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厦门大学

硕 士 学 位 论 文

基于水化学和环境同位素的秦皇岛洋戴河平原海水入侵机理研究

Mechanism of Seawater Intrusion Using Hydrochemistry and Environmental Isotopes in Qinhuangdao Yang Dai River Plain

章 斌

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摘 要

海水入侵是滨海地区面临的主要资源、环境与生态问题之一。它不仅威胁人类稀缺的淡水资源，危及人类生命和健康，而且破坏生态环境平衡，制约社会经济的可持续发展。上世纪 80 年代以来，秦皇岛洋戴河平原因集中式过量开采地下水引发了海水入侵灾害，致使区内地下水水质整体咸化、恶化，大量开采井报废，并引发土壤盐碱化等次生环境地质灾害。海水入侵灾害造成了秦皇岛一系列的经济损失，直接制约秦皇岛经济的可持续发展和人民生活质量的提高，而开展海水入侵的时空分布特征以及成因机理的研究，可以为秦皇岛因地制宜地防治海水入侵，以及合理开发、利用和保护滨岸地区珍稀的地下淡水资源提供科学的依据。

咸淡水过渡带的空间分布形态和物质迁移规律是海水入侵机理研究的关键科学问题。本研究以秦皇岛高庄-洋河口为典型的海水入侵研究剖面，在野外系统网络式布点采样（采集水样 29 组，其中，地下水 23 组、河水 5 组，海水 1 组）、室内测试和整理（阴阳离子组成、δD 和 $\delta^{18}O$）以及大量文献调研和综述基础之上，分析了洋戴河平原的自然地理、地层、构造和水文地质等背景条件，运用数理统计和模糊数学方法评价了海水入侵程度的空间分布及供水指示意义，将研究区地下水的渗流场、化学场以及温度和电导率场耦合起来，揭示了研究区地表水和地下水的形成演化规律和多种水体的相互作用，以及高庄东南部咸水带和海水入侵区的水文地球化学特征与形成过程，建立了研究地下水流动系统的概念模型，探讨了咸淡水过渡带的空间分布形态和物质迁移转化规律。主要结论如下：

（1） 洋戴河平原海水入侵的方式，以沿河床的带状入侵及侧渗和沿洋戴河间冲积含水层的面状入侵为主，入侵动态主要受控于年内地下水位和潮汐的波动变化，表现为规律的季节性入侵。

（2） 依据水化学成分或指标与 Cl^-浓度的相关程度，将 Cl^-、电导率（*EC*）、总溶解固体（*TDS*）和潜在盐度作为海水入侵识别的主要指标，建立了相应的海水入侵等级的指标体系，采用模糊数学综合评价法评价了研究区海水入侵程度以及供水意义，结果显示：地下水样品中海水入侵程度 II 级和 III 级水样占到了 74%，

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研究区总体上属于海水入侵程度中等水平的地区；洋戴河间的浦河一带是海水入侵程度最强烈的地区；海水入侵程度越高，水质危害越大，对人体健康、农业灌溉和工业生产越为不利。

（3） 选择 GNIP 天津观测站作为本区降水同位素的参考站点，探讨了降水的同位素效应，建立了当地降水线方程；运用氯离子和氢氧同位素，揭示了研究区地表水和地下水的形成演化规律以及多种水体的相互作用过程。结果显示：天津降水同位素的变化受控于降雨量效应和温度效应的共同作用，依据降水数据建立的当地参考降水线为：$\delta D=6.57\delta^{18}O+0.31$；研究区汛期的地表河水来源于中上游库水和大气降水的混合；山前丘陵区地下水主要接受降水直接补给，洪积扇及山麓地带地下水受到了一定的蒸发作用，除了接受山前丘陵区地下水补给外，洋河附近的地下水还受到了洋河库水的混合；在高庄东南部咸水带，西部咸水带的地下水由径流区上游地下水和大泥河地热咸水混合而成，地热咸水的混合比率约为 13%，东部咸水带的地下水主要由径流上游地下水和本地污水混合而成，地热咸水的混合比率不超过 9%；在洋戴河海水入侵区，地下水主要由本区地下淡水和海咸水（混合比率不超过 10%）混合而成，并且受到了不同程度的地表水或灌溉水补给，其中，浦河一带是农田灌溉水或地表水补给较为明显的地段。

