Influence of watershed topographic and socio-economic attributes on the climate sensitivity of global river water quality

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Abstract

Surface waters exhibit regionalization due to various climatic conditions and anthropogenic activities. Here we assess the impact of topographic and socio-economic factors on the climate sensitivity of surface water quality, estimated using an elasticity approach (climate elasticity of water quality (CEWQ)), and identify potential risks of instability in different regions and climatic conditions. Large global datasets were used for 12 main water quality parameters from 43 water quality monitoring stations located at large major rivers. The results demonstrated that precipitation elasticity shows higher sensitivity to topographic and socio-economic determinants as compared to temperature elasticity. In tropical climate class (A), gross domestic product (GDP) played an important role in stabilizing the CEWQ. In temperate climate class (C), GDP played the same role in stability, while the runoff coefficient, slope, and population density fueled the risk of instability. The results implied that watersheds with lower runoff coefficient, thick population density, over fertilization and manure application face a higher risk of instability. We discuss the socio-economic and topographic factors that cause instability of CEWQ parameters and conclude with some suggestions for watershed managers to bring sustainability in freshwater bodies.

1. Introduction

Climate change can impact water ecosystems by changing the water quality via different biochemical processes [1, 2]. Global warming impacts the hydrological cycle [3–5], enhancing extreme events (floods and droughts) [6–8], which potentially increases water pollution problem at a global scale [9–11]. Moreover, the particular influences on water chemistry exhibit regionalization owing to climatic and non-climatic factors [11, 12]. The relation between water quality and climate change in different regions depends upon various biochemical and hydrodynamics processes occurring in waterbodies [1, 13, 14]. Previous studies, which used statistical approaches or process-based approaches, have discussed the river water quality relationship with, or response to, air temperature and precipitations. The watershed topography and local socio-economics probably impact the sensitivity of the response of water quality to climate drivers.

Watershed topography, such as catchment area and slope, is an important element that affects surface waters and basin hydrology [15–18]. Ye et al (2009) found that topographic characteristics in the Xiangxi River in the Three Gorges Reservoir Region explained 26% variations in water quality [18]. Chang (2008) found that slopes act as a sink for suspended solid, biological oxygen demand, chemical oxygen demand (COD), total phosphorous (TP) and total nitrogen (TN) parameters [16]. Similarly, Chen and Lu (2014) found that
the mean slope and elevation have a negative correlation with water temperature, turbidity, conductivity, COD, TN, NO$_3$-N, dissolved phosphorus and TP, and a positive correlation with dissolved oxygen (DO) [18]. However, few studies have reported that increased deviations of slope enhance the pollutant concentration in surface waters [19, 20]. Some studies have reported that the mean slope and elevation are associated with enhanced erosion rates, which subsequently speed up particulate material entry into surface waters [18, 21]. By contrast, the impact of topographical features on the response of typical water quality parameters to climate factors has not been investigated.

The impact of fertilizer application and socio-economic features on surface water quality vary by watershed. Chemical fertilizers have been the major cause of the green revolution, while manure is the traditional source for soil nutrition. Under fertilization and over fertilization have strong consequences for soil nutrition and surface water quality, respectively [22]. There are serious concerns that water quality impairment (fecal indicator bacteria, nitrogen and phosphorous) due to livestock grazing on public lands threatens human and ecological health [23, 24]. Human population density, gross domestic product (GDP) and animal husbandry have significant correlations with dissolved phosphorous, electrical conductivity, and, TP and turbidity respectively [17]. Xian et al. (2007) found that Cu, Zn, NO$_3$+ NO$_2$, oil grease, and total suspended solid are strongly correlated with population density [17, 25]. The intensification of human socio-economic activities, along with fertilizer and manure application for crop production, has strong consequences for surface water quality. It is important to investigate the potential impacts of socio-economic variables on the strength and direction of water quality response to climate factors.

Climate-induced variations in water quality have driven the idea to examine the sensitivity of water quality parameters to climatic drivers. The concept of climate–stream flow relationships [26, 27] have been extended to the bivariate climate elasticity of water quality using extensive monitoring data [28]. Moreover, Jiang et al. (2014) partly discussed the impact of determinants (land use and soil) on the relationships of water quality parameters and climatic drivers using the non-parametric Kruskal–Wallis test [28].

