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Effects of downstream environmental flow release on enhancing the groundwater recharge and restoring the groundwater/surface-water connectivity in Yongding River, Beijing, China

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Construction of the regional groundwater model of Beijing Plain

Beijing Plain is located in the north-eastern part of China and is surrounded by mountains on the west and north, making it a piedmont plain. The total area of Beijing is 16,800 km^2, with 62% mountainous area and 38% plain area. The climate in Beijing is temperate monsoon, with hot and humid summers and cold and dry winters. The average annual temperature is 12 °C and the average annual precipitation is 593 mm, with 75% of rainfall occurring in the rainy season (from June to September). The groundwater system in the Beijing Plain is recharged from various sources, including precipitation infiltration, surface water leakage, lateral flow from the mountains, irrigation return flow in the suburbs, and pipe leakage in the urban area. Groundwater discharge occurs through evapotranspiration, drainage along lower streams, and abstraction for domestic, agricultural, and industrial purposes.

The aquifer systems were divided into five groups based on depth for groundwater resources development, monitoring, and management in the Beijing Plain. These five groups were the phreatic aquifer less than 50 m below the surface, and the semi-confined aquifers in the depth range of 50-100 m, 100-180 m, 180-300 m and deeper than 300 m below the ground surface. Groundwater abstractions were mainly for agricultural use in the first aquifer group, domestic water supply in the second and third aquifer groups, and industrial water supply in the fourth and fifth aquifer groups.

The top and bottom elevations were the same for three alternative models, with the top elevation taken from a digital elevation model (DEM) of 90 m resolution and the bottom elevation taken from a regional geological map. The model was discretized into nine layers to represent the five aquifers and four aquitards. The deeper aquifers and aquitards were truncated with the bedrock towards the mountains, and each model layer terminated where the representing aquifer or aquitard intersected with the bedrock. A schematic diagram that summarizes the conceptual model setup is shown in Figure S1.

