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Research article

Attributes of successful actions to restore lakes and estuaries degraded by nutrient pollution

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ABSTRACT

As more success is achieved in restoring lakes and estuaries from the impacts of nutrient pollution, there is increased opportunity to evaluate the scientific, social, and policy factors associated with achieving restoration goals. We examined case studies where deliberate actions to reduce nutrient pollution and restore ecosystems resulted in ecological recovery. Prospective cases were identified from scientific literature and technical documents for lakes and estuaries with: (1) scientific evidence of nutrient pollution; (2) restoration actions taken to mitigate nutrient pollution; and (3) documented ecological improvement. Using these criteria, we identified 9 estuaries and 7 lakes spanning countries, climatic regions, physical types, depths, and watershed areas. Among 16 case studies ultimately included, 8 achieved improvements short of stated restoration goals. Five more were successful initially, but condition subsequently declined. Three of the case studies achieved their goals fully and are currently managing to maintain the restored condition. We examined each case to identify both common attributes of nutrient management, grouped into 'themes', and variations on those attributes, which were coded into categorical variables based on thorough review of documents associated with each case. The themes and variables were organized into a broad conceptual model illustrating how they relate to each other and to nutrient management outcomes. We then explored relationships among the themes and variables using multiple correspondence analysis (MCA). Results of the MCA suggested that the attributes most associated with achieving restoration goals include: (1) leadership by a dedicated watershed management agency; (2) governance through a bottom-up collaborative process; (3) a strategy that set numeric targets based on a specific ecological goal; and (4) actions to reduce nutrient loads from all sources. While our study did not provide a comprehensive road map to successful nutrient management, it suggested attributes that could be emulated in future efforts. The quantitative approach that was applied could be used to provide ongoing analysis as new examples of nutrient management success emerge.

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1. Introduction

Nutrient pollution of aquatic ecosystems accelerated globally starting in the 1950s, reflecting a variety of causes associated with growing human population and the necessary increased provision of developed land, food, and energy (Davidson et al., 2012). Extensively documented negative water quality responses often include harmful algal blooms, hypoxia, habitat degradation, and adverse changes in aquatic food webs (National Research Council, 2000). Significant efforts have been undertaken in some cases to reduce loading of nutrients to lakes or estuaries, or to otherwise mitigate the impacts of nutrient pollution. As these efforts have matured, the number of cases in which management actions have achieved some success has increased, enabling examination of the ecological patterns and processes associated with recovery and restoration (Borja et al., 2010; Duarte et al., 2009; Jeppesen et al., 2005; Kemp et al., 2009; Verdonschot et al., 2013). Examples of successful restoration also present the opportunity to evaluate what scientific, social, and policy factors are associated with successful restoration, with the idea that this information could inform new or ongoing programs that seek to restore lakes and estuaries

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from nutrient pollution.

Papers examining policy, planning, and management of natural resources in general, and water resources in particular, have identified a variety of relevant issues and concepts. These include studies of the 'focusing events' that lead to new policy initiatives (Birkland, 1996; Prokopy et al., 2014), the antecedents to forming managing partnerships (Selin and Chavez, 1995; Waddock, 1989) and the effectiveness of partnerships in terms of their implementation of plans and satisfaction of stakeholders (Koontz and Newig, 2014; Leach and Pelkey, 2001). Some studies have begun with examples of policy efforts, then evaluated factors associated with achieving the policy objectives, whatever those may be. For example, Ansell and Gash (2008) examined cases of collaborative governance to identify factors associated with successful collaboration. In their study, successful collaboration was defined by having generated the desired governance process, not necessarily by achieving the desired environmental outcomes, which until recently have been relatively uncommon. Similarly, Leach and Pelkey (2001) defined a successful watershed partnership in organizational terms or "capacity building," while acknowledging that watershed managers would generally focus on ecological outcomes.

As more remedial actions are implemented, research – often utilizing the results of long-term monitoring data – has documented ecosystem responses to these actions. This includes reviews and comparative studies of recovery from various stressors, including nutrient enrichment in rivers, lakes, estuaries, and coastal systems (Borja et al., 2010; Jeppesen et al., 2005; Verdonschot et al., 2013). Many concepts in restoration ecology have been defined and explored, such as recovery, resistance, and resilience (Elliott et al., 2007), hysteresis and shifting baselines (Duarte et al., 2009), passive and active restoration (Simenstad et al., 2006), adaptive management (Rist et al., 2013; Williams, 2011), and integrated environmental management (Margerum and Born, 1995). These restoration concepts are relevant to nutrient management.

In this study, we examined case studies in which documented improvements in ecological condition of lakes and estuaries resulted from deliberate policy actions to manage and reduce nutrient pollution or its impacts. We define "success" with respect to such improvements and provide further clarification of our definition below. Because it is not possible to identify and fully understand the potentially numerous cases in which nutrient pollution effects are present but policy responses have not yet resulted in improved ecological outcomes, we did not evaluate cases of non-success. We did consider cases where success was qualified in some way (e.g., partial, temporary). Our hypothesis is that there are common themes present in examples of successful nutrient management in lakes and estuaries and that some variations of these themes are more commonly associated with unqualified or sustained management success.

2. Methods

Our overall approach can be characterized as having four steps. These include: (1) identifying case studies of ecological improvement, (2) identifying themes and variables related to nutrient management, organizing via a conceptual model, and categorizing each case study, (3) evaluating relationships among themes and variables using multiple correspondence analysis and (4) evaluating the resulting relationships to draw overall conclusions.

2.1. Case studies of ecological improvement

We identified prospective case studies from a survey of scientific literature and water resource agency documents for lakes and estuaries with: (1) scientific evidence of nutrient pollution; (2) restoration actions implemented to mitigate nutrient pollution and its effects; and (3) documented medium to long-term ecological improvement at the whole ecosystem scale. Examples of ecological improvements include reduction in harmful algal blooms (HABs), reduced abundance of nuisance macroalgae, increased submerged aquatic vegetation coverage (seagrass or freshwater macrophytes); increased coral abundance, and increased benthic faunal diversity and species richness. Water quality improvement alone, such as decreased extent of hypoxia, did not meet our criteria unless accompanied by a biotic response such as improved benthic community condition. Literature sources were initially drawn from reviews addressing ecological recovery (Borja et al., 2010; Jeppesen et al., 2005). Additional case studies were identified from the National Estuarine Eutrophication Assessment Update (Bricker et al., 2007), the European Union Freshwater Eutrophication Assessment (Lyche-Solheim et al., 2010), Australian Department of the Environment Water Quality Hotspots (Australian Department of the Environment), and the US Environmental Protection Agency Non-Point Source Success Stories (US Environmental Protection Agency). Additional cases were identified from literature associated with the case study reviews. Details of restoration actions were obtained directly from agency websites, technical documents, and from reports prepared by the respective management agencies and their reviewers.

2.2. Model of nutrient management themes

Once case studies were selected, general aspects of the nutrient management effort that were common to each case, but with different variations, were grouped into 'themes.' These themes were defined based on similar groups of factors from the public policy, natural resource management, and restoration ecology literature, and from published reviews of freshwater and estuarine restoration. Whenever possible, existing terms, definitions, and models were used to bridge the disciplines and ensure consistency with previous work. A conceptual model was developed using the resulting themes, and was then applied to each case of successful nutrient management.

To evaluate the cases, the restoration actions that local researchers and other experts believed were most responsible for ecological improvements (e.g. improved sewage treatment, agricultural controls, wetland restoration, etc.) were identified based on their peer reviewed publications and other technical documents. Other initiatives that local experts did not believe were a significant factor in the recovery (as expressed in reviewed documents) were not considered. Information related to each theme was gathered from the literature, and then the variations in each theme were coded into categorical variables to enable a systematic, reproducible analysis of the information (e.g. Biddle and Koontz, 2014; Leach and Pelkey, 2001). The resulting mutually exclusive variables were determined for each case, then added to the conceptual model. Useful details illustrating application of theme variables to our case studies are presented in the Supplementary Material including supplementary tables (Table S1, Table S2, Table S3).

2.3. Multiple correspondence analysis

Relationships among themes and the theme variables that characterized each case study were explored using multiple correspondence analysis (MCA). MCA is an ordination technique applied to reduce the dimensionality of the data when observations (i.e. case studies) are described by multiple categorical variables (Le et al., 2008). MCA was implemented using the FactoMineR package version 1.31.5 in R version 3.2.3 ("Wooden Christmas-Tree") with the FactoMineR plug-in 1.6–0 in the Rcmdr version 2.2–3 graphical user interface. FactoMineR allowed for designation of both active variables to construct the dimension axes and supplementary variables that can be plotted on dimension axes but were not used in the calculations evaluating variation between cases (Le et al., 2008). All themes were included as active variables except for *Progress to Restoration*, which characterized the restoration outcome or degree of success. This was included as a supplementary theme to enable exploration of the combinations of variables associated with each restoration outcome without using the outcome itself to define the axes. Use of categorical variables allowed an analysis of management themes and variables without confounding factors identified by Biddle and Koontz (2014) such as the scale and complexity of watersheds, time since restoration actions were initiated, or number of restoration goals.

To evaluate the sensitivity of the analysis to inclusion of any particular case, we repeated the analysis with one case removed (i.e., jackknife resampling) until all the cases were omitted once. We then evaluated whether any of the significant conclusions reached using the analysis changed when one of the cases was omitted. Because the axes changed slightly with each resampling, we focused on whether the correlation and significance of each theme and variable changed with omission of one or more sites (sensitivity) and whether omission of specific sites resulted in larger changes than omission of other sites (influence).

3. Results

3.1. Case studies of ecological improvement

We selected 9 estuaries and 7 lakes from the source documents and literature search that met the case study selection criteria (Table 1). We found other ecosystems that are responding to nutrient load reductions and other restoration actions with reduced ambient nutrient or chlorophyll-*a* concentrations, but do not yet have documented improvements in other established biological indicators. Examples were also identified, but not included, in which only portions of larger managed ecosystems improved (e.g., Boynton et al., 2014). We also focused on lakes and estuaries, which have some similarity as "receiving water" systems (i.e., they receive and respond to nutrient loading from their watersheds), and did not consider streams and rivers, which also respond to nutrient pollution.

The setting and physical characteristics of the included lakes and estuaries spanned a range of climatic regions, mean depth, and watershed area (Table S1). The range in these variables encompasses much of the population of lakes and estuaries worldwide, although the sites probably do not span the significant ecological diversity among all lakes and estuaries. The cases are located in North America, Europe, and Australia, probably because significant management actions, with documentation that we could access, were most common on these continents. The sample of estuaries included coastal bays, river-dominated estuaries, and a shallow fjord. Mean depth was 1.0–9.5 m and catchment area was 9–96,001 km^2. The lakes included both shallow and deep lakes with mean depth between 1.4 and 177 m and catchment area from 1.8 to 17,000 km^2 (Table S1).

The sources of nutrient loading were similar across most cases, with sewage effluent cited as a major source of nutrient loading in 14 of 16 cases (excluding Mondego Estuary and Bass Lake). Urban (12 cases) and agricultural (11 cases) non-point sources were also common to most systems, with industrial point sources (7 cases) and atmospheric non-point sources (2 cases) also noted as contributing to the nutrient load in some cases. Hydrologic modification was identified as the primary cause of eutrophication only in the Mondego River estuary (Lillebø et al., 2005), although sewage, industrial discharge, and agricultural run-off were also noted as contributing to nutrient enrichment (Flindt et al., 1997; Verissimo et al., 2012).

Indicators of nutrient impairment varied by climatic region and system type. Seagrass loss was the most commonly cited indicator of nutrient-related impairment in the sub-tropical and temperate estuaries (7 cases). A nearly abiotic benthos was the principal indicator of impairment in the hydrologically modified Nervion River estuary (Diez et al., 2014). Coral loss to nuisance macroalgae was the primary symptom of eutrophication only in the tropical Kaneohe Bay (Banner and Bailey, 1970), whereas a decline in coral diversity was noted in sub-tropical Moreton Bay (Lybolt et al., 2011). Harmful algal blooms (4 cases) and nuisance macroalgae (5 cases) were also common eutrophication responses in estuaries.

