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REVIEW ARTICLE

Integrated watershed management: evolution, development and emerging trends

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Abstract Watershed management is an ever-evolving practice involving the management of land, water, biota, and other resources in a defined area for ecological, social, and economic purposes. In this paper, we explore the following questions: How has watershed management evolved? What new tools are available and how can they be integrated into sustainable watershed management? To address these questions, we discuss the process of developing integrated watershed management strategies for sustainable management through the incorporation of adaptive management techniques and traditional ecological knowledge. We address the numerous benefits from integration across disciplines and jurisdictional boundaries, as well as the incorporation of technological advancements, such as remote sensing, GIS, big data, and multi-level social-ecological systems analysis, into watershed management strategies. We use three case studies from China, Europe, and Canada to review the success and failure of integrated watershed management in addressing different ecological, social, and economic dilemmas in geographically diverse locations. Although progress has been made in watershed management strategies, there are still numerous issues impeding successful management outcomes; many of which can be remedied through holistic management approaches, incorporation of cutting-edge science and technology, and cross-jurisdictional coordination. We conclude by highlighting that future watershed management will need to account for climate change impacts by employing technological advancements and holistic, cross-disciplinary approaches to ensure watersheds continue to serve their ecological, social, and economic functions. We present three case studies in this paper as a valuable resource for scientists, resource managers, government agencies, and other stakeholders aiming to improve integrated watershed management strategies and more efficiently and successfully achieve ecological and socio-economic management objectives.

Keywords Adaptive management · Climate change impacts · Social-ecological systems analysis · Traditional ecological knowledge · Watershed management

Introduction

A watershed is a topographically delineated area that is drained by a stream system—it is the total area above some point on a stream or river that drains past that point. A

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watershed is also a hydrological response unit, a biophysical unit, and a holistic ecosystem in terms of the materials, energy, and information that flow through it. Therefore, as well as being a useful unit for physical analyses, it can also be a suitable socioeconomic-political unit for management planning and implementation. Watersheds can vary in size from thousands of square kilometres to a small area drained by a freshet.

Watershed management is the process of organizing and guiding land, water, and other natural resources used in a watershed to provide the appropriate goods and services while mitigating the impact on the soil and watershed resources. It involves socio-economic, human-institutional, and biophysical inter-relationships among soil, water, and land use and the connection between upland and downstream areas (Ffolliott et al. 2002). In essence, it is resource management with the watershed as the basic organizing unit.

The concept of watershed management dates back to 2000 BC (Zheng 2004; Chen 2007), and it has continuously evolved and improved over time. Watershed management can broadly be defined as "the study of the relevant characteristics of a watershed aimed at the sustainable distribution of its resources and the process of creating and implementing plans, programs, and projects to sustain and enhance watershed function that affect the plant, animal, and human communities within a watershed boundary" (California Department of Conservation 2015). Through the evolution of watershed management, the practice of integrated watershed management has now become more prominent. Integrated watershed management builds upon the foundational principles of watershed management to integrate various social, technical, and institutional dimensions, as well as conservation, social, and economic objectives (German et al. 2007). This integration generates "An adaptive, comprehensive, integrated multi-resource management planning process that seeks to balance healthy ecological, economic, and cultural/social conditions within a watershed. It serves to integrate planning for land and water; it takes into account both ground and surface water flow, recognizing and planning for the interaction of water, plants, animals, and human land use found within the physical boundaries of a watershed" (Red Deer River Watershed Alliance 2015).

The integrated watershed management approach exemplifies the importance of looking at multiple uses of watershed resources, rather than simply the hydrology. It attempts to balance human and environmental needs, while simultaneously guarding ecosystem services and biodiversity (Bakker 2012). Managing watersheds in this manner allows the needs of society and the environment to be accounted for, even with increasing population pressures and demand for higher productivity and multiple uses of forests and related landscapes (Dortignac 1967). For the purpose of this paper, we define integrated watershed management as an adaptive, integrated, and multidisciplinary systems approach to management that aims to preserve productivity and ecosystem integrity regarding the water, soil, plants, and animals within a watershed, thereby protecting and restoring ecosystem services for environmental, social, and economic benefit.

Improvements to this integrative approach over the last few decades are largely accredited to the rapid development of computer science and geo-spatial technology. The integration of remote sensing imagery, geographical information systems, global positioning systems, meta-analysis approaches, and computer simulation models, as well as access to large databases have provided explicit interfaces for decision makers, communities, public interest groups, and other stakeholders to interact with each other. The development of the democratic process, as well as public participatory and outreach programs integrated with web-based technologies, have improved watershed management quality and led to sustainable watershed management.

This paper focuses on the development of watershed management, potential uses of new technologies, current issues, and the future direction of watershed management and research. It also examines three case studies from China, Europe, and Canada to evaluate their major management issues and the strategies and technologies used to overcome them.

Evolution of watershed management

The concept of watershed management has existed for millennia. The Atharva Veda text from 800 BC contains what may well be the first written reference to watershed management. Atharva Veda verse 19, 2.1 states that: "one should take proper managerial action to use and conserve water from mountains, wells, rivers and also rainwater for use in drinking, agriculture, industries" (Chandra 1990). In the West, Benjamin Franklin recognized the need for watershed management as early as 1790. However, watershed management as a holistic concept was not defined until the mid-20th century.

By the late twentieth century, population growth in many areas was resulting in increasing constraints on the availability of land, water, and other natural resources. Scarcity of fresh water supply, contamination of agricultural land, and polluted streams were affecting millions of lives. Currently, almost half of the countries in the world have low to very low fresh water availability. The importance of watershed mismanagement can be illustrated by the history of the Aral Sea Basin (Aladin and Potts 1992;

Glantz 1999; Cai et al. 2002). Stream diversions for cotton cultivation starting in the 1950s hindered the ability of the world's fourth largest lake to keep up with the 33–36 km^3 of annual water loss through evaporation. The result has been the progressive shrinkage of the Aral Sea, with a 74 % decrease in area and 90 % decrease in volume, isolation of coastal villages, destruction of local economies, extinction of 20 fish species, and a 30- to 60-fold increase in human kidney, liver, arthritic, and bronchial diseases (Jensen et al. 1997; Nearly 2000; Small et al. 2001; Micklin 2007). This situation increased recognition of the significance of and need for a holistic, ecosystem-based, multiple-use approach to land stewardship.

Watershed management has evolved from a focus on water resource management and the hydrological cycle to the current integrated approach of managing the biological, physical, and social elements in a landscape within a watershed's boundaries (Ffolliott et al. 2002). A strong global consensus is emerging around the notion that watersheds are the best units for the management of not only water resources, but also ecosystems in general (Montgomery et al. 1995). The World Bank uses watershed management assessment approaches as the key to identifying the linkages between landscape improvements, productivity increases, and attainment of true natural resource sustainability. Their approach to watershed management extends well beyond hydrological considerations—it aims to utilize the land and resources within a watershed to obtain the desired goods and services without harming the soil and water, while recognizing the links between upstream and downstream areas (Nearly 2000). Brooks et al. (2013) adopted a similar definition that emphasized that by having a good perspective of how a watershed functions and a clear understanding of the linkages between the uplands and downstream areas, a watershed manager should be able to design long-term, sustainable solutions to human natural resource problems, and avoid disasters that can cause human suffering due to lack of water or water pollution (Nearly 2000).

These ideas have been expanded in studies of the nature of the relationships between human health and the sustainability of natural ecosystems, particularly as they relate to watersheds (Gleick 2000). However, watershed management for human health and well-being requires the ability to move beyond typical reductionist approaches towards more holistic methods (Bunch et al. 2014). Understanding these complex relationships has required the development of interdisciplinary studies of catchments to resolve complex problems (Rapport et al. 1998) with an emphasis on the links between land-use change and hydrological systems, ecosystems and human health, as well as scientific and political aspects of watershed management (Bakker 2012) and how these all relate to socio-economic development (Witten et al. 2000). Such ideologies and relationships can be extended to an examination of the links between natural resource management, rural and community development, and public and environmental health (Parkes and Panelli 2001).

In summary, integrated watershed management is the process of creating and implementing plans, programs, and projects to sustain and enhance watershed functions that provide the goods, services, and values desired by the community affected by conditions within a watershed boundary. The management is integrated and complex, including components inside (e.g., upstream, midstream, downstream) and outside the watershed, affecting both man-made and natural factors.

Concepts of watershed management

Many countries are now trying to place watershed management within the context of natural and human systems (Bunch et al. 2014; Sanchez et al. 2014). The World Bank and the United Nations Food and Agriculture Organization (FAO), amongst others, use watershed management approaches to assess the environmental benefits of development projects and aim to improve the provision of goods and services from watersheds including agriculture, forestry, and fisheries in a sustainable manner (Kumar et al. 2014; Sha et al. 2014). Components of watersheds such as low-lying lakes can serve as indicators for overall ecosystem health and change as they aggregate materials from the water and air (Hampton 2013) and thus are an appropriate means to assess the larger system. Watershed management recognizes that people are affected by the interaction of water with other resources and that people can influence the nature and magnitude of those interactions (Manuelli et al. 2014).

Watersheds for sustainable resource management

Watersheds are natural environmental and land management units that determine the health of a nation. Poor ecosystem management within watersheds has and will result in the impaired functioning of the watershed, which in fragile environments can lead to ecosystem collapse (Eswaran and Samra 1997). Watershed management has moved from a focus on physical water and soil utilization and conservation to the integration of social, economic, and environmental development.

As part of these changes, traditional watershed management must shift its conventional focus away from wildlands to include the urban fringe and urbanized areas if it is to satisfy society's needs (Nearly 2000). Watershed management must also be capable of providing solutions to watershed problems such as plans for water augmentation or watershed restoration. That being said, watershed management can be difficult to regulate; while regulations can prevent people from undertaking harmful actions, the regulations often provide no incentive for people to take beneficial actions. As such, watershed management requires the application of the three “Ps”: planning, partnership, and participation by stakeholders (Blomquist and Schlager 2005). Public–private partnerships (PPPs) are becoming a more prevalent way to improve management success; PPPs join these two sectors to work towards a common goal and enables each to benefit from the other’s strengths and resources to more effectively meet management objectives (PPPIRC 2016).

