DOI:10.13476/j.cnki.nsbdqk.2020.0090
吴蓉，王慧敏，刘钢，等. 生态优先视角下跨流域预留水权确权与配置[J]. 南水北调与水利科技(中英文)，2020，18(5)：13-37.
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生态优先视角下跨流域预留水权确权与配置

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摘要：在生态优先、绿色发展前提下，提出生态需水差分整合移动平均自回归预测模型（autoregressive integrated moving average model，ARIMA），据此在生态需水确权的基础上进行流域预留水权确权，并在水权确权的基础上探索水权期权交易模式下预留发展水权再配置方案，实现跨流域水资源优化配置的同时规避水权买卖双方风险，为跨流域特殊水权的确权与再配置提供参考。研究表明：受气候、政策的影响区域生态需水量呈现出较大变化；南水北调中线受水区天津和河北不具备自备预留发展水量的能力，需要依靠流域调度中心的统一协调；流域调度中心可以根据预测年预留发展水量的使用风险情况进行价格方案的灵活配置，实现预留发展水量经济与社会效益的最优化。

关键词：生态优先；跨流域预留水权；水权期权；南水北调中线

中图分类号：TV213；X321　　**文献标志码**：A　　**开放科学(资源服务)标志码(OSID)**：

预留水权概念的提出为跨界精准、高效、灵活的水资源管理指明了新方向。中国预留水权的研究起始于初始水权分配原则，2005年王浩等[1]在《关于我国水权制度建设若干问题的思考》一文中明确提出预留水权确权的相关原则。水利部2006年审议通过的《水量分配暂行办法》规定："为满足未来发展用水需求和国家重大发展战略用水需求等，水量分配方案制订机关可以与有关行政区域人民政府协商预留一定的水量份额。预留水量的管理权限由水量分配方案批准机关决定。"《水法》规定："流域范围内的区域规划应当服从流域规划……"，明确了预留水权的定义核心。2007年范可旭等[2]将政府预留水量在长江流域初始水权分配时纳入思考。2013年周晔等[3]指出政府预留水权的设定对于缓解水源地突发水污染公共安全事件有着突出贡献。政府预留水量是为应对未来不确定用水事件而配置的水量，是一种储而备用的行为[4]，但当未发生预留水量的需求时，会产生部分水量的闲置，另一方面，水权的划分难以做到分毫不差，必然会出现部分地区富余而部分地区短缺。因此，有必要对这部分富余或者未使用的水量进行二次配置，以达到跨界水资源配置的最优效率。

预留水权确权基于初始水权的分配，基于国家对于生态优先的需求，在初始水权分配时需要优先保证生态需水。目前我国最为常用的初始水权确权方法为综合了定性和定量研究的层次分析法（analytic hierarchy process，AHP）[5]或者按固定比例分配法[4]。AHP法体系构建的主观性极强，难有统一标准，产生的结果差异极大；固定比例分配方法过于笼统不能因地制宜。由于我国2003年才有生态需水量的统计，且近年来国家对于生态标准要求以及人们对于生态环保意识的不断提升，传统的分配方

收稿日期：2020-02-20　　**修回日期**：2020-04-26　　**网络出版时间**：2020-05-11
网络出版地址：https://kns.cnki.net/KCMS/detail/13.1430.TV.20200511.1144.004.html
基金项目：国家社科基金重大项目(17ZDA064)

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式不再适用于受多复杂因素影响的生态需水确权。相比之下 ARIMA 模型（autoregressive integrated moving average model，ARIMA）可操作性上具有其独特的优势，能够在多重不确定因素下进行分析[6]。ARIMA 模型是 Box 等[7]于 20 世纪 70 年代初提出的时间序列预测方法，在国外能源生产和需求[8]、金融价格[9]、城市用水[10]、区域需水[11]等领域都得到了广泛应用。ARIMA 模型在不同尺度不同类型的用水预测方面的研究表明模型有着较高的精准度。

Shenkar Oded[12]指出引入水权市场、充分利用市场机制配置水资源是我国未来发展的方向。相对于我国政府主导的现货水权交易模式，在美国加利福尼亚南加州大都市受水区（MWD）、澳大利亚维多利亚州北部广泛应用的交易主体参与度更高的水权期权交易方式让交易更加灵活，水资源配置效率更加高效。1993 年 Michelsen 等[13]提出了水权期权的概念。水权期权最初交易模式规定了在特定的某一时间以某一个特定的价格从卖方购买一定的水量，买方通过支付一定的权利金只购买水权的使用权，到达契约执行期买方可以选择执行或者不执行该期权契约，如果不执行也仅有权利金的损失。我国水权期权理论的研究虽然起步较晚，但是期权在电力[14]、贵金属[15]、土地[16]、煤矿[17]等其他资源领域的交易已较为成熟。期权在水权交易方面也已经有部分的探讨。2006 年陈洁等[18]指出我国水权期权交易应以流域为单位，在流域内建立一个水权期权交易所。2008 年王慧敏等[19]引入水期权契约作为市场机制应用于南水北调东线水资源配置。因此，本文将水权期权模型应用于预留水权的再配置研究。

考虑到现阶段初始水权分配方法的局限性，以及生态优先、绿色发展的需求，本文提出基于 ARIMA 生态需水预测的前提下结合供需双侧耦合模型对短期流域预留水权进行确权，供给侧为流域最大可供水量，需求侧包括国民经济、生态环境、政府预留需水[20]等 3 个方面；在水确权基础上构建水权期权模型进行预留发展水权再配置；提高水资源利用效率，缓解跨界用水主体水资源供给冲突的同时减少水资源供给的风险，从而对特殊水权的再配置方案进行有益的探索。

1　模型构建

1.1　流域预留水权确权模型

基于生态优先的需求，在初始水权分配时需要优先保证生态需水的分配。目前对于生态用水量的需求波动较大，传统的分配方式不再适用于受多复杂因素影响的生态需水确权。ARIMA 因为其可操作性被广泛的应用于不同尺度不同类型的用水预测且研究表明模型的精确度较高。因此，本文基于 ARIMA 模型对流域生态需水量进行分析。

1.1.1　问题概化

假设：流域 X 存在 i（$i=1,2,3,\cdots,n$）个受水区，有总量为 W_{A} 的可用水资源；流域调水中心将保证国民经济、生态环境用水之后剩余的水量作为预留水量；基于水量是水权的载体，本文中的水权确权量即为需水量。基于现阶段初始水权确权的体系尚未完善以及最大限度鼓励区域积极节水的目标，本文中预留水权确权时效性为 1 a。

1.1.2　参数厘定

根据研究问题需要，本文相关参数界定见表 1。

表 1　预留水权确权模型参数设定

参数	说明	参数	说明	参数	说明
W_{U}	地表水量	W_{CS}	农业需水量	W_{A}	流域供水总量
W_{D}	地下水量	W_{IP}	工业需水量	W_{R}	流域可预留水量
W_{I}	工程调入水量	W_{LE}	生活需水量	W_{RC}	预留应急水量
W_{RE}	再生水量	W_{EC}	生态需水量	W_{RD}	预留发展水量