In each of the lakes, harmful algal blooms were cited as the primary indicator of nutrient impairment. A corresponding loss of submerged macrophytes was noted in the shallow Barton Broad and Lake Apopka (Broads Authority, Undated; Coveney et al., 2005), while a hypoxic hypolimnion was noted in the mid-depth Cobbosse Lake and Bass Lake (Druckrey, 2008; US Environmental Protection Agency, 1980).

3.2. Model of nutrient management themes

Seven nutrient management themes were identified and applied to each of the 16 selected cases (Fig. 1), including *Antecedents*, *Leadership*, *Governance*, *Strategy*, *Actions*, *Partnership*, and *Progress to Restoration* (Table 2). Among all the themes, a total of 19 variables were defined (Table 2) and assigned for each case study (Table 3). Details associated with each variable in the context of case studies are included in the Supplemental Material. Hereafter, themes and associated variables are capitalized and italicized (e.g., *Public Crisis*) to set them apart from other text.

3.2.1. Antecedents

The factors that brought stakeholders together to formulate plans and ultimately take restoration action were defined as *Antecedents* in the model of social partnerships by Waddock (1989) and refined for environmental management by Selin and Chavez (1995). Stakeholders include government, public agencies, private organizations, and individual citizens, whereas partnerships are defined broadly as a group of stakeholders working together to manage or restore an ecosystem. The variables associated with the *Antecedents* theme are *Public Crisis*, *Government Mandate* and *Existing Networks with Funding Incentives* (Table 2).

Public Crisis (8 cases; Table 3) was the most common *Antecedent*, wherein there was an ecological crisis that directly affected the public, was made known to a wider audience in the media, and which led to local public campaigns to demand government action. In most cases, these crises were addressed with local actions since they predated full implementation of national-scale water pollution regulations (e.g. US Clean Water Act). A *Government Mandate* to complete large-scale engineering projects or legislation requiring specific restoration actions provided the framework for nutrient management efforts in 4 cases (Table 3). In most cases since the 1980s, *Existing Networks with Funding Initiatives* (4 cases; Table 3) brought local agencies and interest groups together, most often through cost-share incentives provided by broad government watershed management and anti-pollution programs (e.g., US Clean Water Act, EU Water Framework Directive, Australian National Water Quality Management System).

Table 1
Name and location of lakes and estuaries where ecological improvements were achieved. Source of case indicates documents from which the sites were originally identified. References refer to sources of all further information regarding each case, but are still a subset of all references consulted for each case study.

Location	Source of Case	References for Case Study Variables
Boston Harbor (Massachusetts, US)	Borja et al., 2010; Bricker et al., 2007; Greening et al., 2014	Diaz et al., 2008; Leschen et al., 2010; MassBays, 2014; Neponset River Watershed Association, 2004; Taylor, 2001, 2010, 2014; Taylor et al., 2011; Tucker et al., 2014
Kaneohe Bay (Hawaii, US)	Greening et al., 2014	Banner and Bailey, 1970; Drupp et al., 2011; Hawaii Department of Health, 2014; Hunter, 1995; Jokiel, 1991; Smith et al., 1981; Stimson et al., 2001; Tanimura, 1988
Mondego (Portugal)	Borja et al., 2010; Bricker et al., 2007	Cuhna et al., 2012; Dolbeth et al., 2007; Flindt et al., 1997; Lillebø et al., 2011; Lillebø et al., 2005; Portuguese Environment Agency, 2016; Verissimo et al., 2012
Moreton Bay (Australia)	Australian Department of the Environment; Bricker et al., 2007	Benson et al., 2012; Cottingham et al., 2010; Cutriss et al., 2013; Dennison and Abal, 1999; Gibbes et al., 2014; Hanington et al., 2015; Healthy Waterways, 2014, 2015; Lybolt et al., 2011; Moreton Bay Waterways and Catchment Partnership, 2003; Queensland Department of Environment and Heritage Protection, 2013; Queensland Department of Environment and Resource Management, 2010; Queensland Environmental Protection Agency and Healthy Waterways (Qld.), 2001; South East Queensland Healthy Waterways Partnership, 2007a, b; Waltham et al., 2014; Wulff et al., 2011
Nervion (Spain)	Borja et al., 2010	Basque Water Agency, 2013; Borja et al., 2010; Diez et al., 2014; Garcia-Barcina et al., 2006; Ploger, 2007
Peel-Harvey (Australia)	Australian Department of the Environment	Davis and Rolls, 1987; Mccomb and Humphries, 1992; Rivers et al., 2013; Western Australia EPA, 1994, 2003, 2008; Wildsmith et al., 2009; Williams, 2009
Roskilde (Denmark)	Flindt et al., 1997	Clarke et al., 2003; Kronvang et al., 2008; Lillebø et al., 2011; Pedersen et al., 2013; Dalgaard et al., 2014; Danish Nature Agency 2015; Riemann et al., 2015
Tampa Bay (Florida,US)	Borja et al., 2010 Bricker et al., 2007	Greening, 2001; Greening et al., 2011; Greening and Elfring, 2002; Greening and Janicki, 2006; Greening et al., 2014; Johansson, 1991; Tampa Bay Estuary Program, 2015
Venice Lagoon (Italy)	Bricker et al., 2007; Flindt et al., 1997	Collavini et al., 2005; Facca et al., 2014; Lillebø et al., 2011; Newton et al., 2014; Sfriso et al., 1989; Suman et al., 2005
Barton Broad (UK)	Jeppesen et al., 2005	Bennion et al., 2001; Broads Authority, 2010, 2015, Undated; Kelly, 2008; OURCOAST, 2010; Phillips et al., 2005; Punchard, 2014
Bass Lake (Wisconsin, US)	US Environmental Protection Agency	Druckrey, 2008; Sevener, 2012; US Environmental Protection Agency, 2005; Wisconsin Department of Natural Resources, 2013
Cobbossee Lake (Maine, US)	US Environmental Protection Agency	Gordon, 1980; Halliwell, 1999; US Environmental Protection Agency, 1980, 2007
Lake Apopka (Florida, US)	Jeppesen et al., 2005	Coveney et al., 2005; Florida Department of Environmental Protection (2014); Hoge et al., 2003; Lowe et al., 1999; Magley, 2003; Waters et al., 2015
Lake Maggiore (Italy)	Jeppesen et al., 2005; Lyche-Solheim et al., 2010	Battarbee et al., 2012; C.N.R.-I.S.E. Sede di Verbania, 2014; Callieri et al., 2014; Morabito et al., 2012; Ruggiu et al., 1998
Lake Mjøsa (Norway)	Lyche-Solheim et al., 2010	Hobæk et al., 2012; Holtan, 1979; Løvik et al., 2015; Vassdragsforbundet for Mjøsa med tilløpselver, 2005
Lake Washington (Washington, US)	Jeppesen et al., 2005	Edmondson and Lehman, 1981; Edmondson, 1996; Lane, 1995; Washington Department of Ecology

3.2.2. Leadership

Surveys of coastal managers and reviews of watershed management partnerships have found that dedicated leadership by a coordinating entity with active participation by technically skilled staff from government agencies were all important to a partnership's success (Greening and Elfring, 2002; Koontz and Newig,

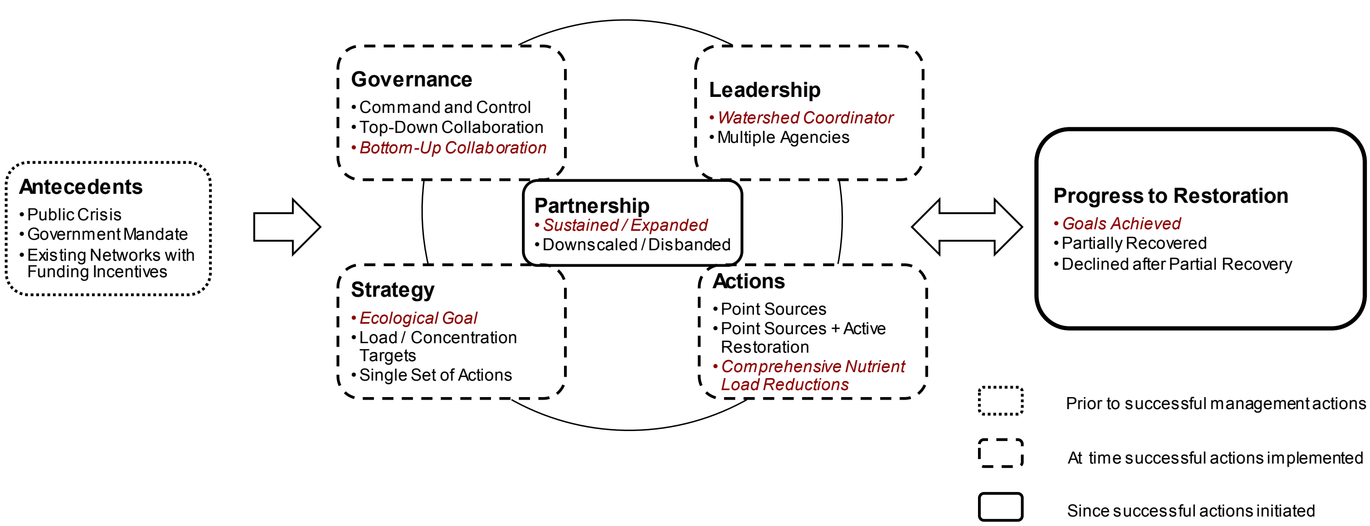

Fig. 1. Conceptual model relating themes in nutrient management associated with ecological improvement, beginning with *Antecedents* leading to the formation of management partnerships under *Leadership*, with a structure for *Governance*, employing a *Strategy* to take *Actions*. The environmental outcome is *Progress to Restoration*. Themes are indicated by rounded rectangles. The categorical variables associated with each theme are shown as bulleted lists within each theme. Variables found to be significantly associated with sustained ecological improvement from the MCA are depicted in red italics. Variables are defined in Table 2. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 2
Definitions of themes and categorical variables. Variables in first 5 themes were determined from the time actions were taken that led to improvement; variables in the last 2 themes were determined from changes since initial improvement. Theme and variable definitions are based on footnoted references. Variable types in the MCA were either Active or Supplemental (Supp.).

Theme	Categorical Variables	Definition	Type
Antecedents[a]	Public Crisis	A highly public ecological crisis motivated local citizens to demand action	Active
	Government Mandate	Partnership and action initiated by government mandate(s)	
	Existing Networks with Funding Incentives	Existing agencies used cost-share opportunities to form partnerships to address known problems	
Leadership[b,c,f,g]	Watershed Coordinator	Actions coordinated by a watershed management agency, usually in partnership with stakeholders	Active
	Multiple Agencies	Several agencies working semi-independently on issues of watershed management and restoration	
Governance[d,f,g]	Command and Control	Policy-makers issued detailed standards and directives for action to be carried out by agencies	Active
	Top-Down Collaboration	Program defined and decision-making done at national, regional, or state level with some local input	
	Bottom-Up Collaboration	Local stakeholders planned and completed actions through consensus-based decision making	
Strategy[c,h]	Single Project	Management planned as a single project time to address a nutrient-related problem	Active
	Load/Concentration Targets	Management planned to meet numeric load/concentration targets derived from reference conditions	
	Ecological Goal	Management planned to meet a numeric targets derived from a system-specific ecological goal	
Actions[e]	Point Source	Treatment, diversion, or elimination of sewage and where applicable, industrial discharges	Active
	Point Sources and Active Restoration	Point source actions and other 'engineered' projects to mitigate nutrient pollution	
	Comprehensive Nutrient Load Reductions	Projects to reduce all major point and non-point source nutrient loads	
Partnership[c,f]	Sustained/Expanded	Partnership structure and relationships with stakeholders and other agencies similar to or expanded since successful actions completed	Active
	Downscaled/Disbanded	Partnership was disbanded, duties shifted to other agencies, or oversight significantly reduced since successful actions completed	
Progress to Recovery	Goals Achieved	System has been restored to goals defined by managing partnership	Supp.
	Partially Recovered	System has improved, but has not yet reached partnership goals	
	Declined after Partial Recovery	System ecological condition declined after achieving improvements in the past.	

