Quantification of Water Supply Services in the Shiyang River Basin Using the HSPF Model

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Abstract: Water supply services are a focal point of research on aquatic ecosystem services, and the quantification of supply services is also a key aspect of water supply service studies. This paper characterizes the availability of water supply in the study area using the Available Water Supply Index to investigate the situation of available water supply in an arid region under human intervention. It establishes a quantitative framework for assessing the reliability and vulnerability of ecosystem service delivery related to available water supply, utilizing reliability and vulnerability indices. These analyses address two primary questions: first, the reliability of regional available water supply services when meeting the most basic ecological water needs, and second, the vulnerability of available water supply services when striving to meet increased production demands in the region.

This study focuses on the Shiyang River Basin and employs the Hydrological Simulation Program-FORTRAN (HSPF) model for runoff simulation, evaluating the model's applicability using criteria such as residual sum of squares and correlation analysis. Building on the subdivision of sub-basins within the Shiyang River Basin and adjustments for extra water diversion data, this research conducts a spatiotemporal analysis of available water supply in the Shiyang River Basin for the year 2017 and addresses the two aforementioned questions. The results indicate that the basin's available water supply services are reliable, but they become vulnerable when the region seeks to increase yields and meet growing demands. Attention should be given to areas at risk, with a focus on areas exhibiting seasonal fluctuations for meteorological crisis preparedness. Policy adjustments should also be considered for areas with consistently high values of available water supply.

Keywords-HSPF Model; Available Water Supply Services; Water ecosystem service Flows; Shiyang River Basin

1. Introduction

The Millennium Ecosystem Assessment [1] has highlighted some conclusions regarding future environmental challenges. It underscores the vulnerability of arid land ecosystems, where approximately sixty percent of ecosystem services are currently undergoing degradation. Water

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plays a pivotal role in the delivery of ecosystem services [2], dynamically and across scales, linking human beings and the environment, thus influencing the sustainability and development of arid land ecosystems [3]. Water scarcity stands as a critical natural factor that constrains socio-economic and ecological security, impacting human survival and regional modernization efforts. Research on water ecosystem services provides valuable insights into addressing issues within arid land ecosystems.

Artificial interventions such as water diversion projects have alleviated the problem of water resource scarcity in arid regions. However, studies on water ecosystem supply services considering these human interventions are relatively scarce. Existing research has predominantly focused on water ecosystem services under natural conditions, posing a challenge in understanding these services in the presence of non-natural factors.

There is an increasing amount of research in the field of aquatic ecosystem services, covering the interaction between human society and the biosphere [3]. Studies on aquatic ecosystem services often focus on drinking water [4] and freshwater [5], with freshwater research frequently involving complex water quality models that increase the complexity of studying watershed ecosystems [6]. Research on aquatic ecosystem services in arid regions should not be limited to the study of drinking water alone. The "Millennium Ecosystem Assessment" defines the amount of water that meets environmental flow requirements as available water and specifies specific indices to describe its availability. Research on the provision of available water services is beneficial for assessing the sustainability of available water supply in the study area and its supply status, among other factors. The key focus should be on how to fully and reasonably utilize water resources to ensure the sustainable development of arid land ecosystems.

Research on aquatic ecosystem services primarily focuses on supply, demand, and regulation. The variation in aquatic ecosystem services under different research contexts is complex, and studies on the supply of aquatic ecosystem services can provide support for understanding these complex changes. Common research indicators for water supply, based on ecological water requirements, represent the supply of regional available water. These indicators, such as hydrological methods, hydraulic methods, holistic analysis, and habitat methods, are relatively coarse. Estimating ecological water threshold values requires a large amount of observational data, and building ecological water demand models is quite complex. Nowadays, finding a quantification method for available water supply that is simple in terms of data requirements and scientifically effective is particularly important.

Modeling aquatic ecosystem services can help address various issues because it enables the simulation of the impacts of changes in aquatic ecosystem services. The Hydrological Simulation Program-FORTRAN (HSPF) model is used to simulate hydrological processes related to water quantity and quality in watersheds of nearly any scale and complexity [7]. It is one of the most widely used watershed hydrology and water quality models internationally [8]. The HSPF model can simulate hydrological processes in watersheds, surface runoff, lakes, and other water bodies at different time scales, allowing for simulations and predictions under various scenarios with high accuracy and reliability. HSPF is commonly applied in arid regions, particularly in areas where most agricultural and irrigation activities are concentrated [9], for assessing watershed water supply [10], and predicting freshwater ecosystem service supply [11]. In 2021, the HSPF model was first used for water supply services [10]. Subsequently, literature has also used the predicted water supply from the HSPF model to represent aquatic ecosystem service supply [11].