1.1.3　ARIMA 生态需水量预测模型

ARIMA 是现代时间序列模型的代表，假定任意时间序列为随机序列的一种方法。通过自相关性的分析描述时间序列建立合适的模型，基于已有的数值对未来的变化进行预测。其具体的表达为

$$\begin{aligned}z_t=&\varphi_1 z_{t-1}+\varphi_2 z_{t-2}+\varphi_3 z_{t-3}+\cdots+\varphi_p z_{t-p}-\\&\theta_1 u_{t-1}-\theta_2 u_{t-2}-\cdots-\theta_q u_{t-q}+u_t\end{aligned}\tag{1}$$

式中：z_t 为时间序列；φ_p 表示自回归系数；p 为自回归阶数；u_t 是独立于 z_t 的随机项，即白噪声；θ_q 为移动平均系数；q 为移动平均阶数。

通过 SPSS 软件完成工程所在流域（$t+1$）年的生态需水量的预测并结合 t 年 i 地区在流域的生态需水量中的占比完成 i 区域生态需水量的预测。预测年区域生态需水量公式为

$$W_{EC_{t+1,i}}=W_{EC_{t+1,\mathrm{A}}}(W_{EC_{t,i}}/W_{EC_{t,\mathrm{A}}})\tag{2}$$

式中：$W_{EC_{t,i}}$ 表示第 t 年的 i 区域的生态需水量；$W_{EC_{t,\mathrm{A}}}$ 表示第 t 年的流域生态需水总量；$W_{EC_{t+1,i}}$ 表示预测年的 i 区域生态需水量；$W_{EC_{t+1,\mathrm{A}}}$ 表示预测年流域生态需水量，流域预测年生态需水量 $W_{EC_{t+1,\mathrm{A}}}$ 通过 ARIMA 预测模型求得。除生态需水量以外的供给侧（地表水、地下水、再生水）可供水量，需

求侧（农业、工业、生活）需水量采用移动平均法进行预测。

1.1.4　生态优先的预留水权确权模型

根据不同目的和用途，松辽流域预留水权相关的研究结果将预留水权又分为预留应急水权和预留发展水权，其中预留应急水权又分为国民经济应急水权、生态环境预留应急水权、水市场预留应急水权。预留发展水权又分为规避经济发展风险水权、协调流域发展水权以及国家重大发展战略水权。根据定义预留水量是满足国民经济与生产生活需水之后剩余的水量，因此可得关于流域预留水量表达为

$$\begin{cases} W_{\mathrm{R}_{t+1}}=W_{\mathrm{A}_{t+1}}-W_{\mathrm{CS}_{t+1}}-W_{\mathrm{IP}_{t+1}}-W_{\mathrm{LE}_{t+1}}-W_{\mathrm{EC}_{t+1}} \\ W_{\mathrm{R}_{t+1}}=W_{\mathrm{RC}_{t+1}}+W_{\mathrm{RD}_{t+1}} \\ W_{\mathrm{A}_{t+1,i}}=(\sum\limits_{t-2}^{t}W_{\mathrm{U}_i}+\sum\limits_{t-2}^{t}W_{\mathrm{D}_i}+\sum\limits_{t-2}^{t}W_{\mathrm{I}_i}+\sum\limits_{t-2}^{t}W_{\mathrm{RE}_i})/3 \\ W_{\mathrm{RC}_{t+1,i}}=(\dfrac{W_{\mathrm{CS}_{t+1,i}}}{12}+\dfrac{W_{\mathrm{IP}_{t+1,i}}}{12}+\dfrac{W_{\mathrm{LE}_{t+1,i}}}{12}+ \\ \qquad \dfrac{W_{\mathrm{EC}_{t+1,i}}}{12})\times 2 \end{cases} \tag{3}$$

供给侧可供水量（地表水、地下水、再生水），考虑到环境的周期性采用3年移动平均值。流域工程调入水采用仲志余等[21]2018年最新的统计结果。据水利部最新的统计数据，中国近3年的农业灌溉用水总量实现零增长，而万元工业增加值用水量稳定下降，用水总量整体微增长，人民生活用水保持稳定，因此需求侧（农业、工业、生活）需水量，在充分尊重现状的原则以及充分考虑经济、环境、技术的不断发展，预测年采用3年移动平均值。预留应急水权部分在综合考虑松辽流域初始水权分配研究结果中关于预留应急水权定量的建议[20]、现阶段中国农业灌溉需水量和工业万元增加值需水量发展的现状、基于市场配置的情况下对于应急需水量以及流域预留水量联动统一协调产生的积极的作用等因素，采用预测年农业、工业、生活以及生态月平均需水量的2倍作为相应部分的国民经济预留应急需水量及生态预留应急需水量，同时因为短期时间内水权交易还极少，因此预留水权交易应急水量暂不考虑。

根据式（3）求得基于生态优先原则的流域预留发展水权确权模型为

$$\begin{cases} W_{\mathrm{RD}_{t+1}}=W_{\mathrm{R}_{t+1}}-W_{\mathrm{RC}_{t+1}} \\ W_{\mathrm{RD}_{t+1,i}}=W_{\mathrm{A}_{t+1,i}}-W_{\mathrm{CS}_{t+1,i}}-W_{\mathrm{IP}_{t+1,i}}- \\ \qquad W_{\mathrm{LE}_{t+1,i}}-W_{\mathrm{EC}_{t+1,i}}-W_{\mathrm{RC}_{t+1,i}} \end{cases} \tag{4}$$

式中：区域预留应急水量$W_{\mathrm{RC}_{t+1}}$是区域必须预留的水量，因此其计算值即为流域的规划量，部分区域自身不能满足预留应急需水时，需要通过流域调度中心协调以满足区域预留应急水量的需求。式中的$W_{\mathrm{RD}_{t+1,i}}$表示根据区域最大供水量和农业、工业、生活、生态、预留应急需水量求出的区域可预留发展水量计算值，当其值小于0时表示区域自身不具备预留发展水量的能力，当其值大于0时，表示区域具备自备预留发展水量的能力。流域的预留发展水量由流域统一协调配置，在流域满足所有区域的预留应急需水量后，剩余的总水量即为流域预留发展水权确权量。

1.2　流域预留水权期权配置模型

预留水权在确权期内可能因为未发生特殊用水需求而产生闲置，现阶段水权交易市场模式中，政府只能根据水权交易现货价格进行宏观调控，对水资源的未来发展缺乏规划能力。期权市场产生的价格所反应的水资源需求具有真实性和超前性，政府结合宏观经济数据反馈，引导区域内企业调整生产经营规模与方向，使其符合政府对于未来宏观发展以及未来水资源市场配置的需要，切实发挥流域水资源高效管理目标。因为对水权期权的研究还极少，本文在综合现有水权期权[22]及电力期权[23]模型的基础上构建基于成本与收益的水权期权配置模型。预留应急水量因其应急公益属性不可再配置，由流域调控中心统一管理。本文主要讨论预留发展水权再配置问题。

1.2.1　问题概化

因为主要讨论流域预留发展水权的市场配置问题，因此可假设：卖方为拥有预留水权的流域水资源调度中心，买方为省级供水公司；在水权期权交易系统中，水权卖方提供水权期权交易契约，买卖双方信息对称，均可根据所获得信息判断对方最优决策，且水权交易双方的风险皆为中性；水权买方通过执行水权期权契约或者通过现货水权交易2种方式获得所需水权；现货市场的这部分的需求总可以得到满足，卖方可通过现货水市场出售其剩余未被执行的水权期权。本文所描述的期权皆为买方看涨期权[22]。