Additionally, watershed management relies heavily on the science of watershed (forest/range/wildland/land use) hydrology, a branch of hydrology that addresses the effects of vegetation and land management on water quality, erosion, and sedimentation. Embedded in both watershed hydrology and management is the acknowledgment of the linkages between upstream and downstream areas and interrelationships among land use, soil, and water. With the increasing awareness that land management decisions cannot be made in isolation, the principles of watershed management are being used as the basis for many environmental and natural resource management decisions (Hebin and Ueta 2012; Karcher et al. 2013).

Means of achieving sustainable watershed management

Integrated watershed management grapples with the complexity of interactions between ecosystems and socio-economic systems, and aims to restore and sustain the health, productivity, and biodiversity of ecosystems through strategies that integrate the needs of society and the economy (Szaro et al. 1998; Einar 2010; Qi and Altinakar 2013). The concept of integrated watershed management is fairly easy to envisage, but the practice of integration is complicated. It is a dynamic process that crosses temporal-spatial spectra, jurisdictional boundaries, and social, cultural, economic, and environmental systems. In order to succeed, it must be participatory, adaptive, and experimental, involve all pertinent stakeholders, identify an appropriate balance between development and protection, and integrate all relevant scientific knowledge and user-supplied information about the social, economic, and environmental processes affecting natural resources within the watershed (Calder 1999; Yang et al. 2006; VanHouten 2014). Additionally, effective integration is largely dependent on current regional development levels and the aims of future development (Thorburn 2012; Mutekanga et al. 2013; Ozturk et al. 2013). Through monitoring of and research on ecological and socio-economic interactions and processes, integrated watershed management can remain adaptable and help to develop strategies to sustain ecosystem composition, structure, and function through policies, protocols, and practices that are based on sound research.

Adaptive management (AM) can be coupled with integrated management and can improve the ability to cope with the inherent uncertainties of managing complex, dynamic systems such as watersheds by learning from the outcomes of management implementation and adjusting future approaches accordingly (Allan et al. 2008; Porzecanski et al. 2012). For AM to be successful, it requires set timeframes for management evaluation where failures and inadequacies can be openly discussed and dealt with. Management strategies need to be continuously improved by learning from the implemented policies and remaining flexible (Raadgever et al. 2008). This requires financial support as well as the dedication of time and resolution of those involved to critically and objectively evaluate their own work (Allan et al. 2008). Without the dedication and means to identify mistakes and rectify them, AM will not be successful.

The use of Traditional Ecological Knowledge (TEK) is also a key component in successful watershed management and can be incorporated into adaptive and integrated management techniques. It is the accumulation of knowledge, experience, and values regarding the local ecosystem held by communities with a history of subsistence living that addresses the interactions among and between organisms (including humans) and their environment (Berkes et al. 2000; Olsson and Folke 2001; Ellis 2005). Traditional knowledge approaches are holistic and adaptive by nature, acknowledge ever changing environmental conditions, and are often derived with the purpose of maintaining ecosystem structure and function while providing resources to the local community—a goal similar to those of today’s watershed management strategies. There are several components of TEK that may be complementary to adaptive management techniques, such as management regulations that are locally developed and enforced by the users; the flexible use of resources through rotations; innate flexibility within the approach of decision-makers to respond to environmental feedbacks; the use of an array of resources to minimize environmental risk; and the use of qualitative measurements to evaluate the direction of future management strategies (Berkes et al. 2000). However, there are several barriers to the successful incorporation of TEK into modern management strategies. These include conceptual barriers due to differing values, communication barriers arising from different languages, and political barriers resulting from the unwillingness to acknowledge traditional knowledge that opposes political or industry agendas

(Ellis 2005). For instance, certain traditional practices may be preferentially selected because they conform more to Western-style governance and values. To integrate TEK in watershed management more successfully, there needs to be a shift from forcing selected elements of traditional practices into conventional strategies to making current methods more malleable so that they may be integrated with TEK.

In general, the watershed management process has 6 steps (Fig. 1): (1) Survey the status of the watershed and identify its situation; (2) identify stakeholders; (3) identify interests and objectives; (4) determine the target and plan; (5) implement the plan; and (6) evaluate management success and failures, reassess objectives, and adjust the plan to improve management success. In the first step, the implementing agency, whether it is private, governmental, academic, etc., needs to survey indicators of ecosystem health to evaluate ecosystem function, such as physico-chemical (e.g., pH, water temperature, concentration of nutrients), biological (e.g., flora and fauna biodiversity, algal growth), habitat (e.g., riparian habitat species composition, degree of bank erosion), and water flow indicators (e.g., peak flow, base flow) (Queensland Government 2016). This step will help identify any ecological issues and trends, which will help inform the decision-making and planning process. Next, stakeholders need to be identified; this includes communities, people, and organizations that have an interest in the watershed and who will be influenced by management decisions and outcomes. The third step is to identify stakeholders' interests and management objectives. This information can be obtained through surveying and engagement with stakeholders and from the initial ecosystem surveys. The next step is to determine the management target and plan based on the information gathered during the ecological survey and the concerns and needs of stakeholders. For the fifth step, the management plan needs to be implemented by the responsible agency; they should oversee implementation, monitoring, and enforcement of management strategies. Lastly, throughout the life of the management plan, the implementing agency needs to assess and improve their management plan to account for changes in the environment and stakeholder needs and address management activities that are insufficiently meeting management objectives. This self-assessment and evaluation involves reflection and evaluation of the effectiveness of the management plan in meeting its objectives; development of solutions to improve management in areas where objectives are not being met; identification of new social or ecological issues related to the watershed; adjustment of management objectives where needed to more effectively meet existing and new management issues; and redevelopment of the management action plan to reflect the new and improved objectives that account for lessons learned in the self-assessment of management success. Developing site-specific management plans based on these generalized steps can lead to watershed management strategies that achieve the goals of sustainability in relation to land resource use, the ecosystem, the ecological economy, and human health and well-being.

In summary, watershed management provides a framework to integrate decision-making to help assess the nature and status of the watershed; identify watershed issues; define and re-evaluate short- and long-term objectives, actions and goals; assess benefits and costs; and implement and evaluate actions. Sustainable utilization and management of resources and the environment is the key to watershed management (Wagner et al. 2002; Sungjun 2007; Davenport and Seekamp 2013). Additionally, an equitable partnership between stakeholders is a crucial component to watershed management (Davenport and Seekamp 2013; Mutekanga et al. 2013; Manuelli et al. 2014). Now, sustainable watershed management has become a common process, and sustainability guidelines on watershed management are available for industrialized, newly industrialized, and developing countries to generate better, more locally specific, watershed management strategies.

Technologies and tools for management of watersheds

One of the underlying principles of watershed management is the recognition of the interrelationships among land use, soil, and water, and the linkages between upland and downstream areas. Physical changes in a watershed can result in a variety of responses ranging from short-term events, such as flooding, landslides, and point-source pollution, to long-term processes, such as soil degradation, water depletion, and non-point-source pollution. The development and assessment of watershed management, therefore, requires the integration of a vast array of spatial information and temporal data.

Remote sensing

Remote sensing (RS) technology utilizes electromagnetic radiation reflected or emitted from Earth's surface to derive information and images about Earth's land and water surfaces (Campbell 2002; Brooks et al. 2013). This accurate and real time data source provides a means of surveying, identifying, classifying, and monitoring various components within a watershed, such as land use/cover, physiography, soil distribution, and drainage characteristics (Singh and Woolhiser 2002; Pandey et al. 2007), as well as

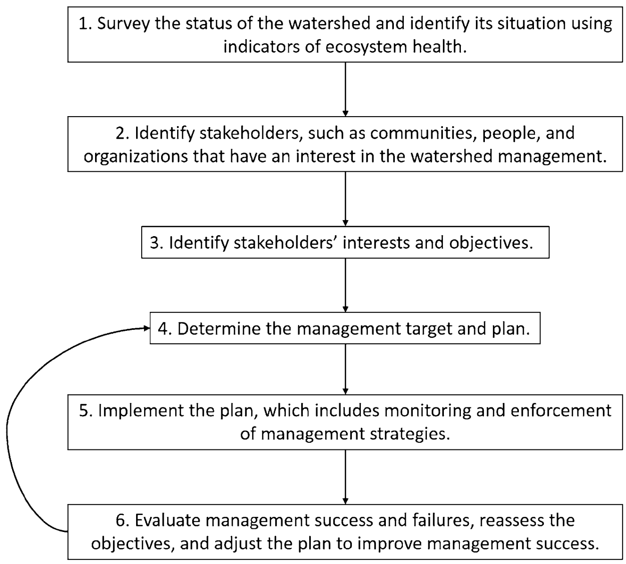

Fig. 1 Conceptual model for developing an integrated watershed management plan

lake temperature, water level, and algal dynamics (Hampton 2013). RS can be used alone or in combination with geographic information systems (GIS) to provide spatial input data for watershed management models. This is especially useful for remote, inaccessible areas within a watershed (Pandey et al. 2007). Additionally, utilizing RS as model input data can generate real-time information, such as seasonal snow melt, evolution of watershed management strategies for conservation planning, environmental impact assessments of water resource projects, flood damage and drought assessments, and many others (Singh and Woolhiser 2002). This technology can also assist policy makers to produce watershed management plans efficiently through the development of alternative management scenarios (Pandey et al. 2007). Overall, using remotely sensed data such as satellite imagery enables analysis across a broader spatial extent than could otherwise be achieved using in situ data alone. However, it is not a replacement for in situ measurements, as RS cannot (so far) provide the necessary detailed species data, and the relationship between satellite-derived and in situ data still requires further investigation (Hampton 2013).

Geographic information systems

GIS are a critical tool for watershed management, as they can be used to assess watershed conditions through modelling impacts of human activities, as well as to visualize the impacts of alternative management scenarios. These modelling and visualization capabilities are fundamental tools to understand the processes and dynamics that shape the physical, biological, and chemical environment of watersheds (Singh and Woolhiser 2002; Tim and Mallavaram 2003). Incorporating GIS into hydrological simulation models generates more spatial detail that most other hydrological models and leads to the ability to analyse combinations of slope, aspect, and hydrological-response units in the simulation (Brooks et al. 2013). As well, GIS enables the watershed to be subdivided into more discrete units vertically and horizontally, which enhances the resultant model outputs (Singh and Woolhiser 2002). GIS coupled with the Internet's increased accessibility of data and information have provided a means of overcoming the limitations of computer-based models regarding data preparation and visualization (Choi et al. 2005). There are some publicly available tools utilizing GIS such as the understanding your watershed program created by the institute of water research of Michigan State University. This tool is a web-based mapping program that can be applied to any watershed within the state (Shi et al. 2004; Michigan State University 2014). GIS's high-quality outputs, easy updating capabilities, and potential for testing management options make it a useful tool for providing management information to decision-makers (Pandey et al. 2007).

