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Assessment of the impact of island development on water security based on the elements nexus for the water system in Zhoushan archipelago

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ABSTRACT

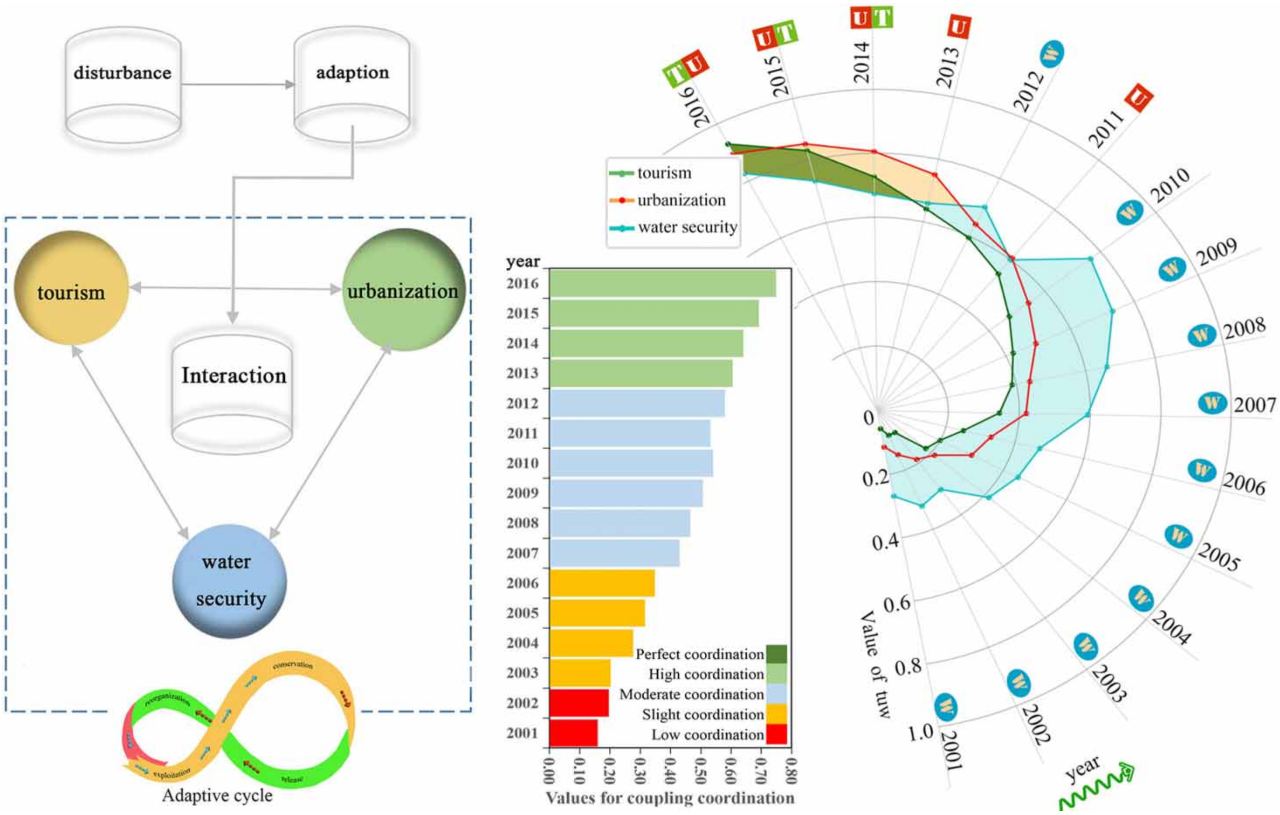
Water security is the premise for island sustainable development. Rapid urbanization and rising tourism industry have reshaped the water system in China's island cities, and it is necessary to reveal the characteristics of the aforementioned impacts in relation to strength and duration. Here, we present a framing to interpret the nexus between island developments and water security. Subsequently, their coevolutionary trend and mutual impact effects (coupling coordination degree and response period) were measured by mathematical models, respectively. Results demonstrated that the equilibrium of the water system has shifted from nature- to human-dominated since 2010. Interestingly, the coupling coordination degree between water security and island development showed an upward increasing trend, across the study periods. Moreover, water security exhibited positive and negative shock responses to tourism and urbanization, over 1- and 7-year response periods, respectively. Overall, the findings from this case study provide a quantitative paradigm for island sustainable management, and are expected to inform local decision makers on warning signals of sustainability loss, at a temporal scale.

Key words: coordination, island, nexus, resilience, socio-ecological system, water security

HIGHLIGHTS

- Nested links deeply interpret the nexus between island development and water security.
- The impact of island development on water security was quantified by mathematical models.
- Trigger points of the water crisis were detected by the coevolutionary trend of the tourism-urbanization-water security (TUW) system.

GRAPHICAL ABSTRACT



1. INTRODUCTION

Currently, widespread concern over island water crises derives from rapid economic development (Diamantopoulou & Voudouris 2008; Strauß 2011). Rapid industrialization and urbanization in many small island developing states (SIDS) are often achieved at the expense of ecology (Heinrich Blechinger & Shah 2011; Monrose & Tota-Maharaj 2018). At a regional dimension, notable conflicts are in place between China's island development and water security (Ni *et al.* 2012; Luo *et al.* 2018), resulting in frequent emergencies in relation to water resources (Gu *et al.* 2018).

Previous attribution research with respect to island water crises has focused on the human-environment aspect, and mosaic human beings into the island water system, when diagnosing trigger mechanism of island water security issues (South *et al.* 2004; van der Velde *et al.* 2007; White *et al.* 2007; Smith 2008; Schwerdtner Máñez *et al.* 2012). However, a qualitative description of the impact effect is a critical issue in these studies, which jeopardizes the objectivity of results. Therefore, developing methods for the quantitative expression of the impact of island development on water security has become a critical topic to serve regulations.