1.2.2　参数厘定

根据研究问题需要，本文界定相关参数见表2。

表2中p_{s}根据上文假设为随机变量，则其概率密度函数为$f(p_{\mathrm{s}})$，为保证一般性假设在$[0,Z]$的区间范围内服从均匀分布。上下游市场之间价格

存在着传递机制则 $p_r(p_s)$，即 p_r 是与 p_s 相关的变量。下级市场的需求是关于零售市场价格 p_r 的函数，而 p_r 又是关于 p_s 的函数因此假设水权买方零售市场的需求函数为 $D=K-ep_s$，其中 K、e 为常量且皆大于 0。本文研究重点是“准市场”环境下基于不同价格的预留发展水权的配置方法，水权期权权利金参考王慧关于水期权价值的研究成果[24]。

表 2　预留发展水权期权配置模型参数设定

参数	说明	参数	说明
D	T_1 时刻供水公司零售市场水资源的需求量	Q	T_0 时刻水权期权买方期权购买量
K	流域预留水权交易市场最大可交易水量	q_e	T_1 时刻买方执行的水权期权数量
p_r	零售市场供水公司出售水资源零售价格	q_s	T_1 时刻买方现货市场水权购买量
p_s	T_1 时刻水权交易市场中现货水权的价格	S	水权期权的价格即权利金
β	T_0 时刻预留水权公平性分配原则振幅区间	p_e	水权期权的执行价格
e	水资源需求量与现货市场价格相关系数		

1.2.3　预留发展水权期权配置模型

结合上述假设构建买方收益-成本函数，即省级供水公司的水权期权市场利润最大化，公式为

$$\max\Pi_r=p_rD-(sQ+p_eq_e+p_sq_s) \tag{5}$$

$$s.t\begin{cases}q_s=D-q_e\\ q_e=\min(Q,D)\chi(p_s-p_e)\\ \chi(p_s-p_e)=\begin{cases}1 & p_s\geqslant p_e\\ 0 & p_s<p_e\end{cases}\\ D\in[0,(\mathrm{GDP}_{t-1,i}/\mathrm{GDP}_{t-1,A})\times\\ (1+\beta)]\times W_{\mathrm{RD}_{t+1}}\end{cases} \tag{6}$$

式中：Π_r 为区域水权期权买方的利润；p_rD 为买方在下级零售市场所获收入；$(sQ+p_eq_e+p_sq_s)$ 表示买方在期权市场和现货市场购买水权所有花费的总成本。式(6)表示相关的约束条件包括：水权现货市场中购买水权的数量约束；执行水权期权的数量约束，执行期权的数量不会超过零售市场水权的需求量；执行水权期权的前提条件，当且仅当 $p_s\geqslant p_e$ 时买方才会选择执行期权；公平性的约束条件，预留发展水权交易是“准市场”交易，不能完全地按照市场进行配置。

因此，本文在充分考虑公平性原则条件下，流域受水区域对于预留发展水量的需求上限基于 $(t-1)$ a 即上一年的区域 GDP 与流域 GDP 比值增幅 β 的区间内。基于以上约束流域预留发展水权期权协调配置模型的构建分为以下 4 个步骤。

步骤 1　建立现货市场价格和执行价格对于期权执行量的影响分析。当 $p_s\geqslant p_e$ 时水权买方才会选择执行期权实现利润更优。结合买方需求量与期权执行量以及现货市场购买量之间函数关系，买方期望收益为

$$E\Pi_r=\int_{p_e}^{\infty}\{p_rD-[sQ+p_e\min(Q,D)+ p_s[D-\min(Q,D)]]\}f(p_s)\mathrm{d}p_s+ \int_0^{p_e}[p_rD-(sQ+p_sD)]f(p_s)\mathrm{d}p_s \tag{7}$$

步骤 2　根据买方下级零售市场水权需求函数，建立 T_1 时刻零售市场水资源的需求与水权期权的购买量之间的关系。因为在实际的情况中 T_1 时刻买方即省级供水方不会购买超过用户需求的水量，因此存在以下关系。

(1)当 $D=K-ep_s>Q$ 时，$q_e=\min(Q,D)=Q$，且有 $p_s<(K-Q)/e$。

(2)当 $D=K-ep_s\leqslant Q$ 时，$q_e=\min(Q,D)=D$，且有 $p_s\geqslant(K-Q)/e$。

步骤 3　根据步骤 1、2 中 q_e 关于 D、Q 取值的关系以及 p_s 与 p_e 的关系构建不同价格方案下的期望利润函数。

(1)$p_s\geqslant p_e$ 且 $p_e\geqslant(K-Q)/e$，$p_s\geqslant(K-Q)/e$，$q_e=\min(Q,D)=D$ 有

$$E\Pi_r=\int_{p_e}^{\infty}\{p_r(K-ep_s)- [sQ+p_e(K-ep_s)]\}f(p_s)\mathrm{d}p_s+\int_0^{p_e}[p_r(K- ep_s)-(sQ+p_s(K-ep_s))]f(p_s)\mathrm{d}p_s \tag{8}$$

对式(8)中的变量 Q 求导 $\dfrac{\partial E\Pi_r}{\partial Q}=-s$，因为 s 恒大于 0，因此 $-s$ 恒小于 0，因此可知水权期权买方的期望是关于 Q 的减函数[22]，Q 在边界时可以取得最值。根据上文的约束条件 $q_e=\min(Q,D)=D$，因此 $Q=K-ep_e$ 时可能求得最值。

(2)当 $p_s>p_e$，$p_e<(K-Q)/e$，且 $p_s\in(\dfrac{K-Q}{e},\infty)$，有 $p_s>(K-Q)/e$，$\min(Q,D)=D$；$p_e<(K-$

$Q)/e$，且 $p_s \in [p_e, \frac{K-Q}{e}]$，有 $\min(Q, D) = Q$。因此将式(7)转化具体表达公式为

$$
\begin{aligned}
E\prod{}_{r} = & \int_{\frac{K-Q}{e}}^{\infty} \{p_r(K-ep_s) - \\
& [sQ+p_e(K-ep_s)]\} f(p_s) \mathrm{d}p_s + \\
& \int_{p_e}^{\frac{K-Q}{e}} \{p_r(K-ep_s) - [sQ+p_eQ+ \\
& p_s(K-ep_s-Q)]\} f(p_s) \mathrm{d}p_s + \\
& \int_{0}^{p_e} \{p_r(K-ep_s) - [sQ+p_s(K-ep_s)]\} f(p_s) \mathrm{d}p_s = \\
& \int_{0}^{\infty} p_r(K-ep_s) f(p_s) \mathrm{d}p_s - \\
& \int_{\frac{K-Q}{e}}^{\infty} [sQ+p_e(K-ep_s)] f(p_s) \mathrm{d}p_s - \\
& \int_{p_e}^{\frac{K-Q}{e}} [sQ+p_eQ+p_s(K-ep_s-Q)] f(p_s) \mathrm{d}p_s - \\
& \int_{0}^{p_e} [sQ+p_s(K-ep_s)] f(p_s) \mathrm{d}p_s
\end{aligned}
\tag{9}
$$

对式(9)求 Q 关于 p_s 的一阶导数，p_s 在 $[0, Z]$ 的区间范围内服从均匀分布，所以其概率密度函数 $f(p_s) = 1/Z$，将其代入式(9)中联合求解关于 Q 的表达式，最终可求得 Q 关于 K、e、p_e、Z、s 的一元二次方程表达式为

$$
\begin{aligned}
& Q^2 + (2ep_e - 2K)Q + (K^2 + p_e^2 e^2 - 2ep_eK) - \\
& 2Ze^2 s = 0
\end{aligned}
\tag{10}
$$