Global positioning system

The Global Positioning System (GPS) is a freely accessible space-based global-navigational system that provides users with their precise location and time for almost anywhere on Earth (Brooks et al. 2013). The precision of data can be increased by using GPS to track the exact location of gauges, monitoring devices, study plots, etc. This information can be incorporated into database management systems or GIS to improve data quality and accuracy (Brooks et al. 2013). GPS combined with radio-tracking has proved invaluable for tracking the movement of animals, birds, and fish within watersheds, enabling detailed studies to be made of where and when particular habitats are being used.

Internet

Several government organizations, institutions, and universities have made tools, data, and educational information regarding watersheds easily accessible through the Internet. The US environmental protection agency (EPA) website (EPA 2013) has abundant information that can be used for managing watersheds or organising stakeholders on a watershed basis. They also have numerous online tools to address all stages of watershed management and planning including education and outreach tools, data collection and technical tools, resources for mapping and accessing data and models, as well as planning and management tools (EPA 2015a). Additionally, the EPA offers training for all the tools they offer (EPA 2015b) and Online Training in Watershed Management that consists of a variety of self-paced training modules for a basic to broad introduction to the field of watershed management (EPA 2015c). The Institute of Water Research offers the watershed comprehensive assessment tool (Institute of Water Research 2014), making it easy and accessible to understand the current conditions of a watershed of interest, even for those with little experience in running models and analyzing data related to watersheds. All the major components for watershed management are now offered online, which should facilitate well developed watershed management strategies.

Big data

Big data is a popular term used to describe the exponential growth and availability of data, both structured and unstructured; it has five basic characteristics: volume, velocity, variety, variability, and complexity (Davenport and Dyché 2013; SAS 2014). Big data is beneficial as it can dramatically reduce the cost and time dedicated to computing tasks (Davenport and Dyché 2013). Large volumes of data can provide more accurate analyses that may lead to more confident and well-informed decision-making, subsequently facilitating greater operational efficiencies, cost reductions, and reduced risk. Time should be devoted to collecting detailed data that can be used to model and test alternative management scenarios of watersheds. This is not only important locally for the watershed of interest, but it is globally important that watersheds be managed sustainably and to the best of our abilities (Gizjen 2013). Data mining is a commonly used technique to make sense of big data. It uses pattern recognition technology with statistical and mathematical techniques to sift through large repositories of data to discover new correlations, patterns, and trends, as well as classify and cluster information into groups (Loucks et al. 2005; Larose 2014).

Meta-analysis

Meta-analysis is a statistical technique for integrating quantitative findings from several studies and distilling them into broad conclusions (Joshi et al. 2005; Locatelli and Vignola 2009). Using this approach, one can collate studies that may themselves be inconclusive and generate a statistically conclusive synthesis. Although it is not a common approach for evaluating hydrology, an analysis of its usefulness indicates that it is a promising approach for integrating results from several studies (Locatelli and Vignola 2009). This comprehensive amalgamation of information can be beneficial for policy and decision-makers who are dealing with an abundance of information, often undertaken as individual studies and reviews and some of which may be conflicting. However, for meta-analysis to be successful, there needs to be sufficient data and research available to synthesize, which may be a limiting factor when using this technique for certain elements of watersheds.

Multi-level social-ecological system analysis

There have been several advances in analytical models for watershed management. These include: system dynamic modelling, watershed simulation modelling, watershed decision-making systems, stakeholder analysis modelling, and so on (e.g., Westervelt 2001; Anil et al. 2003; Davenport and Seekamp 2013; Mutekanga et al. 2013; Qi and Altinakar 2013). Additionally, watershed management models embrace the rapid advances occurring in remote sensing and satellite technology, GIS, database management systems, error analysis, risk and reliability analysis, and expert systems (Singh and Frevert 2006).

System dynamic (SD) modelling was first introduced by Forrester (1961) and is a concept based on systems thinking whereby dynamic interactions between the elements of the system are considered to reflect the behaviour of the system as a whole. As the name suggests, the behaviour of the system is monitored over time and is thus dynamic. The main idea of SD modelling is to understand the behaviour of the system by the use of simple mathematical structures. According to Anil et al. (2003), SD concepts can help describe the system; understand the system; develop quantitative and qualitative models; identify how information feedback governs the behaviour of the system; and develop control polices for better management of the system. This type of analysis is crucial for watershed management issues as a variety of components are interrelated with each other leading to complicated systems that are dynamic, interactive, and uncertain (Qi and Altinakar 2013).

Watershed simulation modelling, or hydrologic simulation, is a useful tool to achieve optimal management strategies that balance several benefits of land and water resources in a watershed. This is done through the analysis of watershed processes and their interactions and the development and assessment of management scenarios (He 2003) that simultaneously consider upstream soil conservation, midstream land use, and downstream reservoir level sediment control (Lee et al. 2013; Qi and Altinakar 2013). These models simulate the dynamic behaviour of flow and storage processes and generate water balance information (quantity and associated hydraulic characteristics, source and pathway, residence time, etc.) for past, present, and future streamflow regimes (Brooks et al. 2013). Simulation modelling for watershed management allows users to generate models that are site-specific and tailored to the characteristics of the environment and anticipated changes or management strategies that will be applied over time (Westervelt 2001; Brooks et al. 2013). This makes them more useful for managers than model results published in previous research, which provide insight and information into watershed dynamics, but may not be relevant outside the context of the watershed in which those research models were run (Westervelt 2001). These types of models often need to be combined with GIS or remote sensing technologies to develop input parameters and to analyse and visualize simulation results (He 2003).

Recently, there have been many studies of watershed decision-making support systems designed for various purposes, such as water supply (Koutsoyiannis et al. 2003; Ghahraman and Sepaskhah 2004; Chung et al. 2008), soil conservation (Rahman et al. 2009; Markose and Jayappa 2016; Rejani et al. 2016), pollution (Djodjic et al. 2002; Santhi et al. 2006; Ouyang et al. 2007), sustainable resource development (Smith et al. 2003; Prodanovic and Simonovic 2010; Weng et al. 2010; Mocanu et al. 2013), the impact of land-use change (Engel et al. 2003; Mango et al. 2011), and stakeholder analysis in integrated watershed management (Luyet et al. 2012; Mutekanga et al. 2013). User-friendly decision support systems (DSS) are needed to help watershed managers and planners develop, understand, and evaluate alternative watershed management strategies, while accounting for the interests and goals of several stakeholders (Loucks et al. 2005). The DSS should integrate computer programs with components of database management systems (DBMS), GIS, simulation models, decision models, and easy-to-understand user interfaces (Miller et al. 2004). One such DSS is the multiple-criteria decision-making (MCDM) technique, whereby multiple discrete alternatives are evaluated against specified criteria to generate management strategies that meet multiple objectives (Brooks et al. 2013). However, the success of DSS developed thus far remains inconclusive, as they are often found to be poorly suited for real-world issues and face general problems such as data availability. Further development of these tools will be beneficial, as they have the potential to generate better understanding of environmental feedbacks and make use of the increased availability of watershed simulation models (Mysiak et al. 2005).

Stakeholder analysis (SA) is a holistic approach used to understand a system and assess the impacts of changes to that system through the identification of key stakeholders and their interests in the system (Mutekanga et al. 2013). SA is recognized as a suitable tool to avoid inflaming conflicts, to represent diverse interests, and to identify key stakeholders and assess their respective interests in the system. The steps involved in SA for sustainable watershed management include: (1) identification of natural resource management problems and stakeholders involved; (2) selection of key stakeholders to be involved in decision-making for integrated watershed management; and (3) workshops at community and watershed levels to formulate concrete action and work plans (Mutekanga et al. 2013).

There has been increasing recognition that public participation can lead to better management of common resources. Benefits include a better-informed public, reduced conflict amongst different users, greater democracy through greater involvement of people in decision-making, and more effective implementation of conservation measures. Public participation is a vitally important aspect of planning watershed management, but it needs to be conducted in an appropriate way to be successful (Konisky and Beierle 2001; Webler and Tuler 2001). A management plan requires the active involvement of all interested parties in developing the best approach to achieve its objectives. However, involving the public and stakeholders in decision-making requires forethought and planning as to what their involvement will be so that the interaction and outcomes are positive and beneficial. Nine steps are recommended in the development of a general public participation plan: (1) identify the watershed problem(s); (2) set project goals and objectives; (3) define the study area and pilot projects to be completed; (4) identify objectives for public involvement; (5) identify the stakeholders and interest group; (6) outline the benefits of and obstacles to public participation; (7) outline methods of public participation; (8) establish an action plan; and (9) put the plans into action. Another means of enhancing community involvement in watershed management is through the multilevel community capacity model (MCCM) for sustainable watershed management developed by Davenport and Seekamp (2013). This model addresses community conditions, characteristics, and interactions that are essential for sustainable watershed management and provides a framework for resource managers and decision makers to understand, evaluate, and build community capacity for responding to natural resource stressors or problems. It is organized in four levels: member engagement, relational networks, organizational development, and programmatic coordination.

Overall, multi-level social-ecological system analyses are required for effective watershed management and involve responsible government agencies, locally led partnerships, corporations and other institutions, and all other stakeholders. The goals and objectives of sustainable watershed management will be realized through planning, partnership, and participation by stakeholders.

Case studies: watershed management in China, Europe, and Canada

We have selected three watershed management case studies for the purpose of this paper—Poyang Lake basin, China; Rhine River basin, Europe; and Fraser River basin, Canada. We use these case studies to highlight the success and failure of various management strategies and different approaches to integrated watershed management under vastly different ecological, social, and political contexts. Each watershed is also ecologically and socio-economically important to the local and national economies. In each region, there were numerous ecological and social issues that needed to be addressed, and although not all have been fully resolved, these examples showcase progress through integrated watershed management to improve the quality of the ecological and social components of the watershed.

