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The mediating effect of urban water system climate resilience in the impact of sponge city pilot policy on ecological welfare

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Water system safety is critically linked to socio-economic development and ecological welfare (EW). Under climate change, there is an urgent need to develop effective solutions that synergistically enhance urban water system climate resilience (UWSCR) and human welfare. The sponge city pilot policy (SCPP) implemented in China from 2015 to 2016 highlighted the importance of urban water systems for climate adaptation. Utilizing panel data from 280 prefecture-level and above cities in China from 2010 to 2020, this study adopts the multi-period difference-in-difference model to evaluate the effectiveness and heterogeneity of SCPP on improving EW, and examines the mediating role of UWSCR in the impact of SCPP on EW. The research conclusions are as follows: (1) SCPP has significantly improved EW. (2) SCPP is more effective in cities with medium heavy rain hazard, high or medium drought hazard, medium water resources endowment and high or low economic development level. (3) UWSCR, the direct objective of SCPP implementation, has played a mediating role in the effect of SCPP to enhance EW, indicating that SCPP is an effective policy instrument for synergizing climate adaptation and welfare improvement. Finally, suggestions were put forward to optimize SCPP. This study provides a scientific basis for promoting sustainable urban development under climate change.

Keywords Sponge city, Ecological welfare, Urban water system, Climate resilience, Resilient city, Policy effectiveness

Abbreviations

UWSCR	Urban water system climate resilience
SC	Sponge city
SCC	Sponge city construction
SCPP	Sponge city pilot policy
EW	Ecological welfare
DID	Difference-in-differences
ENR	Engineering resilience
ECR	Ecological resilience
EVR	Evolutionary resilience

The safety of water systems is critically linked to national economic development, people's livelihood, and ecological well-being. Global economic losses attributed to climate change-induced droughts and floods over the past five decades have reached approximately 3.6 trillion US dollars, accompanied by 2 million fatalities[1], significantly impacting human well-being. Sound ecological environment is the most inclusive benefits to people's well-being, and clean water and air, as well as a beautiful environment, are the growing needs of the people for a better life. Recent decades of rapid urbanization in China, however, have imposed severe challenges on urban areas, including degradation of aquatic ecosystems, reduction of conservation forests, persistent deterioration of water quality, and diminished water storage capacity[2,3]. This has resulted in the degradation or loss of multiple

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ecosystem services, adversely affecting human welfare[4]. Consequently, there is an urgent need to develop effective plans that synergistically enhance urban water system climate resilience (UWSCR) and human welfare. In 2015–2016, China launched two batches of 30 national level sponge city (SC) pilots. The main approaches include protecting the original urban ecosystem, restoring and repairing the ecology, and low-impact development[5]. The aim is to achieve the natural accumulation, infiltration, purification and sustainable water cycle of rainwater, enhance the natural restoration capacity of the water ecosystem, and maintain the good ecological functions of the city[5]. Urban water system is an important component of urban ecological environment, playing a crucial role in flood control, drainage and improvement of urban ecological environment[5]. Therefore, the focus of sponge city construction (SCC) is on the ecosystem centered around the water system. However, what is the relationship between UWSCR and ecological welfare (EW)? What is the policy effect of SCC on improving the UWSCR and enhancing EW? There are few studies specifically addressing this issue, and further exploration and answers are urgently needed.

To bridge this research gap, this study aims to evaluate the impact of sponge city pilot policy (SCPP) on enhancing the UWSCR and improving EW, and answer the following research questions. (1) What are the underlying mechanisms linking SCC, UWSCR, and EW? (2) Has SCPP become an effective instrument for enhancing EW? (3) Has UWSCR played a mediating role in the impact of SCPP on EW? (4) How can SCPP be further optimized? This study utilizes panel data from 280 prefecture-level and above cities in China from 2010 to 2020. A multi-period difference-in-differences (DID) model is applied to examine the impact of SCPP on EW. Furthermore, a mediation effect model is used to explore the mediating role of UWSCR in the SCPP's effects on EW. Finally, this study combines theoretical analysis and empirical results to propose some suggestions for promoting the development of SCs.

The marginal contributions of this study are primarily threefold. (1) A theoretical analysis framework of "resilience—ecological functional services—welfare" is innovatively constructed, the relationship between UWSCR, water ecosystem services, and EW is clarified, and the economic connotation of the impact of UWSCR on EW are expanded. It provides a new economic perspective for understanding the impact of water system resilience on EW under climate change. (2) The implementation of SCPP is regarded as a quasi natural experiment, and its effect on enhancing EW is quantitatively evaluated. (3) The mediating effect of UWSCR on the impact of SCPP on EW is examined, with the proposal that SCC is not only an effective measure for addressing climate change but also a key policy tool for improving EW. The innovative research perspective enriches and expands the study of EW and SCPP evaluation. Furthermore, the research results provide scientific support for China's systematic and comprehensive promotion of SCC, offer references for urban sustainable development planning and policy formulation, and also provide Chinese experience for promoting global urban collaborative climate change adaptation and EW improvement under climate change.

Literature review

SC

Since China launched the SC pilot construction, scholars have conducted research from the perspectives of urban planning, hydrology, and engineering, focusing on the concept of SCC[6], performance evaluation[7], risk assessment[8], urban resilience evaluation[9], and specific benefits[10]. A SC refers to a city that has good resilience in adapting to environmental changes and responding to natural disasters, and can absorb, store, infiltrate, and purify water during rainfall, and release and utilize the stored water when needed[5]. The core concept of SCC is to change the traditional and extensive urban development and construction mode, and minimize the adverse effects of urban development and construction on the original ecological and hydrological characteristics as much as possible[11]. On the basis of practice, the concept of SC has evolved from building a low impact rainwater comprehensive management system to transforming the concept of urban construction and development, with a focus on improving the overall function of the city and enhancing comprehensive response to urban water problems[6]. Research shows that SCs can alleviate urban rainstorm and flood disasters[12], urban waterlogging[13], urban water shortage[14] and other problems to varying degrees, and effectively improve the resilience of ecosystems with water system as the core[15]. However, research has shown that there are small, scattered, and fragmented phenomena in the pilot projects of SCs[16]. SCC mainly relies on traditional grey infrastructure[17], and its overall effectiveness in managing water cycles and maintaining ecosystem functions is questionable[18]. However, SCC in China is still insufficient to prevent flooding risks effectively[19], especially extreme rainfall events[20]. The reduction effect of sponge measures on runoff gradually weakens with the increase of rainfall recurrence interval[21]. The SCC requires the integration of ecosystem service frameworks into the mainstream of spatial planning[22] to achieve urban water resilience[23]. Research has shown that the SCC can bring multiple benefits, including disaster reduction benefits[24], alleviation of urban heat island effect[25], and savings in urban water treatment and pipeline operation costs[26]. Meanwhile, the SCC can also enhance the quality and overall image of the city, increase employment opportunities[27], promote the appreciation of surrounding real estate[28], encourage investment in green industries[29], and improve residents' satisfaction[30]. The commonly used method for evaluating the effectiveness of SCPP is the DID model[15,31], which can control the influence of unobservable characteristic variables to a certain extent[32]. The advantage of the DID model is that it can effectively utilize policy exogeneity, solve endogeneity bias, and avoid reverse causality problems. Its fixed effects estimation can reduce bias caused by omitted variables[33]. Multi-period DID model is an extension of the original DID model, aimed at studying the effects of implementing the same policy in different pilots at different implementation points, and applicable to the scenario of policy implementation in batches[15].