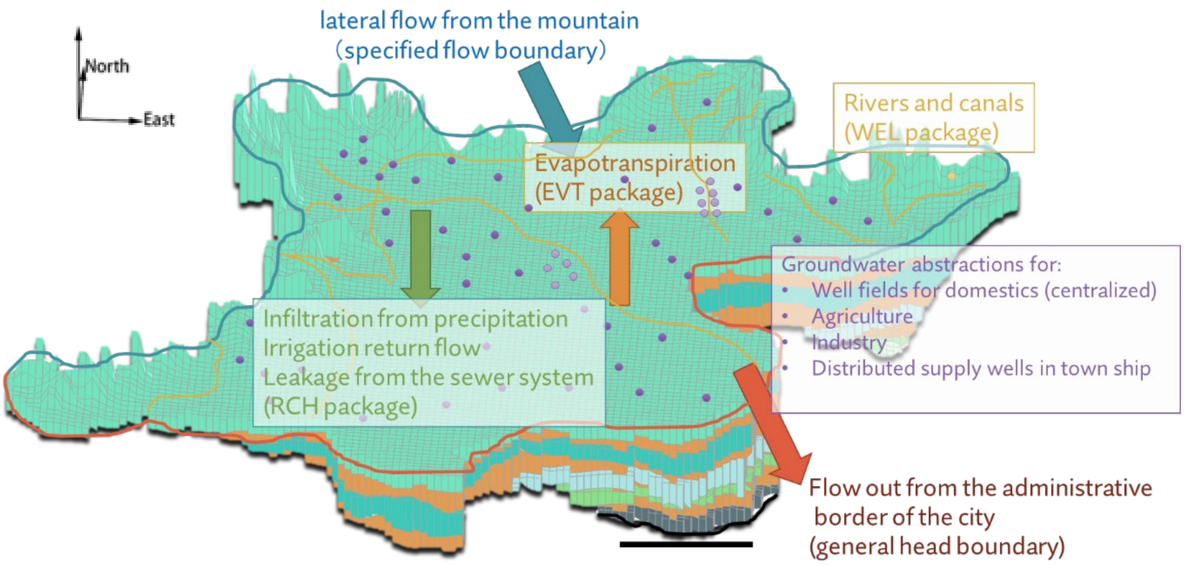
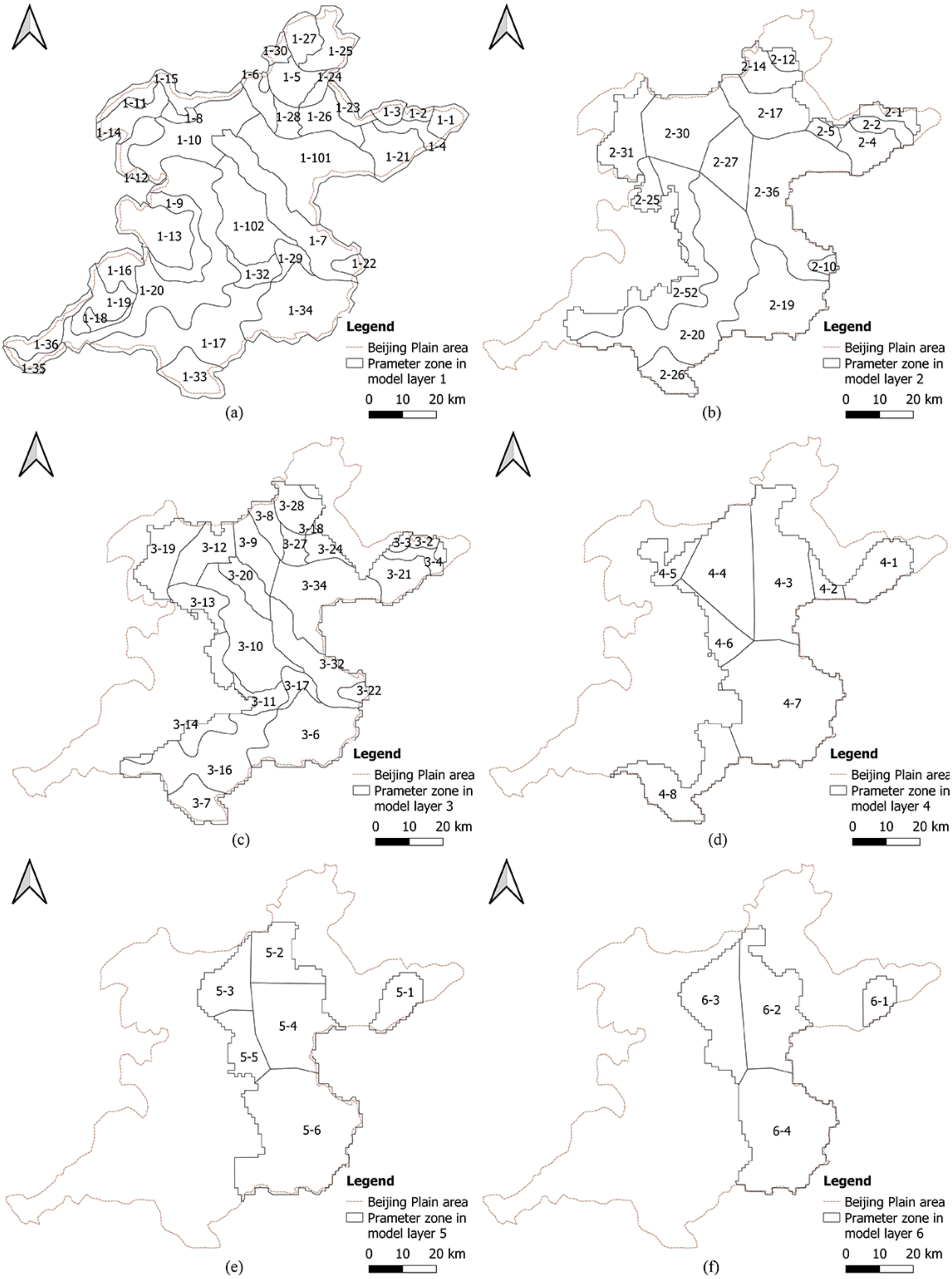


Figure S1.1. Model conceptualization of the groundwater flow model of Beijing Plain.