Poyang Lake basin

Setting and issues

Poyang Lake is situated on the south bank of the mid-lower reaches of the Yangtze River with its watershed being entirely contained within Jiangxi province. Located in a 162,250 km^2 catchment, it is the largest freshwater lake in China (Fig. 2). Poyang Lake has five main tributaries, Gan, Fu, Xin, Rao, and Xiu Rivers, and releases water into the Yangtze River (Shen and Wu 2004). The geographic alignment of the watershed and Jiangxi provincial boundary in principle enables more effective management to be applied to the entire basin as it eases administrative functions and conflict resolution between economic development and ecological protection and allows for greater control over industrialization and zoning throughout the watershed (Chen et al. 2011).

Poyang Lake lies within a migratory corridor for waterfowl known as the East Asian Flyway (Takekawa et al. 2010) and provides wintering grounds for 19 species of birds listed as threatened by IUCN (Ji et al. 2007). As such, the area is extremely important for migrating birds, with 98 % of the world population of the critically endangered Siberian crane (*Grus leucogeranus*) over-wintering there (Global Nature Fund 2016). Due to its importance in supporting several rare and critically endangered bird species, Poyang Lake and surrounding area is designated as a Wetland of International Importance (Global Nature Fund 2016).

Degradation in the Poyang Lake basin is linked to the rapid increase in population, which has led to the conversion of forest to grain production, land reclamation from the lake, sand-dredging, pollution, ship traffic, and over-fishing. In the early 1980s, the area impacted by water and soil erosion in the upper reaches of the Gan River reached 17,732 km^2 (Gong et al. 2006), while forest cover was reduced to 31.5 % of its original extent in the catchment (Shen and Wu 2004). Furthermore, impoundment of the Three Gorges Dam (TGD) in 2003 altered the interaction between the lake and the Yangtze River as the dam reduced river flow causing increased outflow from Poyang Lake, reducing the lake's volume, altering hydrological processes, and impacting water resources (Guo et al. 2012; Liu et al. 2013; Lai et al. 2014). As a result of this and several other factors, the surface area of Poyang Lake has been drastically reduced over the last few decades (Liu et al. 2011), its ecological functions have become compromised, and floods have occurred regularly (Liu et al. 2015). There have been several adverse effects on the ecosystem, including loss of biodiversity, loss of wetland habitat, spread of schistosomiasis (a disease caused by parasitic worms), and degradation of water quality. In addition, the degradation of the ecosystem has been accompanied by increasing poverty that has proven extremely difficult to eradicate because of the connections between the environmental state of the watershed and its economy (Huang et al. 2012).

Remediation and management

Although management strategies for Poyang Lake have yet to resolve several issues related to environmental degradation, they provide a unique example of collaboration among local government, local communities, and international partners to develop comprehensive monitoring and research in the watershed that can be used to improve economic and ecological conditions. Several large-scale projects have been implemented in Poyang Lake basin over the last 30 years that aim to sustainably manage water resources, preserve ecosystem function, and support economic development through a holistic approach. One such program is the Mountain–River–Lake (MRL) program, developed and implemented by the Jiangxi provincial government in 1983 (Shen and Wu 2004). The MRL program aims to promote the sustainable development of the region through environmentally sound policies, integrated regional management, cooperation between agencies and organizations located along the upper and lower reaches of the watershed, and the protection of water resource based on extensive research that identifies the principal problems and cause-effect links for those problems in the watershed (Shen and Wu 2004). The MRL management strategy emphasizes the inter-dependency among the surrounding mountains, lake, tributaries, and human populations in maintaining productivity and quality of the watershed. Numerous

Fig. 2 Poyang Lake Basin, China

collaborations between local universities and international organizations have been carried out to improve research and monitoring of conditions within the basin (MRL 2006) [e.g., elimination of schistosomiasis carried out with the World Bank (Yuan et al. 2000; Xianyi et al. 2005)].

MRL's research approach, level of planning, and intensive implementation led to the program being selected as a key Chinese project presented at the technical fair associated with the 1992 UN Conference on Environment and Development in Rio de Janeiro, Brazil. It was also featured at the Hannover World Expo in 2000 and at the sustainable development summit in Johannesburg, South Africa in 2002 (Shen and Wu 2004). Although there have been some setbacks in the program, such as the failure of two thirds of pilot site experiments due to the mismatch between technology and local circumstance (Shen and Wu 2004), there has also been substantial progress; the MRL had successfully increased forest cover from 33 % in the 1980s to 63 % in 2010 (Statistics Bureau of Jiangxi 2014) and improved the livelihood of about 4 million poor farmers in the area (Shen and Wu 2004). Furthermore, between 1996 and 2012, fifteen regulations and acts were implemented by the government, such as the Poyang Lake wetland protection act and Poyang Lake environmental protection act to protect water ways, wetlands, migratory birds, and biodiversity and reduce pollution in the basin.

The Poyang Lake eco-economic zone is a project developed out of the MRL and was approved by the state council in 2012. The program acts as a natural demonstration site for the development of lakes in China (Cao et al. 2012). It aims to increase the economic well-being of residents of Jiangxi, one of China's poorest provinces, while improving wetland conservation, pollution prevention, and schistosomiasis control (Adameit 2010; Cao et al. 2012). The World Bank has also developed a 5-year project in conjunction with MRL's Eco-Economic Zone program focusing on ecological economic development in small towns; this project will be carried out until 2018 (The World Bank 2016).

There are 237 natural reserves in the Poyang Lake basin operating at various levels (i.e., national, provincial, and county) that cover 1,208,581 ha (State Forestry Administration 2014). The Poyang Lake national nature reserve (PLNR), established in 1983, has made significant contributions to environmental protection and watershed management through research and management activities (Global Nature Fund 2016). In 1992, the 22,400 ha reserve was designated a Ramsar site by the Chinese government (Finlayson et al. 2010). PLNR won Best Protection Practice of 11th World Living Lake Convention in 2006 (Global Nature Fund 2016) and is the most important reserve in Poyang Lake Basin for cranes and other migratory birds. Scientific research and monitoring is carried out in the PLNR in partnership with numerous research institutions and universities in China and abroad including research related to wintering migratory birds, aquatic plants, fish populations, hydrology, and meteorology of the watershed (Global Nature Fund 2016).

Currently there are fifteen protected areas for waterfowl (Finlayson et al. 2010) and 77 wetland parks (State Forestry Administration 2014) in the basin, which reflects the importance of waterfowl protection in management activities. In 1998, the International crane foundation and PLNR initiated the Siberian Crane wildlife project, a long term study that aims to improve ecological knowledge, particularly in regards to plants and wintering waterfowl, to improve the design of conservation programs for the entire watershed and better management strategies in the basin's protected areas (Siberian Crane Wetland Project 2011). In 2010, the Poyang Lake area wintering bird and wetland joint protection committee was established to supervise and assess wintering migratory birds and wetland protection (Global Nature Fund 2016).

Management strategies have also focused on ecosystem restoration. The returning land from farming to forest program increased the forest area by 623,333 ha between 2001 and 2008 through replanting of agricultural land and afforestation of bare land (State Forestry Administration 2008). This initiative increased forest landscape connectivity, and decreased ecological risk in the project areas, which was previously high due to landscape fragmentation and exploitation associated with conversion to agricultural land (Xie et al. 2013). Reforestation has also significantly delayed the average timing of flow and reduced the duration and magnitude of flow during high flow periods, countering the effects of deforestation in the previous decades that had increased magnitude, return period, and timing of flow (Liu et al. 2015).

However, despite these efforts, there are still numerous issues in the watershed such as biodiversity loss and habitat degradation. The situation of decreasing lake area and volume and worsening water quality has yet to be successfully managed. Since the early 2000s, Poyang Lake has experienced continuous extreme low water levels and an earlier onset of the dry season (Du et al. 2014; Mei et al. 2015). This has resulted in negative social and environmental consequences, such as water shortages for irrigation and domestic use, reduction in suitable habitat for wintering migratory birds, depletion of fisheries resources, and deterioration of water quality (Finlayson et al. 2010). In 1999, the majority (58.33 %) of Poyang Lake's water ranked Grade II on a five-class grade scale. By 2009, the best quality water was Grade III (41.67 %) with 16.67 % of the water classified as Grade V, the lowest quality water class (Wu et al. 2011). Although ecosystem quality has improved in some areas of the watershed, an analysis of ecological risk across the basin revealed that the overall environmental quality of the basin has still declined, with the proportion of high level ecological risk areas increasing from 4.46 % in 1995 to 18.2 % in 2005 (Xie et al. 2013). Furthermore, although forest areas increased, grassland and wetland habitat decreased by 44.4 and 39.0 %, respectively, from 1989 to 2000 (Chen et al. 2006). Although overall vegetation area expanded from 1995 to 2013, the expansion was towards to the lake centre as a result of a reduction in lake size (Han et al. 2015). The decrease in water level has impacted wetland biodiversity, particularly aquatic plants and waterfowl, the numbers of which have dropped significantly (Finlayson et al. 2010).

A serious challenge to managing the Poyang Lake watershed is the altered flow dynamics between Poyang Lake and the Yangtze River as a result of the TGD reducing river flow in the Yangtze. Poyang Lake has naturally high seasonal variability in lake volume and area, with the outflow from Poyang Lake being controlled by the interaction with the Yangtze River (Liu et al. 2013). The reduced streamflow in the upper Yangtze River caused by the impoundment of TGD in 2003 has profoundly changed the hydrology of the lake (Lai et al. 2014); outflow from Poyang Lake to the Yangtze has increased and resulted in significant changes to Poyang Lake such as an earlier start to the dry-season (Feng et al. 2013; Lai et al. 2014; Dia et al. 2015) and reduction in lake volume and area (Liu et al. 2013; Zhang et al. 2014, 2015). Although changes in climate, such as increasing temperature and evapotranspiration, have contributed to the decrease in lake volume and area (Feng et al. 2013; Liu et al. 2013), the modifications caused by the TGD have had a much greater impact on the lake's seasonal dryness (Zhang et al. 2014). The degradation of water quality mentioned above is also partially linked to the TGD, as there was a drastic decline in quality after 2003 (Wu et al. 2011). The issues caused by the impoundment of the TGD are challenging to overcome as they result from an external factor; nonetheless these issues need to be addressed as they may lead to severe and irreversible environmental degradation.

