不同气候条件下华北粮食主产区地下水保障能力时空特征与机制

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华北平原是我国小麦、玉米等粮食作物主产区，粮食产量占全国的10.6%。同时，该平原也是我国地下水超采最为严重地区之一，在13.92万km^2的国土面积上分布着石家庄漏斗、保定漏斗和邯郸漏斗等地下水位降落漏斗群，漏斗面积超过9 700 km^2。该灌溉农业以开采地下水为主要供给水源，农业开采量占华北平原地下水总开采量的65%以上。2009年12月《科学时报》刊发文章指出，华北平原地下水危机影响我国的粮食安全。农业灌溉用水及其开采地下水的强度和超采程度，与气候变化密切相关。气候变化不仅影响粮食作物灌溉需水量变化，而且，还显著影响农业开采量和地下水补给量变化，尤其连年降水枯水或连年降水丰水，对粮食主产井灌区地下水流场及其保障能力影响十分明显，是一个重要研究课题。深入开展该课题研究，对华北平原农业区地下水资源合理开发利用和提高粮食安全保障能力具有重要意义。

本文针对华北平原灌溉农业对地下水依赖程度日益提高和地下水超采不断加剧问题，着眼于进一步认识未来30年气候变化条件下不同分区灌溉农业的地下水保障能力状况，应用地学统计分析、灰色数学、地理空间插值和彭曼-蒙蒂斯(Penman-Monteith)公式等研究方法，通过对华北平原近50年来气象、水文、农业灌溉和地下水动态相关资料的深入分析，以及基于大气环流模式预测的2016—2050年降水量和气温等相关数据，开展了不同气候条件下华北平原粮食主产区地下水保障能力时空特征与机制研究，揭示了华北平原不同类型区农业活动对地下水流场变化影响机制，阐明了不同气候条件下粮食主产区地下水保障能力的时空特征及主控因素，取得的主要进展和创新成果:

(1)气候变化对华北平原粮食作物灌溉需水量具有显著影响，不同水文年份之间存在较大差异性；这种差异性的合理利用，具有较大节水潜力。在降水偏丰年份，冬小麦灌溉需求指数以 0.6~0.7 的分布区为主，夏玉米以 0.3~0.4 的分布区为主，分布面积占华北全区的比率分别为 60.1%和 41.5%。在平水年份，冬小麦以 0.7~0.8 的分布区为主，夏玉米以 0.4~0.5 的分布区为主，分布面积占华北全区的比率分别为 92.8%和 76.1%；在降水偏枯年份，冬小麦以 0.8~0.85 的分布区为主，夏玉米以 0.6~0.7 的分布区为主，分布面积占华北全区的比率分别为 52.9%和 47.3%。

未来情景期(2016—2050 年)作物灌溉需水量较历史基准期(1961—2015 年)异变明显。从历史基准期到未来情景期，燕山山前平原和中部平原的冬小麦灌溉需水量均呈显著下降趋势，下降速率分别为 97.8 mm/10 年和 71 mm/10 年，滨海平原呈显著上升趋势，灌溉需求指数演变趋势不明显；燕山山前平原、太行山前平原和滨海平原三个地区的夏玉米灌溉需水量和需求指数均呈显著上升趋势，需水量上升速率分别为 15.5 mm/10 年、13.7 mm/10 年和 34.9 mm/10 年，需求指数上升速率分别为 0.025/10 年、0.015/10 年和 0.041/10 年，中部平原的上升趋势不显著。

(2)华北平原粮食主产区地下水开采量与降水量和农业灌溉量关系密切，且不同区位对气候变化响应差异明显。在山前平原子牙河平原，降水量每增大100 mm，农田灌溉水量和地下水开采量分别减少1.2亿m^3和0.9亿m^3，降水平衡点498 mm对应粮食作物灌溉水量为23.19亿m^3，地下水开采量为38.56亿m^3；在中部平原陡骇马颊平原区，降水量每增大100 mm，农田灌溉水量减少0.23亿m^3，地下水开采量减少0.13亿m^3，降水平衡点545 mm对应粮食作物灌溉水量为28.07亿m^3，地下水开采量为24.39亿m^3；在滨海平原降水量与粮食作物灌溉量和