通过求根公式可以求得关于 Q 的两个根的表达式为

$$
Q_1 = K - ep_e + e\sqrt{2Zs}, \quad Q_2 = K - ep_e - e\sqrt{2Zs}
\tag{11}
$$

根据上文的条件公式 $p_e < (K-Q)/e$ 而 $e\sqrt{2Zs}$ 恒大于 0，因此在式(11)中可能求得最小值的根式为 $Q_2 = K - ep_e - e\sqrt{2Zs}$。

步骤 4　构建与 T_0 时期水权期权购买量相关的期望成本。式(9)最终表达前项为水权期权买家的收入、后面的减项为买家成本，可知收入最大、成本最小时可获得最优订货量，因此令成本为 C，具体表达为

$$
\begin{aligned}
C = & \int_{\frac{K-Q}{e}}^{\infty} [(sQ+p_e(K-ep_s))] f(p_s) \mathrm{d}p_s + \\
& \int_{p_e}^{\frac{K-Q}{e}} [(sQ+p_eQ+p_s(K-ep_s-Q))] f(p_s) \mathrm{d}p_s + \\
& \int_{0}^{p_e} [sQ+p_s(K-ep_s)] f(p_s) \mathrm{d}p_s
\end{aligned}
\tag{12}
$$

通过公式的求解，C 的表达式为

$$
\begin{aligned}
C = & sQ + (K-Q)^3/6Ze^2 - p_e(K-Q)^2/2Ze + \\
& p_eK - p_eeZ/2 - p_e^2 Q/2Z
\end{aligned}
\tag{13}
$$

综上所述，可能使买家期望 $E\prod{}_{r}$ 最大、C 期望最小的 3 个 Q 值表达式为

$$
\begin{cases}
Q_1 = 0 \\
Q_2 = K - ep_e - e\sqrt{2Zs} \\
Q_3 = K - ep_e
\end{cases}
\tag{14}
$$

将其代入式(12)分别求导，得期望成本 C 的表达为

$$
C_{Q_1} = K^3/(6Ze^2) - p_eK^2/(2eZ) + p_eK - ep_eZ/2
\tag{15}
$$

$$
\begin{aligned}
C_{Q_2} = & -seP_e - ep_eZ/2 - p_e^2K/(2Z) + \\
& ep_e^3/(6Z) + p_eK + sK - (2se\sqrt{2sZ})/3
\end{aligned}
\tag{16}
$$

$$
\begin{aligned}
C_{Q_3} = & ep_eZ/2 + ep_e^3/(6Z) + sK - sep_e + \\
& p_eK - p_e^2K/(2Z)
\end{aligned}
\tag{17}
$$

根据公平性约束条件以及不同的价格配置方案，成本期望 C 最小值所对应的 Q 值即为 T_0 阶段买方最优预留发展水权期权购买量。

2　实例分析

2.1　研究地区概况

选取南水北调中线工程受水区开展实证研究。2014 年 12 月 12 日，南水北调中线工程正式通水，主要解决河南、河北、北京、天津等 4 省（直辖市）的缺水问题。根据工程建设的规划最终实现平均每年 130 亿 m^3 的调水量。南水北调中线工程水源地位于长江最大支流汉江中上游的丹江口水库。根据中国统计年鉴 2018 年数据：2017 年北京、天津、河北、河南的人口分别为 2 171 万、1 557万、7 520万和9 559万人，总体占比为全国人口的 15%；2017 年4 省（直辖市）的 GDP 产出分别为 28 014.94 亿、18 549.19 亿、34 016.32 亿和 44 552.83亿元，总量全国占比为 15.17%。

2.2　数据来源

数据来源包括 2004—2018 年《中国统计年鉴》、2004—2018 年各省《统计年鉴》《中国水资源公报(2017)》以及南水北调（http://www.nsbd.gov.cn/）官网数据、北京市水务局（http://www.bjwater.gov.cn/）官网数据。其中，南水北调中线工程所在流域的预留发展水权价格配置方案制定参考的典型数据：北京市零售市场非居民用水价格 9 元/m^3，来源于北京市水务局 2018 年 1 月 22 日公布的京发改[2018]115 号文件。

2.3　分析与讨论

2.3.1　流域预留水权确权

2.3.1.1　流域生态需水量预测

基于 ARIMA 模型的确认路径，在尽量减少自回归、差分、移动平均对于数据影响的前提下，对中线工程所在流域的生态需水量进行 27 个 ARIMA 模型的分析，最终选定 ARIMA(2，3，1)模型，此时 $R^2=0.742$，同时无离群值出现，模型可信度较高。基于移动平均算法与基于 ARIMA 预测模型的流域生态需水量预测结果分别见图 1、2。

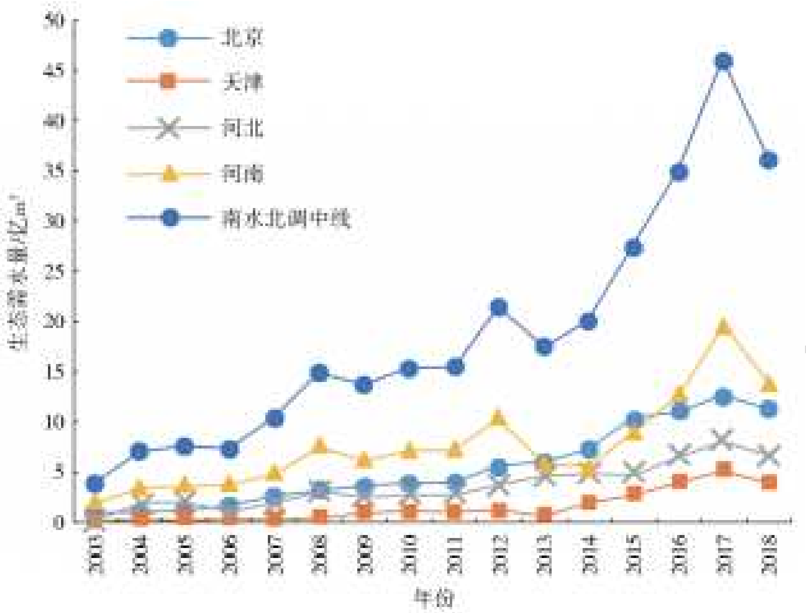


图 1　2018 年移动平均模型流域生态需水量预测

图 2　2018 年 ARIMA 模型流域生态需水量预测

通过图 1、2 的对比可知，相对于移动平均预测模型 2018 年 36.07 亿 m^3 呈现下降趋势的生态需水量预测结果，显然 ARIMA 生态需水量 59.07 亿 m^3 呈现较大幅度增长的预测结果更加符合国家政策调控下的流域生态需水量的变化趋势。ARIMA(2，3，1)模型历史拟合数据见图 3。