The provincial government has proposed the Poyang Lake hydraulic project, which would involve damming the river linking Poyang Lake to the Yangtze River to control lake area and volume, increase development and management of water resources, and conserve protected areas in the watershed (Finlayson et al. 2010). The initial proposal put forward in 2002 was met with opposition and debate amongst local scientists and the international community. As a result, it was restructured in 2008 with less control of the waterway during the flooding season so that the river and lake would naturally be connected, with control implemented in the dry season to establish the lake as a water reserve (BaiduBaike 2015). However, there has still been concern related to the ecological consequences of manipulating water levels (Finlayson et al. 2010; Harris and Hao 2010; Jiang et al. 2014) in an ecosystem adapted to natural seasonal fluctuations (Han et al. 2015). The water depth is a critical component of the Poyang Lake ecosystem, as submerged vegetation needs shallow water to receive adequate sunlight and birds that feed on this vegetation, including the endangered Siberian Crane, need to access it (Barzen et al. 2009). In the most recent proposal, the controlled water depths closely mimic the natural seasonal fluctuations in Poyang Lake (Lai et al. 2015). Waterflow will be controlled starting September 1st to maintain a depth of 15.5 m until September 30th (Lai et al. 2015), which is similar to historical depths ranging from 1814 m (Zhang et al. 2015). From October 1st to the end of November, the lake level will decrease from 14 to 11 m, again tracking similar natural progressions, and from December to the end of March, the water level will be allowed to fluctuate between 10 and 11 m depending on the ecological needs of the area, but will not exceed 11 m (Lai et al. 2015; Zhang et al. 2015). Modelling shows that controlling lake level at 11 m will actually uplift the average water level from December to April (Lai et al. 2015). From the end of March to the end of August, water level will not be controlled using the dam, allowing natural interaction between Poyang Lake and the Yangtze River during the high water period (Lai et al. 2015). The proposed low water period from October to the end of March corresponds to the lake's natural low water period when birds migrate to Poyang Lake to overwinter (Zhang et al. 2015). The maximum winter water depth is recommended to be 12 m, the historic average depth (Harris and Hao 2010), as this is the optimal depth for Siberian Cranes and would prevent a large decrease in wetland habitat (Barzen et al. 2009; Jiang et al. 2014). By the end of October the water depth would be 11.5 m and then remain no higher than 11 m until the end of March, which is below the recommended maximum of 12 m and thus should have minimal impacts on waterfowl habitat. There is still concern, however, regarding the reduction in the current rapid water exchange rate between the lake and the Yangtze River that helps maintain relatively good water quality (Harris and Hao 2010). As the lake already receives high nutrient inputs (Finlayson et al. 2010), the increased residence time during dam closure may increase turbidity and phytoplankton concentrations and cause a decline in water quality (Lai et al. 2015). This would adversely affect sensitive aquatic vegetation and the species dependent on it (Harris and Hao 2010) as well as the surrounding human population. Further investigation into the effects of the dam on factors such as water quality, biodiversity, and disease spread are essential. The Chinese government's plans to assess the dam's impact on these factors, as well as reviewing the engineering proposal for the project during the next 5-year plan (2016–2020). This will then inform a decision on whether or not to proceed with the project (BaiduBaike 2015).

Rhine River basin

Location and issues

The Rhine River flows from its source in Switzerland 1320 km through France, Germany, and the Netherlands to the North Sea, encompassing a catchment area of 170,000 km^2 that includes parts of Italy, Austria, Liechtenstein, Luxembourg, and Belgium (Dieperink 2000; Frijters and Leentvaar 2003) (Fig. 3). As Europe's most densely navigated shipping route, it is lined with many densely populated urban areas, and several major industrial complexes and chemical production plants border it (Frijters and Leentvaar 2003). The Rhine serves a multitude of purposes, such as industrial, agricultural, waste disposal, energy generation, recreation, and drinking water, all of which differ in importance between countries. This can lead to numerous conflicts and concerns, such as problems with water quality, river ecology, and native habitat loss (Frijters and Leentvaar 2003).

Pollution in the Rhine River became increasingly problematic after the industrialization and population growth that occurred from 1850 onwards. The river was contaminated by heavy metals, pesticides, hydrocarbons, organic chlorine compounds, as well as wastewater discharge by households, industries, and agriculture. This led to severe toxicological problems in the ecosystem (Frijters and Leentvaar 2003). By the 1970s, it had become "a dead river" (Dieperink 2000, p 353). The issue of water quality was especially pertinent to the Netherlands, being the most downstream point, so an international agreement with upstream states was essential for the Netherlands to achieve its desired water quality standards (Dieperink 2000).

The Rhine basin states have dealt with several conflicts between ecological concerns and increasing development (Frijters and Leentvaar 2003). Despite a salmon treaty having been in force amongst all riparian states since 1885, the Rhine's salmon population crashed in the 1950s due to overfishing, declining water quality (Dieperink 2000), and the emphasis on socio-economic gains through activities such as navigation and hydropower generation (Frijters and Leentvaar 2003). The prioritization of these industries increased the development of dams and weirs, preventing salmon from reaching their spawning grounds, as well as harming the ecosystem through altered river velocity and sedimentation conditions in spawning areas (Frijters and Leentvaar 2003). Moreover, the river passes through a diverse array of ecosystems, such as alluvial forests, reed plains, wooded fringes, and swamps, and development along the river has resulted in damage to some regions and habitats. Several dams and dikes have been constructed and some channels have been completely cut off along the river to control flooding, reducing its length by about 100 km (Frijters and Leentvaar 2003; Loucks et al. 2005). The reduced inundation has enabled agriculture to develop along the river, but it has also resulted in an 85 % reduction in the natural alluvial floodplains area over the last two centuries, and thus reduction in habitat for animals and plants dependent on those floodplains (Frijters and Leentvaar 2003).

Remediation and management

An essential component to sustainably manage the ecological and socio-economic concerns in the Rhine basin has been the collaboration between upstream and downstream states. The establishment of organizations at the catchment level enabled research, information sharing, policy development, and initiatives to be cross-jurisdictional, which was necessary to address the issues encompassing the entire watershed (Dieperink 2000). There are several organizations focused on watershed and resource management related to the Rhine basin. Some of the organizations and strategies that are in place are detailed below.

The International commission for the hydrology of the Rhine basin (CHR) is a permanent, autonomous, international commission that was developed in 1970 to promote international cooperation among countries associated with the Rhine. It comprises representatives from each member state who are responsible for involving their nations' public and private sector research organizations in watershed management. It encourages increased hydrological knowledge through joint research, as well as exchange of data, methods, and information. It aims to solve cross-border issues through the management and use of information systems such as GIS and models such as those for hydrology and resource management. This international collaboration has generated complex, uniform databases and projects that can relate to the entire Rhine basin, rather than discrete river segments. Projects have included: hydrological interests in water management and flood control; sedimentation management; hydrological forecasts and models; research into climate change; and investigations of the interactive relationships between various factors influencing hydrology within the Rhine basin (Frijters and Leentvaar 2003).

The International commission for the protection of the Rhine (ICPR) is responsible for investigating the type, source, and extent of Rhine pollution, recommending measures to reduce it, and preparing agreements between involved countries (Dieperink 2000; Frijters and Leentvaar 2003; Raadgever et al. 2008). Additionally, ICPR is responsible for any task that states jointly agree upon, such as the rehabilitation of ecosystems in 1987, and managing flood problems in 1995 (Frijters and Leentvaar 2003).

Fig. 3 Rhine River Basin, Europe

However, the ICPR is only a negotiation platform and an advisor to basin governments; the implementation and funding of research and projects is the responsibility of individual states. That being said, the ICPR has been an integral part of the development and exchange of knowledge as well as negotiations between the Rhine states, which has led to the successful management of the Rhine watershed (Dieperink 2000). ICPR encourages member states to share data, cooperate in research, and exchange information, and implemented legal obligations for states to make information available at some levels, with the ICPR helping to disseminate that knowledge through its website (Raadgever et al. 2008).

After water quality in the Rhine reached an all-time low in 1971, the conventions on the protection of the Rhine against chemical pollution and chloride pollution were established by ICPR and ratified by all parties in 1976. They established legally binding threshold values for the discharge of toxic substances (Frijters and Leentvaar 2003; Dieperink 2000). Since their implementation, oxygen levels in the downstream region have rebounded, most chemicals have declined to appropriate levels, the salinity has returned to a more natural state, and some of the biodiversity has returned (Frijters and Leentvaar 2003; Dieperink 2000). They have been largely successful, although some targets have not been met. An international target of 50 % reduction of surface water phosphorous and nitrogen inputs was set; however, by the early 2000s the reduction target had not been met for N (reduced by 23 %) in the Swiss region of the Rhine (Prasuhn and Sieber 2005).

The Rhine action plan (RAP) is a flexible and adaptable plan that was introduced in 1987 (Raadgever et al. 2008) to encourage industry to continually improve technology to avoid environmental pollution and to promote ecosystem restoration (Dieperink 2000; Frijters and Leentvaar 2003; Loucks et al. 2005). Although it is not legally binding, it has been highly successful in achieving its goals. RAP included initiatives to improve the Rhine ecosystem to encourage the return of migratory and native species. Habitat for some endangered species, such as the European otter (*Lutra lutra*) and European beaver (*Castor fiber*), has been restored. The Ecological Master Plan, referred to as the "Salmon 2000″ Action Plan was implemented in 1991 to re-establish the Rhine's Atlantic salmon (*Salmo salar*) populations by the end of the decade (Dieperink 2000; Frijters and Leentvaar 2003). Fish passages were built to bypass physical barriers, while action was taken to restore the alluvial areas along the Rhine, improve the habitat in spawning grounds, reduce chemical discharge, and improve the Rhine's hydrology (Dieperink 2000; Frijters and Leentvaar 2003). Since the salmon population was almost unviable, young fish were reared and released into the river, and by the end of the twentieth century the populations of salmon and sea trout (*Salmo trutta*) had begun to rebound (Frijters and Leentvaar 2003).