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地下水开采量之间, 同样表现出密切的负相关关系。

气候变化对不同分区地下水位的影响状况明显不同, 这种变化特征与各分区水文地质条件的区域差异性密切相关。山前平原石家庄粮食主产区, 灌溉需水量每增大100 mm, 地下水位下降的幅度将增大0.26 m; 中部平原德州粮食主产区, 灌溉需水量每增大100 mm, 地下水位下降幅度增大0.36 m; 滨海平原沧州农业区, 灌溉需水量减少100 mm, 地下水位下降幅度将减少0.60 m。

在山前平原, 丰-丰水年组合水文条件下, 地下水位年内大幅回升; 在平-枯水年以及枯-枯水年组合条件下, 地下水位均大幅下降。在中部平原, 平-枯水年组合条件下, 地下水位呈下降趋势, 平-平水年组合条件下, 地下水水位可恢复至年初水平。在滨海平原, 丰-平水年组合条件下, 地下水位呈小幅下降态势, 平-枯水年组合条件下, 年内地下水位则大幅下降。

(3)气候变化对农业区地下水保障能力具有较大影响, 是灌溉农业合理开发利用地下水的重要约束条件。降水偏丰年份, 华北粮食主产区地下水保障能力处于“较高保障”状态, 评价指数大于 80%; 平水年份, 地下水保障能力处于“基本保障”状态, 评价指数均值为 54%; 偏枯年份, 地下水保障能力处于“较低保障”状态, 评价指数均值为 45%。

从地下水保障能力情势发生概率的角度分析, 山前平原发生“较高保障”情势的概率最大, 概率值为 0.47, 中部平原发生“较低保障”情势的概率最大, 概率值为 0.65, 滨海平原发生“基本保障”情势的概率最大, 概率值为 0.59。

在华北全区尺度上, 水资源承载力的变化是影响华北粮食主产区地下水保障能力的主控因素, 地下水保障能力与地区水资源模数的灰色关联系数为 0.79, 其次为降水, 灰色关联系数为 0.76。从不同区位尺度来分析, 降水量的多少是影响地下水保障能力的主控因素, 华北不同区位降水对地下水保障能力的影响强度均在 22%以上, 降水量每增大 100 mm, 燕山山前平原粮食主产区地下水保障能力增长 4.07%, 太行山前平原将增加 6.41 个百分点, 中部平原将增长 5.99 个百分点, 滨海平原将增长 5.41%。

(4)在 RCP4.5 气候情景下, 太行山前豫北平原地下水保障能力处于“较高保障”状态, 燕山山前平原为“基本保障”状态, 太行山前冀中平原、华北平原中部的鲁北、豫北平原和东部滨海平原处于“较低保障”状态, 中部的冀中平原为“难以保障”状态。

从地下水保障能力情势发生概率角度分析, 燕山山前平原发生“基本保障”情势的概率值最大, 概率值为 0.77; 太行山前平原处于“较高保障”状态的概率最大, 为 0.90, 但区域内部有较大差异, 太行山前豫北平原发生“较高保障”情势的概率为 1, 太行山前冀中平原则发生“较低保障”情势的概率最大; 中部平原处于“较低保障”状态的概率最大, 概率值为 0.6; 滨海平原发生 “较低保障”情势的概率最大, 为 0.7。

从历史基准期到气候情景期, 燕山山前平原农业区地下水保障能力在 1%的水平上呈显著上升趋势, 上升速率为 3.3%/10 年; 太行山前平原、中部平原和滨海平原均呈下降趋势, 但均没有达到显著水平, 下降速率分别为 1.6%/10 年, 0.2%/10 年和 0.1%/10 年。

创新点: 本课题突出气候变化与灌溉农业开采地下水等人类活动叠加影响的地下水保障能力机制研究, 基于大气环流模式预测的 2016—2050 年降水量和气温相关数据, 以系统观念认识华北平原粮食主产区地下水演变过程、特征和规律, 以动态观点和非线性动力学理论方法, 比选 IPCC 公布的气候预测模式, 建立适宜表达研究区气候变化的气候预测模式, 并对关键气象因子进行降尺度, 揭示不同水文年份组合条件下粮食生产区地下水保障能力衰变特征与涵养修复机制, 首次阐明了华北平原不同分区、不同水文年组合条件下农业区地下水位变化特征和趋势, 为针对性调控和涵养华北平原农业区地下水保障能力提供科学依据。