References.
[a] Waddock, 1989/Selin and Chavez 1995.
[b] Leach and Pelkey 2001.
[c] Greening and Elfring 2002.
[d] Lubell 2004.
[e] Simenstad et al., 2006.
[f] Ansell and Gash 2008.
[g] Koontz and Newig 2014.
[h] Biddle and Koontz 2014.

2014; Leach and Pelkey, 2001). Variables in the *Leadership* theme are *Watershed Coordinator* and *Multiple Agencies* (Table 2).

In half (8) of the cases, a *Watershed Coordinator* served as the single "coordinating entity" that led the efforts of agencies and other stakeholders to plan the strategy, implement actions, and report on progress (e.g., Greening and Elfring, 2002, Table 3). While the scale of the partnerships and scope of operations varied widely, a principle common to each was a focus on providing watershed management at the local level with participation and support from higher-level government agencies.

For the other 8 cases, *Multiple Agencies* acting within more complex management structures made notable gains toward restoration (Table 3). Multiple local agencies and small partnerships often worked actively on issues of watershed management and restoration within their jurisdictions, sometimes in cooperation with other agencies. However, no single group coordinated restoration on a watershed scale. Ecosystem-wide improvements were the result of large-scale projects such as sewage system upgrades or other engineering projects completed by one of the multiple agencies.

Within the *Leadership* theme, all the estuaries except for Tampa Bay and Moreton Bay had *Multiple Agencies* working on different aspects of ecosystem restoration. In contrast, all of the lakes except Lake Washington had single *Watershed Coordinators* leading implementation of management actions (Table 3).

3.2.3. Governance

Governance refers to the framework for managing stakeholder interactions to guide collective decision-making and action, based on the definitions of structuring in environmental management partnerships (Selin and Chavez, 1995) and of governance in public administration (Ansell and Gash, 2008; Stoker, 1998). *Command and Control*, *Top-Down Collaboration*, and *Bottom-Up Collaboration* were the variables identified in the *Governance* theme (Table 2).

The *Command and Control* approach (6 cases; Table 3) was defined based on Lubell (2004) and Koontz and Newig (2014) for those cases when detailed standards and directives for nutrient management actions were issued by government entities, usually at the national or regional level.

Top-Down Collaboration (6 cases; Table 3) was defined based on the concepts of mandated participatory planning (Koontz and Newig, 2014) and similar consultative and managerial approaches to management (Ansell and Gash, 2008). Within these frameworks, standards and action plans were established under national, regional, or state policy, and implementation was guided by government agencies in consultation with local stakeholders. Decision-making authority was not delegated below the regional or state level.

Partnerships engaged in *Bottom-Up Collaboration* (4 cases; Table 3) when stakeholders initiated plans and actions at the local level through consensus-based decision-making. Although the management framework of the US Clean Water Act provides for regulatory implementation by states with Federal leadership and oversight (Copeland, 2002), many partnerships in the US achieved success with more local, or "bottom-up" management. This approach was more common in lakes (3 of 4) than in estuaries.

3.2.4. Strategy

The *Strategy* theme was derived from research indicating that setting goals, specifically pollution reduction goals, is associated

Table 3
Case study categorical variables as determined from references in Table 1. Actions: Sewage Discharges (Sew), Industrial Discharges (Ind), Agricultural Run-Off (Ag), Urban Run-Off (Urb), Atmospheric (Atmos), Hydrological Manipulation (Hydro-M), Hydrological Restoration (Hydro-R), Macroalgae Harvesting (MacA-H); Wetlands Restoration (Wetland-R); Seagrass Planting (SeaG-P); Littoral Zone Restoration (Littoral Zone-R); Fish Removal (Fish-Rem); Phosphorus Sequestration (P-Sequest).

Location	Antecedents	Leadership	Governance	Strategy	Actions			Partnership	Progress to Restoration
					Point Source	Non-Point Source	Point Source + Active Restoration		
Boston Harbor (Massachusetts, US)	Public Crisis	**Multiple Agencies**: Mass. Water Resources Assoc.; MassBays NEP; Local Watershed Groups	Command & Control	**Single Project**: Sewage Diversion	Sew	–	–	Sustained/ Expanded	Partial Recovery
Kane'ohe Bay (Hawaii, US)	Public Crisis	**Multiple Agencies**: Kane'ohe Bay in Crisis; Kane'ohe Bay Task Force; Hawaii Dept of Health	Top-Down Collaboration	**Single Project**: Sewage Diversion	Sew	–	–	Downscaled/ Disbanded	Declined after Partial Recovery
Mondego (Portugal)	Government Mandate	**Multiple Agencies**: National Water Council; National Water Institute; Regional Directorate for Env. and Spatial Planning; Board of the Mondego River Basin	Command & Control	**Single Project**: Hydrological Restoration	–	–	Hydro-R	Sustained/ Expanded	Partial Recovery
Moreton Bay (Australia)	Existing Networks with Funding	**Watershed Coordinator**: SEQ Healthy Waterways Partnership	Top-Down Collaboration	**Load/Concentration Targets**: Ref. Conditions	Sew	–	–	Downscaled/ Disbanded	Declined after Partial Recovery
Nervion (Spain)	Government Mandate	**Multiple Agencies**:Consorcia de Aguas; Regional, Provincial, and Municipal Governments	Command & Control	**Single Project**:Sewage System	Sew, Ind	–	–	Sustained/ Expanded	Partial Recovery
Peel-Harvey (Australia)	Public Crisis	**Multiple Agencies**: Western Australia Env. Protection Authority	Command & Control	**Load/Concentration Targets**: Trophic State Index	–	–	HydroM; MacA H	Sustained/ Expanded	Declined after Partial Recovery
Roskilde (Denmark)	Public Crisis	**Multiple Agencies**: Danish EPA; County/ Region Water Mgmt	Top-Down Collaboration	**Load/Concentration Targets**: National Reduction Goals	Sew	Urb, Ag	SeaG -P	Sustained/ Expanded	Partial Recovery
Tampa Bay (Florida,US)	Public Crisis	**Watershed Coordinator**: Tampa Bay Estuary Program	Bottom –Up Collaboration	**Ecological Goal**: Seagrass Coverage	Sew, Ind	Urb, Ag, Atmos	SeaG-P; Wetland-R	Sustained/ Expanded	Goals Achieved
Venice Lagoon (Italy)	Government Mandate	**Multiple Agencies**: Venice Water Authority; Consorzio Venezia Nuova; Veneto Region; Province of Venice	Command & Control	**Load/Concentration Targets**: Ref. Conditions	Sew, Ind	–	HydroM; MacA-H	Sustained/ Expanded	Partial Recovery

(*continued on next page*)

Table 3 (*continued*)

Location	Antecedents	Leadership	Governance	Strategy	Actions			Partnership	Progress to Restoration
					Point Source	Non-Point Source	Point Source + Active Restoration		
Barton Broad (UK)	Existing Networks with Funding	**Watershed Coordinator**:Broads Authority	Top-Down Collaboration	**Ecological Goal**: Clear Water/Macrophyte Dominated	Sew	–	Fish-Rem; Suction Dredging; Wetland-R	Sustained/ Expanded	Partial Recovery
Bass Lake (Wisconsin, US)	Existing Networks with Funding	**Watershed Coordinator**: Marinette County Land & Water Conservation Dept.	Bottom –Up Collaboration	**Load/Concentration Targets**: Trophic State Index	N/A	Ag	P Sequest; Wetland-R	Sustained/ Expanded	Goals Achieved
Cobbossee Lake (Maine, US)	Public Crisis	**Watershed Coordinator**: Cobbossee Watershed District	Bottom –Up Collaboration	**Ecological Goal**: No HAB/Stable Trophic State	Sew	Ag, Urb	P Sequest (Upstream Lakes)	Sustained/ Expanded	Goals Achieved
Lake Apopka (Florida, US)	Government Mandate	**Watershed Coordinator**: St Johns River Water Management District (2015)	Bottom –Up Collaboration	**Ecological Goal**: Clear Water/ Macrophyte Dominated	Sew, Ind	Urb, Ag	Fish-Rem; Hydro-R; Wetland-R; Treatment Wetland; Littoral Zone-R	Sustained/ Expanded	Partial Recovery
Lake Maggiore (Italy)	Existing Networks with Funding	**Watershed Coordinator**: International Commission for Protection of Italian-Swiss Waters	Top-Down Collaboration	**Load/Concentration Targets**: Ref. Conditions	Sew	–	–	Sustained/ Expanded	Declined after Partial Recovery
Lake Mjøsa (Norway)	Public Crisis	**Watershed Coordinator**: Water Resources Association for Mjøsa with Tributary rivers	Top-Down Collaboration	**Load/Concentration Targets**: Ref. Conditions	Sew	Urb, Ag	–	Sustained/ Expanded	Partial Recovery
Lake Washington (Washington, US)	Public Crisis	**Multiple Agencies**: Municipality of Metro. SeattleMunicipal Governments	Command & Control	**Single Project**: Sewage Diversion	Sew	–	–	Downscaled/ Disbanded	Declined after Partial Recovery

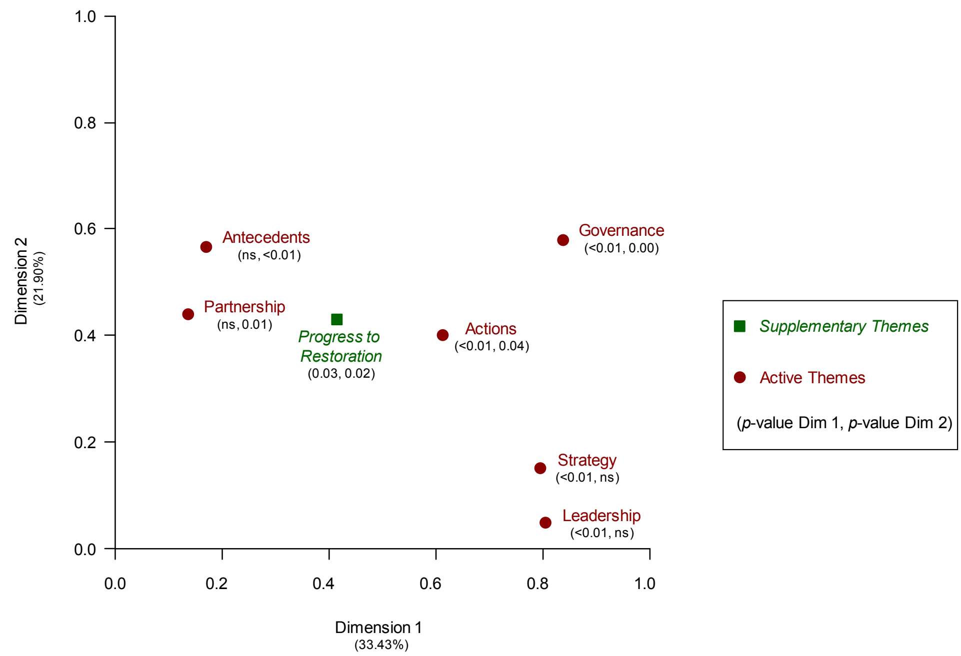

Fig. 2. Correlation ratios (R^2) of themes in constructing dimension 1 and dimension 2. Significance in each dimension noted in (); ns = not significant ($p > 0.05$).

with achieving improved water quality (Biddle and Koontz, 2014; Greening and Elfring, 2002). The variations in this theme, *Single Project*, *Load/Concentration Targets*, and *Ecological Goal*, reflected differences between management strategies to define goals and/or implement projects (Table 2).