The ICPR developed the "Action Plan on Flood Defense" following devastating floods of riparian cities in 1995 and 1997 (Frijters and Leentvaar 2003). Ironically, a few months after the floods in 1995, there was barely enough water for river navigation (Loucks et al. 2005). The Rhine states acknowledged the need for action, and they recognized how upstream action will impact downstream communities and agreed upon interdisciplinary and transboundary cooperation. The action plan was implemented in 1998 and established clear targets to integrate ecological improvements with greater protection of society and development against flood risk (Frijters and Leentvaar 2003).

The use of modelling has increased the understanding of how urbanization and various land-use scenarios around the Rhine influence river runoff (Hundecha and Bárdossy 2004), which compliments the development of flood management strategies. Surface runoff contributes to point-source pollution, particularly after a storm, as well as diffuse pollution from industries such as agriculture. Models, such as SWAT (soil water assessment tool) developed by Abbaspour et al. (2007), can be used to simulate the flow and transport of pollution, as well as physical characteristics such as river discharge and sediment concentration at the watershed scale. These types of tools can increase the understanding of the relationship between land use and runoff (Hundecha and Bárdossy 2004) and enhance initiatives aimed at managing the impacts of different land uses on the watershed.

The Rhine states have shown that successful international watershed management must involve moving from an "upstream–downstream" mindset to a holistic ecosystem protection approach, the use of binding yet flexible agreements, basin-wide research and data sharing, and the even, systematic distribution of information and resources to ensure that agreed measures are implemented (Bernauer 2002).

Fraser River basin

Location and issues

The Fraser River basin catchment covers 234,000 km^2 or 25 % of British Columbia (BC), Canada, and supports a population of over 2.9 million people (FBC 2015a) (Fig. 4). Its headwaters lie in the province's central interior Rocky Mountains, where it flows 1400 km to the southernmost part of the province where it discharges into the Pacific Ocean via the Strait of Georgia (Watson 2004; Ferguson et al. 2011; FBC 2015a). The major environmental issues within the basin include ecosystem degradation and water pollution from agriculture, mining, forestry, and industrial and human development; water depletion; and biodiversity loss from habitat destruction and environmental degradation (Gustavson et al. 1999). More recently, issues related to climate change such as sea level rise, increased risk of flooding (Barron et al. 2012),

Fig. 4 Fraser River Basin, Canada

rising summer water temperatures, and the potential decline in salmon stocks (Reed et al. 2011) have become major concerns.

The Fraser River is the greatest salmonid-producing system in the world, with seven salmonid species living in the basin—sockeye (*Oncorhynchus nerka*), pink

(*Oncorhynchus gorbuscha*), chum (*Oncorhynchus keta*), coho (*Oncorhynchus kisutch*), and Chinook salmon (*Oncorhynchus tshawytscha*); and steelhead (*Oncorhynchus mykiss*) and cutthroat trout (*Oncorhynchus clarki*) (FBC 2015a; Ferguson et al. 2011). The five salmon species are commercially harvested with an economic value of C$41.7 million annually (Ferguson et al. 2011), although this has fluctuated markedly in recent years because of government restrictions on catch limits. Additionally, there are several Indigenous communities within the basin that depend on salmon for non-economic purposes such as cultural and spiritual ceremonies and subsistence needs (Ferguson et al. 2011). Most of the salmonid species migrate up the Fraser River to reach their spawning grounds, which have been severely altered due to human development and increasing population. The gold rush of the mid-to-late ninth century led to the establishment of mines and dams, such as that in Quesnel, which decimated a run of 10 million sockeye salmon (Ferguson et al. 2011). Dams were also constructed throughout the basin for log storage in the early twentieth century, which blocked migratory routes and destroyed eggs when the log booms were floated downstream. Despite the popularity of hydropower dams in British Columbia, there are no dams along the main stem of the Fraser River (Ferguson et al. 2011). There are however seven dams along its tributaries that have altered the downstream flows along the migratory routes of all five salmon species (Ferguson et al. 2011). One of the most devastating events was a rockslide in 1914 in Hell's Gate Canyon, triggered by railroad construction, which blocked passage to the spawning grounds of most of the sockeye salmon, as well as some Chinook and coho. This event, in combination with heavy commercial fishing pressure from the US and Canada, led to the collapse of the sockeye population around 1917. Pink salmon also declined by 75 % at this time due to fishing pressure (Ferguson et al. 2011).

Urban development and increased agricultural production along the Fraser River have also led to issues for terrestrial and aquatic wildlife in the basin. These activities have eliminated natural habitat, altered waterways, reduced diversity of shelter and food, as well as increased pollution of waterways from nutrient and pesticide runoff (Environment Canada 1998). Nutrient loading has led to eutrophication of river segments and its tributaries causing them to become temporarily anoxic, conditions that are lethal to any oxygen dependent species. Some chemicals in pesticides are taken up by aquatic species and bioaccumulate through the food chain (Environment Canada 1998), which can then carry these damaging chemicals throughout the environment as individuals move or migrate. It is not only the damage to the waterways themselves that are of concern, but also the loss and degradation of riparian areas, as these provide food, shelter, and nesting sites for many terrestrial vertebrates, and are important stopovers for migratory birds. However, the expansion of urban areas and agricultural lands, particularly in the Lower Fraser Valley portion of the basin, has eliminated most natural wetland habitat (Environment Canada 1998).

Remediation and management

In the latter half of the twentieth century, a more integrative approach to watershed management in the Fraser River basin began to be adopted. This triggered institutional reform within BC towards the establishment of numerous organizations and management initiatives that provide opportunities for local government, First Nations, and environmental groups to participate in decision-making (Watson 2004). The federal government implemented the Fraser River action plan (FRAP) in 1991 to reduce pollution and restore habitat and fish stocks (Watson 2004). In that same year, they also proposed an integrated management approach for the Fraser River, which led to the development of the Fraser Basin management board (FBMB). Through public consultation, auditing of management activities, and review reports, they identified issues within the Basin and changes to policy and practice that were needed to develop a collaborative program for sustainable development in the watershed (Watson 2004). This eventually led to the Charter for Sustainability that outlined twelve guiding principles for economic, social, and environmental sustainability in the Fraser Basin. Sustainability principles for watershed management were also developed by the Canadian water resources association (CWRA) between 1992 and 1994 that focused on the need for integrated watershed management, consensus through negotiations, and increased public participation in decision-making (Watson 2004), while staying committed to ecological integrity and biological diversity, a dynamic economy, and social equity for present and future generations (CWRA 2015).

An essential component to the integrative watershed management approach for the Fraser River is the Fraser Basin council (FBC). The FBC is a non-profit organization established in 1997 to facilitate sustainable development, healthy waterways and watersheds, action plans on climate change and air quality, and to develop strong, resilient communities in the Fraser River Basin. It is a collaborative effort involving four orders of government—federal, provincial, local, and First Nations—along with the private sector and civil society to develop action plans and solutions collectively to issues in the Basin that account for economic, social, and environmental dimensions (Watson 2004; FBC 2015a). The FBC has played a key role in facilitating collaborative initiatives on flood management, invasive plant species, sustainable fisheries, and economic diversification in rural areas, and operating the provincial information exchange on climate change (Watson 2004; FBC 2015a). In order to monitor and evaluate the outcomes of their initiatives, the FBC developed a set of indicators, covering social, economic, and environmental dimensions, to identify areas where progress had been made and where conditions were deteriorating (Watson 2004). The results are presented in annual reports—*Sustainability Snapshot Indicators Report* (FBC 2010)—and are invaluable tools in evaluating current trends in the watershed, for examining the impact of policy, and for identifying where more attention is needed.

One of the first management initiatives in the Fraser River basin was in 1937 after the collapse of the sockeye and pink salmon populations. The International Pacific Salmon Fisheries Commission (IPSFC) was established; they proposed the development of fish passages at Hell's Gate to enable sockeye to circumvent the blockage to reach their spawning grounds. As a result, sockeye salmon began to slowly increase in the late twentieth century (Ferguson et al. 2011). Carrying on this effort to restore fish populations, the Fraser Salmon and Watershed Program (FSWP) was an initiative co-managed by the Pacific Salmon Foundation (PSF) and FBC between 2006 and 2012. It focused on watershed planning and governance, habitat restoration and stewardship, sustainable fisheries management, and education and engagement of regions and sectors throughout BC to improve the health and sustainability of wild salmon (FBC 2015b). Over 300 projects were carried out over the 6-year period, and FBC has committed to continue funding projects with a similar focus (FBC 2015b, c). Although the populations of Fraser River salmon species have risen and fallen over time, the Fraser remains of the most productive fishery systems in the world (Ferguson et al. 2011).

There has been considerable involvement by First Nations' communities in the Fraser River Basin in management and decision-making. The Fraser salmon management council (FSMC) was established to increase First Nations' involvement in decisions regarding Fraser salmon. These communities negotiate with the Canadian department of fisheries and oceans to build management agreements that consider First Nations' cultural and spiritual connections to salmon, while ensuring preservation of the fish populations (Fraser River Aboriginal Fisheries Secretariat 2015). The BC Ministry of environment also established the roundtable on the environment and the economy in 2014. It aims to bring together representatives from First Nations, communities, industry, and the environmental sector to develop environmental policy that will balance sustainable resource development and protection of the environment and human health (Watson 2004; BC Ministry of the Environment 2015). These types of organizations allow traditionally underrepresented members of the community to be involved in the management of this ecosystem.

The Fraser River Action Plan (FRAP) is a multifaceted approach to deal with numerous issues within the Fraser River Basin, including agriculture, forestry, and urban development through partnerships with local organizations and communities, and education of the citizens and industry. Several programs have been developed to address the loss of riparian and wetland habitat due to agriculture and urban expansion, as well as the pollution and contamination associated with these activities. In 1991, they partnered with local farmers, residents, and environmental organizations in Delta to promote winter cover crops to provide food for birds while reducing soil erosion. Since then, every winter thousands of hectares of farmland are planted with winter crops. The Interior wetlands program was launched in the middle and upper regions of the Fraser in 1992 in partnership with three provincial ministries and Ducks unlimited Canada—a charity for wetland conservation (Ducks Unlimited Canada 2015). The program focuses on habitat conservation, improving water quality and quantity, and sustainable agriculture through the distribution of information, workshops, and working with local landowners to improve irrigation and reduce habitat destruction by livestock (Environment Canada 1998).