In the current study, the principle aim is to uncover the influence of watershed topographic and socio-economic attributes on the climate sensitivity of river water quality based on a global analysis. Firstly, we introduce an elasticity approach (climate elasticity of water quality (CEWQ)) to characterize the response of typical water quality parameters to air temperature and precipitations (or their relationships). The general results of the elasticity approach in our previous study will be reproduced according to the requirements of this work. Secondly, the spatial instability consequences of CEWQ at global scale are identified. Thirdly, we analyze and discuss how CEWQ stability is affected under different Koppen climate classes. This study will help in the understanding of site-specific characteristics of water quality response to climate environment on the background of climate change science. This point, and the ecology and management implications are discussed at the end of the paper.

2. Materials and methods

2.1. Study area and data sources

This study was carried out on major watersheds of the World. Watersheds were selected based on long-term water quality records. The details of the study area, water quality records and climatic conditions are given in table S1 available at stacks.iop.org/ERL/12/104012/mmedia and figure 1 [29].

2.1.1. Water quality data

Water quality records were obtained from United Nations Environment Programme (UNEP)/Global Environment Monitoring System (GEMS)/Water (www.gemstat.org) apart from for the Murray–Darling River in Australia (www.epa.sa.gov.au). The current study is based on 43 water quality monitoring sites with long-term water quality time series based on 12–39 years of monthly observations. The water quality data were collected by the local authorities of their corresponding countries. 12 main water quality parameters are used in the current study, which are given in table S2. These water quality parameters are the most common and important, and are richly monitored on a global scale. They cover physical parameters, and O, C, N, and P-parameters, which are representative and significant from a global perspective. The majority of them are also nutrients leading to eutrophication.

2.1.2. Meteorological data

The monthly air temperature (T, °C) and precipitation (P, mm) data were extracted from the Global Historical Climatology Network (GHCN) [30, 31]. The above-mentioned data sets are publicly available and are at 0.5° × 0.5° latitude/longitude grid resolution.

2.1.3. Other ancillary data

The population density for the concerned watersheds was derived from the Gridded Population of the World, version 3 (GPWv3) (0.5° × 0.5° latitude/longitude) [32]. Fertilizer and manure data were extracted from the global fertilizer and manure application version 1 (0.5° × 0.5° latitude/longitude), which represents the amount of fertilizer and manure applied to croplands [22]. GDP data was obtained from the World Bank (http://data.worldbank.org/indicator/NY.GDP.MKTP.KD.ZG). Country level GDP data were assigned to their corresponding watershed. Runoff coefficients for different Koppen climatic conditions were obtained from Chiew et al’s studies [27]. Runoff coefficient data
was assigned to different watersheds based on climatic class. Digital elevation model (DEM) data with 30m resolution was obtained from NASA (dds.cr.usgs.gov/srtm/version2_1/). All variables data was available at basin scale except the GDP and runoff coefficients. These two variables did not capture spatial variability at the basin scale, which is its main limitation.

2.2. Analysis methods

2.2.1. Climate elasticity of water quality
The concept of bivariate elasticity was introduced by Jiang et al. (2014) in order to measure the response of water quality parameters to precipitation and temperature [28]. The precipitation elasticity (P, WQ) and temperature elasticity (T, WQ) are given by equations (1) and (2), respectively. Preliminary results of the characteristics of CEWQ and comparison with other quality indexes (i.e. correlation analysis) were formerly reported by [28].

\[ \varepsilon_T = \text{median} \left( \frac{WQ_t - WQ}{T_t - T} \right) \]  
\[ \varepsilon_P = \text{median} \left( \frac{WQ_t - WQ}{P_t - P} \right) \]

where \( T \) and \( P \) are the air temperature, precipitation and water quality at any given time, respectively. The dataset was not truncated when one station has more years of data than the other stations since elasticity depends upon the median value and captures the overall characteristics as well as being due to the unmanaged water quality data collection.