In some cases, the strategy was a *Single Project* (5 cases; Table 3) completed in a short period of time to bring about improvements. Other partnerships successfully employed strategies to meet *Load/Concentration Targets* (6 cases; Table 3), which included a series of projects over time to meet nutrient load, nutrient concentration, or

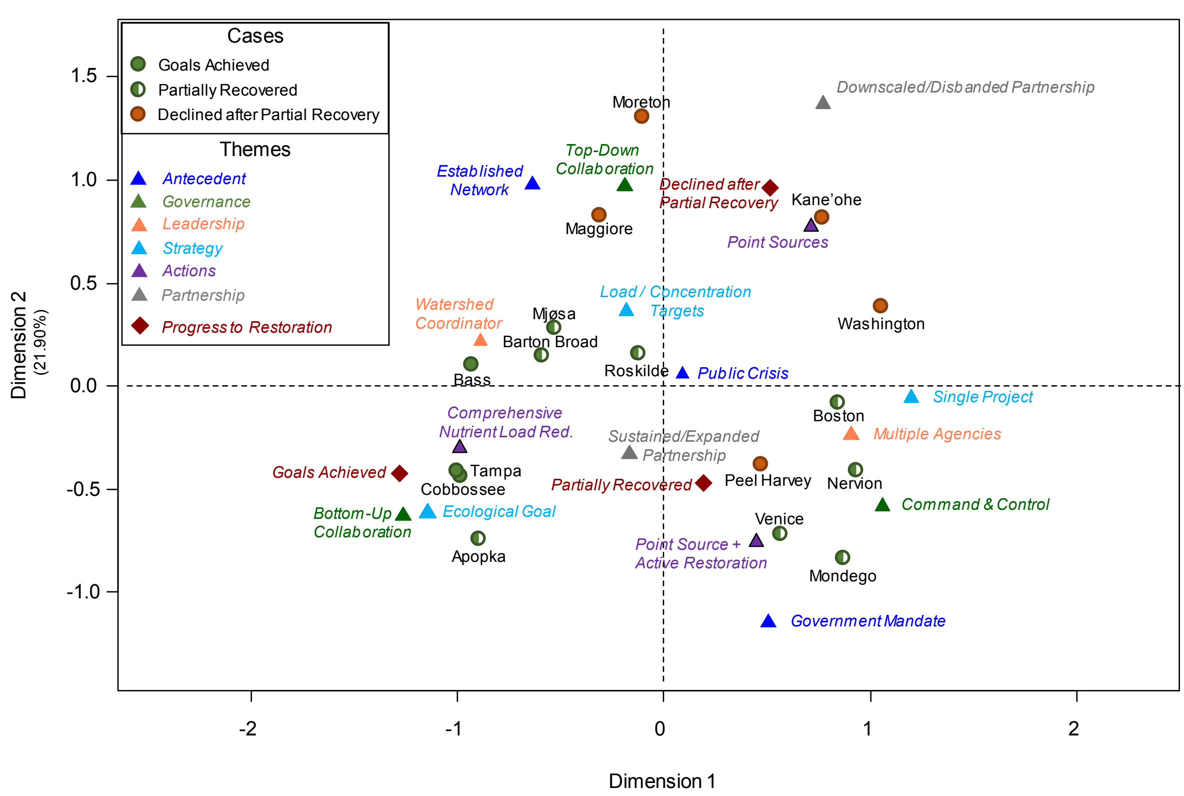

Fig. 3. Relationships between theme variables, cases, and supplementary variable *Progress to Restoration* in Dimensions 1 and 2.

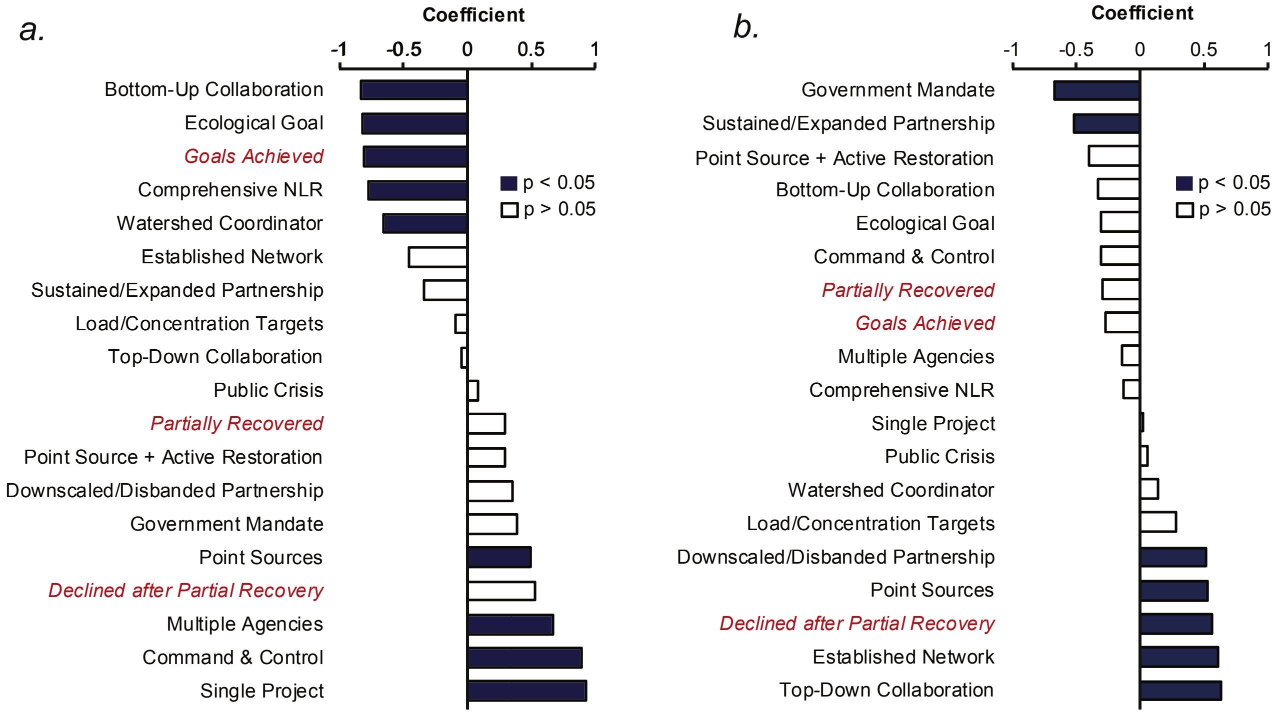

Fig. 4. Coefficients and significance of theme variables in (a.) dimension 1 and (b.) dimension 2. For each variable, the variance coefficient was the result of 1-way ANOVA with coordinates of each case in the dimension. Significance was determined by comparing average of each variable in the dimension with the general average of all variables in the dimension with a student *t*-test. Calculations completed through analysis with R package "FactoMineR". Supplementary variables shown in red italics. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

other water quality targets. These targets were designed to return the system to a previous, minimally impacted state by meeting goals determined from historic reference conditions, similar reference sites, a trophic state index, or general goals for nutrient load reductions.

Another successful restoration strategy included a series of actions taken to meet numeric targets derived from a system-specific *Ecological Goal* (5 cases; Table 3). In these cases, the managing partnerships first defined their restoration target with an ecological endpoint that was representative of desired ecosystem services and functional characteristics (e.g., Elliott et al., 2007), then worked backward to derive nutrient load limits to meet their goal.

3.2.5. Actions

The *Actions* theme described the range of projects implemented in each system that contributed to recovery, and included *Point Sources*, *Point Sources and Active Restoration*, and *Comprehensive Nutrient Load Reductions* (Table 2). Here, restoration measures follow definitions from Simenstad et al. (2006), where passive restoration is the removal of an environmental disturbance (e.g. anthropogenic nutrient loads) to allow reestablishment of natural ecosystem processes, and active restoration involves engineered actions (e.g., habitat restoration, biomanipulation) to recreate ecosystem structure and processes.

In some systems, actions that targeted *Point Sources* (6 cases; Table 3) such as eliminating, reducing or diverting the nutrient load in municipal and industrial point source discharges resulted in substantial ecological improvements. In other systems, partnerships both reduced loads from point sources and completed many active restoration projects, which we identified as *Point Sources and Active Restoration* (4 cases; Table 3) Such projects included wetland and riparian buffer restoration, hydrological manipulation or restoration, macroalgae harvesting, fish removal, nutrient sequestration, and wetland filtering. In the remaining cases, partnerships implemented *Comprehensive Nutrient Load Reductions* (6 cases; Table 3), defined as actions effective in reducing nutrient loads from all major sources in the watershed. Actions in these cases usually also included active restoration measures.

3.2.6. Partnership

The *Partnership* theme considered changes in the structure or membership of the watershed partnerships after successful nutrient management actions were first completed. Selection of the theme is based on research linking sustained participation from stakeholders throughout the management process to positive environmental outcomes (Ansell and Gash, 2008; Biddle and Koontz, 2014; Leach and Pelkey, 2001). Because detailed information on past partnerships was not available to the same degree for all systems, variation among cases was resolved to only two levels, *Sustained/Expanded Partnership* or *Downscaled/Disbanded Partnership* (Table 2).

Sustained/Expanded Partnerships (13 cases; Table 3) included those cases where the fundamental structure of the agency and its relationships with other groups remained essentially unchanged over time, or was expanded to include additional stakeholders and authority. In most of the cases in this category, these groups experienced fluctuations in funding and modest changes in the composition of their membership, but participation by key stakeholders was sustained. The remaining cases had *Downscaled/Disbanded Partnerships* (3 cases) as the groups that initially achieved ecological improvements were either disbanded or otherwise reduced in scale, thereby limiting stakeholder participation and partnership authority.

3.2.7. Progress to restoration

While all the systems experienced improved ecological condition at one point, the trajectory thereafter is addressed by the theme *Progress to Restoration* with variables of *Goals Achieved*, *Partially Recovered*, and *Declined after Partial Recovery* (Table 2). Management partnerships in one estuary and two lakes achieved their restoration goals, represented by the variable *Goals Achieved* (3 cases; Table 3). Where condition was either continuing to improve (4 cases) or had reached an alternate stable state (4 cases), the system was coded as *Partially Recovered* (8 total cases; Table 3). Cases were defined as *Declined after Partial Recovery* (5 cases; Table 3) when overall ecological condition worsened some time after initial improvements were achieved.

3.3. Multiple correspondence analysis of themes

As with other ordination techniques, such as principal components analysis, the MCA implemented in FactoMineR transformed the variables to permit graphical visualization on a small number of orthogonal axes ("Dimension 1, 2, …n"), revealing relationships among observations and variables. Dimension 1 explained 33.4% of the variation in themes between all cases (Fig. 2). The *Governance, Leadership, Strategy*, and *Actions* management themes contributed significantly ($p < 0.01$) to construction of Dimension 1 (Fig. 2). Dimension 2 explained 21.9% of the variation in themes, with *Governance*, *Actions*, *Antecedents* and *Partnership* each contributing significantly to construction of the dimension (Fig. 2). *Progress to Restoration*, the supplementary theme, plotted similarly with respect to the active themes in both dimensions, with a correlation ratio of 0.41 ($p = 0.03$) in Dimension 1 and 0.43 ($p = 0.02$) in Dimension 2 (Fig. 2).

The correlation of themes with each dimension was determined by the importance of each variable in explaining the variation between cases (Figs. 3 and 4). The relationships among the individual cases, themes, and *Progress to Restoration* are depicted at this level. Restoration progress of *Goals Achieved* is closely associated with governance through *Bottom-Up Collaboration*, an *Ecological Goal* strategy, and *Comprehensive Nutrient Load Reductions*, which were all significant in defining the negative side of Dimension 1 (Figs. 3 and 4a). Leadership by a *Watershed Coordinator* was also significant in Dimension 1 (Fig. 4a), and was closer to *Goals Achieved* in the two-dimensional space than the other variables in the *Progress to Restoration* theme.

Significant variables defining the positive side of Dimension 1 were a *Single Project* strategy, governance by *Command & Control*, leadership by *Multiple Agencies*, and *Point Sources* actions (Figs. 3 and 4a). The *Partially Recovered* and *Declined after Partial Recovery* variables in the *Progress to Restoration* theme both plot on the positive side of Dimension 1 but fall on opposite sides of Dimension 2 (Fig. 3). *Sustained/Expanded Partnership* and *Point Source + Active Restoration* actions are associated with *Partially Recovered* and separate this *Progress to Recovery* variable from *Declined after Partial Recovery*, which is related to *Point Sources* actions and a *Downscaled/Disbanded Partnership*.