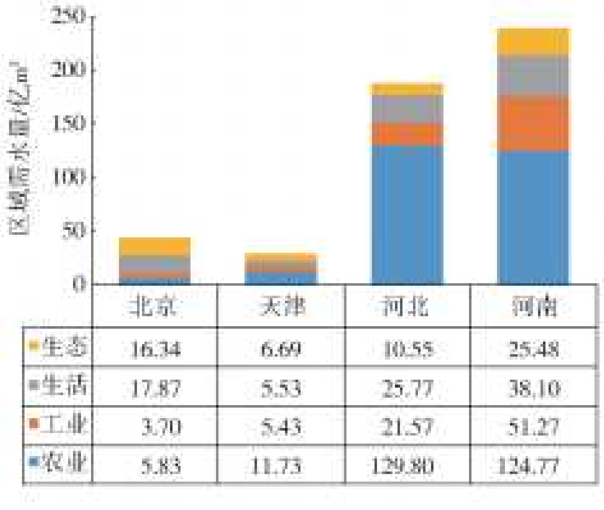
通过图 3 可知，随着时间的推移模型的拟合度趋于完善。2007、2009、2013、2015 年共 4 个年份拟合度偏差较大。通过分析发现，由于中国生态需水量目前可查的数据起始于 2003 年，截至 2018 年仅有 15 a 的数据，3 次的差分会对前期的数据造成一定的影响，导致 2007 年数据预测的拟合度较低。2009 年天气相对于其他的年份变化剧烈：当年全国年平均降水量 573.3 mm，为 1987 年以来最小值；当年全国年平均气温为 9.9 ℃，为 1951 年以来第 4 高值。降雨量大幅度下降，流域在保证农业生产和

居民生活用水的前提下必然约束生态用水量的需求，而明显的温度上升又加快水资源蒸散，因此，出现了观测值低于拟合值的现象。国务院以国发〔2012〕3号文件印发《关于实行最严格水资源管理制度的意见》，明确“三条红线”“四项制度”对于2013的生态用水总量形成了一定的抑制。2015中共中央国务院印发《生态文明体制改革总体方案》，在政策制度上对于生态建设给予了前所未有的关注，因此生态用水量相对于往年增幅较大。这4个值拟合度相对偏差较大的数据，恰恰在数据量、自然天气情况和政策方向对于生态用水量可能产生的影响提供了极佳的案例参考，为后期更加精准地进行生态用水量的预测提供了依据。

2.3.1.2　区域生产、生活、生态需水量预测

根据式(2)、(3)以及基于南水北调中线工程所在流域的生态需水量ARIMA(2,3,1)模型进行预测，南水北调中线工程及其4个受水区的生产、生活、生态需水量见图4。

图3　**ARIMA(2,3,1)历史数据拟合度**



	北京	天津	河北	河南
■生态	16.34	6.69	10.55	25.48
■生活	17.87	5.53	25.77	38.10
■工业	3.70	5.43	21.57	51.27
■农业	5.83	11.73	129.80	124.77

图4　**预测年农业、工业、生活、生态需水量**

由图4可知，4个不同的受水区不同种类的需水量存在者巨大的差别，北京、天津、河北、河南需水总量分别为43.74亿、29.39亿、187.68亿和239.61亿m³。农业需水总量最大，河北省和河南省的农业需水量超过其他3类需水量的总和，河北省农业需水量甚至为其他3类需水量的2倍。不同区域工业和生活需水根据人口以及产业结构在总需水结构中的排序会略微有所不同。北京市的用水结构与其他3个受水区大为不同，其农业、工业占比较少，这与近2年北京市严格执行生态保护政策以及工业企业外迁存在密不可分的关系。

在南水北调中线工程4个受水区中，北京市生态需水量全国占比相对较高，2018年的预测生态需水量16.34亿m³与区域生活需水量近乎持平，天津市的生态需水量相对较低，河南省的生态需水量在4个受水区中最大。环比2017年的数据发现，中线工程所在流域的生态需水量整体有较大提升。以北京市为例，在未印发《生态文明体制改革总体方案》前，2014年的生态需水量为7.25亿m³，而2018年的预测生态需水量为16.34亿m³，增幅125%，年平均增长比例达到31%，可见生态需水受政策影响增幅较大。

2.3.1.3　流域预留水权确权

根据式(3)、(4)对流域预留应急水量及预留发展水量进行确权。结果见表 3。

表 3　2018 预测年中线工程所在流域的预留水权

单位:亿 m^3

区域	可预留水量	预留应急水量	可预留发展水量	流域预留发展水量
北京	10.23	7.29	2.94	—
天津	−4.29	4.90	−9.19	—
河北	7.58	31.28	−23.70	—
河南	147.29	39.94	107.35	—
中线	160.80	83.40	77.39	77.39

从表 3 可知:河南省可预留水量最多,对于流域的可预留水量的总贡献达到了 91.6%。天津市缺水情况严重,自身已经不具备自备预留水量的能力。同时河北省也仅能满足极小部分的预留应急水量需求。河南省预留应急水量最多为 39.94 亿 m^3,接近于当年区域的生活用水。天津市预留应急水量为 4.90 亿 m^3,为 4 个受水区中最小。北京市的预留应急水量为 7.29 亿 m^3,为当年生态需水的 1/2。预留应急水量是区域应对不可知的需水风险所预留的一部分水量,在自身可用水量不能满足的情况下必须通过流域进行统一的协调,这与王浩等[1]在我国水权制度建设中有针对性地提出预留水权应该由流域统一配置的建议相符。预留应急水量需要高度的反应效率,如将这部分的水量存储在丹江口水库,而北京市发生应急突发状况,正常调水需要 15 d 左右。考虑到大型调水工程的开启、运输需要的时间相对较长,应急情况需要高效的反应和控制能力,丹江口水库不太适宜。因此对于预留应急这部分的水量考虑在流域统一管理前提下,流域调度中心建立预留应急水量的风险应对程序,就近储存以便调用,做到高效管理。

分析发现北京市预留发展水量也极少,河南省预留发展水量相对丰富。进一步通过中线流域受水区 3 年供需对比寻找原因,具体见图 5。

对比可知,京津冀地区为典型的资源型缺水地区,除北京依靠自身的领先技术,近 3 年有年平均 10 亿 m^3 的再生水资源的供给,勉强在满足生产和生活用水的前提下有部分水资源的富余外,天津市和河北省处于自身可供水资源不能够满足或者仅能满足正常的生产、生活、生态需水量的现状,因此就自身而言自备预留应急水量和预留发展水量的能力极弱,需要依靠流域调度中心的统一协调。根据上述对比分析总结可知,在流域范围预留发展水量较为丰富,可以通过水权期权高效的市场配置方案进行协调,解决区域不具备自备预留发展水量的问题。下文将基于水权期权模式对流域预留发展水权高效分配进行分析与讨论。