（4） 分析了研究区地下水化学特征的空间分布规律，探讨了洋戴河平原高庄东南部咸水带和海水入侵区地下水化学成分的形成以及盐分的来源。结果显示：研究区地下水化学类型及特征具有明显的空间分带性；在山前丘陵及洪积扇地带，地下水 *TDS* 小于 1g/L，水化学类型以 Cl-Ca 或 Cl•HCO_3-Ca 为主，盐分主要来源于降水、溶滤作用和生活污水；在高庄东南部咸水带，*TDS* 基本上均大于 1g/L，深部地下水水质较差，咸水带西部地下水化学类型为 Cl-Ca•Na，微量元素 Li 和 Sr 含量很高，具有极低的 Mg/Cl 和 SO_4/Cl，盐分主要来源于地热咸水，咸水带东部地下水化学类型以 Cl•SO_4•NO_3-Ca 为主，NO_3^-、SO_4^{2-}含量非常高，具有较高的 Mg/Cl、SO_4/Cl，盐分主要来源于工农业生产及生活污水；在洋戴河海水入侵区，*TDS* 普遍大于 1g/L，水化学类型以 Cl-Na•Ca 和 Cl-Na•Mg•Ca 为主，地下水化学的形成主要受控于咸淡水间的机械混合和阳离子交替吸附作用；海水入侵区地下水中 Na^+、K^+和岩土颗粒的 Ca^{2+}、Mg^{2+}交换是明显的，并以 Na^+-Ca^{2+}为主，Na^+-Mg^{2+}为次，在浦河以及其他地下水补给条件较好的地段，灌溉淡水或地表淡

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水的明显补给，引起了地下水中 Ca^{2+}与岩土颗粒的 Na^{+}、K^{+}和 Mg^{2+}交换，而在近岸带的海相浅层含水层，不仅存在正向的阳离子的交替吸附作用，而且存在无水石膏的脱硫酸过程。

（5）以地下水流动系统理论框架为指导，利用多种技术手段提取和分析有限的、零散的、孤立的多种信息，并将这些信息耦合起来建立滨海地区地下水流动系统的概念模型，可以有效地降低地下水流动系统认识的模糊性与不确定性，进一步提升对海水入侵机理问题认识的准确性和可靠性。

关键词：洋戴河平原；海水入侵；模糊数学；氢氧稳定同位素；水文地球化学；地下水流动系统理论

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ABSTRACT

Seawater intrusion has currently become one of major resource, environment and ecology problems in the world. It not only threatens the resource of our rare fresh groundwater and does considerable harm to the health and life of human own, but also destroys the ecological balance and prohibits the entire society from constantly developing forwards. Since the 1980s, the over-exploitation of groundwater has brought about the seawater intrusion problem which has resulted in groundwater quality's salting and deteriorating, pumping wells' scraping, soil salinization and other secondary environmental geological hazards. Up to the present, seawater intrusion causing Qinhuangdao region a series of life and property losses has severely restricted the sustainable development of local economy and further improvement for quality of human life. Now, it is high time to develop further research for spatial and temporal distribution and formation mechanism of seawater intrusion, because the research work can actually provide government regulators with scientific proofs for protecting and controlling the seawater intrusion problem and promoting the management of utilizing and protecting the precious fresh groundwater.

Study on space-time evolution of salt-fresh water interface and solution transport in transition zone are the key scientific problems of seawater intrusion research. Yang Dai River plain involving scopes from Gaozhuang village to Yang River estuary is taken as a typical study area. For conducting this research, twenty-nine samples were collected and analyzed for major ionic composition, δD and $\delta^{18}O$, and the massive literatures were reviewed in this study. After analyzing the conditions of physical geography, stratum, geological structure and hydrogeology, the mathematical statistics and fuzzy mathematics methods were used together to evaluate the spatial distribution of seawater intrusion and illustrate the corresponding water supply significances of groundwater with various seawater intrusion degrees in the meantime. Furthermore, integrating the fields of groundwater flow, water chemistry, water temperature and