2.2.2. Sectioned-watershed characteristics extraction
The current study is based on a sectioned-watershed (stated as sub-watershed) scale [33, 34]. Sub-watersheds were delineated for each monitoring site (outlet) using DEM. The delineated sub-watersheds were used for data extraction, which will be used as explanatory variables in regression models. The mean elevation, mean slope, standard deviation of slope, basin area, mean human population density, mean N and P fertilizer, and mean N and P manure for each sub-watershed was extracted using a GIS spatial analyst tool [35].

2.2.3. Statistical analyses
Statistical approaches were mainly used to investigate the strength and significance of how the climate sensitivity of water quality is relative to watershed and regional characteristics. Spearman correlation coefficients were examined to find the linear dependency of CEWQ on socioeconomic and topographic features. Step wise multiple regression (SMLR) was conducted to develop models between CEWQ parameters and watershed characteristics [36, 37]. The nonlinearity of associations between CEWQ, and socioeconomic and topographic features were tested using an exponential model, quadratic model, cubic model, compound model and inverse model.

3. Results and discussion

3.1. Generic relationships between watershed attributes and the climate sensitivity of water quality
Figure 2 and figure 3 present a global pattern of CEWQ of the five main water quality parameters: water temperature, turbidity, DO, ammonia (filtered), and P (unfiltered). For more details on the CEWQ results refer to [28, 37]. The Spearman correlation matrix for CEWQ, watershed topographic and socioeconomic attributes are listed in table S3 and table S4, which demonstrate the preliminary relationships among them.
3.1.1. Effects of topographic factors on precipitation elasticity

Generally, topographic features regulate surface water quality variables. Increasing $\epsilon_P$ ($P$, temperature) with sub-watershed area is a direct consequence of atmospheric energy input [38]. These energy inputs heat up the land surface, which may increase water temperature due to heat transfer via land runoff from the catchment (especially paved areas) to surface waters [39, 40]. The increasing level of $\epsilon_P$ ($P$, turbidity) with sub-watershed area may be attributed to several possible reasons: frequent and strong storms that erode the ground surface and re-suspend sediments in surface waters [41], human land use change [6, 42], and stock grazing and agricultural activities [43, 44]. Increase in $\epsilon_P$ ($P$, DOC) is positively supported by the catchment area, which may be due to several potential reasons including inputs from sewage, decomposition of organic yard wastes, leaf litter, grass clippings and plant residue in soil by microorganisms [45, 46]. Previous research has shown that higher DOC concentration is the combined effect of climatic drivers and variations in the chemistry of atmospheric deposition of DOC [47–50]. Moreover, the increasing level of $\epsilon_P$ ($P$, turbidity) and $\epsilon_P$ ($P$, DOC) with increasing basin area is a multifactor context that depends upon population density, socioeconomic and topographic conditions, climatic conditions, treatment measures, etc.

The mean slope and mean elevation of the sub-watershed are negatively and positively linked with $\epsilon_P$ ($P$, P-F) and $\epsilon_P$ ($P$, turbidity), respectively. The literature shows that steep slope and high elevation are concerned with the elevated rate of erosion, which favors the entry of particulate matter into waterbodies.
via land runoff [18, 19, 33]. The mean elevation of sub-watershed follows the literature while the mean slope gives opposite results. The impact of mean slope on water chemistry varies due to physical characteristics of the sub-watershed, which includes surficial geology, land use, morphological variables and surficial debris [51, 52].