Nested links in relation to system thinking provide a useful bridge for the quantitative assessment of abstract relationships for different elements. Quantitative assessment for the impact of island development on water security calls for integrated construction of various inner elements to form an interlinked nexus (Liu *et al.* 2015). Nexus framing is a classical nested link that focuses on unpacking relationships among multiple inner elements and emphasizes the shifts in coupled human-environment systems (Liu *et al.* 2018; Stringer *et al.* 2018). Nested links between system elements deeply interpret the impact mechanism of ecosystems, resources, the environment and human well-being (Lehmann 2018; Li *et al.* 2019; Wang *et al.* 2021). Among all related inner elements on islands, tourism, urbanization, and water security are the key interconnected components to maintain island resilience (Diamantopoulou & Voudouris 2008; Moglia *et al.* 2008; Chen *et al.* 2020; Ma *et al.* 2020). The tourism-urbanization-water security (TUW) nexus on islands highlights interconnections between its components in terms of system succession. The TUW nexus presents a conceptual approach to interpret the nexus between inner elements of a coupled system, which is the basic premise for quantifying their impact effect.

From the perspective of interlinked elements, we aimed to interpret the connection of island development and water security, and conducted a comprehensively quantified analysis of the impact of island development on water security in Zhoushan, an island city in mainland China. We abstracted the aforementioned elements into virtual nodes for a socio-ecological system, and used virtual nested links to interpret their relationship. The element nexus was a premise for quantitative assessment of their impact effect. Subsequently, we presented mathematical models to assess these virtual nodes and their response relationships. Overall, this study provided decision makers with a new paradigm to reveal the trigger mechanism of the water crisis to serve island regulation and planning.

2. MATERIALS AND METHODS

2.1. Study area

Zhoushan, located in China's largest archipelago, comprises 1,390 islands, with a total terrestrial area of 1440.12 km^2 (Figure 1), and it is a densely populated area. Moreover, located in the subtropical monsoon climate, the region's precipitation season is warm (rainfall accounts for 45%), and occurs from June to September. The annual rainfall is between 980.7 and 1355.2 mm, the evaporation is between 1208.7 and 1466.2 mm, and the annual runoff depth about 44% less than that in continental areas of the same latitude in China (Xuan *et al.* 2020). Notably, Zhoushan faces a water crisis, as evidenced by a per capita volume of 600 m^3, which is lower than the threshold proposed by the United Nations Food and Agriculture Organization (FAO). In fact, water levels less than 1,000 m^3/capita are considered a severe constraint on socio-economic development by the FAO (Liu *et al.* 2012).

Regional development and protection are an important conflict for sustainable development in Zhoushan. Zhoushan is a rapidly developing island city with a population of 1.158×10^6. The mainland link project, a sea-crossing bridge, broke its adverse conditions with isolated locations in 2009. Subsequently, rapid urban sprawl has occurred in Zhoushan since 2010, and has increased the construction areas by 58.92 km^2, from 2010 to 2015 (Fan *et al.* 2019b). Similarly, tourism has simultaneously grown with urbanization, thanks to the improved infrastructure. For example, more than 1,000 pristine

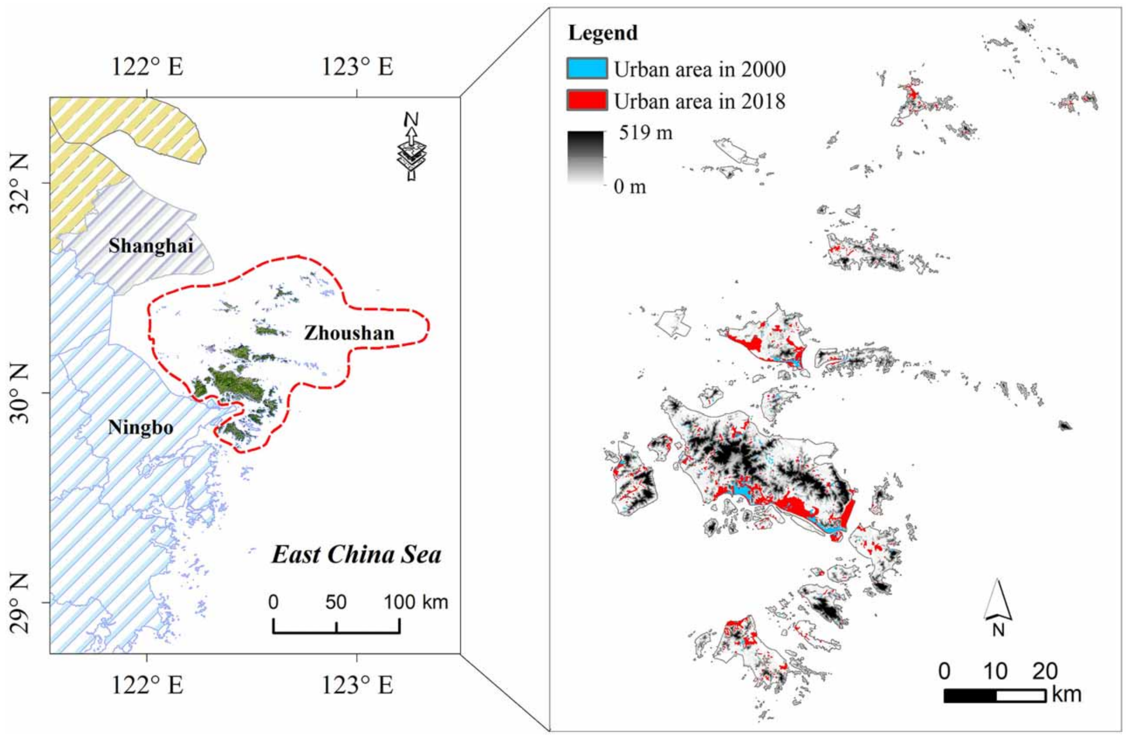


Figure 1 | Location of the Zhoushan archipelago, indicating the region's boundary and urban area. Data source: Resource and Environmental Science and Data Center (RESDC).

landscapes have become popular tourist attractions by commercial exploitation, while the number of tourists increased from 2.14×10^8 in 2010 to 3.88×10^8 in 2015 (Zhoushan Municipal Statistics Bureau (ZMSB) 2019). All of these events have resulted in ecological issues (Fan *et al.* 2019a). As a representative island city in the coastal zone of China, with indicative economic growth and ecosystem changes, Zhoushan is an excellent choice for a case study.