Because the *Progress to Restoration* theme was analyzed as a supplementary theme, its variables are plotted in reduced dimensional space (i.e., Fig. 3) based on relationships among the theme variables and not according to the *Progress to Restoration* variables for the systems themselves. The cases generally do plot in close proximity to their *Progress to Restoration*, but with exceptions. The Peel-Harvey Estuary, which *Declined after Partial Recovery,* has theme variables more consistent with *Partially Recovered* systems, such as Venice Lagoon, Nervion River, and Mondego Estuary. This reflects the fact that *Point Source + Active Restoration* measures have been implemented in the Peel-Harvey and that variable is important on the negative side of Dimension 2 (Fig. 4b). Several *Partially Recovered* systems, including Lake Mjøsa, Barton Broad, Lake Apopka, and to a lesser extent Roskilde Fjord, plot relatively near to systems that achieved restoration goals (Tampa Bay, Cobbossee Lake, and Bass Lake) since they share many of the same theme variables associated with *Goals Achieved*.

The jackknife analysis showed that no one case was exceptionally influential, nor was the MCA overall particularly sensitive to the removal of individual cases. When cases were excluded one at a time, the percentage of variance explained in Dimension 1 varied narrowly between 32.3% and 35.5%, and the 7 variables that were significant in constructing the dimension did not change (Table S2). Lake Apopka and Moreton Bay were more influential than other observations, as their removal made additional themes significant ($p < 0.05$) in Dimension 1, and other themes less significant in Dimension 2 (Table S2). Lake Apopka had similar theme variables to cases with a *Progress to Restoration* of *Goals Achieved*, except that its *Antecedent* was *Government Mandate*. With Lake Apopka removed from the analysis, the other systems with a *Government Mandate* had similar theme variables, making *Antecedents* more significant ($p = 0.028$) in defining Dimension 1 than with Lake Apopka included. Likewise, with Moreton Bay removed, all other systems with a *Downscaled/Disbanded Partnership* had the same variables in all themes except *Governance*, thus making *Partnership* slightly significant ($p = 0.043$) in defining Dimension 1, but again, with a lower correlation ratio than other active themes. This suggests that these two cases have an unusual "management profile" compared to the other cases.

Similar results were obtained when looking at variables (Table S3). Given 19 variables and 16 iterations of the analysis, it would be possible for as many as 304 changes to occur on each dimension. Yet, only 9 changes occurred on Dimension 1, 8 of which were for the marginally significant variable *Point Sources*. The positions of all the important variables changed minimally. Only omission of Lake Apopka resulted in more than one change in significance (*Government Mandate* became significant). Visually, the spatial arrangement of the variables on the plane of Dimension 1 and 2 was similar, although axes occasionally changed sign. Such axis reversal, or "reflection" is not uncommon when bootstrapping ordinations (Knox and Peet, 1989).

4. Discussion

4.1. Attributes of successful nutrient management

Our evaluation of nutrient management efforts in 16 lakes and estuaries identified several themes associated with ecological improvements (Fig. 1). Since the case studies were all examples of nutrient management success, even if qualified, the themes are potentially all positive aspects of nutrient management. However, in only 3 of the 16 cases were the established goals fully achieved and sustained (i.e., *Goals Achieved*, Table 3). While it is encouraging that 16 case studies were identified that met our criteria for inclusion in the analysis, the fact that many more were not readily identified points to the sizeable challenge of reducing nutrient pollution and in particular achieving substantial recovery of ecological condition in whole ecosystems following nutrient impacts. We suspect, and even hope, that there are examples that we did not find. If so, the fact that we did not find them also points to a need to better document and communicate successful management programs so that it is possible to learn from and replicate their successes. Among those systems that we did not include, there are nutrient management programs that either prevented loading increases or reduced nutrient loading but have not yet observed measurable ecological improvements.

One conclusion that we draw from our case studies is that it can be difficult to build consensus and take decisive action to recover ecosystems impacted by nutrients. Moreover, initial progress can undermine the strength of a partnership and the overall support for continued action that may be needed to secure or sustain success. The history of the Clean Water Act in the US illustrates this point more broadly. The Act enjoyed such broad public support when it was first passed in 1972 that the US Congress mustered a super-majority to override a presidential veto (President Nixon vetoed the bill because he felt it was too expensive). Obvious problems that demand action are fewer in the US today, however. William Ruckelshaus, the first administrator of the US EPA noted in 2013 that "we don't see the same kinds of visible pollution that we did [in 1972] … we still have problems today; they tend to be more invisible (Public Radio International, 2013)." Thus, more than 40 years after its passage, solving the most egregious problems may be an obstacle to broader attainment of the goals set forth by the Act. Moreover, nutrient pollution may be among those issues most vulnerable to public indifference and back-sliding because, except in crisis situations, eutrophication effects may seem less urgent than environmental problems more directly impacting human health (e.g., toxic contamination or unhealthful air quality), even when the public is aware that a long-term problem is present (Cha and Stow, 2015).

More optimistically, our analysis of case studies showed that progress is possible and that there are a variety of ways to initiate and advance progress toward recovering ecosystems from nutrient impacts. Each of our cases had antecedents, wherein the environmental problems caused by nutrient pollution were recognized and decisions were made that led to action. These took different forms, whether from public awareness of problems or a government mandate to take action, possibly with little public attention. Management partnerships were sometimes temporary and in other cases have been sustained, but in all cases some organization took up the cause of restoration. Governance mechanisms included both regulation-driven "command and control" and more collaborative approaches. Management pursued both ecological goals and water quality goals, such as nutrient loading or concentration targets. In some cases the goal was simply to implement a single set of remedial actions. Common to all the efforts is the fact that remedial actions were taken and nutrient loading was reduced, contributing to ecological improvements.

While approaches varied among our 16 case studies, the variables most associated with the best outcome, or "Goals Achieved" included: (1) Leadership by a dedicated watershed management agency, (2) Governance through a bottom-up collaborative process that empowers local stakeholders to both define the problem and craft plans of action, (3) Comprehensive actions to reduce nutrient loads from all sources; and (4) a strategy that sets a specific ecological goal and derives numeric targets to reach that goal. While far from a universal "blueprint" for management, the findings could be seen as useful recommendations.

Leadership and *Governance* in the cases examined were related, with those partnerships with a *Watershed Coordinator* all employing a form of collaborative governance. Although multiple government, non-government, public-private, and other interest groups all participated in management and restoration for all the cases that were reviewed, a single watershed management agency coordinated the efforts of these groups in the systems that achieved their restoration goals. That leadership by a *Watershed Coordinator* was associated with *Goals Achieved* was an expected result, as much research in collaborative governance in general, and watershed management in particular, has emphasized the importance of having dedicated, effective leadership to guide stakeholders through the collaborative process (Biddle and Koontz, 2014; Greening and Elfring, 2002; Koontz and Newig, 2014; Leach and Pelkey, 2001). Certainly much depends on the leadership abilities of those individuals appointed to head the restoration effort, and other work has explored the characteristics of effective collaborative leadership (e.g. Ansell and Gash, 2008). These studies recommend that watershed partnerships carefully select and adequately fund staff in critical leadership positions (Koontz and Newig, 2014; Leach and Pelkey, 2001).

Collaborative-type approaches to watershed management and restoration have been employed in the US with many variations and under many names since at least the 1970s (e.g. voluntary or cooperative management, integrated catchment management, watershed protection approach; Gordon, 1980; Margerum and Born, 1995; US Environmental Protection Agency, 1991). The Cobbossee Watershed District was one of the pioneers that successfully employed this style of management since its inception in 1971 (Gordon, 1980; US Environmental Protection Agency, 2007). In 1991, the US Environmental Protection Agency formally adopted the watershed protection approach with stakeholder involvement as one of three cornerstones for integrated watershed management. The Agency's Clean Lakes Program (from which many projects in Cobbossee and Bass Lakes were funded) and National Estuary Program (of which Tampa Bay is a member) were the main work-plans for management of lakes and estuaries, and heavily encouraged community-based stakeholder management. Other types of local, cooperative catchment management developed in Australia and in some EU Member States, but with different degrees of government participation and oversight (Benson et al., 2013).

From these programs and precedents, it was not surprising that some form of collaboration would be associated with *Goals Achieved*, but as researchers have noted, collaborative governance can take many forms (Ansell and Gash, 2008; Benson et al., 2013; Koontz and Newig, 2014). In our cases, *Bottom-Up Collaboration*, with consensus-based decision-making at the stakeholder level, was most associated with sustained restoration. However, this particular style of collaborative governance was only employed in our US cases. In Europe, *Command and Control* policies have been more common generally (Benson et al., 2012), and were the style of governance used in most of the European estuaries that achieved a partial recovery (3 of 4). While these approaches have resulted in some degree of success, the EU Water Framework Directive now recognizes the value of public engagement by requiring catchment-scale, cooperative river basin management planning and a public process for stakeholder participation (Benson et al., 2012; Official Journal of the European Communities, 2000). Although not yet fully implemented in all the EU Member States (Benson et al., 2012), partnerships from Roskilde Fjord, Barton Broad, and Lake Mjøsa are currently implementing plans to transition to a more community-based, collaborative form of governance (Danish Nature Agency, 2015; Punchard, 2014; Vassdragsforbundet for Mjøsa med tilløpselver, 2005). In the US, many Federal programs encourage community-based watershed management, but states have broad discretion in responding to Clean Water Act requirements. Thus, in many cases *Command and Control*-style regulatory programs, or state agency-led participatory programs (i.e. *Top-Down Collaboration*) still guide restoration actions, rather than community-based 'bottom-up' management.

Comprehensive actions to reduce nutrient loads from all sources were most likely associated with success because anthropogenic nutrient loading to lakes and estuaries often comes from many sources and source types (e.g., point source, non-point, agriculture, stormwater, atmospheric). Pursuing point source reductions may be a reasonable strategy when regulatory mechanisms can require it and technological solutions are available to implement it. Focusing action on one source type, the 'low hanging fruit,' however may simply change the problem such that continued progress requires broader actions to reduce the remaining sources. Because nutrient loads can increase with growth of population and associated economic activity, comprehensive actions may include anticipating new sources with offsetting reductions to prevent loads from increasing (Greening et al., 2014). A case has been made that comprehensive nutrient management includes managing both N and P in watersheds (Paerl, 2009). However, the issue remains controversial (Moss et al., 2013; Schindler et al., 2008) and we did not formally consider N vs. P vs. dual nutrient management in our evaluation of actions. Examining our case studies, we find that approaches were variable. Tampa Bay met its goals using an N-focused approach (although P was also addressed; Johansson and Lewis, 1992). The agricultural best management practices implemented to reduce loading to Cobbossee Lake reduced both nutrients, also leading to a successful outcome (US Environmental Protection Agency, 2007). On the other hand, continued high N loading to Lake Mjøsa was cited as one of several reasons that water quality problems may be persisting there (Battarbee et al., 2012; Hobæk et al., 2012), while continued P loading in Moreton Bay was considered to have contributed to N-fixing algal blooms there (Bell and Elmetri, 2007; Wulff et al., 2011). Overall, it seems prudent to include a dual nutrient approach in a comprehensive set of actions, especially watersheds linked to estuaries and coastal waters (Paerl, 2009; but see Schindler et al., 2008).

One of the more interesting results of the MCA was that a strategy to meet an ecological goal was more associated with success than management strategies pursuing narrower goals, such implementing specific actions or limiting nutrient loads or concentrations. An ecological goal is prospective because it defines a desired state for the recovered system. Management then seeks progress toward the solution, pursuing whatever means are needed (i.e., adapting), rather than progress against a set of problems identified at the outset (Margerum and Born, 1995). Nonetheless, reduction of the problem to identify key steps can still be useful to focus management effort. Reducing N loading was a key step toward recovering the condition of Tampa Bay, even though seagrass recovery remained the agreed-upon long-term goal. The overall objective helped ensure support for other programs related to the recovery, such as research and implementation of active seagrass restoration (Fonseca et al., 1996), and helped the TBEP communicate effectively to the public about their progress toward the goal (Greening et al., 2014). The idea of using more direct measures related to uses of aquatic systems is not new. Before proposing use of fish indicators to directly assess biotic integrity, Karr (1981) noted that “it is impossible to measure all factors that may impact biotic integrity” and that “much literature on chemical contaminants is of questionable value for setting standards for aquatic organisms.” More recently, Australian management guidelines noted that goals should reflect valued attributes, should be biologically based, and themselves can serve as management end-points (ANZECC, 2000). Still, water quality measures such as dissolved oxygen or chlorophyll-a, and nutrient measures associated with them, are cheaper to monitor and assess and are more broadly applied than system-specific ecological indicators, and therefore remain a major focus for nutrient management in lakes and estuaries (Environmental Protection Agency, 1998, 2009; Queensland Department of Environment and Heritage Protection (2013)). One possible consequence, we suggest, of failing to adopt broad and meaningful ecological goals for lakes and estuaries is a prevalence of “80% solutions,” whereby restoration is incomplete and a significant risk remains of declining ecological condition in the future if stressors or modulating factors (Cloern, 2001) change. Of course adopting goals is only useful if progress toward the goal, or status with respect to the desired state after restoration, is monitored and assessed into the future.