The HSPF model has achieved research success and widespread application in hydrological process simulation and analysis, particularly in runoff processes [12, 13], but there is still significant room for improvement in arid land hydrology research.

This study explores Hydrological Ecosystem Services (HES flows) [14] in the Shiyang River Basin, an area of increasing interdisciplinary interest. Water supply services in the region are traditionally assessed using the InVEST model, known for simplicity but limited precision. In contrast, the HSPF model, though data-intensive, offers superior accuracy and versatility. Its potential application in the Shiyang River Basin warrants further investigation.

Ecological water use, a core aspect of watershed water demand, profoundly affects industry, agriculture, and domestic needs. Assessing the reliability and vulnerability of ecological water use via the available water index is crucial for the basin's welfare. Balancing basin development, agricultural production, water allocation, and policy formulation is imperative. This research on available water supply services guides water resource policies, addressing the challenge of increasing food production while considering water supply vulnerability.

The study evaluates available water supply's spatial and temporal distribution, incorporating external interventions' impact on water ecosystem services. It utilizes reliability and vulnerability indices to gauge water supply dependability. Leveraging the HSPF model, the research quantifies ecosystem services' available water supply, providing a scientific foundation for enhanced water resource management in the basin.

1.1 The study area

The Shiyang River Basin is situated in the eastern part of the Hexi Corridor in Gansu, China, and it lies within a typical arid region in northwestern China [15]. The elevation in the Shiyang River Basin ranges from 1,243 to 5,207 meters above sea level, and it experiences a continental temperate arid climate characterized by significant temperature fluctuations, limited precipitation, intense evaporation, and dry air [15]. For a long time, the lower reaches of the Shiyang River have heavily relied on regulation through water supply from the upstream and midstream regions [16]. (Figure 1)

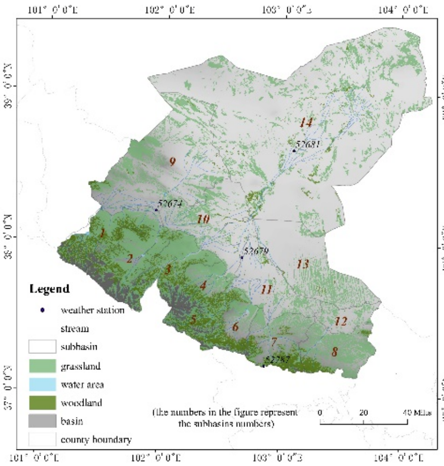

Figure 1. The Study Area

2.1 Data processing

This study relies on multiple datasets, including DEM (Digital Elevation Model), watershed hydrology, land use, and meteorological data. To facilitate their use as input data for the ArcSWAT sub-basin delineation tool and to ensure compatibility with BASINS 4.5 software, specific processing steps have been undertaken. The DEM data, obtained from NASADEM, boasts a spatial resolution of 1 arc-second (30 meters) and employs the GCS_WGS_1984 coordinate system, originating from NASA (National Aeronautics and Space Administration). Meanwhile, the watershed hydrology data is based on the foundational dataset for the Shiyang River Basin from the National Tibetan Plateau Science Data Center, adopting the National 2000 Geodetic Datum and Albers projection coordinate system.

2. Method

2.1 HSPF Modeling

Scientific and accurate simulation and assessment of available water services and their variations in the Shiyang River Basin serve as a critical foundation for evaluating the effectiveness of water resource management and ecological governance within the basin. It also fulfills the demand for further refining comprehensive measures for controlling available water resources throughout the entire basin. In this study, the Hydrological Simulation Program-FORTRAN (HSPF) is employed, specifically utilizing the PERLND and RCHRES modules for modeling and analysis of the basin.