2.2. Methods

We present a framing to enhance our interpretation of methods (Figure 2), which comprises three modules. The first module displays a conceptual network for interpreting the relationship between the human- and nature-system based on the virtual element nexus. The second module comprises a mathematical model, namely linear-weighted sum method, for assessing coevolutionary trends of target elements, while the third module involves two mathematical models, namely the impulse response function and coupling coordination model, for assessing the mutual impacts (including response period and the ability to adapt) with respect to target elements.

2.2.1. A conceptual network for interpreting the elements nexus for a system

The literature meaning of a network implies 'a means of connection between virtual nodes in a series'. Similar to the morphological connection in topology, systematic elements, such as natural resources, social management and economic activities, are conceptualized to be virtual nodes. The links or edges capture the connections of nodes to one another (Liu *et al.* 2015). This conceptual network is a bridge to interpret the element nexus for a socio-ecological system.

We observed a nexus of three virtual nodes, namely tourism, urbanization and water security, for Zhoushan (Figure 3). Urbanization and tourism are the two most typical controlling factors for the island development dimension, while water security is a typical controlling factor for island protection. Island development calls for abundant water resource support. Conversely, island development gives feedback for island protection, for example, water facilities benefit from investment from construction activities, while water systems are exposed to increasing risk with respect to pollution and exhaustion (Gu *et al.* 2018).

According to the characteristics regarding the aforementioned three target elements, we further decompose them into 12 criteria (Figure 3). It is an important step to clarify the characteristics of these abstract elements in their literal meaning to reveal their mutual nexus and to guide parameter selection in the next workflow. Tourism is an identifiable nationally important industry that involves the provision of transportation, accommodation, recreation, food, and related services (Leiper 1979). The characteristics of tourism are generally portrayed in two dimensions, including enterprises' operation and maintenance and tourists' activity, which subsequently can be quantified by four indicators: tourism scale (Kasim 2006), tourism income (Eeckels *et al.* 2012), tourism enterprises (Kilipiris & Zardava 2012) and tourism benefits (Pratt 2015). Urbanization refers to the population concentration in urban areas during certain periods of time, while at the same time, urban material and spiritual civilization keeps extending to surrounding rural areas during the process and producing new spatial patterns

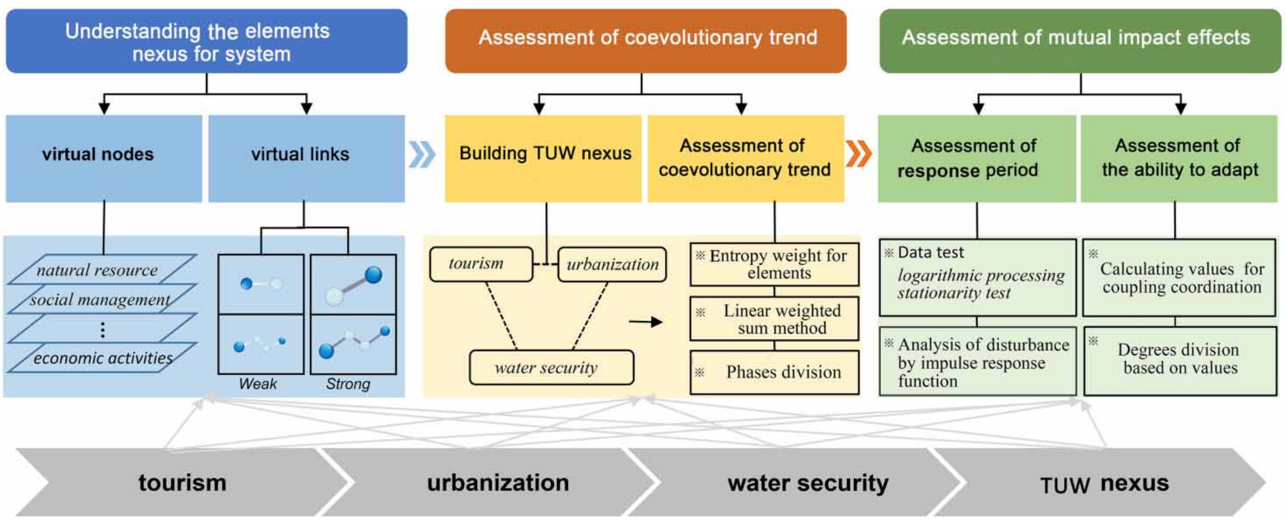


Figure 2 | A framing to enhance our interpretation of methods.

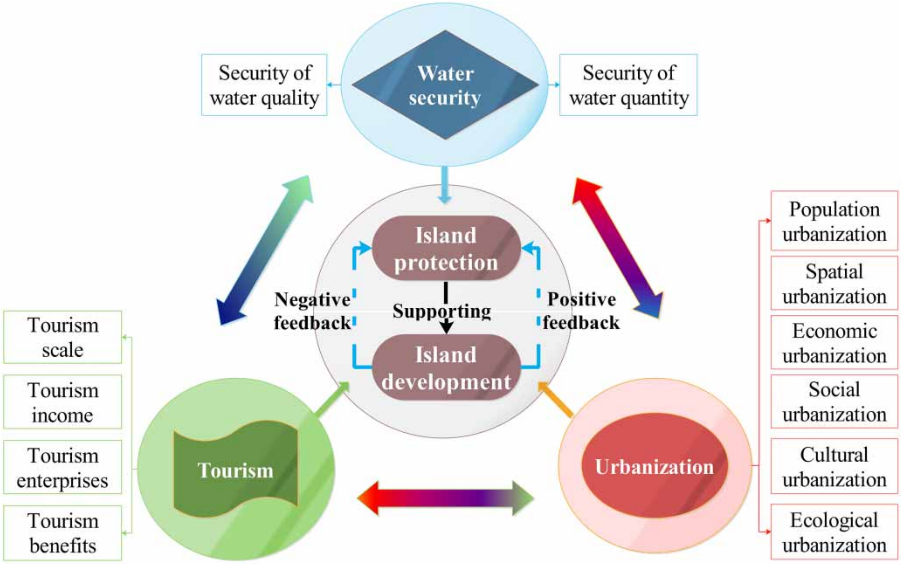


Figure 3 | Nexus of elements, namely tourism, urbanization and water security, for Zhoushan.

and landscapes along with continuous changes in the regional industrial structure (Gu *et al.* 2012). The general characteristics of urbanization mainly include six dimensions: population agglomeration (Shen *et al.* 2012), rapid economic development (Choy *et al.* 2013), changes in residents' lifestyles (Muchadenyika & Williams 2016), enhancing the well-being of society (Supriyadi *et al.* 2012), transformation of regional land covers, and environment (Wang *et al.* 2001; Yu 2021). These characteristics subsequently can be quantified by corresponding indicators: population urbanization, economic urbanization, cultural urbanization, social urbanization, spatial urbanization and ecological urbanization. Water security is defined as the availability of an acceptable quantity and quality of water for health, livelihoods, ecosystems and production, coupled with an acceptable level of water-related risks to people, environments and economies (Grey & Sadoff 2007). The general characteristics of water security mainly include two indicators: security of water quality (Li *et al.* 2016) and security of water quantity (Zeng *et al.* 2013).