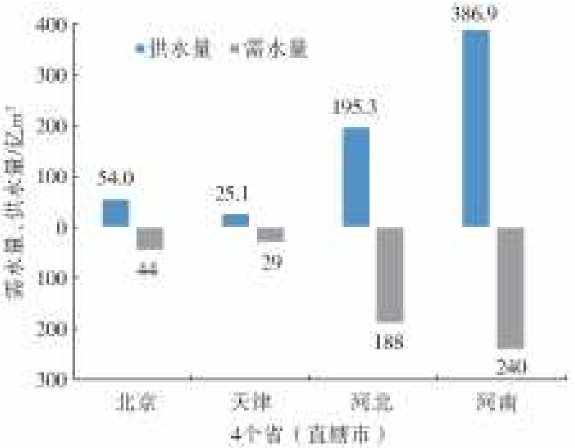


图 5　南水北调中线五年平均水资源供需对比

2.3.2　预留发展水权市场配置分析

基于水权期权的市场配置模型,对北京市区域预留发展水权的可行市场配置量进行分析。基于模型中的假设,基本情况界定如下:(1)水权期权的卖方为中线工程所在流域的水资源调度中心,买方为北京供水公司。(2)流域水资源调度中心可投入的水权市场的最大预留发展水权 $K=77.39$ 亿 m^3。(3)买方市场需求量关于现货市场价格相关的系数 $e=4$ 亿 m^3/元。(4)现货市场价格最大的取值范围,根据 2018 年 1 月 22 日北京市水务局公布的最新非居民用水指导价格为 9 元/m^3,居民用水价格为5 元/m^3,取 $Z=18$ 元/m^3。(5)本文重点讨论“准市场”环境下,不同期权价格策略对于预留发展水权的影响,因此水权期权的价值采用王慧等[24]前期的研究成果,假设期权的价格,即权利金 $s=1$ 元/m^3。(6)以 GDP 为基础的公平性原则,根据专家建议$\beta=15\%$增幅区间较为合理,符合经济发展,则 2018 年北京市预留发展水权需求比例在[0,25.75%],需求量在[0,19.93]亿 m^3。(7)根据买方下级市场与现货市场相关的需求价格函数得 $p_s\in[14.37,18.00]$ 元/m^3。

2.3.2.1　水权期权购买量与水权期权执行价格敏感性分析

结合上述假设对水权期权执行价格与 T_0 时刻的水权期权购买量,即 p_e 与 Q 相关的敏感性进行分析,p_e 以单位 $\alpha=0.5$ 元/m^3 的价格进行变动,结果见图 6。

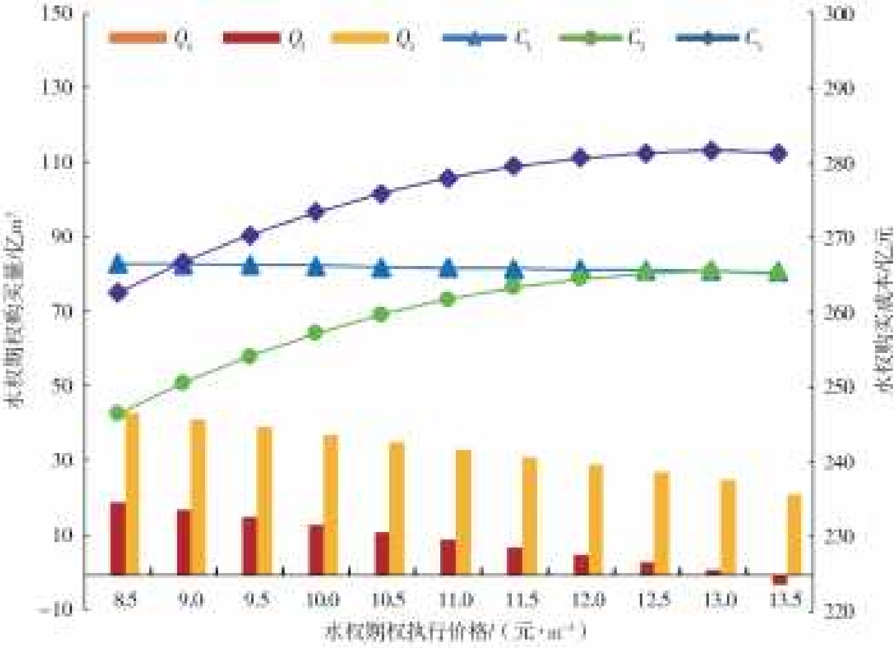


图 6　水权期权购买量与执行价格敏感性分析

通过图 6 得出：(1)随着执行价格的不断增加，T_0 时期关于水权期权的购买量不断下降，在水权执行价格取值为 13.35 元/m^3 时水权期权购买量为 0。(2)在[8.5，13.35]元/m^3 的执行价格的取值范围内，水权期权的买家在第 2 种情况的期权购买量取得最小成本，但是在执行的价格大于 13.35 元/m^3 时，水权期权的买家选择第一方案，即不购买水权期权可以取得最小的成本。(3)在现阶段水务局公布的非居民用水价格 9 元/m^3 基础上，以低于零售市场的价格进行变动，成本的敏感性极大，并且价格敏感系数呈现出明显的阶梯性下降趋势。在 8.5 元/m^3 到 9 元/m^3 的单位 α 价格上升，买方水权购买成本上升 8α 亿元。在 9 元/m^3 至 10 元/m^3 单位执行价格变动，则买方水权购买成本上升 6α 亿元至 7α 亿元。在10 元/m^3 至 12 元/m^3 单位价格变动买方水权购买成本上升 2α 亿元至 4α 亿元。

2.3.2.2　水权期权执行价格与现货市场价格配置方案分析

方案一　假定 T_1 时刻现货市场水权价格为 15 元/m^3。当 $p_s=15$ 元/m^3 时，根据下级市场价格需求函数 $D=17.39$ 亿 m^3。$p_e\in[8.5,9]$元/m^3 范围内期权的购买量超过下级市场可能的需求量，水权期权买方选择执行期权，所有水权的需求通过执行水权期权可以得到满足。在[9，13.35]元/m^3 的范围内期权的购买量小于市场的需求量，北京供水公司选择执行期权的同时，会在现货市场购买未被满足的水权需求量。

方案二　假定 T_1 时刻现货市场水权价格为 18 元/m^3。当 $p_s=18$ 元/m^3 时，根据下级市场价格需求函数 $D=5.39$ 亿 m^3。$p_e\in[8.5,12]$元/m^3 范围内期权的购买量超过下级市场可能的需求量，水权期权买方选择执行期权，所有水权的需求通过执行水权期权可以得到满足。在[12，13.35]元/m^3 的范围内期权的购买量小于市场的需求量，北京供水公司选择执行期权的同时，会在现货市场购买未被满足的水权的需求量。

综上所述，p_s 直接反映了流域水资源供给的现状，当水资源供给短缺时现货市场价格较高，当水资源供给较为富足时现货市场价格较低。流域调度中心可以根据预测年对于预留发展水权的使用量进行综合的分析：在预计需求较少的情境下设定 p_e 较低的价格配置方案，鼓励流域中的需水省份加强预留发展水权的需求；在预计突发需求较多的情况下，可以设定 p_e 较高的价格配置方案，减少流域对于预留发展水权的供给。最终实现流域供需双侧预留发展水权的高效配置。

需要注意的是本文中的价格配置方案建立在 T_1 时刻 p_s 较为稳定，以及受政治、经济、环境影响较大的价格相关系数 e 无波动的基础之上，p_s 和 e 较大的波动都会对水权期权的价格配置方案产生极大的影响，阻碍流域预留发展水权的高效利用。后期需要对现货市场价格和价格相关系数具体的影响因素进一步探索。

3　结论与建议

(1)基础数据量、自然气候变化、国家宏观政策

等对生态需水量有较大影响。国家水资源分配部门需要充分考虑生态用水量的需求，制定节水奖励政策，将这部分节约的水量用于生态可持续发展。

（2）天津市和河北省在现有的可用水资源条件下自身不具备预留发展水量的能力。这类地区应大力发展京津冀一体化，实现流域对于资源的统一协调，在考虑公平性原则时给予高效节水地区适当的政策倾斜，引导区域使用再生水。