UWSCR

According to the resilience theory, it is generally believed that the UWSCR has three meanings: the subject of resilience is the water resource composite system composed of water resources, ecological environment, and human social production activities[34]; The targets of resilience are to cope with climate change and extreme events (such as heavy rain, drought)[35,36]; The core abilities of the subject include resistance, resilience, and adaptability[37]. The framework of urban water resilience includes four aspects of leadership and strategy, planning and funding, infrastructure and ecosystems, and health and well-being[38]. The evaluation logic of UWSCR can be divided into two types. The first type is to construct a resilience assessment framework based on urban water system elements, including water ecology, water resources, water environment, and water security, without considering the disturbance of climate disasters on urban water systems[39]. Alternatively, based on the concept of resilience, an evaluation index system can be constructed from three dimensions, including engineering resilience (ENR), ecological resilience (ECR), and evolutionary resilience (EVR)[40], or based on resilience characteristics, including resistance, recovery and adaptability[37]. However, this evaluation logic has certain limitations and fails to fully consider the relativity of resilience. Resilience should be a concept relative to external disturbances, and there may be significant differences in the response and adaptability of urban water systems in different regions and climate backgrounds. For example, according to this assessment framework, cities in high climate hazard and low climate hazard may have significant differences in their response capabilities and actual resilience levels. Therefore, some scholars introduced climate hazards and development level variables, established a two-dimensional coordinate of "Hazard—Resilience", and classified and evaluated the urban resilience coping with heavy rain[16]. The second evaluation logic is to incorporate climate factors as internal pressure indicators of urban water systems into the resilience assessment framework. For example, Liu et al.[41] believe that the stress dimension refers to the degree of risk of urban systems being affected by floods, and selected the maximum 24-h precipitation to characterize the pressure of cities facing short-term heavy rainfall.

EW

Welfare is a reflection of individual or collective preferences, and is the utility obtained through the consumption of certain goods or services[42]. Human welfare is closely related to the ecological environment, and changes in the ecological environment will have an impact on human welfare. EW refers to the transformation of ecosystem services provided by ecosystems into human welfare through the transmission mechanism formed by distribution and consumption[43]. At present, most research on water resources and EW is based on the logic behind EW performance, and studies on the EW performance of water resources or the EW efficiency of water resources are conducted[44,45]. The EW performance of water resources reflects the level of human welfare produced by unit water resource consumption[46]. The currently common method is the ratio analysis method, which takes water resource consumption[44] and water pollution[45] as input indicators, uses the Human Development Index to measure human welfare levels, and uses it as an output indicator[44] to measure the EW performance of water resources and explore how to maximize welfare output with minimal water resource consumption and pollution costs. Changes in aquatic ecosystem services will have an impact on human welfare[4]. Water ecosystem services firmly link the ecological processes of water bodies with human welfare[47,48], including four types of provisioning service, regulating service, supporting service, and cultural service[49]. The sustainable supply of aquatic ecosystem services is the foundation of sustainable economic and social development, providing direct benefits to humanity. However, at present, research on the UWSCR is limited to the evaluation and analysis of water system resilience itself, and there are few quantitative studies on the impact of water system resilience on social and economic development. Few studies have focused on the relationship between water resource resilience and EW. Under the combined impact of climate change and urbanization, a series of problems such as water scarcity, water environmental pollution, and severe water disaster losses have caused serious socio-economic losses and ecological damage, thereby constraining sustainable urban socio-economic development. Further quantitative analysis is needed on the EW effects of UWSCR, enriching the theoretical research on water system resilience and adaptation policies.

By reviewing relevant literature, it was found that: (1) previous studies analyzed the relationship between ecosystems and human well-being based on the logical framework of "structure function—service—welfare" of ecosystems. However, the increased uncertainty brought about by climate change makes it an inevitable requirement for urban sustainable development to enhance the resilience of ecosystems to disturbances such as floods and droughts. This study further incorporates "resilience" into the analytical framework, clarifying the relationship between UWSCR and EW within the resilience theory framework, thus providing a new approach for the study of the relationship between ecosystems and human welfare. (2) Existing research mostly studies SCs from the perspectives of urban planning, hydrology, and engineering, with few studies based on EW to empirically evaluate the policy effects of pilot projects and test whether SCPP can coordinate climate change adaptation and welfare improvement. (3) At present, economic research on water resources and EW is mostly based on the input–output efficiency perspective, using water resources as a production factor input indicator and pollutants and economic output as output indicators to analyze the EW efficiency of water resources. Existing research has failed to break free from the limitations of environmental economics based on production functions for environmental factor inputs and pollution control, while the concept of water system safety and resilience that SCC relies on is more based on emerging interdisciplinary theories such as ecological economics principles, sustainable development, and complex adaptive systems. Therefore, this study aims to fill this gap by clarifying the relationship between SC, UWSCR, and EW. The SCPP is regarded as a quasi natural experiment, and the impact of SCPP on EW and the mediating role of UWSCR are systematically empirically analyzed.

Theoretical analysis and hypotheses

Theoretical analysis framework of "resilience—ecological functional services—welfare"

The urban water system is a complex system that couples the natural and social water cycles[50,51], consisting of water resource subsystems, water infrastructure subsystems, and socio-economic subsystems[52]. Water ecosystem services refer to the services formed and provided by water ecosystems and ecological processes to maintain natural ecosystems and socio-economic systems[53], including provisioning services, support services, regulation services, and cultural services[54]. The service functions of aquatic ecosystems have binary characteristics. The services that maintain natural ecosystems driven by the natural water cycle and its associated processes include regulating climate, purifying water quality, purifying air, carbon sequestration and oxygen release, and maintaining biodiversity, and the services that maintain economic and social systems driven by the social water cycle process include entertainment and leisure, cultural education, resident health, ecological environment satisfaction, production and domestic water use[55–57].

Broadly speaking, EW refers to the satisfaction and utility that the products and services provided by the ecosystem ultimately bring to humanity through a series of resource allocation, production, consumption, and other processes, including economic welfare, social welfare, and green welfare[58]. Narrowly defined EW separates the ecosystem from the socio-economic system and refers to the green benefits provided by the ecosystem, such as air, water, climate environment, forests, and green spaces[58]. Based on previous research, this study believes that EW actually includes three aspects. Firstly, the ecological benefits of ecosystem service functions in improving water resources and environment, purifying air, flood and drought mitigation, carbon sequestration and oxygen release, and maintaining biodiversity. The second is the economic value created by the ecosystem as a natural capital of the urban socio-economic subsystem. The third is the intrinsic value of ecosystems in maintaining the sustainable development potential of urban social ecological composite systems, including enhancing urban livability, human health and labor productivity, quality of life and other social welfare.

Resilience refers to the ability of a system exposed to hazards to resist, absorb, accommodate, adapt to, transform and recover from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions through risk management[59]. Resilience is an important factor in ensuring the stability of urban water system functional structure and the supply of ecological services. The system function determines the system's services, and changes in the structure and function of urban water systems will directly affect water ecosystem services, leading to changes in EW. Enhancing the UWSCR involves adjusting and optimizing their functions and structures, thereby improving their ability to cope with external disturbances, maintaining and optimizing their supply, regulation, support, and cultural services. The ecological services of urban water systems are combined with human needs and transformed into environmental welfare, economic value, and social welfare. Specifically, enhancing the UWSCR can improve their regulation services, regulate and improve the quality of the ecological environment, including hydrological regulation, water purification, flood regulation, and local climate regulation. It can reduce risks such as local waterlogging and environmental pollution, and generate environmental benefits. The improvement of UWSCR can protect water resources, improve water quality, enhance the supply and service of water resources and aquatic products, meet the demand for clean and hygienic water resources, water environment, aquatic products and other basic materials in human production and life, and participate in production activities as production input capital, generating economic value. The improvement of water-saving technology and sewage treatment technology can promote the transformation of production methods, producing more products and services with less water consumption, thereby enhancing economic welfare. Therefore, improving the UWSCR can enhance the multiple service functions of water ecosystems. Firstly, it helps to improve the supply services of water ecosystems, providing clean water sources and high-quality aquatic products to meet the basic material needs of human survival. Secondly, enhancing UWSCR can also improve the regulatory support services of water ecosystems, providing humans with a beautiful water environment and aquatic ecology, and meeting their demand for a beautiful ecological environment. Thirdly, it can also enhance the social and cultural services of water ecosystems, providing an environmental carrier for leisure, entertainment, cultural education, and aesthetic appreciation for humanity, playing a positive role in improving human health and cognition, and enhancing social welfare.