The runoff coefficient of the sub-watershed is positively linked with $\varepsilon_P$ ($P$, $P$-F) and $\varepsilon_P$ ($P$, turbidity) while negatively associated with $\varepsilon_P$ ($P$, NH$_4^+$-F). Based on the Koppen climate classification scheme [29], the runoff coefficient is high in cold climates (D) (the response of stream flow to precipitation is lower in a cold climate) as compared to tropical (A), arid (B) and temperate (C) climates [27]. Turbidity and $P$-F concentration in cold climate (D) waterbodies are favored by lower values of $\varepsilon_P$($\mu_P$, $\mu_Q$) due to snow storage [26]. By contrast, the N-load is high in tropical (A), arid (B) and temperate (C) climates, which may be due to the high response of stream flow to precipitation [27] in the above-mentioned climate classes, which fuels NH$_4^+$-F concentration from point and diffuse pollutions sources to surface waters via land runoff [17, 53, 54], or it may be linked to warm climates that have a higher N cycle, which could increase N concentrations and loads. Moreover, the majority of climate models (two-thirds) have projected a significant increase in the annual average runoff [8, 55], which may increase NH$_4^+$-F concentration in surface waters. The elevated level of NH$_4^+$-F concentration in surface waters may be a consequence of irrigation tailwater discharges [56, 57] due to favorable cultivation conditions in tropical (A), arid (B) and temperate (C) climate classes.

3.1.2. Effects of socio-economic factors on precipitation elasticity

Population density, which is higher in urban areas, is positively concerned with $\varepsilon_P$ ($P$, NO$_x^-$-F). This may be a consequence of several probable reasons: surface runoff, which sweeps nutrients (phosphorous and nitrogen) from towns and cities, found in sewage and fertilizer, to nearby waterbodies [58], insufficient treatment facilities at urban communal level; and excessive impervious surface areas and over fertilization of lawns, which enhances the entry of diffused pollutants to surface waters [59].

The negative associations of GDP with $\varepsilon_P$ ($P$, DOC) and $\varepsilon_P$ ($P$, turbidity) may be due to conservative efforts at the catchment and buffer scales due to higher development in the region [60], or it may be a consequence of sedimentation of DOC to particulate organic matters, which reduces the DOC concentration in surface waters [61]. GDP positively favors $\varepsilon_P$ ($P$, P-UF), which might be linked with urbanization. Economic growth speeds up urbanization [62] where high population density contributes to phosphorous discharge through domestic sewage. Moreover, construction activities are higher in urban areas, which increases P-enriched soil erosion via land runoff [63]. N-manure is positively associated with $\varepsilon_P$ ($P$, NO$_x^-$-F), which may be a consequence of land runoff, which drains animal discharges from firms or grazing fields to nearby surface waters [23, 24, 54, 60, 64].

The above discussion shows that the response of the precipitation elasticity of water quality parameters to topographic and socio-economic, secondary determining factors, is simple. Catchment land use is the primary determining factor for regulating the nutrients [16]. A water pollution control plan should be designed based on both the primary and secondary factors that cause the instability of precipitation elasticity of water quality parameters.

3.1.3. Effects of topographic factors on temperature elasticity

The mean elevation of the sub-watershed is positively associated with $\varepsilon_T$ ($T$, P-UF) and $\varepsilon_T$ ($T$, PO$_4^{3-}$-F). Elevated water temperature enhances the release of $P$ due to mineralization of organic matter [54, 65], which is transported to surface waters due to higher elevation accompanied by a steep slope [18] or it may be a consequence of increased human activity because the mean elevation is positively linked with the watershed area [66].

The runoff coefficient of sub-watershed is negatively linked with $\varepsilon_T$ ($T$, P-F) and $\varepsilon_T$ ($T$, DOC). P-F and DOC are abundant in tropical (A), arid (B) and temperate (C) climate waterbodies. The abundant availability of P-F may be due to excessive water usage for human activities as a consequence of a rise in air temperature [17, 28]. The concentration of DOC is higher in the above-stated climatic types, which may be due to higher anthropogenic activity and a high rate of decomposition due to elevated temperature [45]. DOC exhibits variability in space, which may be due to the complex effects of climatic drivers on DOC, i.e. hydrological mobilization, solubility and decay. Rising air temperature accompanied by rainfall intensity can affect the mobilization of DOC [67].

3.1.4. Effects of socio-economic factors on temperature elasticity

Population density is negatively linked with $\varepsilon_T$ ($T$, DOC), $\varepsilon_T$ ($T$, PO$_4^{3-}$-F) and $\varepsilon_T$ ($T$, PO$_4^{3-}$-UF). The response of DOC is site specific and complex to climatic drivers [67]. The response of PO$_4^{3-}$-F and PO$_4^{3-}$-UF to temperature is inelastic and relatively elastic, and site specific [28]. The concentration of orthophosphate is highly dependent on point source pollution (phosphorous related industries) rather than watershed characteristics [18].