The modeling process with HSPF involves several key steps. First and foremost is the mathematical representation of the basin, which includes the input of meteorological and hydrological time series data. The SARA Timeseries Utility, a watershed data management program, is utilized for efficient data management and transmission. Subsequently, parameter estimation, calibration, and validation are carried out to ensure the accuracy of the model. Finally, the model simulates and provides output data, including the flow rates at the outlets of each sub-catchment area within the basin. This comprehensive modeling approach is instrumental in understanding and managing available water services and their dynamics in the Shiyang River Basin.

2.2 Available Water Supply Index

The Freshwater Provisioning Index [17] defines freshwater supply as a function of both the quantity and quality of available water. Assuming water quality meets standards and fully satisfies ecosystem needs (in which case the water quality component equals 1), the Freshwater Provisioning Index ($FWPI_t$) can be used as an indicator of whether the available water in the study area meets environmental flow requirements [18]. The calculation formula is expressed as follows:

$$FWPI_t = Q_t \times I_t \tag{1}$$

$$Q_t = \left(\frac{MF_t / MF_{EF}}{(MF_t / MF_{EF}) + qne_t / n_t} \right) \tag{2}$$

In the provided formula, Qt represents the water quantity indicator, It signifies the water quality indicator, MF_t stands for the average flow (m^3/s), MF_{EF} corresponds to the long-term environmental flow requirement (m^3/s), and qne_t denotes the count of instances within the time step where the flow falls below the environmental flow requirement. According to reference[18], the long-term environmental flow requirement for ecosystems is defined as 30% of the mean flow. The calculation of qne_t is done seasonally, with 10% of the mean flow for the periods from October to March and from April to September. When Q_t equals 1, it indicates that the regional water quantity service is in excellent condition. Conversely, if the environmental flow requirement is not met, Qt will be less than 1, signifying a reduction in the regional available water supply service.

In this study, the long-term environmental flow is considered as 30% of the annual average minimum flow, and qnet is calculated as 10% of the annual average minimum flow, with these calculations being performed on a seasonal basis.

2.3 Reliability Index

Both the reliability index and the vulnerability index are part of the energy intensity indices used to assess the amount of energy required to supply each unit of water to the beneficiaries in water ecosystem services. The reliability index is defined as the probability that water resources can meet regional water demands during the simulation period[19], as expressed in Formula 3.

$$\boldsymbol{Reliability}=\frac{D^i=0}{N} \tag{3}$$

In the formula, the denominator N represents the number of times water resources meet consumer demands, while the numerator Di corresponds to the length of the i th simulation period. When the reliability index approaches 1, it indicates a high level of reliability in the region, signifying that water resource supply is more dependable. Conversely, when the reliability index is less than 1, it signifies a decrease in regional reliability, indicating reduced dependability in water resource supply.

2.4 Vulnerability Index

The vulnerability index measures the severity of harm and is used to assess the extent of water resource deficit during the simulation period. It is defined as the proportion of the average deficit to the average demand, representing the degree of water deficit during the simulation period.

$$\boldsymbol{vulnerability}=\frac{\sum_{j=1}^{N} D_j^i / D^i>0}{WD} \tag{4}$$

In the formula, the numerator represents the average deficit when water resources fail to meet consumer demands, and the denominator WD is the average water demand. When the vulnerability index approaches 1, it indicates lower ecological vulnerability in the region. When the index is less than 1, it suggests that regional water resource supply is more fragile and unstable, signifying a higher degree of vulnerability.

3. Results

3.1 Model Parameter Calibration

Calibration is an iterative process employed to establish the most appropriate values for certain model parameters. In the HSPF model, there are multiple adjustable parameters, and the selection and determination of these parameters require a comprehensive consideration of various factors, including watershed characteristics, observed data, model objectives, and more. In model simulations, the calibration process is of paramount importance, as it's often the only way to find reliable values for certain parameters.

3.2 Results and Validation

Using the calibrated parameters in the HSPF model, calculations were performed to estimate the water supply for each sub-basin. The output results were then compared with the monthly data for Da Jing River, Gu Lang River, Huang Yang River, Jin Ta River, Za Mu River, Xi Ying River, and Xi Da River in the Shiyang River Basin for the same year, as reported in the Shiyang River Basin Water Resources Bulletin. To assess the model's performance and suitability, residual sum of squares and Spearman's non-parametric Rho correlation coefficient were employed for simulation effect verification and model applicability evaluation. The calculated residual sum of squares for the HSPF model results was 0.46, and the Spearman's Rho correlation coefficient was found to be 0.347**, signifying a significant correlation at the 0.01 significance level. These statistical measures provide validation and demonstrate the model's ability to closely align with the observed data, indicating its suitability for assessing water supply in the Shiyang River Basin.