The direct impact of SCPP on EW

The SCPP has a direct impact on EW by building and repairing grey municipal infrastructure and green infrastructure, increasing investment in funds and human capital, and enhancing environmental benefits, economic value, and social welfare (Fig. 1). Specifically, the SCPP directly affects the urban ecological environment by improving sewage treatment facilities, flood control and drainage engineering facilities, repairing natural green spongy bodies such as rivers, forests and wetlands, and building green infrastructure such as rain gardens and green roofs. It can increase natural water bodies and vegetation, improve the natural ecological environment, reduce flood risks, optimize and enhance the urban living environment, and thus enhance environmental benefits. Infrastructure investment is an important foundation for achieving economic growth[60], which can induce direct production activities[61], increase output, promote private investment, and improve employment[62]. Infrastructure investment as an input in production also helps to drive an increase in the supply of other inputs, thereby affecting productivity[63]. Through the construction of gray infrastructure and blue-green infrastructure, the SCPP can produce more high-quality ecological products and services with less capital consumption, reduce the consumption of water resources for economic growth, and reduce sewage emissions. SCs adopt rainwater harvesting and utilization measures to store rainwater for use in greening, firefighting, landscaping, road and car washing, etc., improving water resource utilization efficiency[27]. At the same time, by providing policy and financial support for SCC projects, improving private investment productivity, integrating high-quality resources, and using grey, green, and blue infrastructure as production inputs together with other capital, a SC industrial chain is formed to promote economic growth. The level of social welfare not only depends on economic growth, but also on the quality of the environment that humans rely on for survival[64]. The SCC has increased the green area of cities and communities, dredged and repaired old rainwater and sewage pipelines, alleviated urban waterlogging, and treated black and odorous water bodies, which can directly improve the urban living environment and enhance residents' satisfaction with their living

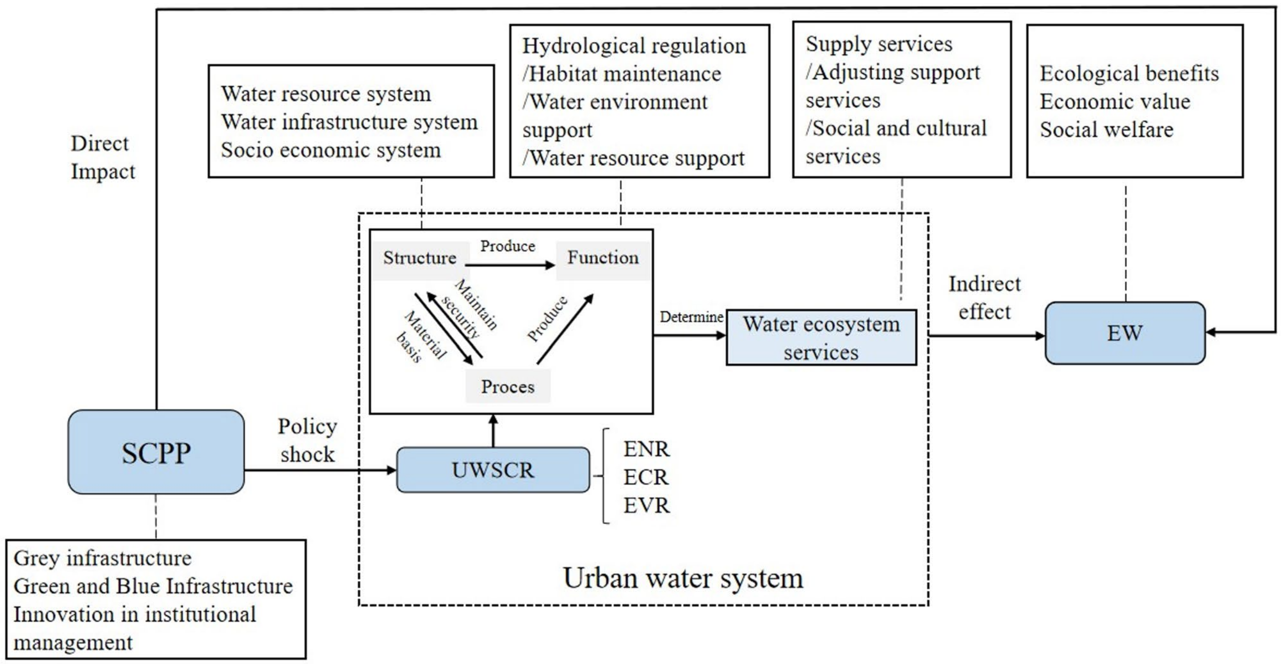

Fig. 1. The impact of SCPP on EW.

environment. Meanwhile, the SCC can provide relevant job opportunities, generate employment, and enhance social welfare. Therefore, the SCC focuses on investing in the construction of ecosystems with water systems as the core, improving the natural ecological environment and urban living environment, promoting economic growth, enhancing residents' satisfaction with life, increasing employment, and improving EW.

In addition, there are significant differences in climate hazards, water resource conditions, and economic development level among cities in different regions of China, and the impact of SCPP on EW may be heterogeneous. First of all, meteorological disasters are mostly related to rainstorm, flood and drought. Flood control and waterlogging resistance are the primary goal of SCC[15]. There is heterogeneity in the impact of SCPP on EW with different climate hazards. In areas with frequent heavy rain, SCs can effectively alleviate waterlogging and flood disasters by improving rainwater collection and drainage capacity, thus improving urban ecological environment and residents' quality of life. In arid areas, SCs focus more on the storage and efficient utilization of water resources, promoting sustainable management of water resources. The differences needs caused by different climate hazards determine the implementation effectiveness of SCPP in different regions, therefore their role in improving EW varies regionally. Secondly, the differences in water resource endowments also have a significant impact on the effectiveness of SCPP. The SCPP improves the efficiency of rainwater resource conversion and EW by optimizing the rainwater collection and utilization system. However, differences in water resource conditions in different regions can affect the effectiveness of policy implementation. Thirdly, the level of economic development is one of the key factors determining the effectiveness of SCPP. Economically developed regions have strong financial support, technological capabilities, and innovative resources, which enable SCC to be more refined and systematic, forming a good ecological, social, and economic cycle and enhancing overall EW. On the contrary, in economically underdeveloped areas, the SCC often faces challenges due to financial and technological constraints, making it difficult to fully realize their EW. Based on the above analysis, this study proposes the following hypothesis:

Research hypothesis 1 *SCPP can improve EW.*

Research hypothesis 1a *The impact of SCPP on EW varies among cities with different climate hazards.*

Research hypothesis 1b *The impact of SCPP on EW varies among cities with different water resource conditions.*

Research hypothesis 1c *The impact of SCPP on EW varies among cities with different levels of economic development.*

The indirect impact of SCPP on EW: the mediating role of UWSCR

The SCPP generates a mediating effect by enhancing the UWSCR, adjusting and optimizing the structure and functions of urban water systems, and optimizing water ecosystem services, thereby indirectly affecting EW, namely improving environmental welfare, economic welfare, and social welfare (Fig. 1). Specifically, the SCPP maintains and increases natural green spaces and water bodies through the construction of sewage treatment facilities, rainwater and sewage treatment facilities, drainage and waterlogging facilities, and the use of artificial natural capital such as rain gardens, green roofs, and artificial wetlands to supplement natural capital, strengthens human capital and capital investment, and promotes innovation in water resource management systems. These measures of SCC enhance the UWSCR.

