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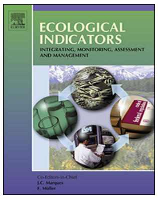

Original Articles

Health comparative comprehensive assessment of watersheds with different climates

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ABSTRACT

Watershed health assessment are intended to provide a better understanding and awareness that natural resources are truly living bodies and processes performing essential ecosystem services. Towards this, watershed health was assessed using the standardized precipitation index (SPI), flow discharge, suspended sediment concentration (SSC), total nitrogen (TN) and total phosphorus (TP). The model was constructed based on the reliability (R_{el}), resilience (R_{es}) and vulnerability (V_{ul}) framework ($R_{el}R_{es}V_{ul}$) for three watersheds viz. Foyle (United Kingdom), Xarrama (Portugal) and Shazand (Iran) with different climatic and hydrologic conditions. According to the framework, the scores of three individual indices i.e., R_{el}, R_{es} and V_{ul} and a watershed health assessment index were calculated using the geometric mean of three mentioned indices using data from 2001 to 2012. The comprehensive health index without considering TN and TP suggested that the watersheds scored medium (0.54 for Foyle and 0.53 for Xarrama), and low (0.37 for Shazand) health levels, respectively. The comprehensive health index also for both the Foyle (0.47) and Xarrama (0.49) watersheds was categorized in medium level considering TN and TP.

1. Introduction

A healthy watershed ecosystem that is "functioning properly" has the required elements in environmental criteria to withstand disturbance and performs a variety of important ecosystem services. Healthy watersheds are the basic building blocks of sound natural resources stewardship (Aju, 2017). Monitoring the health of watersheds is a critical precursor to adaptive resource management on a watershed basis (Jones et al., 2002; Jørgensen et al., 2010; Morrison et al., 2017). Health is usually associated with certain physiological standards, such that the system (watershed) provides expected services and is considered healthy until certain parameters do not conform to the normal range (Rapport et al., 1998; Costanza, 2012; Flotemersch et al., 2016; Peng et al., 2017). The present study used the subject of ecosystem health with a few modifications for watershed health assessment.

Environmental measurable criteria such as flow regime, water quality, biochemical pollution, extreme temperature events and etc. provide reliable evidence of watershed health and can therefore be used as a tool for surveillance or performance evaluation (Xu et al., 2001; Pinto and Maheshwari, 2011; Liao et al., 2018). A healthy watershed ecosystem has the capacity to buffer against and counteract disturbances within certain limits. The capacity of a watershed ecosystem to absorb change and to recover from it is called "ecosystem resilience" (Elliott et al. 2007; Laamanen et al., 2017). The stress level that pushes a watershed ecosystem into a new state is often referred to as a "threshold" or "tipping point" (Laamanen et al., 2017). A healthy watershed needs satisfying only the requirement of providing an acceptable range of ecosystem services. Below the threshold level, one stable state prevails, and above the threshold, an unstable condition occurs. Once a new stable state is accessed, the watershed has a tendency to be self-perpetuating as feedback mechanisms start to stabilize the new regime. However, watershed ecosystem changes, even large ones, can also be gradual with no apparent tipping points (Laamanen et al., 2017).

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There has been a rapid increase in knowledge about the importance of the environmental criteria for watershed health, human health and well-being (e.g., Li et al., 2017). Concerns about effective watershed management and monitoring have also been raised in the literature worldwide (Jones et al., 2002; Habron, 2003). However, the health of the different aquatic and terrestrial ecosystems has been sparsely studied (e.g., Hoque et al., 2016; Chow-Fraser and Fraser, 2016; Ahn and Kim, 2017; Liao et al., 2018; Mallya et al., 2018). In these studies, numerous conceptual frameworks for the requirement of environmental management and decision-making were designed and accordingly assessed based on available local and regional standards based on which the pressure, situation and response of a specific system could be elucidated. However, application of environmental indicators (Hoque et al., 2016; Hazbavi and Sadeghi, 2017; Hazbavi et al., 2018; Mallya et al., 2018) for watershed health assessment has been rarely taken into account. Therefore, the present research was formulated to develop a health assessment model based on the reliability (R_{el}), resilience (R_{es}) and vulnerability (V_{ul}) framework ($R_{el}R_{es}V_{ul}$) for three watersheds with different climatic and hydrologic conditions namely Foyle (United Kingdom), Xarrama (Portugal) and Shazand (Iran). This draws on data from a range of sectors in which watershed health manifest. These included the maximum available and accessible meteorological and hydrological sectors viz. rainfall, discharge, sediment and water contaminants. These 'sectors' capture different dimensions of watershed health across both a natural and social world, and therefore bring different disciplinary perspectives to bear on an understanding of watershed health.

2. $R_{el}R_{es}V_{ul}$ framework background and review

A brief overview of the $R_{el}R_{es}V_{ul}$ framework will be provided here. Rodak et al. (2011) presented the $R_{el}R_{es}V_{ul}$ indicators of the framework in a relatively simple way. So that R_{el} is the likelihood of the watershed being in a state of success; R_{es} is the probability that the watershed will return to a state of success at t + 1 if it is in failure at time step t, and V_{ul} is the severity of failure, which here is defined as the maximum health risk.