（3）随着水权期权执行价格的不断上升，区域对于水权期权的需求量及单位价格变化的敏感性下降。流域调度中心可以根据预留发展水权使用量进行的综合风险分析，通过价格方案灵活调控区域对预留发展水量的需求。

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·译文(Translation)·

DOI:10.13476/j.cnki.nsbdqk.2020.0090

Inter-basin reserved water right confirmation and allocation from the perspective of ecological priority

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Abstract: The Autoregressive Integrated Moving Average Model (ARIMA) prediction model of ecological water demand is proposed on the premise of ecological priority and green development. Based on this model, the reserved water rights confirmation model using ecological water rights is developed. Depended on the confirmed reserved water rights, the feasibility in the reconfiguration of reserved developmental water rights under the options trading model is explored. The model can avoid the risks between water buyers and water sellers, meanwhile, it can achieve optimal allocation of water resources across river basins. It provides a reference for the determination and reconfiguration of special water rights across river basins. The results showed that: the ecological water demand has changed greatly due to climate change and policy, Tianjin and Hebei do not have the capacity of reserved water for development, which needs to rely on the unified coordination of the basin scheduling center. and the basin scheduling center can do flexible price configuration based on the possible use of reserved development water in the forecast year, which can optimize the economic and social benefits.

Key words: ecological priority; inter-basin reserved water right; water rights option; South-to-North Water Transfer Middle Line

The concept of reserved water rights points out a new direction for accurate, efficient, and flexible trans-boundary management of water resources. Research on reserved water rights in China started from principles of initial allocation of water rights. In 2005, Wang et al.[1] clearly put forward relevant principles regarding confirmation of reserved water rights in the article *Discussion on the Construction of Water Rights System in China*. The *Interim Measure for Water Allocation* examined and approved by the Ministry of Water Resources in 2006 gives following stipulations: "In order to meet water demand for future development and major national development strategies, the organ formulating water-allocation plans may consult with the people's governments of relevant administrative districts to reserve certain water shares. Administration authority of reserved water shall be determined by the organ approving the water allocation plans." The national Water Law stipulates

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Received: 2020-02-20 **Revised**: 2020-04-26 **Online publishing**: 2020-05-11
Online publishing address: https://kns.cnki.net/KCMS/detail/13.1430.TV.20200511.1144.004.html
Fund: Major Projects of the National Social Science Foundation of China (17ZDA064)

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Corresponding author: LIU Gang (1981-), male, PhD, associate professor, Taiyuan Shanxi Province, mainly engaged in the research on the principle and method of water resource management. E-mail: lglhm@msn.com that regional planning within the scope of a river basin shall be subject to the planning of the river basin, which clarifies the core of definition of reserved water rights. In 2007, Fan et al. [2] took government-reserved water into consideration during initial allocation of water rights in the Yangtze River basin. In 2013, Zhou et al. [3] pointed out that the setting of government-reserved water rights made an outstanding contribution to alleviating public safety incidents of emergent water pollution in water source areas. Government-reserved water is the water allocated in response to uncertain water use in the future, and this refers to a behavior of water storage for backup use[4]. However, in the case of no demand for reserved water, the reserved water will be in idle. On the other hand, it is difficult to make prefect division of water rights. This will inevitably result in water surplus in some areas while water shortage in some other areas. Therefore, it is necessary to conduct secondary allocation of surplus or unused water in order to achieve optimal efficiency of trans-boundary water-resource allocation.

Confirmation of reserved water rights is based on allocation of initial water rights. Based on national demand for ecological priority, it is necessary to preferentially guarantee ecological water demand during allocation of initial water rights. At present, the most commonly used method for confirming initial water rights in China is AHP (Analytic Hierarchy Process) which integrates qualitative and quantitative research[5], or fixed-proportion allocation[4]. Specifically, AHP-based systems are constructed with strong subjectivity, and it is difficult for them to share a unified standard. Thus, quite different results are produced. The fixed-proportion allocation method is too general to adapt to local conditions. China started to make statistics of ecological water demand in 2003. In recent years, national requirements on ecological standards and people′s awareness of ecological environmental protection have been continuously improved. Consequently, conventional allocation methods are no longer suitable for confirming ecological water demand affected by multiple complex factors. By comparison, an ARIMA (Autoregressive Integrated Moving Average) model has its unique advantages in operability, and can be used for analysis under multiple uncertainties[6]. The ARIMA model is based on the famous time-series prediction method proposed by Box et al. [7] in the early 1970s. It has been widely used in international energy production and demand [8], financial price [9], urban water consumption [10], and regional water demand [11]. Research on the ARIMA models on different scales and of various types of water-use prediction shows that such models have high accuracy.

Shenkar Oded [12] pointed out that China's development direction in the future was to introduce a water-rights market and make full use of market mechanisms for water-resource allocation. Option transaction of water rights with higher degree of participation of transaction agents has been widely used in the metropolitan water district of Southern California, the US and the northern part of Victoria, Australia. This transaction mode makes transactions more flexible and water-resource allocation more efficient, compared with government-dominated spot transaction of water rights in China. In 1993, Michelsen et al. [13] proposed the concept of water-rights options. According to stipulations of initial transaction of water-rights options, when a buyer buys a certain quantity of water from a seller at a specific price in a period, the buyer only buys the right to use the water at certain premiums. When the exercise period of the contract arrives, the buyer can choose to execute the option contract or not. If the buyer does not execute the contract, they will only lose the premiums. Although the research on theory of water-rights options in China started relatively late, option transaction has been relatively mature in other resource fields, such as electric power[14], noble metal[15], land[16], and coal[17]. Options have also been partially discussed in terms of water-rights transaction. In 2006, Chen et al. [18] pointed out that transaction of water-rights options in China should be done based on units of river basins, and that a water-rights option exchange should be established in a river basin. In 2008, Wang et al. [19] introduced water option contracts as market mechanisms and used them for water-resource allocation in the east route of the

South-to-North Water Transfer Project. Therefore, this paper applied a model of water-rights options to the research on the reallocation of reserved water rights.

Considering limitations of initial water-rights allocation at the present stage, as well as the policy demand of ecological priority and green development, this paper presented a new way of water-rights confirmation. It proposed confirming short-term reserved water rights in a river basin in combination with a supply-demand bilateral coupling model on the premise of ARIMA-based prediction of ecological water demand. Specifically, the supply side is maximum available water supply of the river basin, and the demand side includes the three aspects of national economy, ecological environment, and government reserved water demand [20]. In addition, based on confirmation of water rights, the paper established a model of water-rights options for reallocation of reserved development water rights. This can improve the efficiency of water-resource utilization, and reduce risks of water-resource supply while alleviating conflicts of trans-boundary water users over water-resource supply. Thus, beneficial exploration into reallocation schemes of special water rights can be conducted.

1 Model construction

1.1 Confirmation model of reserved water rights in river basins

Based on the national demand for ecological priority, it is necessary to preferentially guarantee ecological water demand in initial water-rights allocation. Due to high fluctuations in ecological water demand at present, conventional allocation methods are no longer suitable for confirmation of ecological water rights affected by multiple complex factors. Because of its operability, ARIMA is widely used in different scales and types of water-use prediction, and relevant research shows that ARIMA models are of high accuracy. Therefore, this paper analyzed ecological water demand of a river basin based on an ARIMA model.