The improvement of UWSCR plays an important role in ensuring the supply of water ecosystem services and enhancing welfare. The SCPP further enhance the urban EW by improving the UWSCR. While improving the UWSCR, the structure and function of urban water systems have been adjusted and optimized, thereby enhancing the supply services, regulation support services, and cultural services of water ecosystems. The improvement of water resources, aquatic products, green spaces and other supply services, as well as hydrological regulation, water quality purification, flood regulation, local climate regulation and other regulatory support services in urban water systems, can reduce water pollution and flood risks[12], improve water ecology and water environment, maintain natural ecological processes and regional ecological environment conditions, thereby indirectly improving environmental welfare. The material products such as water resources and aquatic products provided to society by the supply services of aquatic ecosystems can directly participate in economic production activities as production factors and effectively promote economic growth by increasing total output. Climate regulation, uniform flooding, water quality purification and other regulatory support services play a huge role in ensuring normal urban production and life. For example, water quality purification can increase fishery production, beautiful environment can increase surrounding housing prices[28], attract tourists and drive tourism development, and uniform flooding can increase capital and labor input in other aspects of society, indirectly participating in economic production activities. The contribution of social and cultural services to economic development is mainly reflected in activities such as tourism, leisure and entertainment, which bring economic output and indirectly enhance economic welfare. In addition, aquatic ecosystems provide intangible benefits to humanity in the form of cultural entertainment, education, and aesthetic experience, thereby creating more social value. At the same time, innovation in water resource management systems will increase the demand for water resource management talent positions, play an active role in the utilization and management of ecosystem services, optimize and enhance the supply and demand relationship of ecosystem services, and make the supply of water ecological services more sustainable, thereby indirectly enhancing social welfare. Through three aspects of welfare enhancement, the EW effects brought by SCPP will be internalized in the livability and quality of life of a city, directly or indirectly enhancing its competitiveness.

Based on the above analysis, this study proposes the following hypothesis:

Research hypothesis 2 *The UWSCR plays a mediating role in the impact of SCPP on EW.*

Methodology and data

Econometric model

The basic principle of the DID model is to treat the policy as a quasi natural experiment, and to explore the impact of policy intervention behavior on specific groups by distinguishing between policy pilot groups and non pilot control groups[15]. Currently, the DID model is widely used in the effectiveness evaluation of urban planning policy[15,65]. Multi period DID is applicable to scenarios where the policy is implemented in batches[15,31]. It is possible to more accurately capture the dynamic changes in policy effectiveness. The core idea is to estimate the net effect of the policy by comparing the changes in differences between the experimental group and the control group before and after policy implementation[65]. Specifically, as an effective solution to the problems of selection bias and endogeneity, DID model can effectively eliminate the heterogeneity of individuals before and after policy implementation that does not change over time and the incremental effects that change over time, thereby stripping out the net effects of policy implementation shocks on individuals[66]. The principle is to use individual fixed effects and time fixed effects estimation. It incorporates time dummy variables into the model to control for periodic and long-term factors that affect the explained variable, and incorporates individual dummy variables into the model to control for unobserved inter individual and non temporal differences that affect the explained variable[66].

The SCPP was launched in two batches in 2015 and 2016, which meet the applicable conditions of the multi period DID model. The SCPP can be seen as an exogenous shock to cities. In order to identify the impact of SCPP and eliminate potential endogeneity interference, this study considers SCPP as a quasi natural experiment and uses a multi period difference-in-difference model for estimation. Select panel data from 280 prefecture level and above cities from 2010 to 2020 as research samples, and consider 27 SC pilots as experimental groups, namely the first batch of pilot projects implemented in 2015, including Chongqing, Baicheng, Zhenjiang, Jiaxing, Chizhou, Xiamen, Pingxiang, Jinan, Hebi, Wuhan, Changde, Nanning, and Suining. The second batch of SC pilots implemented in 2016 includes Fuzhou, Zhuhai, Ningbo, Yuxi, Dalian, Shenzhen, Shanghai, Qingyang, Xining, Sanya, Qingdao, Guyuan, Tianjin, and Beijing. Other cities not included in the pilot program serve as control groups. By comparing the EW of the experimental group and the control group, the effect of SCPP on EW can be observed.

To test hypothesis 1, with reference to Chen[67], model 1 was constructed. The specific model is as follows:

$$\mathrm{EW_{it}} = \delta_0 + \delta_1 \mathrm{policy_{it}} + \delta_2 \mathrm{C}X_{\mathrm{it}} + \mathrm{u_i} + \mathrm{u_t} + \varepsilon_{\mathrm{it}} \quad (1)$$

In Eq. (1), i represents the city, t represents the time, and EW_{it} represents the EW of the i-th city in the t-th year. $Policy_{it}$ indicates whether city i was established as a SC pilot in the t-th year. Before being approved as a SC pilot, policy = 0, and policy = 1 in the year of establishment and thereafter. CX_{it} represents a series of other control variables that affect EW. u_i represents the individual fixed effects of each city, u_t represents the year fixed effects, and ε_{it} is the random perturbation term. The coefficient δ_1 is the core parameter that this study focuses on, representing the policy effect of SC pilots on EW. If the SCPP, as an exogenous institutional arrangement, does indeed enhance EW, then the coefficient δ_1 should be significantly positive.

To test the impact of the core explanatory variable on the mediating variable, model 2 is constructed:

$$UWSCR_{it} = \gamma_0 + \gamma_1 \text{policy}_{it} + \gamma_2 CX_{it} + u_i + u_t + \varepsilon_{it} \tag{2}$$

In Eq. (2), γ_1 represents the effect of the SCPP on the UWSCR. If the SCPP, as an exogenous institutional arrangement, does indeed enhance the UWSCR, then the coefficient γ_1 should be significantly positive.

Add mediator variables to the regression model to test whether the combined effect of mediator variables and core explanatory variables has a significant impact on the dependent variable. Construct model 3:

$$EW_{it} = \theta_0 + \theta_1 \text{policy}_{it} + \theta_2 UWSCR_{it} + \theta_3 CX_{it} + u_i + u_t + \varepsilon_{it} \tag{3}$$

In Eq. (3), the regression coefficient θ_1 refers to the direct effect of SCPP on EW with the inclusion of the mediating variable of UWSCR. The regression coefficient θ_2 represents the effect of the mediating variable, UWSCR, on EW, while controlling for explanatory variables.

Variable selection

Dependent variable

The dependent variable of this study is EW. Based on the researches[45,68,69], and the availability of city level data, seven indicators were selected to construct an EW indicator system (Table 1). SCC can improve water quality, sustainable use of water resources, and green space area by increasing urban green spaces, rainwater management, and rainwater pollution treatment facilities. Therefore, this study selected water quality index, per capita water resources, and green space area to characterize environmental welfare. Economic welfare refers to the economic value generated by the participation of ecological environment resources as production input capital in production activities. SCC has promoted investment in green infrastructure and the development of related industries, which helps to enhance the overall economic competitiveness of cities. Therefore, this study selects per capita GDP to represent economic welfare. The Human Development Index is a comprehensive indicator to measure the development level of a country or region, which is mainly evaluated through three dimensions: health level, education level, and income level, reflecting the human well-being level of a country or region[70]. On this basis, this study selects employment, resident health guarantee, and education level to characterize social welfare, and does not consider difficult to quantify social welfare such as leisure and entertainment for the time being. Considering that the World Health Organization usually uses life expectancy to assess the health status of residents[71], but China lacks complete statistical data on life expectancy at the urban level for each year. Professional physicians are a key human resource guarantee for ensuring residents' health, effectively preventing diseases, and providing basic medical services[72]. Referring to Chen et al.[73], select the number of physicians per thousand people to represent residents' health guarantee. Based on the three major goals of sustainable scale of the economic system, fair allocation of resources, and effective allocation within the scope of total utilization of natural resources and services in ecological economics, the weights of the three criterion layers are set to 1/3 using equal weighting method. Secondly, the entropy value method with time variables is used to determine the weights of each indicator under each criterion layer. Multiply the weights of each criterion layer by the weights of the indicators within each criterion layer to obtain the final weight of each indicator (Table 1). Finally, the standardized values of each indicator are multiplied by their weights and summed to obtain the comprehensive EW index.