2.2.2. Indicators selection and data sources

The ideal quantitative expression of a system calls for comprehensive indicators. However, many factors restrict indicator selection in the actual operation process, such as the availability of data. In this section, referencing published literature, we list an experience-based indicator collection following the principles of representativeness and availability of data (Zhang *et al.* 2012; Gao *et al.* 2013, 2016; Li *et al.* 2013; Liu *et al.* 2014; Shu *et al.* 2015; Tang *et al.* 2017).

This indicator set includes 3 target elements, 12 detailed criteria and 55 parameters, as shown in Table 1. The changes in the target elements reflect the stability fluctuation of the system. The function for combined weighted systems of 55 parameters is to quantify the extent of fluctuation. Subsequently, water security changes can be diagnosed by comparing the degree of fluctuation values, in the annual temporal dimension.

Moreover, we assign an entropy weight for each indicator, and entropy weight has been proven to be an objective method compared with the pairwise comparison method (Wang *et al.* 2014) for giving indicator weight in assessment of tourism economic vulnerability, urban flood hazard and water quality (Zou *et al.* 2006; Sepehri *et al.* 2019; Huang *et al.* 2021).

2.2.3. Quantitative assessment of target elements and their impact relationship

2.2.3.1. Model for assessment of coevolutionary trends. The evolutionary trend of the three target elements is calculated by the linear weighted sum method. Summarily, this method makes a linear combination of parameters on the basis of their weights, and synthesizes a comprehensive value (Wang *et al.* 2019), as shown in Equations (1–3).

$$f(x) = \sum_{j=1}^{n} w_j x'_j \tag{1}$$

Table 1 | Indicators and weights for socio-ecological system in the Zhoushan

Target elements	Criteria for elements	Parameters	Parameters contribution	Weight of parameters
Tourism (x)	Tourism scale (x_1)	Number of domestic tourists (x_{11})	+	0.0933
		Number of inbound tourists (x_{12})	+	0.0918
		Tourist density (x_{13})	+	0.0933
	Tourism income (x_2)	Domestic tourism revenue (x_{21})	+	0.1003
		Foreign exchange income from tourism (x_{22})	+	0.0844
		Per capita tourism income (x_{23})	+	0.0975
	Tourism enterprises (x_3)	Number of travel agencies (x_{31})	+	0.0781
		Number of star hotels (x_{32})	+	0.0630
		Number of A-grade scenic spots (x_{33})	+	0.0967
	Tourism benefits (x_4)	Proportion of total tourism revenue in GDP (x_{41})	+	0.0888
		Proportion of tourism employees (x_{42})	+	0.1126
Urbanization (y)	Population urbanization (y_1)	Proportion of urban population (y_{11})	+	0.0380
		Proportion of employees in secondary industries (y_{12})	+	0.0229
		Proportion of employees in tertiary industries (y_{13})	+	0.0260
		Urban population density (y_{14})	+	0.0284
	Spatial urbanization (y_2)	Built-up area per capita (y_{21})	+	0.0188
		Urban road area per capita (y_{22})	+	0.0478
		Urbanization rate of land (y_{23})	+	0.0244
	Economic urbanization (y_3)	Per capita GDP (y_{31})	+	0.0421
		Proportion of secondary industries in GDP (y_{32})	+	0.0280
		Proportion of tertiary industries in GDP (y_{33})	+	0.0410
		Per capita gross industrial output value (y_{34})	+	0.0440
		Investment in fixed assets (y_{35})	+	0.0427
	Social urbanization (y_4)	Per capita disposable income of urban residents (y_{41})	+	0.0463
		Total retail consumption per capita (y_{42})	+	0.0424
		Proportion of non-food excluded expenditure of urban residents (y_{43})	+	0.0272
		Number of medical and health institutions (y_{44})	+	0.0565
		Number of buses owned by ten thousand people (y_{45})	+	0.0378
	Cultural urbanization (y_5)	Number of college students per ten thousand people (y_{51})	+	0.0391
		Number of libraries (y_{52})	+	0.0938
		Number of cultural centers (y_{53})	+	0.0553
	Ecological urbanization (y_6)	Per capita park green area (y_{61})	+	0.0513
		Green coverage rate of built up area (y_{62})	+	0.0359
		Harmless treatment rate of municipal solid waste (y_{63})	+	0.0460
		Investment in environmental protection (y_{64})	+	0.0644
Water security (z)	Security of water quality (z_1)	Water quality standard rate of centralized drinking water source (z_{11})	+	0.0615
		Water quality up to standard rate of water environmental function area (z_{12})	+	0.0450
		Standard rate of industrial waste-water (z_{13})	+	0.0581
		Waste-water discharge amount (z_{14})	–	0.0760
		COD discharge amount (z_{15})	–	0.0607
		Ammonia nitrogen discharge amount (z_{16})	–	0.0621
		Urban sewage treatment rate (z_{17})	+	0.0855
	Security of water quantity (z_2)	Water yield modulus (z_{21})	+	0.0333
		Water supply modulus (z_{22})	+	0.0385
		Water resources per capita (z_{23})	+	0.0314
		Water consumption per capita (z_{24})	–	0.0376
		Development and utilization rate of water resources (z_{25})	–	0.0209
		Water consumption rate (z_{26})	–	0.0549
		Water consumption per 10,000 yuan GDP (z_{27})	–	0.0411
		Comprehensive production capacity of tap water (z_{28})	+	0.0347
		Total urban water supply (z_{29})	+	0.0353