3.3 Watershed External Diversion Data Correction

The Available Water Supply Index that hasn't been adjusted for extra water diversion data often fails to adequately account for the influence of human interventions, which can result in an inaccurate representation of the actual conditions in arid regions. By incorporating a correction factor for water diversion, it becomes possible to better capture the impact of human intervention measures on available water supply. In accordance with relevant data on reservoir operation and irrigation management in the Shiyang River Basin, downstream Minqin Oasis underwent correction for extra water diversion data. The results show a significant improvement in the Available Water Supply Index for this region after the correction was applied. (Figure 2)

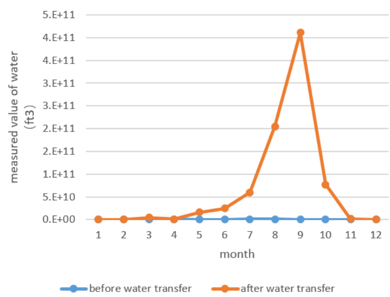

Figure 2. Comparision of monthly runoff volume

Temporal and Spatial Characteristics of Available Water Supply Services. The results of the 2017 Available Water Supply Index for the Shiyang River Basin, calculated using the HSPF model and corrected for extra water diversion data, are displayed in Figure 4. The figure presents the values of the Available Water Index for twelve different months across fourteen distinct sub-basins, with values ranging from 0 to 1. These results reveal that the available water supply in the Shiyang River Basin exhibits significant regional variations and seasonal fluctuations.

3.3.1 Regional Disparity Characteristics

The overall available water supply service in the Shiyang River Basin appears to be relatively stable, but there are significant differences among the various sub-basins. By comparing the annual average Available Water Index with the annual average Available Water Index for each sub-basin, the following observations can be made Sub-basins 6, 14, 2, 8, and 4 have annual average Available Water Supply Index values exceeding the overall average. These sub-basins exhibit relatively good water resource supply and may possess higher potential for sustainable water resource utilization. Sub-basins 9 and 3 also have annual average Available Water Supply Index values slightly higher than the overall average, indicating relatively stable water resource supply at a moderate level. Sub-basins 7, 10, 1, 11, 13, 5, and 13 have lower annual average Available Water Supply Index values, suggesting relatively insufficient water resource supply. Additionally, some sub-basins exhibit notable fluctuations in their Available Water Supply Index, showing significant changes during specific months. For instance, Sub-basin 3 experiences a significant decrease in the Available Water Supply Index in April, while Sub-basin 14 shows a substantial decline in September. These variations highlight the seasonality and temporal dynamics of water resource availability in the region. (Figure 3)