Explanatory variable

The core explanatory variable of this study is the policy variable SCPP. Before being approved as a SC pilot, policy = 0, and in the year of approval and thereafter, policy = 1.

Control variable

In order to examine the net impact of SCPP on EW, it is also necessary to control other economic and social variables that may affect EW. Control the following variables based on data availability:

First-level indicator	Attribute	Second-level indicator	Weight	Type
Environmental welfare(1/3)	Water resource	Water quality index	0.0075	–
		Per capita water resources	0.1368	+
	Green space	Green area	0.1891	+
Economic welfare(1/3)	Economic output level	Per capita GDP	0.3333	+
Social welfare(1/3)	Employment	Growth rate of employees in urban units	0.0470	+
	Resident health guarantee	Number of physicians per thousand people	0.2286	+
	Education level	Proportion of education expenditure to fiscal expenditure	0.0577	+

Table 1. EW evaluation index system. "+" indicates that the indicator is positive, and the larger the value, the higher the EW level.

Urbanization rate (UR), expressed as the ratio of the permanent urban population to the total permanent population. With the advancement of urbanization, the demand for water resources, ecological environment pressure, and water system construction in cities may increase accordingly.

Industrial structure (IS), expressed as the proportion of the added value of the secondary industry to GDP. The industrial structure determines the types of urban economic activities and the consumption patterns of water resources, which in turn affects the resilience of water systems and the improvement of EW.

Intensity of financial expenditure (IFE), expressed as the ratio of financial expenditure to GDP. It reflects the level of government investment in public services and infrastructure construction, especially in the fields of water resource management and ecological environment protection.

Environmental regulation (ER), expressed as the ratio of the frequency of environmental vocabulary words in government work reports to the frequency of words in work reports. It reflects the government's emphasis on environmental protection and the actual implementation of policies.

Energy consumption (EC), characterized by energy consumption per 10,000 yuan of GDP. Referring to Liang et al.[74] and Li et al.[75], the total energy consumption is obtained by adding up the electricity consumption, gas consumption, and liquefied petroleum gas consumption (all converted to 10,000 tons of standard coal). High energy consumption is often accompanied by significant carbon emissions and excessive consumption of water resources, which may have a negative impact on water system resilience and EW.

Population density (PD), expressed as the ratio of permanent population to administrative area. It reflects the pressure of population per unit area on resource demand and ecological environment carrying capacity.

Mediating variable

The mediating variable is the UWSCR. Based on resilience theory and the characteristics of urban water systems, and referring to Yuan et al.[76], this study constructs an evaluation index system for UWSCR from three dimensions of ENR, ECR and EVR (Table 2). Climate pressures are included as internal pressures on UWSCR in the evaluation index system. Among them, ENR is reflected in the ability of water related infrastructure systems to recover to a stable state after being disturbed by floods and droughts, manifested in three aspects: sewage treatment capacity and water supply and drainage capacity[76]. ECR emphasizes the degree to which the ecological hydrological system increases buffering capacity and absorbs disturbances, which is related to climate pressure, water resource endowment, water resource conservation capacity, ecological water replenishment intensity, and groundwater abundance[68–78]. EVR emphasizes the ability of the socio-economic level to adapt and upgrade to floods, droughts, and disasters, including water resource management, technology, and economic support infrastructure[76,79,80]. The comprehensive index of UWSCR is calculated using a combination of Analytic Hierarchy Process and Entropy Method. The selection criteria and specific calculation process of the indicators refer to Yuan et al.[76].

Data sources and descriptive statistics

The data for this study is panel data from 280 cities at or above the prefecture level from 2010 to 2020. Among them, urban socio-economic data comes from the China Urban Statistical Yearbook, China Urban Construction

First-level indicator	Attribute	Second-level indicator	Formula	Ultimate weight	Type
ENR (0.2212)	Sewage disposal capacity	Urban sewage disposal rate	Amount of sewage disposed/total sewage discharged	0.0101	+
	Storm drainage capacity	Density of drainage pipelines in built-up areas	Length of drainage pipelines in built-up areas/area of built-up areas	0.1072	+
	Water supply capacity	Density of water supply pipelines in built-up areas	Length of water supply pipelines in built-up areas/area of built-up areas	0.1039	+
ECR (0.4851)	Climate pressure	Maximum 24-h precipitation	Maximum 24-h precipitation	0.0029	–
		Drought index	Accumulated number of days with moderate drought or above	0.0029	–
	Water conservation capacity	Greenery coverage in built-up areas	Area of greenery coverage in built-up areas/area of built-up areas	0.0916	+
	Ecological water supply	Eco-environmental water use per unit built-up area	Amount of eco-environmental water use/area of built-up areas	0.1997	+
	Climate endowment of water resources	Water yield Coefficient	Total water resources/precipitation	0.0390	+
	Groundwater abundance	Proportion of groundwater resources	Groundwater resources/total water resources	0.1490	+
EVR (0.2937)	Financial input	Fixed assets investment in water-related municipal public facilities	Sum of fixed assets investments in water supply, drainage, landscaping and urban environment & sanitation	0.2118	+
	Human capital input	Practitioners in water conservancy, environment and public facilities management	Number of practitioners in water conservancy, environment and public facilities management	0.0797	+
	Water saving and sewage discharge	10,000 yuan Gross Domestic Product (GDP) sewage discharged	Amount of sewage discharged/GDP	0.0009	–
		10,000 yuan GDP water used	Amount of water used/GDP	0.0013	–

Table 2. The evaluation index system of UWSCR and weight coefficient of each indicator. "+" indicates that the indicator is positive, and the larger the value, the higher the UWSCR level.

	(1)	(2)	(3)	(4)	(5)
Variables	N	Mean	SD	Min	Max
Policy	3,080	0.0481	0.2139	0.0000	1.0000
EW	3,080	0.1184	0.0409	0.0435	0.5381
EC	3,080	0.0881	0.0799	0.0000	1.0269
UDC	3,080	4.5456	0.8454	2.5649	7.3232
UR	3,080	0.5530	0.1457	0.0649	1.0000
FE	3,080	0.2329	0.2274	0.0072	1.7635
IS	3,080	0.4647	0.1078	0.1170	0.8224
ER	3,080	0.0034	0.0014	0.0000	0.0124
UWSCR	3,080	0.0620	0.0306	0.0216	0.3359
PD	3,080	5.7481	0.9895	1.6635	9.8632

Table 3. Descriptive statistics of each variable.

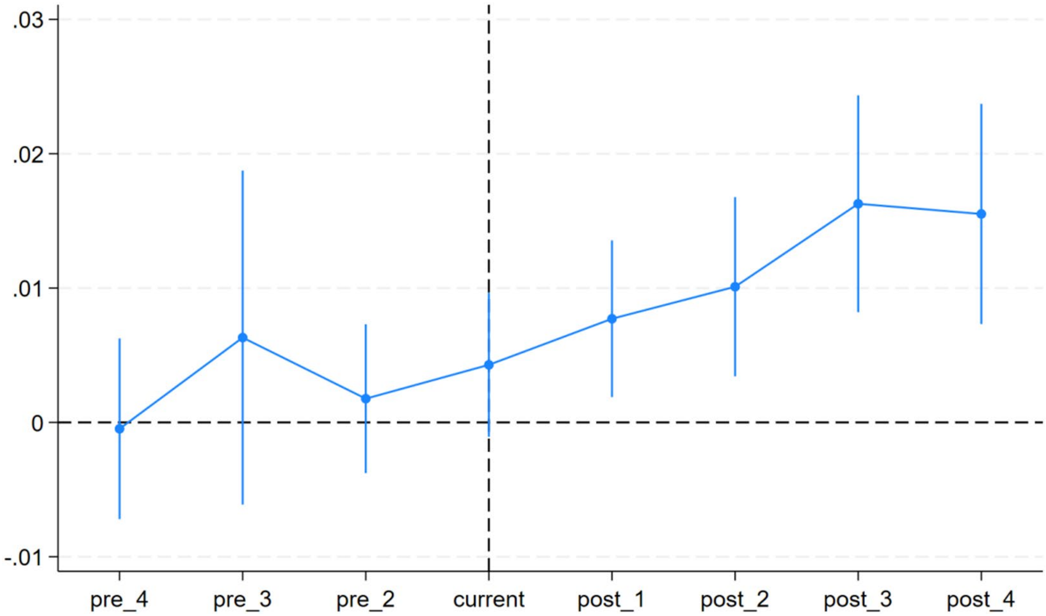

Fig. 2. Parallel trend test.