(*Continued.*)

Table 1 | Continued

Target elements	Criteria for elements	Parameters	Parameters contribution	Weight of parameters
		Water use popularity rate (z_{210})	+	0.0382
		Water saving irrigation area (z_{211})	+	0.0519
		Controlling the area of soil erosion (z_{212})	+	0.0636
		Investment in water conservancy (z_{213})	+	0.0676

Note: '+' and '−' denote a positive and negative indicator for the elements, respectively.
We extract the raw data set of these indicators from statistical bulletins in Zhoushan, which refer to the realm of economic and social development, environmental situation and water resources, in the period 2001–2016.
*Statistical yearbook of Zhoushan, http://zstj.zhoushan.gov.cn/col/col1559852/index.html. Accessed January 5, 2021.
*Water resources bulletin of Zhejiang province, http://slt.zj.gov.cn/col/col1229243017/index.html. Accessed 10 March 2022.
*Statistical bulletin of national economic and social development of Zhoushan, http://zstj.zhoushan.gov.cn/col/col1559853/index.html. Accessed January 5, 2021.
*Environmental situation bulletin of Zhoushan, http://xxgk.zhoushan.gov.cn/col/col1229294458/index.html. Accessed 10 March 2022.

$$g(y) = \sum_{j=1}^{n} w_j y'_j \tag{2}$$

$$h(z) = \sum_{j=1}^{n} w_j z'_j \tag{3}$$

where $f(x)$, $g(y)$ and $h(z)$ indicate time series data of the target elements regarding tourism, urbanization and water security, respectively. w_j represents the weight of each parameter, while all criteria for the elements including x'_j, y'_j and z'_j, are normalized ranging from 0 to 1, indicating parameters for tourism, urbanization and water security, respectively.

In a further step, we evaluated changes in the annual value of each target element, and the dominant elements of TUW nexus system changes were identified as those whose annual changes exceeded values by 0.1. In practice, the function of this step is to reveal coevolutionary trends for the TUW nexus system in Zhoushan.

2.2.3.2. Model for assessment of the ability to adapt. Coupling coordination means a process of dynamic systemic balance to maintain a positive trend by interactive adaptation of its inner elements to realize a disorder to order (Liu *et al.* 2005). We measure the interactive adaptation among the target elements using a coupling coordination degree (CCD) model, as shown in Equations (4)–(6).

$$C = \left\{ \frac{f(x) \times g(y) \times h(z)}{[(f(x) + g(y) + h(z))/3]^3} \right\}^{1/3} \tag{4}$$

$$T = \alpha f(x) + \beta g(y) + \gamma h(z) \tag{5}$$

$$D = \sqrt{T \times C} \tag{6}$$

where C is the value of the coupling degree, ranging from 0 to 1, and T is the comprehensive value of the three elements. D denotes the value of coupling coordination degree, ranging from 0 to 1, with a higher D value implying a stronger interactive effect among the three elements. α, β and γ indicate undetermined coefficients. The sum of their values is 1, whereas their weights are given as 0.3, 0.3 and 0.4, respectively.

Moreover, the value of CCD, ranging from 0 to 1, was classified into five grades at an interval of 0.2, namely low coordination, slight coordination, moderate coordination, high coordination and perfect coordination, respectively.

2.2.3.3. Model for assessment of respond period. The vector auto-regression (VAR) method belongs to the impulse-response function, as shown in Equations (7) and (8). This model has been widely selected to analyze the response periods of one variable suffering disturbance from another variable. The detailed mathematical induction of the impulse response function can be retrieved from Chinco (2015).

$$\underset{Zt}{\begin{bmatrix} xt \\ yt \end{bmatrix}} = \underset{\Gamma}{\begin{pmatrix} \gamma_{x,x} & \gamma_{x,y} \\ \gamma_{y,x} & \gamma_{y,y} \end{pmatrix}} \underset{Zt-1}{\begin{bmatrix} xt-1 \\ yt-1 \end{bmatrix}} + \underset{\varepsilon_t}{\begin{bmatrix} \varepsilon_{x,t} \\ \varepsilon_{y,t} \end{bmatrix}} \tag{7}$$

$$Imp_x(h) = \Gamma^j C_x \tag{8}$$

where x is a shocked variable and h represents a response period (a lagged value) for this shocked variable. Γ indicates a coefficient matrix related to the fluctuation of variable x, C_x is a matrix related to a rescaled vector of shocks, while $Imp_x(h)$ denotes response values for the shocked variable x in periods of h.

We preprocess raw data, including logarithmic processing and stationarity tests, and prior to operation of the impulse response function in Eviews 9.0 to avoid data mistakes that refer to interference of heteroscedasticity and the phenomenon of pseudolinear regression, respectively. Then, we select a cointegration test to check the coexisting relationship among these time series data. In the successfully preprocessed clean datasets $f(x)$, $g(y)$ and $h(z)$, are marked as lf, lg and lh respectively.

3. RESULTS AND DISCUSSION

3.1. Coevolutionary trends of water security, urbanization and tourism

Evolutionary trend analysis revealed an overall upward trend of target elements (Figure 4). Nevertheless, the upward trend of water security exhibited a significant collapse in 2010. Similarly, its equilibrium changes were divided into two periods (2001–2009 and 2010–2016).

Specifically, the annual values of tourism and urbanization increased from 0.0575 to 0.9296 and 0.1144 to 0.8960, respectively, in the study period. Water security showed an upward fluctuation increase, from 0.5994 to 0.8263 in 2011 and 2016, respectively. Notably, we observed a tipping point of regime transformation (a sharp collapse of values) in water security in the temporal node of 2010. Subsequently, values of water security began to exhibit a lower level than that for urbanization and tourism after the temporal nodes of 2011 and 2013, respectively.

3.2. Coupling coordination degree of water security, urbanization and tourism

Notably, the values of coupling coordination for target elements decreased in 2011, but increased from 0.1591 to 0.7484, across the study periods. Similarly, the CCD of target elements maintained a stable upward trend, which exhibited an improvement from low coordination in 2001 to high coordination in 2016 (Figure 5).

3.3. Response period of water security impacted by tourism and urbanization

In this section, we present the results regarding the shock response of water security impacted by tourism and urbanization. Subsequently, we discuss the existing impact caused by island development on water security to increase knowledge about water security. We present a framework to enhance our interpretation (Figure 6).