A number of our case studies shared many attributes associated with full achievement of ecological goals, but were as yet only partially recovered (Fig. 3). Additionally, we found that most of these partnerships are in the process of implementing additional measures that further align their management efforts with partnerships that have succeeded. This implies that these ecosystems, which include Barton Broad, Lake Mjøsa, Lake Apopka, and Roskilde Fjord, may be ‘systems to watch,’ in that they may achieve their goals in the future if they sustain and continue to adapt their management programs.

4.2. Conclusions

This study illustrates one way to evaluate nutrient management efforts to understand the “ingredients” associated with success. Over time, documentation of ongoing – and hopefully successful - management efforts will likely increase the number of available case studies. Thus, continued evaluations of management, with respect to achieving and sustaining recovery, as we have done here, could provide more refined recommendations. Our use of ordination on descriptive, categorical variables is a useful systematic alternative to anecdotal analysis and provides a guide to evaluation of the case studies, thereby increasing objectivity. Importantly, the main principles suggested by our analysis were robust, meaning that they did not change substantially with inclusion or exclusion of individual cases. Classification of sites with respect to themes was based principally on published reports from local experts rather than our own analysis. Advantages of this approach include reducing the analytical effort and the potential for error associated with analyzing unfamiliar datasets. With more cases, it may be possible to evaluate more themes and variables. One area of interest to us as scientists is the role of scientific information vs. scientific uncertainty for increasing the success of management. Since one of our key results was that an ecological goal was important, science could help illuminate what goals are possible (Simenstad et al., 2006) or better inform a dialogue with stakeholders regarding how to accurately define and quantify good ecological condition. This in turn would assist stakeholders as they work collaboratively to develop a common understanding of the problem, which often leads to consensus regarding what the restoration goal or goals should be. Reaching consensus regarding the nature of the problem and the goal of restoration appears to be essential and therefore one area where high quality scientific information, communicated effectively, could have a positive impact.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jenvman.2016.11.018.

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Attributes of Successful Actions to Restore Lakes and Estuaries Degraded by Nutrient Pollution

Supplemental Material

The following provides additional detail regarding themes and variables as applied to individual case studies. Themes and variables are defined in the main body of the manuscript (Table 2). Table S1 provides physical characteristics of each of the case studies, while Table S2 and S3 provide detailed results of the jackknife analysis for the multiple correspondence analysis.

1. Antecedents.

1.1. Public Crisis.

Examples include Lake Washington, where Seattle area residents concerned with uncontrolled algae growth and the resulting beach closures, voted in 1958 to establish the Metropolitan Municipality of Seattle for the specific purpose of building a wastewater system to reduce nutrient loading and improve conditions in the lake (Edmondson, 1996; Lane, 1995). In Tampa, citizens demanded a halt to the municipal and industrial pollution linked to nuisance macroalgae smothering Bay area beaches, which led to the 1972 Wilson-Grizzle Act that required advanced wastewater treatment for all WWTPs discharging to Tampa Bay (Lewis et al., 1998; Parsons et al., 2010).

1.2 Government Mandate.

One example was the 1991 government revitalization plan for the City of Bilbao, Spain, which charged the local water and sewer provider with upgrading the water sanitation system to reduce nutrient and bacterial loads to the Nervion River Estuary (Ploger, 2007). Similarly, serious efforts to restore Lake Apopka after decades of basin modifications and wastewater discharges were initiated with the Florida Lake Apopka Restoration Act in 1985 and the subsequent Surface Water Improvement and Management Act in 1987 (Hoge et al., 2003; Lowe et al., 1999).

1.3 Existing Networks.

Examples of groups coming together under government sponsored cost-share initiatives include Moreton Bay, Bass Lake, and Barton Broad (Broads Authority, 2015; Dennison and Abal, 1999; Druckrey, 2008). The international partnership with oversight of pollution in Lake Maggiore had similar origins, but was initiated earlier (1978) when the founding convention was ratified by both the Swiss and Italian governments (CIPAIS, 2010).

2. Leadership.

2.1. Watershed Coordinator.

In Moreton Bay, the largest water body examined, numerous local municipalities and watershed groups were brought together under the umbrella of the South East Queensland Healthy Waterways Partnership. This group coordinated the activities of stakeholders to reduce the N loads from wastewater plants, which were credited with ecological improvements in Moreton Bay (Bricker et al., 2007; Gibbes et al., 2014). Restoration of Bass Lake, the smallest water body examined, was led by the Marinette County Land and Water Conservation Division. This local agency organized the efforts of federal and state agencies and worked directly with individual farmers to complete a series of projects that ultimately resulted in restoration of a healthy fishery in the lake (Druckrey, 2008; Sevener, 2012; US Environmental Protection Agency, 2005; Wisconsin Department of Natural Resources, 2013).

2.2. Multiple Agencies.

In the Boston Harbor example, multiple local agencies and partnerships were actively working on issues of watershed management and restoration (MassBays, 2014; Neponset River Watershed Association, 2004), but the actions implemented by the Massachusetts Water Resources Association to upgrade sewage treatment and relocate sewage outfalls were credited with ecological recovery from nutrient pollution (Taylor et al., 2011; Tucker et al., 2014). Similarly, the sewage system upgrades that improved conditions in the Nervion River Estuary, Kane'ohe Bay, and Lake Washington were implemented by the local sewer utilities under the direction of local government agencies after research groups identified urban and industrial point source discharges as significant contributors to environmental degradation (Borja et al., 2010; Edmondson, 1996; Garcia-Barcina et al., 2006; Ploger, 2007; Smith et al., 1981; Tanimura, 1988). Roskilde Fjord was slightly different from other examples of *Multiple Agencies*, with different government agriculture and water resources agencies charged with administering their respective provisions of the Danish National Action Plans for the Aquatic Environment (Danish Nature Agency, 2015; Global Water Partnership, 2015; Kronvang et al., 2008).

3. Governance.

3.1. Command and Control.

This was the case in Boston Harbor, Nervion River Estuary, Venice Lagoon, and Lake Washington, where the most successful nutrient management actions were government-directed projects to divert or reduce loads from sewage and industrial point sources (Borja et al., 2010; Edmondson, 1996; Facca et al., 2014; Taylor et al., 2011). The large-scale hydromorphological engineering projects completed in the Peel-Harvey and Mondego estuaries were also completed under a *Command and Control* approach as an alternative to reducing nutrient loads to reverse eutrophication (Verissimo et al., 2012; Wildsmith et al., 2009).

3.2. Top-Down Collaboration.

Kane’ohe Bay was one such example, where university researchers and citizens groups provided input to the State of Hawaii’s Kane’ohe Bay Task Force charged with finding solutions to the problem of widespread coral loss resulting from nuisance macroalgae. Based on the recommendation of the task force, government agencies planned and executed the sewage diversion project that was credited with the initial restoration of the bay (Jokiel, 1991; Tanimura, 1988).

Similarly, in Lake Mjøsa, local residents and the scientific community provided the impetus for the 'Save Mjøsa Campaign' initiated by government authorities, with the majority of nutrient mitigation projects completed by local municipalities (Holtan, 1979; Lyche-Solheim et al., 2010).

3.3. Bottom-Up Collaboration.

This approach was more common in lakes (3 of 4) than in estuaries, with restoration of Cobbossee Lake being the earliest example among our cases. The Cobbossee Watershed District was granted broad powers to improve water quality when it was established in 1971, including eminent domain, taxing authority, ability to issue bonds to pay capital expenses, and regulatory authority (Gordon, 1980). However, with agricultural run-off as the primary source of nutrient loading to the watershed, the District found that a voluntary, cooperative approach working directly with local farmers was most effective (Gordon, 1980; US Environmental Protection Agency, 2007). The District created and administered an innovative program to design, fund, and build manure storage facilities by partnering with county soil and water conservation services, university-based agricultural support services, local construction contractors, and multiple Federal and state agencies. The result was that by 1980 farmers had voluntarily implemented best practices for manure storage and handling for 80% of the animal units in the watershed (Gordon, 1980). Using a similar approach, the District successfully targeted additional non-point source pollution from residential properties and public and private roadways.

When combined with other local efforts, these actions ultimately resulted in restoration of the lake (US Environmental Protection Agency, 2007).

The Tampa Bay Estuary Program (TBEP) used a similar bottom-up collaborative model, and was the one estuary employing this form of *Governance* (Table 3). The TBEP has many committees and working groups of local stakeholders working on various monitoring, research, and restoration initiatives, including the Tampa Bay Nitrogen Management Consortium. This group of state, county, and city governments, regional utility providers, and industry concerns in the Tampa Bay area successfully held TN loading rates at 1992 to 1994 levels through voluntary load allocations between members, despite a 40% increase in population in the watershed since the mid-1980s (Greening et al., 2014). This work, as part of the TBEP overall effort in community-based management, was critical to the successful restoration of seagrasses in Tampa Bay (Greening et al., 2014; Tampa Bay Estuary Program, 2015).

4. Strategy.

4.1. Single Project.

Examples include sewage diversion and treatment upgrade projects in Kane'ohe Bay, Boston Harbor, Nervion River Estuary, and Lake Washington (Edmondson, 1996; Ploger, 2007; Smith et al., 1981; Taylor, 2010). Similarly, the hydrological restoration project in the Mondego Estuary intended to reduce symptoms of eutrophication was credited with partial restoration of seagrasses in the south arm of the estuary (Cuhna, 2012; Dolbeth et al., 2007; Verissimo et al., 2012).

4.2. Load/Concentration Targets.

Managing agencies for Bass Lake, Lake Maggiore, and the Peel-Harvey estuary all selected targets for ambient nutrient concentrations from a trophic state index (CIPAIS, 2010; Davis and Rolls, 1987; Western Australia EPA, 1994; Wisconsin Department of Natural Resources, 2013). The Moreton Bay management partnerships implemented a strategy to meet state Water Quality Objectives, which were based on conditions in similar, minimally disturbed water types and adjusted for social, cultural, and economic factors in Moreton Bay (Queensland Department of Environment and Resource Management, 2010). Nutrient management in the Roskilde Fjord was based on Danish national policy with the overall objective of reducing N loads by 50% and P loads by 80% (Riemann et al., 2015).

4.3. Ecological Goal.

In an estuarine example, the TBEP – working collaboratively with stakeholders - established a goal of restoring seagrass areal coverage in Tampa Bay to 95% of that measured from the early 1950s. Through a step-wise process the partnership then derived N loading limits to achieve that goal, specifically: (1) determined light requirements of target species in the Bay, (2) determined water clarity for light penetration to depths required for coverage goal, (3) determined chlorophyll-*a* concentration to maintain water clarity, and finally (4) determined maximum nutrient loading to meet chlorophyll-*a* concentration target (Greening et al., 2014).

Similarly, but on a smaller scale in a lake, the Broads Authority established the goal of achieving a stable, macrophyte-dominated, clear water state in Barton Broad. Using long-term biological and chemical monitoring data in the Broads, the partnership derived a TP target shown to support that desired state (Kelly, 2008).

In a deep lake example, management of of Cobbossee Lake was directed toward meeting the State of Maine's "goal-oriented" water quality standards, which include being "free of culturally induced algae blooms," where nuisance algae blooms are functionally defined as episodic Secchi disk transparencies of < 2 m (Halliwell, 1999). For Cobbossee, state-wide water quality data for similar lakes were used to determine the ambient P concentrations needed to achieve Secchi disk transparency > 2 m, and then an annual P loading limit specific to Cobbossee Lake was set to meet that goal (Halliwell, 1999). Nutrient limits associated with the *Ecological Goal* strategy are differentiated from the *Load/Concentration Targets* strategy because numeric targets are related explicitly to the ecological endpoint, and not determined based on a reference condition.