Statistical Yearbook, Statistical Yearbooks and Social and Economic Statistics Bulletin of each city and its province. The data related to water resources comes from Water Resources Bulletin and Ecological Environment Status Bulletin of each city and its province, and the Institute of Public and Environmental Affairs. Environmental protection vocabulary comes from Government Work Reports of various cities. Climate data is provided by the National Climate Center. Partial missing data can be obtained by applying to the water resources department of the province where each city is located through open application. In addition, due to the lack of publicly available statistical data for individual cities and years, there is a 4% missing data in the panel data. Some missing data in certain years were completed using the mean method and linear interpolation method. Due to the low proportion and uniform distribution of missing data, its impact on the overall trend of panel data is limited. Except for the comprehensive index and ratio values calculated in this study, all other data were logarithmically processed. Table 3 shows the descriptive test results for each variable.

Empirical results and analysis

Parallel trend test

To test whether the multi period difference-in-difference model satisfies the common trend hypothesis, this paper draws on the parallel trend test method proposed by Bertrand and Mullainathan[81] to generate dummy variables for the experimental groups and time in four periods before and after the policy implementation. To avoid the impact of multiple collinearity, the previous policy period is used as the baseline for estimation. The estimated results are shown in Fig. 2, where the horizontal axis represents the policy implementation time, pre_4 represents the policy dummy variable for the first four years before policy implementation, post_1 represents the dummy variable for one year after policy implementation, others can be inferred in the same way. The vertical axis represents policy effects, with positive values indicating positive impacts and negative values indicating negative impacts. The dots represent coefficient values, and the vertical lines indicate confidence intervals. If the confidence interval intersects with the dashed line with a coefficient of 0, it indicates that the coefficient is not significant. From Fig. 2, it can be seen that there was no significant difference in the trend of changes between the experimental group and the control group before the establishment of the SCPP, but there was a significant difference after the implementation of the policy, which satisfies the parallel trend hypothesis.

Basic regression result

Table 4 reports the regression results of the impact of the SCPP on the EW. The first column shows the estimated results without control variables, and the coefficient of the core explanatory variable policy is significantly positive, indicating that the SCPP helps to improve the EW. The second column shows the results of adding control variables, and the coefficient is also significantly positive. The third column shows the estimated results of further controlling for individual fixed effects, and the impact coefficient of the pilot policy on urban EW is 0.0158, which is significant at the 1% level. The fourth column shows the estimated results of further controlling for the year fixed effects. The impact coefficient of the pilot policy on the EW is 0.0107, which is significant at the 1% level, indicating that the implementation of the SCPP can effectively improve the EW.

Robustness tests

Placebo test

To further eliminate the influence of other unknown factors on EW and clarify that the improvement of EW is brought about by the SCPP, this study adopts the counterfactual assumption method for robustness testing. That is, the experimental group and the control group are randomly shuffled and the same number of groups are selected as the new experimental group. The same treatment is applied at the policy time point, and the above experiment is repeated 500 times to obtain the regression coefficients and corresponding *p* values of 500 random policy shocks[31]. Figure 3 shows the results of the individual placebo test. The mean of the estimated coefficients of the sample regression is concentrated around 0, and all regression coefficients do not exceed the basic regression coefficient (0.0107), indicating that the study passed the individual placebo test. Therefore, the conclusion of this study is robust.

Excluding the impact of other policy

The net effect of SCPP may be affected by other policies. On the basis of considering the sample investigation period and relevant literature[65], climate resilient city pilot policy implemented in 2017 is taken into consideration, constructing a virtual variable "otherpolicy" for climate resilient city policy and incorporating it into model (1). Before the city is approved as a climate resilient pilot, otherpolicy = 0. In the year of its establishment and thereafter, otherpolicy = 1. As shown in column (1) of Table 5, after considering the impact of climate resilient

	(1)	(2)	(3)	(4)
Variables	EW	EW	EW	EW
Policy	0.0466***	0.0170***	0.0158***	0.0107***
	(13.92)	(6.97)	(3.62)	(2.67)
EC		−0.0350***	−0.0247*	−0.0399**
		(−4.90)	(−1.80)	(−2.40)
UDC		0.0182***	0.0235***	0.0070**
		(18.81)	(5.43)	(2.04)
UR		0.1315***	0.1509***	0.0248
		(26.29)	(6.13)	(1.10)
FE		−0.0011	−0.0295**	−0.0395**
		(−0.40)	(−2.38)	(−2.52)
IS		−0.0394***	−0.0577***	0.0217
		(−7.93)	(−3.75)	(1.37)
ER		1.5273***	−0.7836*	−0.4146
		(4.30)	(−1.75)	(−0.96)
PD		−0.0062***	−0.0818***	−0.0894***
		(−9.55)	(−4.14)	(−4.63)
Constant	0.1162***	0.0147***	0.4359***	0.5701***
	(158.37)	(3.05)	(3.99)	(5.08)
Observations	3,080	3,080	3,080	3,080
R^2	0.059	0.534	0.412	0.489
Id FE	NO	NO	YES	YES
Year FE	NO	NO	NO	YES

Table 4. The overall effect of SCPP on EW. T statistics are in brackets, and ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.