GDP is negatively associated with $\varepsilon_T$ ($T$, turbidity). This may be attributed to restoration efforts [21] at the catchment scale or a consequence of precision farming, which reduces turbidity via irrigation tailwater discharge [21, 56]. GDP is positively related with $\varepsilon_T$ ($T$, P-F). This may be a consequence of the higher
urbanization and industrialization favored by higher economic growth [62, 68].

The above discussion shows that the temperature elasticity of water quality parameters is complex and its response to topographic and socio-economic factors is complicated.

3.1.5. Regression models of watershed and regional characteristics, and CEWQ

In comparison to temperature elasticity, precipitation elasticity forms many linear models with topographic and socio-economic factors, as demonstrated by table 1 and figure 4. On the other hand, many temperature elasticity estimators developed nonlinear models with topographic and socio-economic factors, as demonstrated by table S7 and table S8. Some nonlinear relations are reported in table 1 with their corresponding \( R^2 \) and \( P \)-values which include: \( \varepsilon_P (P, NO_2^-F) \) with mean slope \( (R^2 = 0.624, P = 0.001) \), \( \varepsilon_P (P, PO_4^{3-}F) \) with P-manure with \( (R^2 = 0.624, P = 0.001) \), \( \varepsilon_T (T, NO_2^-F) \) with N-manure \( (R^2 = 0.563, P = 0.001) \), \( \varepsilon_T (T, P-F) \) with P-fertilizer \( (R^2 = 0.695, P = 0.010) \) and \( \varepsilon_T (T, P-F) \) with P-manure \( (R^2 = 0.920, P = 0.000) \).

Some points should be mentioned. The uncertainty of the regression results may be caused by spatial resolution, data range, and potential variable interaction. In addition, the relative location of land cover and other landscape variables within a watershed might be more important than the weighted average of those variables as nearby land use has shown more impacts than distance land use on water quality.

3.2. Influence patterns at two typical climatic class areas

SMLR outputs for CEWQ on various Koppen climatic areas are listed in table S6.

3.2.1. Influences on climate sensitivity in tropical climate class (A)

The positive sign of GDP coefficient for \( \varepsilon_T (T, DO) \) may be attributed to conservative practices and better
3.2.2. Influences on climate sensitivity in temperate climate class (C)

GDP shows a negative coefficient for $\varepsilon_T$ ($T$, turbidity). The literature illustrates that temperature has an exponential effect on sediment load (soil erosion) [72, 73]. Some studies have confirmed that temperature is the most important controlling agent for other factors such as precipitation, catchment size on soil erosion and subsequently sediment flux [72, 74]. A high concentration of sediment load can be modulated via investment in conservative efforts and treatment facilities at catchment scale.

The runoff coefficient has a positive coefficient for $\varepsilon_T$ ($T$, NO$_3^-$-F). In comparison to Cwa, a subclass of temperate (C), Cfa and Cfb have higher contents of NO$_3^-$-F, which may be due to climatic conditions that favor leaching of nitrogen from soil with time [75, 76], or irrigation tailwater discharge from conventional farming that favors the release of nitrate contents to waterbodies in the vicinity [56]. Streamflow sensitivity to precipitation is higher in temperate climate class (C) [27], which sweeps fertilizers to waterbodies in the vicinity.

The mean slope has a positive coefficient for $\varepsilon_T$ ($T$, NO$_x^-$-F). Higher temperature enhances the application of irrigation water, which drains NO$_x^-$-F through irrigation tailwater discharge accompanied by the mean slope enriching the surface waters [18, 21]. The mean slope has a negative coefficient for $\varepsilon_T$ ($T$, PO$_4^{3-}$-UF), which acts as a sink [16]. Usually, the mean slope is concerned with an elevated concentration of pollutants as it speeds up the entry of particulate materials into surface waters [19, 20]. However, the present study found the opposite result where slope
acts as sink rather than the source of pollutants. Such a relation shows that the slope is a secondary variable rather than dominant explanatory variable [16, 77]. Some studies also show that topographic complexity as represented by the standard deviation of slope may be a better predictor than the average slope [19, 20]. Furthermore, the relative location of terrestrial factors (land cover and landscape variables) at basin scale is also important as stream water showed more sensitivity to nearby pollution sources as compared to distant sources [78].