In 2009, the Canadian government established the *Commission of Inquiry into the Decline of Sockeye Salmon in the Fraser River*, or the *Cohen Commission,* to identify factors contributing to the recent declines in population and productivity of Fraser River sockeye salmon. The report, published in 2012, investigated both natural and anthropogenic causes of population decline, and the current state and long-term projections for the population. Although Canada adopted the Wild Salmon Policy (WSP) in 2005 to sustainably manage fisheries and maintain genetic diversity, habitat, and ecosystem integrity for wild Pacific Salmon, the report found that little had been done to implement the policy. Furthermore, inconsistencies were found in management statistics, monitoring, and reporting between various sectors that may have impacted the accuracy of fishery management practices and statistics. Thus, the report recommended changes to the management of the sockeye salmon fishery, and suggested several procedures and programs to improve fisheries statistics. However, the government's Department of Fisheries and Oceans was under no obligation to act on the recommendations, and there has been a lack of serious action on the Commission's recommendations (Cohen Commission 2015).

Dealing with climate change related issues is a high priority in the Fraser River Basin. As such, the BC Regional Adaptation Collaborative (BC RAC) program was implemented as part of a national strategy for adapting communities to climate change. Its partnership with FBC and the BC Ministry of the Environment is focused on developing tools and resources to plan for climate change adaptation, securing water resources, minimizing water-related risks, and generating opportunities to collaborate with First Nations communities, researchers, government agencies, and resource planners. Climate and hydrological modelling are essential tools for the development of climate change mitigation and adaptation strategies. The Government of Canada and the BC Ministry of Environment have both developed hydraulic models for the lower Fraser Valley to determine changes to extreme flooding events for both coastal and inland communities. This type of information has helped communities develop long-term flood management strategies, improve the understanding of the risks of climate change, and update infrastructure such as dikes to deal with potential inundation (BC Ministry of Forests, Lands and Natural Resources Operations 2014; FBC 2015d). Models can also be used to understand how climate change will impact salmon migration and spawning (Rand et al. 2006; Macdonald et al. 2010). Understanding how the salmon populations will fair under a warmer climate is critical for decisions regarding annual allowable catch and development of strategies to facilitate salmon spawning and survival.

Although not all management initiatives in the Fraser River Basin have been successful, this system serves as an excellent example of the success of integrative management strategies and engagement of local communities and interest groups. Several initiatives are thought to provide an excellent framework for engagement of First Nations, local communities and industry in decision-making and resource management (Watson 2004; Blomquist et al. 2005; Mitchell 2005).

Conclusions from the case studies

The three case studies described here should not be viewed as unqualified successes. Each has numerous strong points, but each has also failed at some point, so there is no room for complacency. However, it is evident that success emerges when integrated watershed management is utilized to address the complexity of the social, economic, environmental, and cross-jurisdictional issues through the involvement of industry, local communities, and environmental organizations with government decision-making bodies. As well, models and technological advances can better the knowledge of the system and allow for more beneficial long-term strategies to be developed.

Issues in watershed management

Land-use and water resource concerns are often as diverse as the different countries' cultures, economies, and stage of technical development in which they arise. To successfully develop and implement an integrated watershed management strategy under various conditions, there needs to be clear goals and objectives based on sound science that consider all elements within the watershed and how they will change temporally, while accounting for the needs and opinions of the public and stakeholders. Obstacles to this process mainly arise from the following:

Lack of unified organization for management and clear boundaries

Management authority is often decentralized with different managers controlling different areas, especially between upstream and downstream regions and between regions inside and outside the watershed. Defining the watershed can be challenging, as there is often tension between the natural contours of a watershed and social and political boundaries (Blomquist and Schlager 2005). In addition, some components of a watershed may lie within national parks or protected areas, but their effectiveness may be limited if the headwaters lie outside their boundaries (Soares-Filho et al. 2006). These factors can seriously affect the effectiveness of integrated management. Watersheds may also be nested within one another; a major watershed may contain hundreds of moderate- to small-sized watersheds that can generate issues when trying to determine at which scale the integrated watershed management should be organized, particularly if the major watershed crosses regional or national boundaries. Managing small, nested watersheds independently discourages integration, but management at a larger scale may result in localized problems being neglected with management strategies being unable to account for all the issues and interactions that occur in such a complex system (Blomquist and Schlager 2005). Small-scale management may sometimes be necessary, however, depending on restrictions imposed by watersheds crossing jurisdictions where management strategies, priorities, and objectives may greatly differ making watershed assessment and management planning difficult (Wickham et al. 2011).

Lack of appropriate big data and sharing mechanisms for watershed research

The lack of standardized and available data makes it difficult to compare data from different locations (Hampton 2013), or for the same location from different sources. Statistical frameworks for integrating these data exist, but they are often unfamiliar to environmental scientists. There needs to be increased availability of adequate computational infrastructure for data sharing, analysis, and archiving, as well as training for researchers on its use (Hampton 2013). In addition, there is often a lack of control data, which can hinder the ability of researchers to classify and interpret the results of the watershed management strategies. Additionally, one cannot assume that there were similar conditions within the watershed pre- and post-implementation of management strategies, so the necessary data must be available for impact evaluations. Post-implementation satellite images should be compared to pre-implementation images from the same time of year, as even a minor difference in date can have a dramatic impact of the greenness of vegetation, especially at the beginning or end of a season (Kumar et al. 2014). Overall, adequate data are necessary to identify the main issues and establish an effective management plan. However, to use the data to their full capacity, expertise is needed in database management systems, GIS, computer operating systems, RS, data collection from the Internet, and graphics, as well as knowledge of watersheds and the processes that affect them. Few professionals have all these skills, much less the typical watershed stakeholder, so the development of these skills among management team members is critical. Additionally, the required information is often held in many different databases by various agencies, not all of which are openly accessible (Environment Canada 2010). This system needs to be improved so that decision makers can access the information necessary and collaborate with people/institutions to properly analyse the data to study the watershed of interest and develop the most appropriate management strategies.

Lack of interagency communication and cooperation and tools for the development and application of sustainable watershed management

Due to watersheds potentially spanning multiple regional and international jurisdictions, cooperation and coordination of management strategies can be difficult to achieve. Improving watershed management under these conditions requires better data and information-sharing among parties, an integrated management approach, greater transparency and accountability, stakeholder involvement, and clear goals. The development of a legal framework between all parties involved will help to ensure cooperation and progress towards the outlined goals and strategies (Environment Canada 2010). In addition, there has been little development regarding a set of criteria and indicators on which to base a plan for sustainable development. Some progress was made by De Steiguer et al. (2003), who proposed an Analytical Hierarchy Process (AHP), which is a Multi-Attribute Decision Method (MADM). It provides a systematic process for decision-making by comparing multiple competing criteria and alternatives, including situations involving subjective judgements, to select the best watershed plan. It provides numerical weights to alternatives, which can aid in group-decision making and allow easy comparison between competing factors.

Lack of a long-term perspective and quantitative goals for the whole watershed over the next 50 years

There needs to be more use of GIS and simulation models in long-term research and decision-making. It is particularly important to account for the potential impacts of climate change in the long-term management of watersheds, and as such this aspect needs to be integrated into models and decision support tools.

Lack of consideration of public opinion and positive public participation in watershed management

Often, there is little involvement with the public or the main stakeholders in the watershed and little encouragement for cooperation between the different agencies. Decision makers are often evaluating several alternative management plans to determine which best serve the watershed's social and environmental goals (Blomquist and Schlager 2005). Public participation can help clarify the social goals and how they may change over time. Even in complex modelling exercises, public participation is possible but requires an informed and skilled public. The exact processes taken to include the public and develop management activities are context-dependent. However, it is increasingly clear that unilateral processes that exclude the public will fail (Heathcote 2009).

Moving forward with integrated watershed management

Watershed management needs to be a standard component in development programs that focus on water resources, forestry, agriculture, and related land and resource use. To be effective, land-use administrators, water resource managers, foresters, and agriculturalists, along with professional watershed managers, must all be involved.

Integrated watershed management neither seeks nor needs a cure-all watershed model. It needs to be based on the interdisciplinary integration of the physical, biological, chemical, social, economic, and political sciences as they relate to the watershed of interest. Successful future integrated watershed management plans need to incorporate a holistic approach that accounts for environmental as well as socio-economic elements of the system, that embraces the advances in technology and modelling, and that are based on clear legal obligations that are understood by all parties involved. The future development of watershed management will be focused on the following aspects.

Holistic sustainable watershed management

Integrated watershed management is a holistic approach that regards a watershed as a holistic system where social, cultural, economic, and environmental components interact and interweave together, and the principles of sustainable development are used to guide watershed management (Muschett and Campbell 1997). A key component of integrated watershed management is to balance development and protection in such a way that it is consistent with local social, economic, and environmental needs (Heathcote 2009). The integration needs to be broad and should include all aspects of watershed resources (natural, human, and political resources; science and technology) and watershed issues (economic development, water shortages, natural disasters, biodiversity, soil erosion, sedimentation, resource depletion, poverty), as well as involving multiple agencies and jurisdictions and local communities (CCICED 2005; Smit 2005; Yang et al. 2006; Heathcote 2009). To achieve this, integrated watershed management needs to evaluate and consider several elements, such as the spatial and temporal scale, the relationship between ecosystem function and structure, diversity and integrity of the system, ecosystem dynamics in space and time, and natural resource utilization and management by stakeholders. It needs to be adaptive and responsive to changing environmental, social, economic, and political aspects. This will involve revisiting the initially outlined strategies to determine if they need to be improved, and continuously incorporating new technology and knowledge into the management framework (Heathcote 2009).