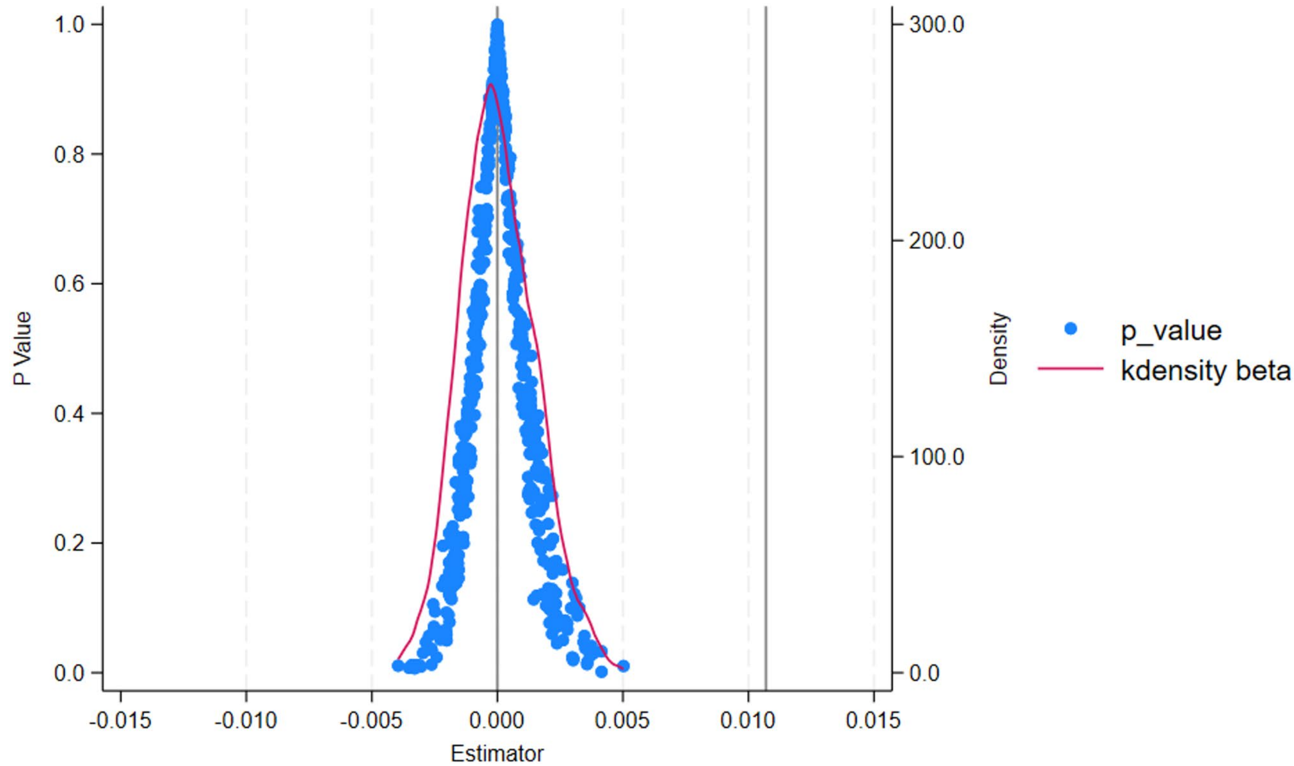

Fig. 3. Placebo test results of EW.

Variable	(1) Excluding the impact of other policy	(2) Excluding the impact of Covid	(3) Winsorization
Policy	0.0102**	0.0097**	0.0080***
	(2.53)	(2.41)	(2.60)
Constant	0.5710***	0.6293***	0.3203***
	(5.09)	(5.19)	(8.04)
Control variables	Yes	Yes	Yes
City FE	Yes	Yes	Yes
Year FE	Yes	Yes	Yes
Observations	3,080	2,800	3,080
R^2	0.490	0.446	0.481

Table 5. Robustness test results. Robust t-statistics are in brackets, and ***$p<0.01$, **$p<0.05$, *$p<0.1$.

city pilot policy on EW, the impact of SCPP on EW is still significant, and the regression coefficient is not significantly different from the basic regression, indicating the robustness of the basic regression results.

Exclude the impact of Covid

Considering that the sample time interval selected in this paper includes the year 2020, when the COVID-19 epidemic that affects the world occurred, the public health emergencies are strictly exogenous external shocks to the complex urban system[31]. If this factor is not considered, it may lead to endogenous problems. After excluding the special samples from 2020, the regression was conducted again, and the significance of the core explanatory variable policy remained consistent with the previous conclusion (Table 5).

Winsorization

To eliminate the influence of extreme values in the EW index of the dependent variable on the regression results, referring to Zhang et al.[65], the winsorization is used to deal with it. The column (3) of Table 5 shows that the coefficient of policy is still positive at the significant level of 1% under the condition of 1%-99% winsorization, so it passes the winsorization test.

Variable	Group of heavy rain hazard			Group of drought hazard		
	High	Medium	Low	High	Medium	Low
Policy	0.0081	0.0131*	0.0092	0.0127*	0.0126*	0.0053
	(1.34)	(1.86)	(1.07)	(1.89)	(1.87)	(0.77)
Constant	0.8179***	0.5351**	0.1263	0.7693***	0.3216***	0.5884***
	(5.12)	(2.60)	(1.65)	(4.25)	(4.03)	(3.30)
Control variables	YES	YES	YES	YES	YES	YES
City FE	YES	YES	YES	YES	YES	YES
Year FE	YES	YES	YES	YES	YES	YES
Observations	1,023	1,023	1,034	1,023	1,023	1,034
R^2	0.611	0.631	0.275	0.562	0.410	0.561

Table 6. Heterogeneity analysis results of pilot policy effects based on climate hazard. Robust t-statistics are in brackets, and ***$p<0.01$, **$p<0.05$, *$p<0.1$.

Variable	Group of water production coefficient			Group of economic development		
	High	Medium	Low	High	Medium	Low
Policy	0.0008	0.0099***	0.0107	0.0130**	−0.0047	0.0062**
	(0.09)	(3.03)	(1.59)	(2.26)	(-0.70)	(2.17)
Constant	0.6643***	0.3663***	0.6707***	0.7128***	0.3274***	0.1541***
	(5.18)	(4.89)	(3.28)	(5.02)	(5.02)	(3.51)
Control variables	YES	YES	YES	YES	YES	YES
City FE	YES	YES	YES	YES	YES	YES
Year FE	YES	YES	YES	YES	YES	YES
Observations	1,023	1,023	1,034	1,023	1,023	1,034
R^2	0.502	0.499	0.578	0.639	0.526	0.366

Table 7. Heterogeneity analysis results of the impact of the SCPP on the EW. Robust t-statistics are in brackets, and ***$p<0.01$, **$p<0.05$, *$p<0.1$.

Heterogeneity analysis

Heterogeneity of climate hazards

Heavy rain and drought are selected as the main meteorological disasters. Referring to the calculation method of Yuan et al.[76], the multi-year average heavy rain days and drought days of representative meteorological stations in 280 cities from 1981 to 2010 were calculated, and these data were normalized to calculate the urban heavy rain hazard index and drought hazard index of 30 year climate cycle respectively. Referring to the classification method of Zhang et al.[65], based on their numerical values, 280 cities were divided into three types of high, medium, and low. Table 6 shows that among the groups with moderate heavy rain hazard, the SCPP has a significant effect on improving EW. However, in the grouping of high-hazard and low-hazard of heavy rain, the coefficient of policy is not significant. The reason is that in cities with moderate heavy rain hazard, through improving blue-green infrastructure and strengthening water resources management, the water environment can be effectively adjusted, air quality can be improved, green space can be increased, employment can be driven, and EW can be improved. In cities with high hazard of heavy rain, extreme precipitation occurs frequently. Although the policy has contributed to the improvement of the ecological environment, the policy effect may not be significant due to the excessive risk of heavy rain in high-hazard areas. Heavy rain low-hazard cities have low demand for water resources management, so the ecological environment improvement benefits of SCPP are limited, and the effect of improving EW is not significant. In the grouping of high hazard and medium hazard of drought, SCPP has a significant effect on improving EW. Because these cities have stronger demands in dealing with water scarcity and ecological vulnerability, measures such as rainwater collection and groundwater recharge in SPs have a direct impact on improving the ecological environment. In cities with low drought hazard, the water conservancy and ecological environment problems in these cities are not as urgent as in high-risk areas, so the effect of SCPP is not significant.

Heterogeneity of water resource endowment

Referring to Yao et al.[15], the per capita water resources are selected as the indicator of water resources stock to distinguish urban water resources endowment. Divide 280 cities into three types: high, medium, and low, based on the average per capita water resources from 2010 to 2020. Table 7 shows that in the group with moderate urban water resource endowment, SCPP significantly improved EW. Although these cities have relatively moderate water resources, they face certain pressures in water resource use and management. Measures related to SCs, such as rainwater collection, drainage system optimization, and ecological landscape restoration, can effectively

Variables	(1) EW	(2) UWSCR	(3) EW
Policy	0.0107***	0.0073**	0.0100**
	(2.67)	(2.17)	(2.56)
UWSCR			0.0963**
			(2.30)
Constant	0.5701***	0.0735***	0.5630***
	(5.08)	(3.32)	(5.02)
Observations	3,080	3,080	3,080
R^2	0.489	0.097	0.492
Control variables	YES	YES	YES
Id FE	YES	YES	YES
Year FE	YES	YES	YES

Table 8. The indirect impact and intermediary mechanism of the SCPP on the EW. Robust t-statistics are in brackets, and ***$p<0.01$, **$p<0.05$, *$p<0.1$.

improve the efficiency of water resource utilization and have a significant promoting effect on improving EW. However, in the groups of high and low urban water resource endowments, the coefficient of policy is positive but not significant. The reason is that in cities with high water resource endowments, water resources are abundant and the ecological environment is relatively stable. The impact of SCPP may be relatively small, so the effect is not significant. For cities with low water resource endowments, due to high population density or insufficient precipitation, they face great water resource pressure, resulting in less significant improvement in policy effectiveness.