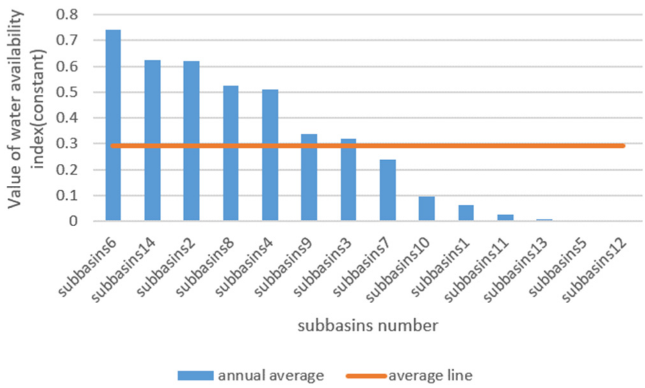

Figure 3. Annual average of water availability index

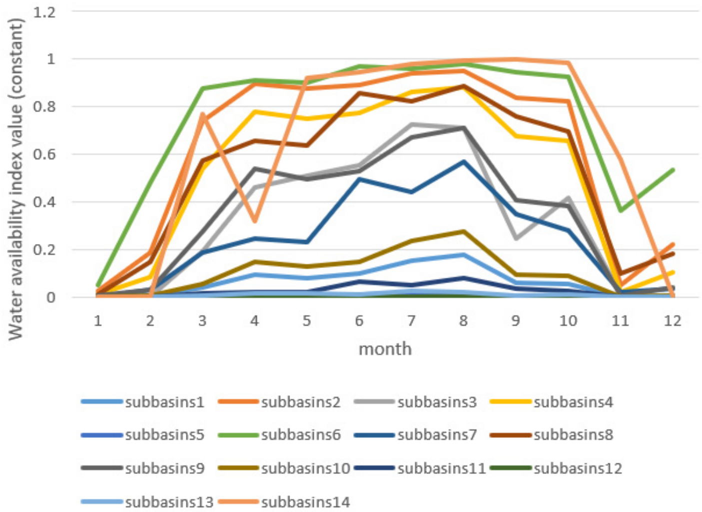

Figure 4. Available Water Supply Index for the Shi Yang River Basin in the Seasonal Variation Characteristics

The Available Water Index (AWI) in the basin shows seasonal variations, with different sub-basins exhibiting varying trends. Summer and autumn have higher AWI values, indicating better water supply services, while winter and spring have lower values, signifying reduced services. The 14 sub-basins can be categorized into three change pattern modes: Stable High, Seasonal Fluctuation, and Hazardous. Stable High sub-basins like Sub-basins 14 and 4 maintain consistently high AWI values throughout the year. Seasonal Fluctuation sub-basins, including Sub-basins 8, 2, 6, 9, 7, and 3, show significant AWI variations between months. Hazardous sub-basins (Sub-basins 12, 5, 13, 11, 1, and 10) have consistently low AWI values, indicating inadequate water supply services throughout the year.

3.4 Reliability Assessment of Available Water Supply Services

The reliability index for the different sub-basins exhibits varying patterns when compared to the average. Some sub-basins have reliability indices higher than the average, while others have reliability indices lower than the average (as shown in Figure 5). Sub-basins 5, 12, and 13 all have reliability indices of 0, indicating that there is no reliable water resource supply in these sub-basins. Sub-basin 6 has the highest reliability index. This suggests that in these two sub-basins, the reliability is the highest, making the water resource supply more dependable compared to other sub-basins. In contrast to the average, Sub-basins 1 and 11 have reliability indices below average, indicating relatively less reliable water resource supply in these sub-basins.

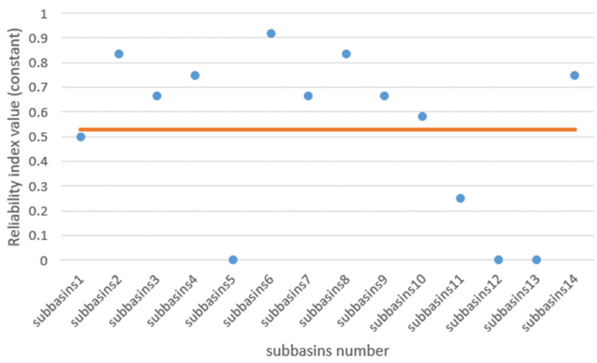

Figure 5. Sub-Basin Reliability Chart

3.5 Vulnerability Assessment of Available Water Supply Services

Understanding and evaluating the vulnerability of sub-basins can help identify potential water resource supply risks (as shown in Figure 6). Sub-basins 3 and 5 exhibit higher vulnerability indices in most months, with February and December standing out as months where their vulnerability indices are significantly higher compared to other sub-basins. This suggests that during these months, the water resource supply in these sub-basins is more fragile and unstable.

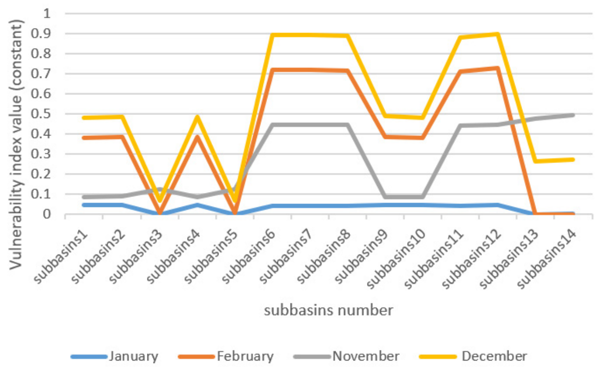

Figure 6. Sub-Basin Vulnerability Degree Chart

4. Discussion

4.1 Quantitative Framework for Available Water Supply Services

To advance regional studies in water ecosystem services flow, precise modeling and accurate quantification under human interventions are crucial. The Hydrological Simulation Program-FORTRAN (HSPF) model offers finer quantification of water supply services, particularly in arid regions, and has substantial potential for broader applications. Establishing an HSPF model database for China would enhance its usage and development.