3.3.1. Shock response occurred in water security to tourism and urbanization

Notably, water security was positively correlated with tourism, but negatively correlated with urbanization. The target elements show a long-term linear relationship from the stationary test, as shown in Table 2. Consistently, the analysis of interactive disturbance of target elements by VAR model shows that the most significant positive and negative impacts of shock response occurred in water security to tourism (Figure 7(e)), and water security to urbanization (Figure 7(f)), respectively.

3.3.2. The effects of tourism growth on water carrying capacity

Water security exhibited a positive response to tourism. As shown in Figure 6(a1), a one standard deviation shock to water security, from tourism, caused a maximum response value of water security that reached 0.0724, over a 1-year lag period. The response value then showed an obvious downward trend, and returned to the original value of 0 over an 8-year period.

Water carrying capacity has benefited from moderate tourism construction. The tourism sector has strived to avert any water-related crisis, and this effort has included diversion projects and water desalination to adapt to soaring tourist numbers in the tourism season (Gu *et al.* 2018; Zhu *et al.* 2018). A continental water diversion project has provided enough

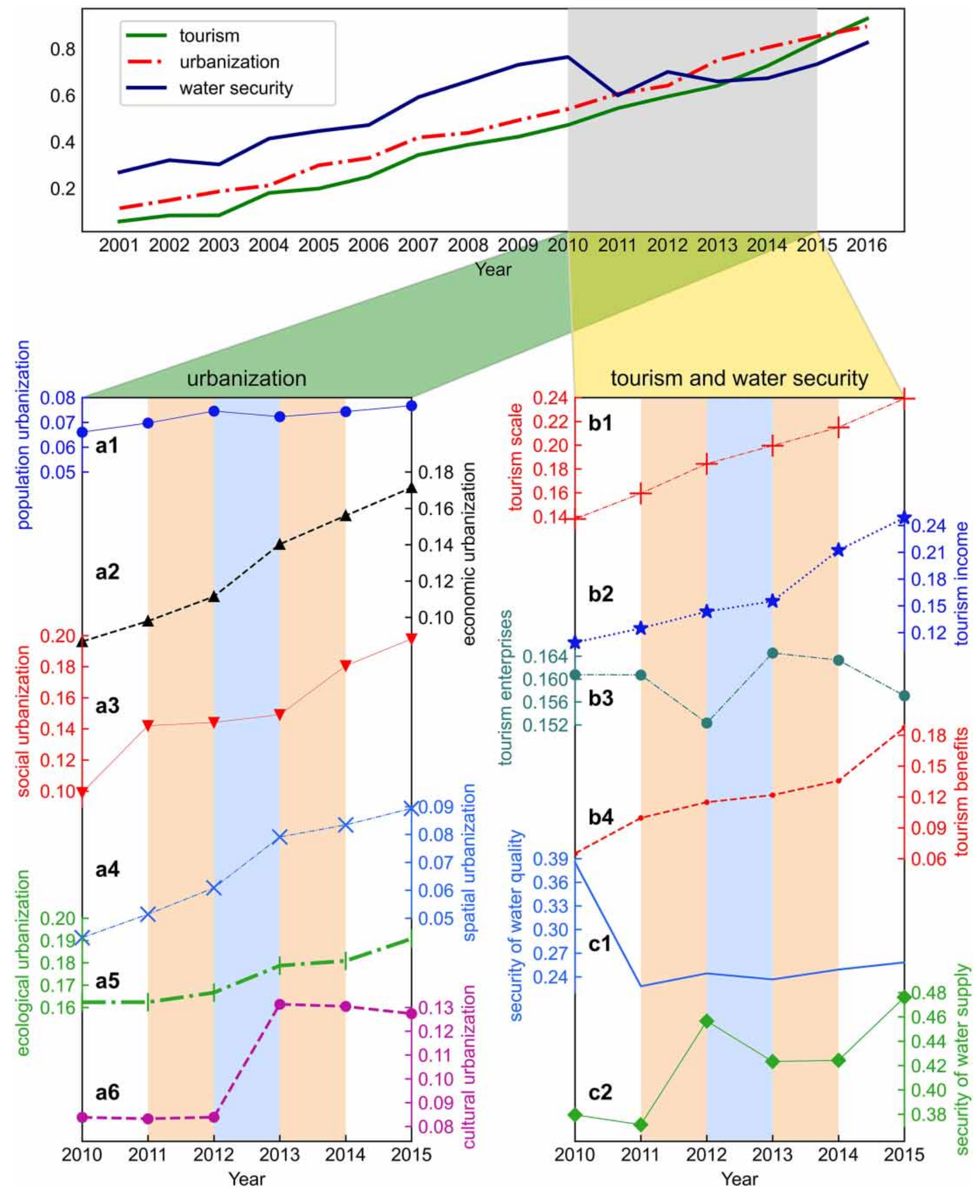


Figure 4 | Trends across tourism, urbanization and water security elements in Zhoushan.

water for Putuo Island in Zhoushan, the largest religious venue for Kwan-yin culture in China, which has enabled it to increase the number of tourists from 1.673 million in 2001 to 7.497 million in 2016 (ZMSB 2019). Moreover, the environmental protection administration of Zhoushan (EPAZ) determines to implement desalination in the tourism season (occurring between May and October), and these regulation measures have alleviated the periodic water crisis caused by soaring numbers of tourists on Miaozihu Island, one of the national ocean parks located in Zhoushan. As shown in Figure 6(c1), this island has experienced high-intensity tourism development, and is vulnerable in water storage (small terrestrial area with 2.64 km^2 and poor facilities).

Conversely, there is an attenuation trend regarding the positive impacts of tourism on water security. The solidified nexus between tourism and water security from artificial regulation may lead to the ability regarding self-adaption for a water system decrease in Zhoushan. Enterprises always pursue economic benefit, but mask implicit costs (consumption of public resources, such as ecosystem service) regarding ecosystem degradation in their activities (Xiao *et al.* 2011). Environmental economists have proposed terminology namely 'free-riding' and 'Limit to growth' to interpret this economic behavior (Liao & Yi 2021). These terms have revealed a phenomenon that human well-being stagnates despite economic growth.