Heterogeneity of economic development
Based on the average per capita GDP from 2010 to 2020, 280 cities are divided into three types of high, medium, and low. Table 7 shows that in the groups with high and low levels of economic development, SCPP significantly improved EW, while for cities with moderate levels of economic development, the effect of SCPP was not significant. This may be related to the resource allocation and demand structure of the city. Cities with high levels of economic development usually have better infrastructure and financial support, which can effectively implement SC measures such as rainwater collection and drainage system optimization, thereby improving EW. Cities with low levels of economic development, although relatively weak in economy, may face greater ecological pressure due to rapid urbanization or overdevelopment. Therefore, SC measures can also bring significant ecological improvements in these areas. However, for cities with a moderate level of economic development, due to their relatively stable economic development, infrastructure construction may be relatively lagging behind or uneven, and the investment and effectiveness of SC measures may not meet expectations.

Analysis of impact mechanism
According to analysis, the SCPP improves the UWSCR, thereby enhancing the EW. Table 8 reports the test results of the mediating effects of the SCPP on the EW and UWSCR. The first list indicates that SCPP can significantly improve EW. The results in column (2) indicate that SCPP can significantly enhance the mediating variable of UWSCR. By observing the results in column (3), it can be seen that the mediating variables of UWSCR and the core explanatory variables have positive and significant impact coefficients on EW, indicating that the mediating effect of UWSCR in the impact of SCPP on EW is established.

Conclusions and policy recommendations
This study uses a multi period difference-in-difference model and panel data from 280 prefecture level and above cities in China from 2010 to 2020. The implementation of SCPP is considered a quasi natural experiment to test the policy effects and heterogeneity of SCPP on improving the EW, and further examine the mediating role of UWSCR in the impact of the SCPP on the EW. The main research conclusions are as follows: (1) The SCPP has achieved significant results and can effectively improve the EW. However, after a series of robustness tests, the conclusion is still valid. (2) Heterogeneity analysis found that the implementation effect of SCPP varies under different climate hazards, water resource conditions, and economic development levels. The SCPP is more effective in areas with medium heavy rain hazard, high or medium drought hazard, and areas with medium water resources endowment and high or low economic development level. (3) The UWSCR, which is a direct target of SCC, has played a mediating role in the policy effects of SCC to enhance the EW. The SCPP can improve the EW by enhancing the UWSCR, and is an effective policy tool for coordinating climate change adaptation and welfare improvement.

Based on the above conclusions, this study proposes the following policy recommendations: (1) Guided by the concept of water resilient cities, strengthen the construction of SCs. The UWSCR plays a mediating role in the policy effects of SCPP on the EW. Therefore, the SCC should pay more attention to enhancing the resilience of water systems. Specifically, investing in green infrastructure such as permeable paving, rain gardens, and wetland restoration can enhance the self-regulation of urban water systems and their ability to respond to extreme weather events. At the same time, it is recommended to strengthen the water resource management system, promote efficient allocation and recycling of water resources, in order to cope with the increasingly severe climate change and water resource pressure. (2) Adopt differentiated policy support for different types of pilot cities. In areas with moderate hazard of heavy rain, the SCC can significantly improve the EW. Therefore, it is necessary to increase investment in rainwater collection, infiltration, and storage facilities, promote green infrastructure construction such as wetland restoration and green space expansion, and improve water resource utilization efficiency and ecological environment quality. For areas with high hazard of heavy rain, focus on improving drainage system capacity and emergency response, reducing flood disaster risk, and strengthening urban hydrological monitoring. For low hazard areas of heavy rain, it is necessary to focus on improving rainwater permeability and ecological restoration, reducing dependence on traditional drainage systems, and optimizing rainwater management. SCC can help improve EW in high hazard and medium hazard areas of drought. Therefore, in high hazard areas, efforts should be made to strengthen the construction of rainwater collection and storage facilities, promote the use of recycled water, restore vegetation and wetlands, and enhance soil moisture retention capacity. Areas with moderate drought hazard should focus on optimizing water resource management and scheduling, and improving the efficiency of water resource recycling. In low hazard areas, ecological restoration can be promoted by increasing green infrastructure, improving the ecological function of green spaces, enhancing rainwater infiltration and natural evaporation. In areas with good water resources, it is necessary to further increase the construction of rainwater collection and storage facilities, increase the proportion of green spaces and permeable surfaces, optimize urban drainage systems, and enhance the sustainability of the ecological environment. In areas with poor water resource conditions, efforts should be made to improve the efficiency of water resource utilization. Measures such as improving water resource scheduling capabilities, optimizing reservoir and storage facility construction, and strengthening the application of water-saving technologies should be taken to better cope with water scarcity and enhance the potential for ecological restoration. In regions with high levels of economic development, due to abundant financial resources and mature technological conditions, investment in SCC can be increased, with a focus on promoting the construction of facilities such as rainwater collection, storage, and recycling, in order to achieve ecological protection and economic development. At the same time, it can encourage technological innovation and intelligent management, promote the development of green infrastructure, and further improve EW. For cities with moderate economic development levels, policy support and financial investment should be increased to enhance project management capabilities, promote technology promotion and application, focus on improving existing drainage systems and ecological environments, and gradually improve policy effectiveness. In areas with lower levels of economic development, due to financial and technological limitations, low-cost and high-efficiency measures should be prioritized, such as optimizing urban planning and land use, increasing the proportion of green spaces and permeable ground, making reasonable use of local natural resources, and gradually improving the coordination between local economy and ecological construction through government guidance and policy support. (3) Strengthen cross departmental collaboration and policy integration. The SCC involves multiple fields such as water resource management, environment, urban planning, municipal facilities, and climate. Therefore, establish a cross departmental policy collaboration mechanism to promote information sharing and resource integration among various departments in the process of SCC. By formulating a comprehensive policy framework to ensure synergy in urban planning, infrastructure construction, ecological protection, and other aspects, multiple goals of climate change adaptation, ecological environment governance, and social welfare improvement can be achieved.

Compared with previous studies, the contribution of the above research lies in evaluating the effectiveness of SCPP in enhancing the EW and their applicability under different climate and economic conditions, examining the mediating effect of UWSCR, which is a direct target of SCC, on the policy effect of improving the EW through pilot construction, providing scientific basis and reference for collaborative climate change adaptation and welfare improvement. This study also has some limitations, as data availability issues did not include indicators such as residents' health and satisfaction with their living environment that better reflect the EW. In the future, a multidimensional indicator system can be further integrated, such as through resident survey data, environmental health monitoring data, to more comprehensively evaluate the impact of SCC on the EW. As the research period of this study was from 2010 to 2020, it failed to cover the COVID-19 pandemic and the subsequent economic adjustment period. Therefore, it was impossible to test the effect of SCPP in maintaining EW stability in an economic downturn environment. Therefore, future research should be extended to a longer time series, incorporating data from post-pandemic and subsequent stages, to comprehensively assess the effectiveness of SCPP in maintaining EW stability and promoting recovery against the backdrop of downward economic pressure. In addition, longer time span data can also be considered to explore the response capabilities and adaptability of SCs to different climate scenarios. Due to data availability issues, the 30 SC pilot cities established in 2015–2016, including one county-level city and two National New Areas, were not included in the sample of pilot cities for this study. Quantitative research methods mainly focus on quantifiable data and indicators, making it difficult to capture some non quantitative factors and explain the underlying mechanisms and key factors. Future research can combine case analysis and field research to explore the impact of non quantitative factors in policy implementation on the effectiveness of SCC.

Data availability

The datasets used and/or analysed during the current study available from the corresponding author on reasonable request.

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Declarations

Competing interests
The authors declare no competing interests.

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