Multilevel objectives social-ecological system project

The social-ecological system of a watershed has several functions, and different regions have different requirements. Those involved in watershed management need to identify the various regions and functions of the watershed in order to develop the appropriate strategies for each region. First, there is a need to try to understand the watershed ecosystem; then, via a bottom-up approach in which the local people are truly involved, alternative livelihoods that conflict as little as possible with nature should be identified. Market mechanisms could be combined with the financial leverage of government so that watershed management can better balance the benefits of all stakeholders and thus gain their support (Smit 2005, p 35). Governance approaches should include enhancing water use efficiency, environmental laws and regulation enforcement, the use of smart economics and market mechanisms, and improving public involvement (Gleick 2008). Additionally, sustainable watershed management must consider the implementation of zoning and projects for different goals and objectives. The zoning includes: land-use functional zoning, ecological function regionalization, water resource function zoning, ecological protection zones, and so on. This approach will help to achieve the goals for watershed sustainable management that include: (a) clean water and sufficient water flows and water reserves for environmental, industrial, agricultural, and urban use; (b) profitable land-using enterprises which provide regional development and food production and support resilient communities and economies; (c) terrestrial and aquatic biodiversity protection; and (d) resources that meet aesthetic, recreational, and spiritual needs.

Integrated up-to-date science and technologies

Watershed managers need to utilize a multidisciplinary approach by bringing together the developments of computer science, geo-spatial technologies, the support of big data, simulation modelling techniques, as well as optimized decision making approaches to systematically integrate various dimensions of data to develop a comprehensive management tool. This will enable managers and stakeholders to work together effectively and generate the best possible solutions to watershed management problems. To achieve this, more interdisciplinary research is needed to solve the complex integration of population, resources, environment, and development.

Innovative watershed management legal systems and institution structures

There is a need for an international convention promoting the development of watershed management that legally requires the cooperation between jurisdictions, inter-governmental agencies, and upland and downstream regions, with the coordinated organizations having full authority to exercise the duty to facilitate, implement, and monitor the watershed development. Such conventions have been created and implemented for specific rivers, such as the Rhine, but there are many other watersheds encompassing multiple nations that do not have this level of cooperation. A convention would provide the necessary framework for such specific agreements. There is a need to classify agency and institutional jurisdictions over watershed management activities and improve the coordination between the agencies and institutions. An improvement in inter-governmental agency communication and in the communication between stakeholders throughout the entire watershed is necessary. Future watershed management must consist of more and improved regional cooperation, community empowerment, active democracy, as well as political decision-making that involves effective public participation to solve poverty problems and ensure equity and justice for all stakeholders. As evident from the MRL program in China, each stakeholder group needs clear responsibilities, with the government adopting a leadership role, individual departments fulfilling their statutory responsibilities, adequate supervision by the environmental agency, appropriate treatment of effluents by local enterprises, and surveillance and participation by the public.

Widely expand public participation

Key factors that determine the success of watershed management include the degree of public input, contribution of local knowledge, democratic decision-making processes, and whether all the stakeholders can be brought together in planning and implementing watershed development strategies. The experiences from Poyang Lake (CCICED 2005), from the International Rhine Commission (Smit 2005), Tennessee Valley Authority (USA) (Tan and Wan 2002; Yang et al. 2006; Heathcote 2009), the Fraser Basin Council (Blomquist and Schlager 2005), and from many others (USEPA 1997; Mody 2004) suggest that most problems have stemmed from centralized management approaches that failed to take into account the emphasis placed by local stakeholders on rapid economic growth (Wang 1999; Yang et al. 2006). In order to incorporate ever-changing social values and priorities, these components initially have to be known, and the plan must adapt to accommodate them over time. To achieve this, all major public and stakeholder viewpoints need to be considered, with the views of the majority reflected in the management strategies. The exact form of public involvement will depend on the current issues and the community and its values (Heathcote 2009). There must be efforts to continuously enhance public environmental education and to encourage public participation in watershed planning and monitoring (Yang et al. 2006), as well as improve the stakeholders' awareness about the importance of sustainability and to fairly distribute the outcomes associated with upland natural resource development in order to ensure the success of management strategies.

Future research

Efforts are needed in research focusing on the growing concerns over several water-related human and ecosystem vulnerabilities, such as threats to drinking water supply, loss of water-related ecosystem services due to pollution and increased water consumption, and increasing hydrological variability associated with climate change (Bakker 2012). There needs to be emphasis on research that examines watersheds across the broad range of interconnected socio-economic and environmental components. Researchers need to make use of the large data sets and technology available and do what they can to make their own data and technological advancements available to their fellow colleagues. Based on big data and advanced technologies and from macro- and micro-perspectives, comprehensive studies of watershed management need to focus on the optimization of management strategies. Research needs to be presented in a straightforward manner so that policy makers and managers can integrate knowledge into practical applications.

Accounting for the impacts of climate change in large-scale watershed

A key component of future watershed management will be to account for the potential impacts of climate change. Milly et al. (2008) concept that "stationarity is dead" due to anthropogenic climate change suggests that the environment is moving away from familiar patterns of hydrology and ecosystem dynamics and that previous methods of understanding ecosystems and developing long-term plans will be ineffective. Climate change may significantly affect the ecological and socio-economic components of watershed management through altered precipitation patterns, increased risk of drought/flooding, changes to volume and timing of peak flows, and other changes (Brooks et al. 2013; Khedum and Singh 2014; Singh et al. 2014). However, there is uncertainty associated with predictions of how climate change will affect the hydrology of various regions. In order to achieve integrated watershed management in the long-term, management needs to account for and be adaptable to climatic variability and weather extremes (Brooks et al. 2013). This is particularly important for developing nations and regions that are already struggling to manage water resources, as they are most vulnerable to climate change (Vörösmarty et al. 2000; Tompkins and Adger 2004; Khedum and Singh 2014; Singh et al. 2014). Developing long-term management strategies based on past climatic conditions is not sufficient (Milly et al. 2008) and will undoubtedly result in social, economic, and environmental losses due to unsuitable management strategies that could potentially lead to conflicts over water resources (Bakker 2012; Khedum and Singh 2014).

The use of tools and technology that can predict local future changes in climate is essential, as the impacts of climate change on the hydrologic system will vary across the globe and within a country (Milly et al. 2008; Singh et al. 2014). Tools such as hydrological simulation models, stochastic models (Brooks et al. 2013), GIS, and high-resolution regional climate models (Christensen and Christensen 2003) should be used to guide the development of long-term watershed management plans. Within the context of global climate change, the big data network system could lead to better analyses of the changing ecological and environmental dynamics of watersheds. It could also enable the evaluation of the influence of human and natural factors, enabling more objective evaluations of watershed condition and the implementation of more scientific management (Gizjen 2013). It is important to utilize technology and models that are downscaled (Milly et al. 2008) and regionally specific, as this enables management strategies to be tailored to the specific ecological and socio-economic needs of the watershed of interest to ensure they remain viable and contribute to mitigating climate change. However, the current tools and technologies need to be improved upon to generate more accurate projections of how the future climate will influence watershed dynamics. Some countries such as China have already dedicated themselves to increasing their capacity to cope with climate change—expanding technology research and development and improving adaptive capacity of key sectors such as water resources to climate change—and other countries need to follow suite.

A recent study by Zhou et al. (2015) highlights future research opportunities in studying how climate and watershed characteristics interactively affect hydrological responses within a watershed. It was found that when $m < 2$, where m represents watershed characteristics in Fuh's model (Fuh 1981) and the watershed is thus smaller or more simplistic, watershed characteristics can play a larger role in hydrological responses than climate change. Watershed characteristics (m) are positively related to forest cover and watershed areas and negatively to watershed slope. As such, land cover and land-use change should be incorporated into climate change scenarios to increase the accuracy of predicting the response of water resources to climate change (Zhou et al. 2015). If watershed characteristics are excluded, the models may miss the most important factors influencing the hydrology of the watershed, leading to inaccurate predictions and thus ineffective watershed management strategies.

There are several other strategies to better integrate future climatic variability into watershed management. These include improving watershed resilience (social and ecological); improving and sharing knowledge about climate variability and changes to water resources; incorporating climate variability into planning efforts; and developing practices that protect, maintain, and restore watershed processes and services (Tompkins and Adger 2004; Brooks et al. 2013). Flexibility in management strategies is also crucial due to the uncertainty associated with climate predictions. In addition, the environmental, social, and economic costs associated with climate change and the interactions between them need to be considered for successful future management (Brooks et al. 2013). This reiterates the importance of a holistic approach to watershed management that encompasses managing the total environment (Singh et al. 2014) and considers the interactions among land, water, natural resources, and the community and industry dependent on them (Vörösmarty et al. 2000; Brooks et al. 2013).

Conclusion

It is evident that watershed management has transitioned to a more holistic resource management approach, employing integrated and adaptive management strategies to account for biological, physical, and social elements within the landscape. Technological advancements have significantly contributed to this well-rounded approach. Information is now more easily shared within and across disciplines, there is improved accuracy in data collection techniques and model development, and it has become possible to develop integrated, multi-level analysis that generates more complete information about the watershed system both socially and ecologically. These improvements in watershed management and technology provide more comprehensive and multi-dimensional information for decision makers to assess the status of a watershed and implement necessary regulations. As evident in the case studies, social, economic, and environmental issues of concern are unique to each watershed. However, the use of integrated management strategies, local knowledge, cross-jurisdictional cooperation and information sharing, advanced data collection and analysis methods, and the consideration of both ecological and socio-economic concerns can remedy social issues, environmental degradation, and improve the health and management of a watershed. That being said, there is still room for improvement in watershed management strategies and research. Future watershed management should involve integrated watershed management techniques based on the latest science and technologies, as well as local knowledge and stakeholder input. Strategies should account for social and ecological needs and the potential changes associated with climate change. By developing management strategies in this way and continuing to improve research techniques and technology, environmental and social situations within watershed should continue to improve and thrive.

This paper has highlighted the importance of employing integrated watershed management strategies and has outlined numerous methods for improving management strategies, such as incorporation of new technologies and models, inclusion of holistic and adaptive management strategies, stakeholder participation, cross-jurisdictional partnership, and the consideration of climate change impacts in management planning. This evaluation of integrated watershed management and presentation of tools and strategies to improve sustainable watershed management represents an important synthesis of knowledge for scientists, stakeholders, resource managers, and government agencies. Our work can be used to improve agencies' management strategies and better the ecological and socio-economic conditions within watersheds of concern. By employing the steps outlined for developing and maintaining watershed management strategies, integrating appropriate technologies and resources, and gleaning lessons from the case studies presented, future watershed management applied to any circumstances and location may be improved and more successful achieve ecological, social, and economic management objectives.

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