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electrical conductivity were applied to indicate the groundwater formation and interactions among various water bodies and demonstrate the hydrogeochemical characteristic and forming processes in study area. Finally, the conceptual model of groundwater flow system was established to discuss the evolution of salt-fresh water interface and solution transport pattern in transition zone. The principal conclusions in this study can be drawn as follows:

(1) Intrusion through riverbed and alluvial aquifer located between Yang River and Dai River is the primary seawater intrusion mode. The dynamic of seawater intrusion dominated by changes of groundwater level and tidal height within a year reveals a regular seasonal intrusion mode.

(2) According to the correlation between water chemical components or indicators and chloride concentration, Cl^-, electronic conductivity (*EC)*, total dissolved solids (*TDS*) and potential salinity are selected for the indicators for seawater intrusion, which were used to build up corresponding index system of seawater intrusion evaluation. The mathematical statistics and fuzzy mathematics methods were combined to evaluate the spatial distribution of seawater intrusion and illustrate the corresponding water supply significances of groundwater identified as different seawater intrusion degrees. The research result shows as follows. That the groundwater samples identified seawater intrusion degree as rank II and rank III make up 74% of all reveals the seawater intrusion degree of study area belongs to the medium level on a whole. The seawater intrusion degree of the alluvial aquifers in Pu River region is highest. The higher the seawater intrusion degree, the worse the water quality, and the more disadvantageous for human body, agricultural irrigation and industrial production.

(3) Choose Tianjin precipitation isotopes observation station in GNIP as a reference site for study area, and discusses isotopic effects of precipitation and establish the Local Meteoric Water Line (LMWL). Chloride ion, deuterium and oxygen-18 were applied to indicate the formation of surface water and groundwater and the interactions among various water bodies. The result is provided as follows. The changes of precipitation isotopes in Tianjin observation station is simultaneously

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controlled by precipitation amount effect and temperature effect. Based on the data of isotopic composition in precipitation, the Local Meteoric Water Line can be calculated as δD=6.57$\delta^{18}O$+0.31. The surface water mainly derived from the reservoir water located in upstream of Yan River and the precipitation during high flow period. The groundwater in hilly land are primarily recharged by precipitation, and the groundwater in proluvial fan and piedmont experienced varying evaporation, which is not only recharged by groundwater from hilly land aquifer, but also mixed with Yang River reservoir water. In the western saline groundwater region lieing in southeast Gaozhuang, the groundwater is composed of about 87% groundwater from upstream and 13% geothermal salt water distributed around Da Ni River. In the eastern saline groundwater region lieing in southeast Gaozhuang, the groundwater is mainly composed of the groundwater from upstream and the local sewage, wherein the mixing ratio of geothermal water is up to 9%. In the seawater intrusion region of Yan Dai River plain, the groundwater is mainly constituted of local fresh groundwater and seawater mixing ratio of which is up to 10%, which is also varyingly recharged by surface water and irrigation water, especially in the place near Pu River region where recharge of agricultural irrigation is quite conspicuous.

(4) Analyze the spatial distribution of hydrochemical characteristic of groundwater and discuss the formation and salt origin of groundwater in the saline groundwater zone located in the seawater intrusion area and the southeastern Gaozhuang. The result can be showed below. The spatial distribution of hydrochemical types and characteristics of groundwater reveals as an obvious spatial zoning pattern. In the hilly land and proluvial fan, *TDS* of groundwater is less than 1g/L, the hydrochemical type is primarily dominated by Cl-Ca or Cl•HCO_3-Ca, and the salt of groundwater mainly derives from precipitation, lixiviation and domestic sewage. In the saline groundwater region located in the southeastern Gaozhuang, *TDS* of groundwater is generally less than 1g/L, and groundwater quality of deep layer in the aquifer shows even worse. In the western saline groundwater zone, that the groundwater hydrochemical type of which is dominated by Cl-Ca•Na is identified as pretty high Li and Sr concentration and very low Mg/Cl and SO_4/Cl implies the salt of groundwater

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