5. Actions.

5.1. Point Sources.

Point source actions were the primary nutrient management initiatives in the Nervion River, Kane'ohe Bay, Boston Harbor, Lake Maggiore, and Lake Washington (CIPAIS, 2010; Edmondson, 1996; Morabito et al., 2012; Ploger, 2007; Smith et al., 1981; Taylor, 2010).

5.2. Point Sources and Action Restoration.

The Broads Authority implemented a series of projects after first reducing the point source load from an upstream wastewater plant. These actions included suction dredging, wetland restoration, and removal of sediment-disturbing benthivorous fish within fish 'exclosures,' which resulted in increased macrophyte abundance both inside and outside the clear water exclosure areas (Broads Authority, Undated). In an estuarine example, the biomass of nuisance macroalgae and incidence of harmful algal blooms in the Peel-Harvey estuary was greatly reduced after local authorities constructed the Dawesville Channel to increase salinity and reduce the residence time of nutrient-rich waters from the catchment (Western Australia EPA, 2003, 2008). With these interim successes, however, researchers and management agencies in all the cases in this category (Peel-Harvey, Barton Broad, Mondego Estuary, and Venice Lagoon) found that additional actions to reduce diffuse nutrient loads would also be necessary to achieve restoration goals (Broads Authority, 2010; Collavini et al., 2005; Verissimo et al., 2012; Western Australia EPA, 2008).

5.3. Comprehensive Nutrient Load Reductions.

In the case of Roskilde Fjord, nutrient management policies required measures such as upgrades in wastewater treatment, restrictions on manure storage and application, mandatory crop rotation and fertilizer application plans, ammonia protection zones, and funding incentives for reforestation, establishing wetlands, and creating waterside buffers (Dalgaard et al., 2014; Kronvang et al., 2008). In a similarly extensive suite of measures, partnerships restoring Lake Apopka first reduced the nutrient loads from wastewater in the 1970s, then addressed diffuse nutrient inputs from surrounding farms and urban areas (Coveney et al., 2005; Florida Department of Environmental Protection, 2014). These actions included purchasing farmland in the floodplain to restore wetlands, constructing a wetland treatment system, fish removal, littoral zone restoration, street sweeping, and structural stormwater upgrades, all of which resulted in a 75% reduction of the TP load to the lake and partial reestablishment of submerged macrophytes (Coveney et al., 2005; Florida Department of Environmental Protection, 2014; Hoge et al., 2003; St Johns River Water Management District, 2015).

6. Partnership.

6.1. Sustained/Expanded Partnership.

For 5 of 7 cases in the EU, (Roskilde Fjord, Nervion River Estuary, Mondego Estuary, Barton Broad, Lake Mjøsa), implementation of the Water Framework Directive prompted an overhaul of watershed management and many partnerships evolved to comply with new directives. These included establishing new agencies, combining different agencies with similar goals, including more local stakeholders and public participation, and extending oversight to the catchment scale (Basque Water Agency, 2013; Danish Nature Agency, 2015; Portuguese Environment Agency, 2016; Punchard, 2014; Vassdragsforbundet for Mjøsa med tilløpselver, 2005).

6.2. Downscaled/Disbanded.

With the sewage diversion project completed in Kane'ohe Bay, the Kane'ohe Bay Task Force was disbanded and issues of water quality faded from public concern. Later, however, the Hawaii Department of Health, which is responsible for administration of the Clean Water Act in the Bay, launched new initiatives to support local non-profit partnerships engaging in community-based watershed management (Hawaii Department of Health, 2014).

In another case, the South East Queensland Healthy Waterways Partnership in Moreton Bay successfully reduced N loads from wastewater based on their 2001 strategy, and additionally negotiated over 500 actions to improve water quality between its 100+ partners as part of their 2007 strategic plan (South East Queensland Healthy Waterways Partnership, 2007a, b). However, a change in regional government emphasis led to decreased funding (Cottingham, 2010) and a new national program required regional partnerships to bid for funding under a business plan model, which resulted in a major restructuring of the partnership (Benson et al., 2012; Healthy Waterways, 2014). The new Healthy Waterways strategy focuses on four core objectives (monitoring, education, outreach, return on investment) while assisting with grant applications and technical support for restoration actions for some of its 35 members. However, it no longer directly coordinates restoration actions in the watershed (Healthy Waterways, 2014).

7. Progress to Restoration.

7.1. Goals Achieved.

In 2015, the biennial seagrass survey in Tampa Bay found that the areal extent of seagrasses had exceeded the TBEP goal of reaching 95% of the 1950s coverage. This represents a restoration of over 13,000 acres of seagrasses since the TBEP originally established the goal in 1996 (Tampa Bay Estuary Program, 2015). Cobbosse Lake was removed from the USEPA 303(d) list of Impaired Waters in 2006 after meeting state water quality standards of being free of algae blooms induced by cultural eutrophication or non-point source pollution (defined by summer Secchi depths > 2m) and having a stable or improving trophic state (US Environmental Protection Agency, 2007). Bass Lake was determined to be meeting its designated use as a warm water sport fishery and removed from the USEPA 303(d) list of Impaired Waters in 2010 (Sevener, 2012). Electrofishing surveys conducted in 2008 indicated restoration of healthy fish populations (Druckrey, 2008), and Wisconsin DNR assessments in both 2009 and 2014 found the chlorophyll *a* concentrations, Secchi disk transparency, and TP concentrations within the good to excellent range on the state standard TSI (http://dnr.wi.gov/Water/impairedDetail.aspx?key=11866).

7.2. Partially Recovered.

Boston Harbor and Venice Lagoon both experienced slow early responses following diversion or reduction of point source nutrient loads (Lillebø et al., 2011; Taylor et al., 2011). Boston Harbor benthic condition was continuing to improve as of 2014 (Diaz et al., 2008; Tucker et al., 2014) while seagrass coverage was also expanding in Venice Lagoon (Facca et al., 2014). Likewise, a suite of management actions in Barton Broad and Lake Apopka led to increased water clarity and partial restoration of submerged macrophytes (Broads Authority, Undated; Coveney et al., 2005; Phillips et al., 2005; St Johns River Water Management District, 2015).

The other 4 *Partially Recovered* systems appeared to be in an alternate stable state. Years of organic matter deposition under eutrophic conditions in Roskilde Fjord resulted in slurry-like sediments that have not supported full recovery of seagrasses, despite comprehensive nutrient load reductions and extensive efforts to plant seagrasses (Lillebø et al., 2011). Researchers theorize that further nutrient loading reductions may be necessary for restoration (Lillebø et al., 2011; Pedersen et al., 2013). Similarly, even though TP concentrations have reached reference levels in Lake Mjøsa, paleolimnological evidence indicates that current diatom assemblages and sediment chlorophyll *a* are not consistent with the reference state, which investigators suggest results from consistently high N loads and high N:P ratios or climate warming (Battarbee et al., 2012; Hobæk et al., 2012).

7.3. Declined after Partial Recovery.

This was the case for Lake Washington, which was widely heralded as a nutrient management success story in the 1980s and 1990s. In 2008 the Washington State Department of Environmental Protection placed Lake Washington on the state's impaired waters list, citing TP concentrations that exceed State standards (Washington Department of Ecology). The frequency of toxic cyanobacteria blooms also increased after 2007 (Washington Department of Ecology et al.). Likewise, Kane'ohe Bay was cited in 2006 by the Hawaii Department of Health for nutrient-related impairments (Hawaii Department of Health, 2014; US Environmental Protection Agency, 2016), 20 years after the last point source sewage discharge was diverted out of the bay (Hunter, 1995) and a comprehensive evaluation of the response suggested that the system was on a recovery trajectory (Smith et al., 1981). Opening of the Dawesville Channel in 1994 led to improvements in the Peel-Harvey estuarine system, but with nutrient loading still high and increasing (Rivers et al., 2013), benthic condition continued to decline (Wildsmith et al., 2009) and water quality and environmental problems still persisted in the system (Western Australia EPA, 2003, 2008).

Supplementary Tables

Table S1. Physical characteristics of case study sites.

Location	Type	Region	Catchment Area (km^2)	Water Surface Area (km^2)	Catchment to Surface Area Ratio[1]	Mean Depth (m)
Boston Harbor	Coastal Bay Estuary	Temperate	759	125	Small	4.9
Kaneohe Bay	Coastal Bay Estuary	Tropical	97	61	Small	9.5
Mondego Estuary	River-Dominated Estuary	Temperate	6670	3.4	Large	4.0
Moreton Bay	Coastal Bay Estuary	Sub-Tropical	22807	1494	Medium	6.5
Nervion Estuary	River-Dominated Estuary	Temperate	1700	30	Large	7.0
Peel-Harvey Estuary	River-Dominated Estuary	Sub-Tropical	96001	133	Large	1.0
Roskilde Fjord	Fjord-Type Estuary	Temperate	1127	122	Small	3.0
Tampa Bay	Coastal Bay Estuary	Sub-Tropical	5700	1036	Small	4.0
Venice Lagoon	Coastal Bay Estuary	Temperate	1839	550	Small	1.0
Barton Broad	Shallow Lake	Temperate	118	0.77	Large	1.4
Bass Lake	Deep Lake	Temperate	1.83	0.15	Medium	9.1
Cobbosse Lake	Deep Lake	Temperate	340	22.4	Medium	8.1
Lake Apopka	Shallow Lake	Sub-Tropical	480	125	Small	1.7
Lago Maggiore	Deep Lake	Temperate	6600	212	Large	177.4
Lake Mjosa	Deep Lake	Temperate	16568	369	Large	150
Lake Washington	Deep Lake	Temperate	1448	87.6	Medium	32.9

[1] Catchment to Surface Area Ratio: Small = Ratio > 0.1; Medium = Ratio > 0.05 and < 0.1; Large = Ratio < 0.05

Table S2. Correlation and significance of each theme in jackknife analysis. Results for all cases and with each case removed. Themes significant (p<=0.05) in constructing the dimensions are shown in green; themes minimally significant (0.05<p<=0.1) are shown in yellow; other themes not significant. Supplementary theme shown in italics.