关键词: 地下水; 农业区保障能力; 气候变化; 农作物需水量; 主控因素

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Groundwater Ensure Capacity Spatial-temporal Characteristics and Mechanism in Main Grain Producing Areas of North China Plain under Different Climatic Conditions

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North China Plain (NCP) is the main winter wheat and summer maize production area in china, grain production accounted for 10.6% of the country. At the same time, NCP is one of the most serious groundwater over exploitation areas, in 13.92 million km^2 of land area distributed Shijiazhuang, Baoding and Handan groundwater level drawdown funnel group, and the funnel area of more than 9 700 km^2. Agricultural mining accounted for more than 65% of the total exploitation of NCP. In December of 2009, “scientific times” pointed out that the water resource in the NCP crisis of our country food security. Irrigation water and groundwater over-exploitation density is closely related to climate change. Climate change is not only affecting irrigation water, agricultural exploitation and groundwater recharge, but also groundwater field and groundwater ensure extent of well irrigation area, especially in continuous wet years or continuous dry years. So, It is of great significance to study the groundwater ensure extent in different climatic conditions.

In this paper, aiming at the problems which the irrigation agriculture dependent and influence on groundwater is continuous rising, focus on further understanding groundwater ensure extent under climate change condition of next 30 years. Utilizing the methods of statistical analysis, penman formula, based on GCM predicted data of precipitation and air temperature data in 2011–2050, carried out the study of spatial and temporal characteristic and influence mechanism groundwater ensure extent, reveals the impact mechanism of agricultural activities on the groundwater flow field; Clary the temporal and spatial characteristics and the main controlling factors of the groundwater ensure extent. The main results as follows:

(1) Climate change has significance influence on grain crop irrigation water requirement in NCP, and there is a great difference in different hydrological years. Reasonable utilization of this difference has great potential for water saving. In wet year, the main distribution area of winter wheat irrigation water demand index (IDI) was in between 0.6 and 0.7, and summer maize was in between 0.3 and 0.4, distribution area of the North China region accounted for 60.1% and 41.5%, respectively. In normal flow years, the main distribution area of winter wheat IDI was in between 0.7 and 0.8, and summer maize was in between 0.4 and 0.5, distribution area of the North China region accounted for 92.8% and 76.1%, respectively. Under dry years, the main distribution area of winter wheat IDI was in between 0.8 and 0.85, and the summer maize was in between 0.6 and 0.7, distribution area of the NCP accounted for 52.9% and47.3%, respectively.

Comparing with historical period (1961–2015), there is great change of crop irrigation water demand in Scenarios in the future period (2016–2050). From historical period to scenarios future period, winter wheat irrigation water requirement was significantly decreased in Yanshan piedmont plain and Central Plains, the decline rate were 97.8 mm/10 years and 71 mm/10 years, coastal plain showed a significant upward trend, the IDI evolution trend is not obvious. Summer Maize irrigation water demand and IDI showed a significant upward trend in Yanshan piedmont plain, Taihang Piedmont and coastal plain regions, the increase rate of irrigation water demand is 15.5 mm/10 year, 13.7 mm/10 year and 34.9 mm/10 year respectively, and the IDI rate is 0.025/10 year, 0.015/10 years and 0.041/10 year. The Central Plains rising trend is not significant.

(2) The amount of groundwater exploitation in the main grain producing areas of the NCP is closely related to precipitation and agricultural irrigation amount, and the response of different location to climate change is obvious difference. An increase of 100 mm for precipitation, the irrigation water and groundwater exploitation will decline 1.2 billion m^3 and 0.9 billion m^3, the precipitation equilibrium point 498 mm corresponding to crop irrigation water is 23.19 billion m^3, groundwater exploitation is 38.56 billion m^3 in piedmont plain. in central plain, the irrigation water and groundwater exploitation will decline 0.23 billion m^3 and 0.13 billion m^3, the precipitation equilibrium point 545 mm corresponding to crop irrigation water is 28.07 billion m^3, groundwater exploitation is 24.39 billion m^3.in coastal plain, the precipitation and crop irrigation water demand, groundwater exploitation also showed a close negative correlation relationship.