The Available Water Index is valuable for assessing ecological water conditions in the study area, especially in arid regions. It allows for the evaluation of reliability and vulnerability of water supply services. By individually considering watershed elements, their roles and contributions can be better understood, enabling accurate assessments. The HSPF model-based Available Water Index is suitable for analyzing water supply services under human interventions in arid regions. Spatiotemporal Distribution Pattern of Available Water Supply Services and Policy Requirements

The research reveals regional disparities and seasonal variations in water supply within the Shiyang River Basin. Policies have improved water supply in Sub-basin 14, enhancing reliability and reducing vulnerability. Cross-basin water transfers improved ecological water supply but posed limitations on agriculture and industry. In downstream areas, drip irrigation is favored, but surface irrigation and groundwater extraction persist. A detailed study of water supply distribution informs comprehensive water resource management.

Stable High-Value regions, including Sub-basin 14 and 4, can benefit from policies promoting efficient water use. High-Risk areas are suitable for ecological water use only. Seasonal Variability regions should manage high-demand, low-supply months. Climate change may worsen water resource vulnerability. Strengthening climate monitoring, warnings, and adaptive measures is crucial to mitigate crises in water supply services and climate impacts on water resources.

4.2 Reliability of Available Water Supply

Reliable water supply services are achieved when demand meets basic ecological water needs, ensuring ecosystem health and biodiversity. Regional water supply reliability is closely linked to efficient water utilization. Minqin Oasis faced water shortages before cross-basin water transfers, impacting daily life and agriculture. These projects significantly improved water supply, especially during critical crop growth periods. This led to higher crop yields, increased income, and improved living standards. Water supply reliability directly affects people's lives and economic activities. Stable water supply to high-value areas promotes rational water resource allocation. Assessing water supply in areas with seasonal variability and high risk is crucial for basin-wide water reliability. Seasonal variability regions may face greater impacts from climate change and water supply policies, necessitating adaptive measures to ensure water reliability.

4.3 The Impact of Increased Food Production on the Vulnerability of Water Supply Services

When regional needs for increased production are pursued, the fragility of available water supply services is exacerbated. With economic development and population growth driving demand for water resources, especially in agriculture and industry, the pressure on available water supply services can increase as a result. The realization of these increased production demands can often lead to over-exploitation and excessive use of water resources, placing greater stress on water supply. It may also result in uneven distribution of water resources and heightened conflicts. In other aspects of water resource utilization within the entire basin, such as agriculture, industry, and urban water supply, there exists a degree of uncertainty and vulnerability. This is because the water demand in these sectors is more complex and diversified, influenced by a multitude of factors. When formulating regional water resource management and planning strategies, it is essential to comprehensively consider the demands of various sectors and the sustainable supply capacity of water resources.

Furthermore, prioritizing environmental protection and ecosystem restoration to ensure the sustainable supply and ecosystem integrity in high-risk areas of available water supply services can contribute to enhancing the stability and resilience of water resource supply services within the basin.

5. Conclusion

This study utilized the HSPF model to simulate the water supply in the Shiyang River Basin. Based on this simulation, it analyzed the spatiotemporal characteristics of available water supply services in the basin using the Available Water Index. Furthermore, it evaluated the reliability and vulnerability of water supply services in the basin using reliability and vulnerability indices, thus establishing a quantitative framework for assessing the available water supply in the Shiyang River Basin. The research indicated that the changes in available water supply caused by cross-basin water transfer projects under human intervention had a significant impact on the improvement of the overall ecosystem in the Shiyang River Basin. The study's analysis of the spatiotemporal distribution of available water supply services led to the identification of stable high-value areas, seasonally fluctuating areas, and high-risk areas. Among these, high-risk areas were identified as critical zones for ensuring the ecological water supply in the basin, while seasonally fluctuating areas were highlighted as focal points for meteorological crisis warning and policy adjustments.

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