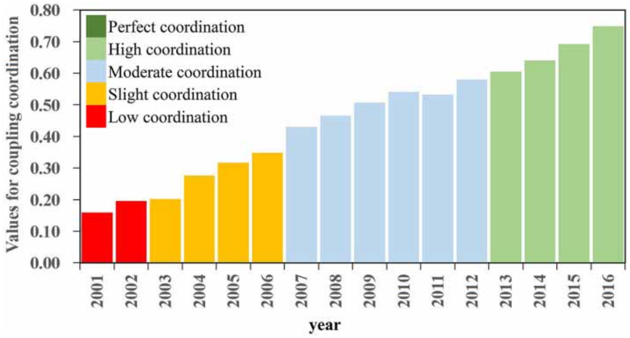


Figure 5 | The coupling coordination degree among tourism, urbanization and water security across study periods.

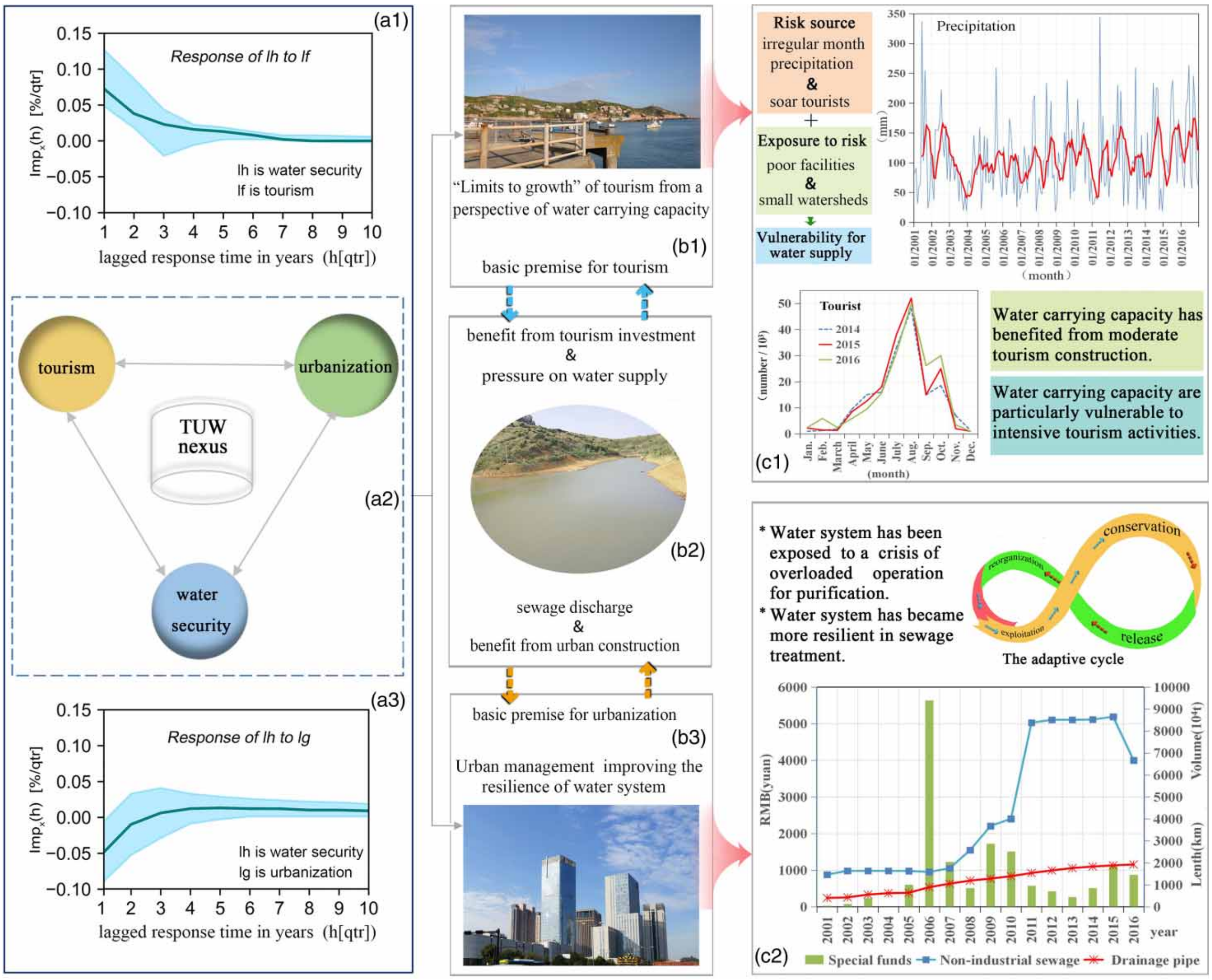


Figure 6 | A framework describing our discussion in relation to the impacts of island development on water security.

In this context, island sustainable development needs to embrace moderate construction activities and entail tradeoffs in ecological protection and development against exceeding the carrying capacity of the water system.

Overall, moderate tourism development promotes water security, but tourism activities should be well controlled under the threshold of carrying capacity for the water system to achieve island sustainable development.

Table 2 | Results of the stationary test

Null hypothesis of co-integration relationship	Eigenvalue	Trace statistics	5% critical value	*P* value	Maximum eigenvalue	5% critical value	*P* value
No	0.8270	38.1898	29.7971	0.0043	24.5662	21.1316	0.0158
At most one	0.5439	13.6237	15.4947	0.0939	10.9910	14.2646	0.1547

