrates that joint spatial analysis of policies and ecosystem services can provide a foundation for assessing spatial fit of policies and enhancing their effects in safeguarding ecosystem services.

Our analyses revealed that policies were less concentrated in agriculture-dominated regions. This pattern is of concern because agricultural runoff is mostly responsible for impairing water quality in the region (i.e., an indication of spatial misfit) (Strand Associates, 2013). Several factors may explain lower water policy coverage in rural subwatersheds, including reliance on voluntary participation, limits on information availability, and programmatic and funding constraints (Genskow 2012; Shortle et al. 2012). Our subwatershed-scale analysis revealed the need for greater attention to agricultural areas, and agricultural conservation literature emphasizes the importance of targeting those farms and fields that are the greatest sources of nutrient runoff within subwatersheds (Nowak et al. 2006). In agricultural nonpoint source programs, the pattern of enrollment is largely driven by voluntary participation through environmental stewardship, market- or government-based incentives (Perez 2015). Relying on voluntary enrollment is well recognized as a barrier to improving agricultural environmental quality, because volunteers are likely already the stronger environmental stewards (Ribaudo 2015). Funding availability is another important factor that determines the spatial extent of policy application; insufficient financial support can create governance gaps. Urban areas had a disproportionately high policy coverage relative to their contribution to freshwater eutrophication. This difference could be attributed to greater resources and political attention in urban areas and the relative ease of implementing regulatory policies in incorporated municipalities.

Policies aimed at improving surface-water quality targeted areas of concern for other hydrologic services including freshwater supply, groundwater quality and flood regulation (Figs. 4, 5), suggesting the potential of policies to achieve multiple objectives and maximum benefits. This is especially valuable for ecosystem services that have less developed policy or management frameworks, such as groundwater quality or groundwater recharge (Lavoie et al. 2013). In these cases, policy goals and management prescriptions could directly address multiple ecosystem services, in particular when the provision of different services shows spatial overlap. Ecosystem services are also not independent of each other, underscoring the importance of considering multiple services and their interactions in ecosystem management (Bennett et al. 2009). In the Yahara Watershed, surface and groundwater quality, or freshwater supply and flood regulation, appear as synergies where multiple services could be enhanced together (Qiu and Turner 2013). Policy benefits could be enhanced by leveraging their interactions to manage multiple hydrologic services concurrently.

Individual policies varied considerably in their spatial patterns and relationships with each hydrologic service (Fig. 5), likely reflecting differences in the institutional dynamics associated with each policy tool (Doremus 2003; Newig et al. 2010). For example, the State Agricultural Nonpoint Runoff Management Rule (Wisconsin Administrative Code Natural Resources 151, Subchapter II)—a Wisconsin program that requires all farms to meet soil loss requirements, avoid tilling within 5-ft (1.5 m) of surface waters, and have a nutrient management plan if spreading manure or fertilizer—showed negative correlations with water quality services, because this policy primarily targets agriculture-dominated lands with intensive nutrient inputs. On the other hand, policies such as County Phosphorus Lawn Fertilizer Restrictions (Dane County Ordinance Chapter 80) and the County/Municipal Erosion Control Permits (Dane County Ordinance Chapter 14) showed positive correlations with water quality because both of them targeted lawns or shoreland districts concentrated in urban areas that contribute proportionally less phosphorus runoff compared to rural areas. The variation in spatial concordance between individual policy implementation and service provision indicates that it is important to examine individual and cumulative effects of policies. It also speaks to the importance of policy analysis that accounts for the full portfolio of actions across government agencies (Doremus 2003; Young et al. 2006).

Spatial variation across types of policy tool is not surprising, given their diverse goals, functions, costs, and level of acceptance in urban and agricultural areas. Regulatory restrictions may be applied to a large area for lower cost than incentives (Bengston et al. 2004), yet restrictions are often more accepted in urban and industrial areas than in agricultural areas (Warren et al. 2011), which may explain the greater application of regulation in the Yahara's urban core. Incentives for environmental best management practices encourage private landowner program participation to a greater degree than regulation in agricultural and natural area settings, with less backlash (Lubell 2004; Langpap 2006). However, incentive programs are spatially fragmented and may impact only a small proportion of landowners, particularly where economic returns are high. As for land acquisition, the Midwestern Corn Belt has few public lands relative to other regions; public lands in the Yahara Watershed include scattered reserves in rural areas and urban parks. Where few public lands were preserved historically, acquisition is expensive and likely to influence an even smaller proportion of the landscape than incentives to private landowners (Fairfax et al. 2005). Because the choice of policy tool involves political, financial, and equity considerations (Salamon and Elliot 2002), ecosystem targeting may not be the primary factor driving the spatial pattern of policy implementation (Wardropper et al. 2015). Our analysis also suggests the need to expand the literature on spatial fit beyond the analysis of spatial extent. Our focus on multi-level policies across a heterogeneous landscape reveals the spatial pattern of implementation and allows for analysis of a policy portfolio. Bridging the institutional literature on spatial and functional fit, which concerns how institutional function adequately accounts for ecosystem function and dynamics (Ekstrom and Young 2009), as well as the conservation planning literature on spatial targeting will be a fruitful area of future research.

Looking to the future of Yahara Watershed management, we identified locations where increased policy attention may be beneficial for enhancing surface and groundwater quality. Most identified areas were in agriculture-dominated subwatersheds, reinforcing the need to reduce nonpoint source pollution to improve water quality. Specific efforts that may be helpful include careful evaluation of existing water policies, identification of the causes of freshwater problems in these subwatersheds (for example, locating areas of excessive nutrient application, uncovered barnyards, and fields where manure is spread in winter), and implementation of appropriate policies to fill governance gaps.

Our approach has several limitations. First, we did not assess effectiveness of policies nor how they directly affect hydrologic services, because temporal data are lacking. Policy effectiveness is difficult to evaluate because of the lack of experimental controls and spatial and temporal disconnects with ecosystem responses (Rissman and Smail 2015). Second, the policy analysis mainly focused on surface-water quality, and how these policies may provide additional benefits in protecting other hydrologic services, because surface-water quality is the major concern in our region. While ideally it would be worthwhile to assess the spatial fit between each hydrologic service and all policies targeting that service, such analysis is limited in our study region due to lack of spatial data. Future efforts should make spatial data on conservation policy publicly available to better assess spatial targeting at the farm or field scale (Morris and Rissman 2009). Future research could also compare spatial fit of additional policies targeted toward water supply, groundwater quality or other water-related recreational services. Finally, we recommend that analysis of institutional fit be expanded in the future to include functional fit. Overall, we believe that our approach to analyzing institutional spatial fit will be useful for ecologists to expand beyond simple gap analysis and for social scientists to embrace spatial and landscape perspectives in environmental governance studies.

In summary, our study demonstrates a spatial misfit of policy application and non-point source pollution, a governance gap prominent in many agriculture-dominated landscapes. Our results reflect a pattern of uneven water policy implementation across the urban–rural divide, and highlight the need for greater policy implementation in agriculture-intensive regions. This research is among the few spatially explicit attempts to assess implementation of a water policy portfolio spanning local to federal action through incentives, regulation, direct management, and land acquisition. This research also contributes to an emerging literature on landscape sustainability science and management that aims to enhance the long-term capacity of landscapes to provide essential ecosystem services (Wu 2013).

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