However, for calculating the indicators, and the conceptual framework and rationale for how it is constructed, we refer to detailed descriptions elsewhere (i.e., Hashimoto et al., 1982; Kjeldsen and Rosbjerg, 2004; Jain, 2010; Hoque et al., 2014b; Hazbavi and Sadeghi, 2017). Originally, the $R_{el}R_{es}V_{ul}$ framework was developed for the water resources community by Hashimoto et al. (1982). Hashimoto et al. (1982) used 10,000 years of synthetic data and then Vogel and Bolognese (1995) used 100 million years of data for performance evaluation of water resources system using the $R_{el}R_{es}V_{ul}$. The application of the $R_{el}R_{es}V_{ul}$ framework in water resources management was continued by Loucks (1997), Kay (2000), Kjeldsen and Rosbjerg (2004), Jain and Bhunya (2008), Jain (2010) and Alemaw et al. (2016).

The application of the $R_{el}R_{es}V_{ul}$ framework in other subjects than water reservoirs is summarized in Table 1. As can be seen from Table 1, a potential of the $R_{el}R_{es}V_{ul}$ framework for assessing watershed sustainability was proposed by Sood and Ritter (2011). Consequently, it was applied to watershed health assessment with respect to water quality (WQ) by Hoque et al. (2012, 2014a, 2014b, 2016) and Mallya et al. (2018). During the past decade, there has been a surge in the development of techniques for assessing various aspects of the watersheds. Towards this, the $R_{el}R_{es}V_{ul}$ framework with respect to hydrological criteria viz. rainfall anomaly index, flow and high flow discharges and suspended sediment concentration was conceptualized and customized for an arid and semi-arid watershed by Hazbavi and Sadeghi (2017). Hence, Sadeghi and Hazbavi (2017), analyzed the spatiotemporal variations of standardized precipitation index (SPI)-$R_{el}R_{es}V_{ul}$ watershed health index for the Shazand Watershed, Iran. Recently, Hazbavi et al. (2018) connected the $R_{el}R_{es}V_{ul}$ framework with one of the most important climate change driver, i.e. rainfall in the different watersheds of Shazand, Xarrama and Foyle located in Iran, Portugal and Northern Ireland, respectively. According to their findings, the SPI, and reliability and resilience indicators were not significantly influenced by climatic gradient. However, the watershed vulnerability and drought based $R_{el}R_{es}V_{ul}$ index were significantly affected by climatological gradient. But, there is a lot of questions on the how the $R_{el}R_{es}V_{ul}$ framework behave in regards to different environmental stressors in the different conditions of climatic and location. The $R_{el}R_{es}V_{ul}$ indicators are calculated using the following equations (Hashimoto et al., 1982; Kjeldsen and Rosbjerg, 2004):

$$\mathit{Reliability}\,(R_{el}) = 1-\sum\nolimits_{j=1}^{M} d(j)\Big/T \tag{1}$$

where M is the number of failure events, d(j) is the duration of the *j*th failure event, and T is the total number of time intervals.

$$\mathit{Resilience}\,(R_{es}) = \left\{ {}^{1}\!\big/_{M} \sum_{j=1}^{M} d(j) \right\}^{-1} \tag{2}$$

$$\mathit{Vu}\ln \mathit{erability}\,(V_{ul}) = {}^{1}\!\big/_{M} \sum_{i=1}^{T} \left\{ \left[{}^{L_{obs}(i)-L_{std}(i)}\!\big/_{L_{std}(i)} \right] H\,[L_{obs}(i) - L_{std}(i)] \right\} \tag{3}$$

where $L_{obs}(i)$ is the observed study constituent at the i^{th} time step, $L_{std}(i)$ is the corresponding compliance standard, and H[ ] is the heaviside function which ensures that only failure events are involved in the V_{ul} calculation in Eq. (3). The heaviside function is a mathematical and discontinuous function whose value is zero for negative argument and one for positive argument.

In the present study, a number of accessible environmental criteria were selected for three watersheds with different climates in different parts of the world to assess the watershed health status using three indicators of R_{el}, R_{es} and V_{ul} in individual and in aggregation as well.

3. Materials and methods

The present study was planned to assess the watershed health for three watersheds with different climatic and hydrologic conditions. Various health indices were also customized to fulfil the study needs. A flowchart of the study procedure has been shown in Fig. 1.

3.1. Study watersheds

This study was conducted in the three watersheds of Foyle, Xarrama and Shazand (Fig. 2 and Table 2) located in the United Kingdom (UK), Portugal and Iran, respectively.

The Foyle Watershed in Northern Ireland (UK) discharges north from the island into the Atlantic Ocean in the North coast of Ireland. The fertile Foyle Watershed supports intensive and arable farming. The Foyle River flows into the Lough Foyle coastal lagoon, the main wintering site in Northern Ireland and a very important aquaculture site, where eutrophication induced by terrestrial nutrient loads is the main water-quality problem (Barry et al., 2015).

The Xarrama Watershed is representative of southern Portuguese conditions (Pereira et al., 2016). The river feeds the multi-purpose Vale do Gaio Reservoir used mainly for irrigation, coupled with a small hydroelectric generating capacity. This watershed experiences water scarcity issues due to the dry climate associated with the need for agricultural irrigation and recurrent severe drought episodes (Nunes et al., 2017). The reservoir also experiences eutrophication problems due to terrestrial loads of Phosphorus (Nunes et al., 2017).

The Shazand Watershed is located in Markazi Province, Iran, and drains into the main branch of the Qareh-Chai River, and finally enters the Saveh Al-Ghadir dam. Population, urbanization and increasing migration in this region have resulted in a higher demand for water. In

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