P-fertilizer has a positive coefficient for $\varepsilon_P$ ($P$, temperature). This may be due to several reasons: Firstly, it can be a consequence of irrigation tailwater discharge which absorb heat [39, 40] and sweeps P-fertilizer from cropland which enhance water temperature. Secondly, the sensitivity of streamflow to precipitation is higher in temperate climate class (C) [27] where surface land runoff absorbs heat from the ground surface to elevate the water temperature. Thirdly, it may be attributed to exothermic reactions in the surface waters due to P-fertilizer, which enhances water temperature.

Population density has a positive coefficient for $\varepsilon_P$ ($P$, NO$_3^-$-F), which may be due to lawn fertilization in urban areas, which drains NO$_3^-$-F to enrich surface waters [59, 79]. GDP has a negative coefficient for $\varepsilon_P$ ($P$, NO$_2^-$-F), which may be a consequence of precision farming in the locality, which decreases the amount of NO$_2^-$-F swept to surface waterbodies in the vicinity [56]. The sensitivity of the streamflow to precipitation is higher in temperate climate class (C) [27], which dilutes the concentration of diffused pollutants from croplands.

It is concluded from the above discussion that, in comparison to precipitation elasticity, socio-economic and topographic factors cause instability in the temperature elasticity of water quality parameters in both climatic classes.

3.3. Ecological and management implications
In this study we found that socio-economic and topographic factors cause instability in the CEWQ parameters. Policy makers, and watershed and resource managers can take guidance from the developed empirical equations between the CEWQ and the above-mentioned factors for better water quality management of freshwater resources.

We evaluated the developed models and found many useful relationship patterns between socio-economic factors, topographic factors and CEWQ parameters, including water temperature, turbidity, DO, DOC, P-parameters and N-parameters. Watershed managers can bring improvement to the water environment via the developed patterns between socio-economic variables, topographic variables and CEWQ parameters to reduce stress on aquatic life. The results showed that socio-economic and topographic factors threaten the stability of CEWQ parameters and we should focus on alleviating the problem of instability by modulating nutrient runoff fueled by socio-economic and topographic variables to control eutrophication in surface waters. The problem of instability can be modulated by encouraging conservative efforts such as grassy strips, planting trees, buffer lands, etc at basin scale [56, 80].

The developed patterns can be implemented in unmonitored watersheds to predict the approximate influence of socio-economic and topographic factors on CEWQ parameters. Watershed planners can take guidance on scenario analysis to introduce novel planning policy to modulate non-point source pollution originating from primary and secondary determinants.

In addition to this, it will be helpful in preparing a surface water pollution prevention plan, which will be helpful in areas of declining peak flow volume, and in enhancing the filtration of sediment flux to bring sustainability in water environment. Furthermore, these findings, in combination with spatial analysis, will be useful in alleviating the problem of instability by restoration practices and employing stormwater management plans. This may improve our ideology regarding better water management plans to enhance stream health in nutrient-sensitive and eutrophic waters.

4. Conclusion
In the current study, we evaluated how the site-specific socio-economic and watershed topographic factors impact the response strength and direction of river water quality to climate factors at a global scale. The elasticity approach was used. We found that precipitation elasticity showed comparatively higher sensitivity to socio-economic and topographic factors at a global scale. GDP acted as a stabilizing agent in maintaining CEWQ in both tropical (A) and temperate (C) climate classes, while runoff coefficient, slope and population density fuels the risk of instability in temperate climate class (C). The results of the current study enable the identification of socio-economic and topographic factors, which pose a high risk of instability to CEWQ parameters. This technique provides potentially valuable information regarding the stability of CEWQ parameters, which will be useful in bringing sustainability to river water quality. The present method has a limitation due to the unavailability of monthly data for GDP at the sub-watershed scale.

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