Themes in Dimension 1	All Cases	Apopka	Barton	Bass	Boston	Cobbossee	Kaneohe	Maggiore	Mjosa	Mondego	Moreton	Nervion	PeelHarvey	Roskilde	Tampa	Venice	Washington
Governance	**0.836**	**0.855**	**0.889**	**0.845**	**0.824**	**0.810**	**0.955**	**0.819**	**0.852**	**0.764**	**0.776**	**0.796**	**0.839**	**0.839**	**0.810**	**0.816**	**0.869**
Leadership	**0.801**	**0.803**	**0.802**	**0.746**	**0.772**	**0.813**	**0.816**	**0.804**	**0.793**	**0.739**	**0.830**	**0.757**	**0.802**	**0.885**	**0.813**	**0.793**	**0.810**
Strategy	**0.795**	**0.733**	**0.772**	**0.866**	**0.776**	**0.772**	**0.766**	**0.810**	**0.809**	**0.829**	**0.817**	**0.792**	**0.841**	**0.787**	**0.772**	**0.862**	**0.717**
Actions	**0.608**	**0.538**	**0.744**	**0.622**	**0.604**	**0.526**	**0.544**	**0.709**	**0.617**	**0.646**	**0.652**	**0.607**	**0.595**	**0.664**	**0.526**	**0.596**	**0.567**
Antecedents	0.169	**0.448**	0.137	0.065	0.174	0.251	0.242	0.152	0.163	0.102	0.193	0.100	0.183	0.169	0.251	0.151	0.252
Partnership	0.134	0.064	0.097	0.131	0.181	0.113	0.044	0.150	0.137	0.251	**0.280**	0.236	0.153	0.131	0.113	0.174	0.013
Progress to Restoration	**0.409**	**0.461**	**0.467**	**0.407**	**0.432**	0.315	0.338	**0.480**	**0.465**	**0.442**	**0.436**	**0.457**	0.380	**0.418**	0.315	**0.393**	0.382
Themes in Dimension 2	All Cases	Apopka	Barton	Bass	Boston	Cobbossee	Kaneohe	Maggiore	Mjosa	Mondego	Moreton	Nervion	PeelHarvey	Roskilde	Tampa	Venice	Washington
Governance	**0.579**	**0.442**	**0.624**	**0.716**	**0.572**	**0.526**	**0.552**	**0.501**	**0.637**	**0.641**	0.307	**0.540**	**0.573**	**0.661**	**0.526**	**0.621**	**0.649**
Antecedents	**0.567**	0.329	**0.611**	**0.732**	**0.556**	**0.553**	**0.537**	**0.538**	**0.618**	**0.658**	**0.542**	**0.631**	**0.589**	**0.575**	**0.553**	**0.602**	**0.447**
Partnership	**0.440**	**0.599**	**0.425**	**0.325**	**0.462**	**0.486**	**0.389**	**0.595**	**0.422**	**0.295**	**0.412**	**0.381**	**0.411**	**0.428**	**0.486**	**0.313**	**0.570**
Actions	**0.400**	**0.579**	**0.483**	0.285	**0.503**	**0.452**	0.374	0.390	0.373	0.194	**0.563**	**0.575**	0.378	0.384	**0.452**	0.237	**0.458**
Strategy	0.152	0.115	0.243	0.182	0.122	0.131	0.302	0.048	0.134	0.131	0.033	0.077	0.241	0.165	0.131	0.382	0.205
Leadership	0.051	0.021	0.045	0.105	0.057	0.042	0.033	0.046	0.073	0.117	0.021	0.098	0.032	0.069	0.042	0.038	0.019
Progress to Restoration	**0.434**	**0.504**	**0.439**	**0.415**	**0.439**	**0.450**	**0.469**	0.355	**0.457**	0.312	0.276	0.356	**0.604**	**0.460**	**0.450**	**0.393**	**0.502**

Table S3. Coefficients and significance of each variable in jackknife analysis. Results for all cases and with each case removed. Variables significant (p<=0.05) in constructing the dimensions are shown in green; variables minimally significant (0.05<p<=0.1) are shown in yellow; other variables not significant. Variables associated with *Goals Achieved* in dimension 1 remain significant for all analyses. Supplementary variables shown in italics.

Variables in Dimension 1	All Cases	Apopka	Barton	Bass	Boston	Cobbossee	Kaneohe	Maggiore	Mjosa	Mondego	Moreton	Nervion	Peel-Harvey	Roskilde	Tampa	Venice	Washington
Bottom-Up Collaboration	**-0.845**	**0.857**	**0.896**	**0.935**	**-0.853**	**0.841**	**-0.723**	**0.851**	**0.886**	**-0.853**	**-0.817**	**-0.867**	**-0.838**	**0.837**	**0.841**	**-0.836**	**-0.819**
Ecological Goal	**-0.826**	**0.818**	**0.917**	**0.925**	**-0.839**	**0.807**	**-0.800**	**0.834**	**0.856**	**-0.866**	**-0.808**	**-0.855**	**-0.762**	**0.812**	**0.807**	**-0.765**	**-0.794**
Comprehensive NLR	**-0.781**	**0.782**	**0.908**	**0.802**	**-0.780**	**0.737**	**-0.750**	**0.821**	**0.808**	**-0.703**	**-0.794**	**-0.767**	**-0.756**	**0.859**	**0.737**	**-0.738**	**-0.754**
Watershed Coordinator	**-0.668**	**0.680**	**0.680**	**0.639**	**-0.656**	**0.668**	**-0.678**	**0.681**	**0.669**	**-0.642**	**-0.702**	**-0.646**	**-0.677**	**0.718**	**0.668**	**-0.671**	**-0.662**
Established Network	-0.466	0.682	0.434	0.271	-0.413	0.565	-0.502	0.486	0.459	-0.357	-0.567	-0.350	-0.459	0.466	0.565	-0.456	-0.468
Sustained/Expanded Partnership	-0.351	0.240	0.294	0.334	-0.396	0.311	-0.231	0.367	0.347	-0.466	**-0.598**	-0.450	-0.368	0.345	0.311	-0.393	-0.121
Load/Concentration Targets	-0.102	0.114	0.014	-0.064	-0.106	0.130	-0.164	0.081	0.029	-0.111	-0.145	-0.085	-0.200	0.101	0.130	-0.208	-0.100
Top-Down Collaboration	-0.045	0.104	-0.017	-0.039	-0.040	0.065	-0.261	0.000	-0.047	0.016	-0.039	0.019	-0.094	0.045	0.065	-0.074	-0.108
Public Crisis	0.080	0.130	-0.039	0.010	-0.024	-0.229	-0.004	-0.114	-0.147	0.182	0.179	0.181	0.039	-0.099	-0.229	0.118	-0.064
Point Source + Active Restoration	0.290	-0.368	-0.579	-0.297	0.324	-0.266	0.350	-0.192	-0.295	0.071	0.170	0.267	0.257	-0.337	-0.266	0.208	0.418
Downscaled/Disbanded Partnership	0.351	-0.240	-0.294	-0.334	0.396	-0.311	0.231	-0.367	-0.347	0.466	**0.598**	0.450	0.368	-0.345	-0.311	0.393	0.121
Government Mandate	0.385	**-0.812**	-0.395	-0.281	0.436	-0.336	0.506	-0.372	-0.312	0.175	0.388	0.170	0.420	-0.367	-0.336	0.338	0.531
Point Sources	**0.490**	-0.414	-0.329	**-0.505**	0.456	-0.471	0.400	**-0.629**	**-0.514**	**0.632**	**0.624**	**0.500**	**0.499**	**-0.522**	-0.471	**0.530**	0.336
Multiple Agencies	**0.668**	**-0.680**	**-0.680**	**-0.639**	**0.656**	**-0.668**	**0.678**	**-0.681**	**-0.669**	**0.642**	**0.702**	**0.646**	**0.677**	**-0.718**	**-0.668**	**0.671**	**0.662**
Command & Control	**0.891**	**-0.960**	**-0.880**	**-0.895**	**0.892**	**-0.906**	**0.984**	**-0.851**	**-0.839**	**0.836**	**0.856**	**0.848**	**0.932**	**-0.882**	**-0.906**	**0.910**	**0.927**
Single Project	**0.928**	**-0.931**	**-0.931**	**-0.861**	**0.945**	**-0.937**	**0.964**	**-0.915**	**-0.885**	**0.977**	**0.953**	**0.941**	**0.962**	**-0.914**	**-0.937**	**0.973**	**0.894**
Goals Achieved	**-0.814**	**0.854**	**0.865**	**0.909**	**-0.796**	**0.807**	**-0.730**	**0.866**	**0.851**	**-0.779**	**-0.837**	**-0.791**	**-0.784**	**0.818**	**0.807**	**-0.770**	**-0.746**
Partially Recovered	0.286	-0.452	-0.375	-0.304	0.229	-0.289	0.345	-0.210	-0.329	0.161	0.198	0.170	0.291	-0.305	-0.289	0.231	0.407
Declined after Partial Recovery	0.528	-0.402	-0.490	-0.604	0.568	-0.518	0.385	-0.656	-0.522	0.618	0.639	0.620	0.493	-0.513	-0.518	0.539	0.340

Table S3. (Continued)

Variables in Dimension 2	All Cases	Apopka	Barton	Bass	Boston	Cobbossee	Kaneohe	Maggiore	Mjosa	Mondego	Moreton	Nervion	Peel-Harvey	Roskilde	Tampa	Venice	Washington
Government Mandate	**-0.668**	-0.533	**-0.719**	**-0.732**	**-0.663**	**0.673**	-0.525	**-0.676**	**-0.646**	**0.674**	**-0.580**	**0.785**	**0.689**	**-0.639**	**0.673**	**0.705**	**-0.559**
Sustained/Expanded Partnership	**-0.513**	**-0.570**	**-0.519**	**-0.445**	**-0.523**	**0.527**	**-0.554**	**-0.573**	**-0.498**	**0.396**	**-0.528**	**0.478**	**0.488**	**-0.505**	**0.527**	**0.422**	**-0.695**
Point Source + Active Restoration	-0.400	**-0.446**	-0.541	-0.274	-0.473	0.431	-0.225	-0.471	-0.331	0.264	**-0.611**	**0.567**	0.433	-0.324	0.431	0.252	-0.339
Bottom-Up Collaboration	-0.332	-0.347	-0.385	-0.447	-0.277	0.354	**-0.492**	-0.218	-0.331	0.257	-0.022	0.193	0.332	-0.386	0.354	0.380	-0.409
Ecological Goal	-0.307	-0.333	-0.467	-0.255	-0.284	0.339	-0.391	-0.184	-0.257	0.237	-0.045	0.220	0.361	-0.310	0.339	0.384	-0.387
Command & Control	-0.303	-0.198	-0.329	-0.286	-0.353	0.251	-0.132	-0.362	-0.359	**0.371**	-0.353	**0.408**	0.296	-0.326	0.251	0.270	-0.278
Multiple Agencies	-0.136	-0.085	-0.135	-0.203	-0.147	0.123	-0.109	-0.127	-0.166	0.200	-0.082	0.194	0.108	-0.162	0.123	0.118	-0.086
Comprehensive NLR	-0.124	-0.155	-0.065	-0.181	-0.137	0.107	-0.292	-0.017	-0.178	0.094	0.153	0.068	0.085	-0.197	0.107	0.156	-0.263
Single Project	0.026	0.181	0.096	-0.106	0.047	-0.094	-0.012	0.044	-0.033	0.026	0.139	-0.024	0.017	-0.002	-0.094	0.114	0.086
Public Crisis	0.055	0.067	-0.033	-0.116	0.079	-0.161	-0.132	0.144	-0.027	0.034	**0.391**	-0.119	-0.125	-0.004	-0.161	-0.025	-0.027
Watershed Coordinator	0.136	0.085	0.135	0.203	0.147	-0.123	0.109	0.127	0.166	-0.200	0.082	-0.194	-0.108	0.162	-0.123	-0.118	0.086
Load/Concentration Targets	0.282	0.153	0.371	0.360	0.238	-0.245	0.403	0.140	0.291	-0.262	-0.093	-0.196	-0.378	0.312	-0.245	**-0.498**	0.300
Downscaled/Disbanded Partnership	**0.513**	**0.570**	**0.519**	**0.445**	**0.523**	**-0.527**	**0.554**	**0.573**	**0.498**	**-0.396**	**0.528**	**-0.478**	**-0.488**	**0.505**	**-0.527**	**-0.422**	**0.695**
Point Sources	**0.524**	**0.602**	**0.607**	**0.455**	**0.610**	**-0.538**	**0.516**	**0.488**	**0.509**	-0.357	**0.459**	**-0.634**	**-0.518**	**0.520**	**-0.538**	-0.408	**0.602**
Established Network	**0.613**	0.466	**0.751**	**0.847**	**0.583**	-0.512	**0.656**	0.533	**0.673**	**-0.707**	0.189	**-0.666**	**-0.565**	**0.642**	-0.512	**-0.680**	**0.585**
Top-Down Collaboration	**0.635**	**0.545**	**0.714**	**0.733**	**0.629**	**-0.605**	**0.625**	**0.579**	**0.690**	**-0.628**	0.374	**-0.601**	**-0.628**	**0.712**	**-0.605**	**-0.650**	**0.687**
Partially Recovered	-0.299	-0.215	-0.320	-0.197	-0.330	**0.316**	-0.207	-0.336	-0.339	0.256	-0.353	0.344	**0.371**	-0.309	**0.316**	0.243	-0.264
Goals Achieved	-0.270	-0.393	-0.269	-0.406	-0.231	0.241	-0.437	-0.162	-0.229	0.195	0.023	0.140	0.337	-0.278	0.241	0.299	-0.422
Declined after Partial Recovery	**0.568**	**0.608**	**0.589**	**0.603**	**0.561**	**-0.557**	**0.644**	**0.497**	**0.569**	**-0.451**	0.330	**-0.484**	**-0.708**	**0.587**	**-0.557**	**-0.543**	**0.686**

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