Calibration of the hydraulic conductivity parameters was carried out by matching the computed and observed head at 202 data points. The zones for horizontal (Kh) and vertical (Kv) hydraulic conductivity parameters shown in Figure S2 were determined based on a combination of lithological types and structural geological maps, and initial parameter values were obtained from the results of pumping tests and empirical values.


1-1
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1-29
1-30
1-32
1-33
1-34
1-35
1-36
1-101
1-102
Legend
Beijing Plain area
Prameter zone in model layer 1
0 10 20 km
(a)
2-1
2-2
2-4
2-5
2-10
2-12
2-14
2-17
2-19
2-20
2-25
2-26
2-27
2-30
2-31
2-36
2-52
Legend
Beijing Plain area
Prameter zone in model layer 2
0 10 20 km
(b)
3-2
3-3
3-4
3-6
3-7
3-8
3-9
3-10
3-11
3-12
3-13
3-14
3-16
3-17
3-18
3-19
3-20
3-21
3-22
3-24
3-27
3-28
3-32
3-34
Legend
Beijing Plain area
Prameter zone in model layer 3
0 10 20 km
(c)
4-1
4-2
4-3
4-4
4-5
4-6
4-7
4-8
Legend
Beijing Plain area
Prameter zone in model layer 4
0 10 20 km
(d)
5-1
5-2
5-3
5-4
5-5
5-6
Legend
Beijing Plain area
Prameter zone in model layer 5
0 10 20 km
(e)
6-1
6-2
6-3
6-4
Legend
Beijing Plain area
Prameter zone in model layer 6
0 10 20 km
(f)

Figure S1.2. Spatial distribution of the parameter zones for the hydraulic conductivity and storage coefficient. (a) to (i) are the model parameter zones for model layers 1 to 9, respectively.

The regional model was constructed in a steady state using the recharge and discharge data of year 1995, which showed a balance between total groundwater recharge and discharge. A transient regional flow model was then developed to simulate changes in groundwater flow in the Beijing Plain from 1995 to 2018, using the MODFLOW 2005 program with monthly stress period. Groundwater recharge was calculated using monthly meteorological data, simulated by the Recharge package, while groundwater evaporation was simulated by the Evapotranspiration package using pan evaporation data. Groundwater abstraction was simulated using the Well package. The annual abstraction amounts for each usage were obtained from the Beijing Water Resource Bulletin and mapped to the corresponding district and grid cells in the model. Irrigation return flow was calculated based on agricultural groundwater use and simulated using the Recharge package, while pipeline leakage and leakage from rivers and canals were simulated as injection wells using the Recharge and Well packages, respectively. Lateral boundary flow from the mountainous region was calculated based on the annual water balance of the Beijing Plain and simulated as injection wells using the Well package. The administrative borders in the south and east were specified as head-dependent boundaries using the General Head Boundary package. The model inputs were then examined and adjusted to ensure consistency between the simulated groundwater level and the observed groundwater level time series. This calibrated model was used to evaluate changes in groundwater level and storage in response to reductions in abstraction and to design and simulate the managed aquifer recharge (MAR) scheme in the Chaobai River in a previous study (Liu et al., 2022).

In this study, the simulation period of this regional groundwater flow model was extended to 2020 by the same methods mentioned above and there was further refinement of the grid near the Yongding River region, to simulate the effect of the EFR project on the groundwater system.

ESM1 Reference

Liu, S., Zhou, Y., Luo, W., Wang, F., McClain, M.E., Wang, X., 2022. A numerical assessment on the managed aquifer recharge to achieve sustainable groundwater development in Chaobai River area, Beijing, China. J. Hydrol. 613, 128392. https://doi.org/https://doi.org/10.1016/j.jhydrol.2022.128392