Note: The time series elements of lf, lg and lh showed an integration of 1-order in the stationary test after logarithmic processing, which met the premised condition of subsequent co-integration analysis. Moreover, at 95% confidence level, the value of $P<0.05$ indicates that the null hypothesis of co-integration relationship was refused, while the value of $P>0.05$ indicates the null hypothesis was accepted. The linear relationship among water security (lh) and another two elements is shown in Equation (9):

$$lh = 1.2134\,lf - 1.4328\,lg - 0.0433 \tag{9}$$

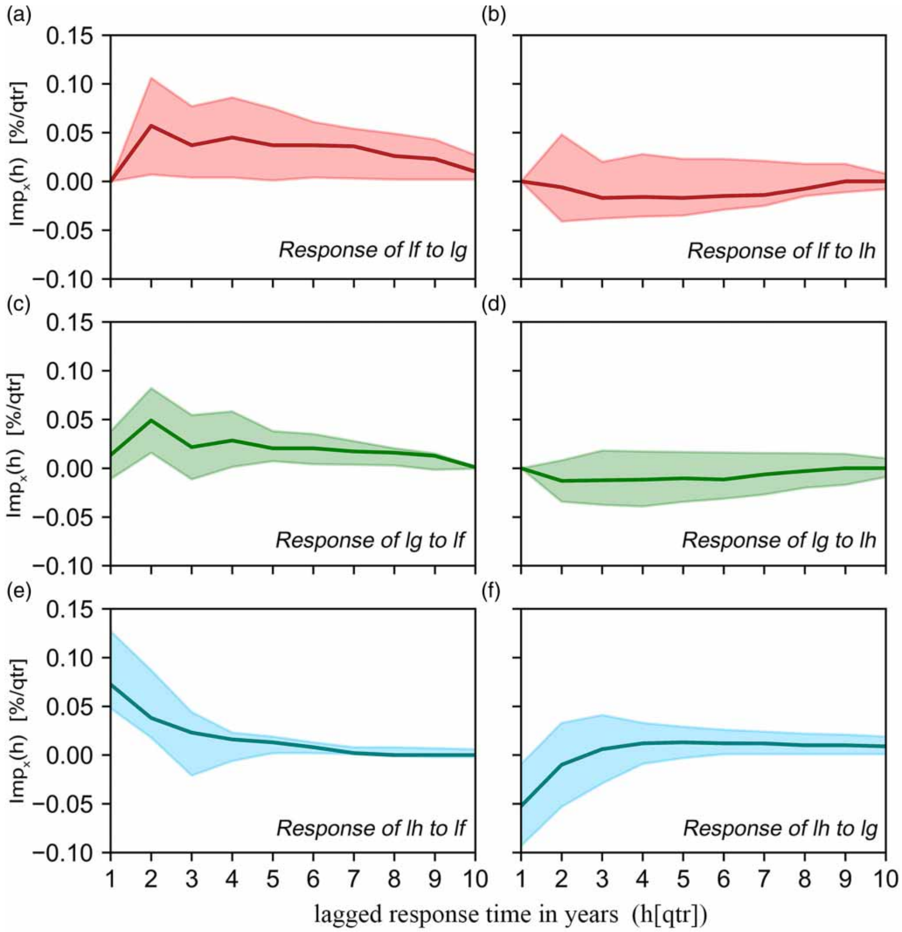


Figure 7 | Results of the impulse response function test (curve reveals the response time for one element crashed by another element, in an unexpected 1σ shock).

3.3.3. Urban construction improving the resilience of the water system

Water security exhibited a negative response to urbanization. As shown in Figure 6(a3), a one standard deviation shock in water security, from urbanization, caused the response value of water security to increase from −0.0524 to 0.0119 over 1- and 7-year, lag periods, respectively.

The water system has been exposed to a crisis of overloaded operation for purification. Urbanization has promoted population increase, which has led to increased sewage production. As shown in Figure 6(c2), sewage discharge into non-industrial settings suddenly increased to a high volume with an annual mean of 4.563×10^7 t during 2010–2016, in marked contrast to an annual mean of 1.173×10^7 t during 2001–2009 (ZMSB 2019). Consequently, as previously mentioned in the adaptive cycle, the vulnerability of the water system falls from the equilibrium to collapse phase, driven by urbanization.

What's more, as shown in Figure 6(a3), the water system has become more resilient to adapt to the impacts of urbanization in Zhoushan. For example, the water system is more able to return to the designed capacity with respect to purification under the current environmental constraints, as well as emerging shocks from urbanization. This resilience has benefited from improvement activities supported by special funds for urban construction from the Zhoushan government. The Zhoushan government provided special funds worth 1.77 billion RMB to improve the urban sewerage system from 2006 to 2010 (ZMSB 2019). So far, this has enabled integration of the domestic sewers into the sewage treatment system. An official report from the Zhoushan government's website showed that 96.64% of all industrial sewage was treated by the sewerage collection system in 2011 and in marked contrast to unorganized discharge in historic periods (ZMSB 2019). Consequently, resiliently managing water systems in Zhoushan has carefully improved the sewage collection system, and limited exposure to pollutants from sewage discharge. This will also enhance the benefits of environmental management and help to realize the goal of sustainable development.

Overall, the water system has been exposed to a crisis caused by urban construction. But, the Zhoushan government has invested to improve local vulnerable water systems, controlled the previously unorganized discharge of domestic sewage, and put in place measures to monitor pollution and ensure environmental protection.

4. CONCLUSIONS

In this study, we analyzed the impact of island development on water security from the perspective of the target element nexus in a socio-ecological system. We abstracted target elements into virtual nodes, and mathematical models quantified their mutual feedback and coupling coordination, on a temporal scale. This workflow is a bridge tool for us to understand the adaptation transitions of the water system in relation to disturbances driven by island development. This information is imperative for indicating the warning signals of water security loss.

Our main results showed that water security exhibited positive and negative shock responses to tourism and urbanization, over 1- and 7-year response periods, respectively. Furthermore, the equilibrium of the system has shifted from nature- to human-dominated since 2010. Interestingly, the water system has stably adapted to the interactions from island development, over the study period in Zhoushan, although it has experienced water shortages since 2010. We conclude that future urban planning programs should prioritize the water security of Zhoushan.

These findings provide a quantitative paradigm to island planners and decision makers for risk-informed management in relation to water systems in small island regions. The regime shift of interactive elements is simulated by signal recognition of adaptation fluctuation in the temporal dimension. The presented framework is flexible and can serve as a reference for the socio-ecological management of China's island cities, which face high-density anthropogenic activities and reduced resilience.

This study also had some limitations. Firstly, we were limited by insufficient data. This neglected spatial heterogeneity characteristics of the archipelago among individual islands. Secondly, we did not elaborate the topological relationship among the target elements, and the discussion only has a few significant proposals, due to the complexity of the socio-ecological system. Therefore, more comprehensive and scientific evaluation indicators are required to verify our findings. In future research, we will consider incorporating more influencing factors and data into the framework to verify our findings.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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