The influence climate impact on groundwater level in different regions is obviously different, which is closely related to the regional hydrogeological conditions. In Shijiazhuang plain, an increase of 100 mm for crop irrigation water demand, the groundwater level change amplitude will incline 0.26 m. In Dezhou area, the groundwater level change amplitude will incline 0.36 m. In Cangzhou plain, the groundwater level change amplitude will incline 0.60 m.

In the piedmont plain, in the combined climate conditions of wet-wet years, the groundwater level years will rebound sharply. In the combined climate conditions of normal flow-dry years, dry-dry year, the groundwater level years will significantly decline. In the Central Plains, under the combined climate conditions of normal flow-dry years, the groundwater level has the tendency of declining, in the combined condition of normal flow-normal flow year, the groundwater level can be recovered to the level of the beginning of the year. In the coastal plain, under the combined climate conditions of wet-wet years, the groundwater level was slightly downward trend, in the condition of normal flow-dry year, groundwater level will significantly decline.

(3) Climate change has a great influence on groundwater ensure extent, and it is an important constraint for the rational exploitation of groundwater in irrigation agriculture. In wet years, the groundwater ensure extent of NCP is 81%, is belong to higher extent. In normal flow year, the groundwater ensure extent is 54%, is the state of basic ensure extent. In dry years, the groundwater ensure extent is 45%, is under inferior state.

From groundwater ensure extent occurrence probability situation analysis, higher extent situation occurrence probability was maximum, and the probability was 0.47 in piedmont plain, in central plains, inferior ensure extent situation occurrence probability was maximum, and the probability was 0.65; in coastal plain, basic ensure extent situation occurrence probability was maximum, and the probability was 0.59.

In NCP scale, water resource carrying capacity is the driving factor of groundwater ensure extent. The grey correlation coefficient of groundwater ensure extent and region water resource modulus was 0.79, followed by precipitation, the grey correlation coefficient was 0.76. Form different location scale analysis, precipitation is the main driving factor, the effect intension in all partition of NCP was over 22%.an increase 100 mm for precipitation, the groundwater ensure extent will increase 4.07%, 6.41%, 5.99% and 5.41% respectively, in Yanshan piedmont plain, Taihang piedmont plain, central plain, coastal plain.

(4) Under the climate scenarios of RCP4.5, In Taihang Piedmont of North Henan plain, the groundwater ensure extent is in higher state, Yanshan Piedmont plain is under basic ensure extent, Taihang Mountain of Hebei Plain, Henan central plain and the coastal plain is in a state of inferior, and the Hebei central plain is under the state of difficult to ensure.

From groundwater ensure extent occurrence probability situation analysis, the maximum probability of groundwater ensure extent will be basic ensure extent situation in Yanshan piedmont plain, and the probability value will 0.77. In Taihang piedmont plain, higher ensure extent situation occurrence probability will be maximum, and the probability will 0.90, but there will be great difference in region inside, in North of Henan Province of Taihang piedmont plain, higher ensure extent situation occurrence probability will 1, in central of Hebei province of Taihang piedmont plain, inferior ensure extent occurrence probability will be maximum. The maximum probability of groundwater ensure extent will be inferior ensure extent situation in central plain, and the probability value will be 0.6, in coastal plain, the probability value of inferior ensure extent will get 0.7.

From history period to future scenario period, the groundwater ensure extent will be significantly rise in level of 1%, and the rise rate is 3.3%/10 year; there will be descend trend in Taihang piedmont plain, central plain, and coastal plain, and the descend rate will be 1.6%/10 year,0.2%/10 year,0.1%/10 year.

Innovation point: Prominent the mechanism research of climate change and agriculture exploitation impact on groundwater ensure extent. Based on the GCM predicted date in the period of 2016–2050, understanding the process, characteristics and law of groundwater evolution in NCP main grain producing area with the concept of system, utilizing the methods of dynamic viewpoint and nonlinear dynamic theory, compare to elects the suitable GCM of NCP, and downscale the key meteorological date, reveal groundwater ensure capacity spatial - temporal characteristics and mechanism in main grain producing areas of NCP under different climatic conditions, clarified the characteristics and development trends of groundwater ensure extent of different regions of NCP in different hydrological years, for the first time. To provide pertinence scientific basis for regulation and conservation groundwater in agricultural areas of NCP.

Key words: groundwater; ensure extent; climate change; irrigation water requirement; driving factor

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