1.1.1 Problem generalization

It is assumed that a river basin X contains i ($i=1,2,3,\cdots,n$) water-receiving districts, with a total available water of W_A, the scheduling center of the basin takes the remaining water after ensuring water use for national economy and ecological environment as reserved water, and based on the fact that water is the carrier of water rights, confirmed quantity of water rights in this paper is quantity of water demand. Due to imperfect systems of initial water-rights confirmation at the present stage, as well as the goal of maximally encouraging regional active participation in water conservation, the time effectiveness for confirmation of reserved water rights was 1 a in this paper.

1.1.2 Parameter determination

According to the needs of the research, the related parameter bounds in this paper are shown in Tab. 1.

Tab. 1 Parameter setting of reserved water rights confirmation model

Parameter	Description	Parameter	Description	Parameter	Description
W_U	Surface water	W_{CS}	Agricultural water demand	W_A	Total water supply of river basin
W_D	Underground water	W_{IP}	Industrial water	W_R	Reserved water of river basin
W_I	Project-transferred water	W_{LE}	Living water demand	W_{RC}	Reserved emergency water
W_{RE}	Reclaimed water	W_{EC}	Ecological water demand	W_{RD}	Reserved development water

1.1.3 ARIMA model for prediction of ecological water demand

An ARIMA model is a representative of modern time-series models, which assumes that any time series is random. An appropriate model can be established by autocorrelation-based analysis and description of time series, so that future changes can be predicted based on existing values. The specific expression is as follows

$$z_t=\varphi_1 z_{t-1}+\varphi_2 z_{t-2}+\varphi_3 z_{t-3}+\cdots+\varphi_p z_{t-p}-\theta_1 u_{t-1}-\theta_2 u_{t-2}-\cdots-\theta_q u_{t-q}+u_t \quad (1)$$

where: z_t is a time series; φ_p is an autoregressive coefficient; p is an autoregressive order; u_t is a random term independent of z_t, namely white noise; θ_q is a moving-average coefficient; q is a moving-average order.

By SPSS, the ecological water demand of $(t+1)$ a in the river basin can be predicted where the project is located. In addition, in combination with the proportion of ecological water demand of t a in district i to that in the river basin, the ecological water demand in district i can be predicted. The formula of regional ecological water demand in the forecast year is as follows

$$W_{\mathrm{EC}_{t+1,i}}=W_{\mathrm{EC}_{t+1,\mathrm{A}}}(W_{\mathrm{EC}_{t,i}}/W_{\mathrm{EC}_{t,\mathrm{A}}}) \tag{2}$$

where: $W_{\mathrm{EC}\,t,i}$ represents ecological water demand of the t^{th} year in district i; $W_{\mathrm{EC}\,t,\mathrm{A}}$ represents total ecological water demand of the t^{th} year in the river basin; $W_{\mathrm{EC}\,t+1,i}$ represents ecological water demand of the forecast year in district i; $W_{\mathrm{EC}\,t+1,\mathrm{A}}$ represents ecological water demand of the forecast year in the river basin. The ecological water demand of the forecast year in the river basin, $W_{\mathrm{EC}\,t+1,\mathrm{A}}$ was obtained by the ARIMA prediction model. Except ecological water demand, available water supplies on the supply side (surface water, underground water, and reclaimed water) and water demand on the demand side (agricultural, industrial, and living water demands) were predicted through a moving average method.

1.1.4 Ecological-priority-based confirmation model of reserved water rights

According to different purposes and uses, in the research related to reserved water rights in Songliao river basin, the reserved water rights were divided into reserved emergency water rights and reserved development water rights. Specifically, the reserved emergency water rights were divided into reserved emergency water rights for national economy, those for ecological environment, and those for water markets. The reserved development water rights were divided into water rights for risk avoidance of economic development, those for coordinated river-basin development, and those for national major development strategies. According to the definition, reserved water is the remaining water after the water demand of national economy, production, and household is met. Therefore, reserved water in the river basin can be expressed as follows

$$\begin{cases} W_{\mathrm{R}_{t+1}}=W_{\mathrm{A}_{t+1}}-W_{\mathrm{CS}_{t+1}}-W_{\mathrm{IP}_{t+1}}-W_{\mathrm{LE}_{t+1}}-W_{\mathrm{EC}_{t+1}} \\ W_{\mathrm{R}_{t+1}}=W_{\mathrm{RC}_{t+1}}+W_{\mathrm{RD}_{t+1}} \\ W_{\mathrm{A}_{t+1,i}}=(\sum\limits_{t-2}^{t}W_{\mathrm{U}_i}+\sum\limits_{t-2}^{t}W_{\mathrm{D}_i}+\sum\limits_{t-2}^{t}W_{\mathrm{I}_i}+\sum\limits_{t-2}^{t}W_{\mathrm{RE}_i})/3 \\ W_{\mathrm{RC}_{t+1,i}}=(\dfrac{W_{\mathrm{CS}_{t+1,i}}}{12}+\dfrac{W_{\mathrm{IP}_{t+1,i}}}{12}+\dfrac{W_{\mathrm{LE}_{t+1,i}}}{12}+ \\ \qquad \dfrac{W_{\mathrm{EC}_{t+1,i}}}{12})\times 2 \end{cases} \tag{3}$$

The available water supplies on the supply side (surface water, underground water, and reclaimed water) were predicted by three-year moving averages under the consideration of environmental periodicity. For project-transferred water in the river basin, the latest statistical results in 2018 from Zhong et al.[21] were used. According to the latest statistics from the Ministry of Water Resources, the total water consumption for agricultural irrigation in China has achieved zero growth in the past three years, while the water consumption for every CNY 10-thousand worth of industrial value added has declined steadily. The total amount of water consumption has increased slightly as a whole, and people′s living water consumption has remained stable. Therefore, the water demand on the demand side (agriculture, industry, and daily life) was predicted by three-year moving averages, under the principle of fully respecting current situations and with the full consideration of continuous development of economy, environment, and technology. For confirmation of reserved emergency water rights, suggestions on quantification of reserved emergency water rights in the research on initial water-rights allocation in Songliao River basin[20] were considered. The current water demand for agricultural irrigation in China and present development situations of water demand for every CNY 10-thousand worth of industrial value added were also taken into account. In addition, the positive effects produced by coordination between emergency water demand and total reserved water in the river basin based on market allocation were considered as well. Under comprehensive consideration of the above factors, twice the average monthly water demand of agriculture, industry, living, and ecology in the forecast year were taken as corresponding reserved emergency water demand for national economy and that for ecological environment. Meanwhile, due to few water-rights transactions available in a short time, the reserved emergency water of water-rights transaction was not considered for the time being.

According to Formula (3), the ecological-priority-based confirmation model of reserved development water rights in the river basin can be obtained as follows

$$\begin{cases} W_{\mathrm{RD}_{t+1}} = W_{\mathrm{R}_{t+1}} - W_{\mathrm{RC}_{t+1}} \\ W_{\mathrm{RD}_{t+1,i}} = W_{\mathrm{A}_{t+1,i}} - W_{\mathrm{CS}_{t+1,i}} - W_{\mathrm{IP}_{t+1,i}} - \\ \qquad W_{\mathrm{LE}_{t+1,i}} - W_{\mathrm{EC}_{t+1,i}} - W_{\mathrm{RC}_{t+1,i}} \end{cases} \tag{4}$$

In this formula, regional reserved emergency water $W_{\mathrm{RC}t+1}$ refers to the water that must be reserved in districts, so its calculated value is the planned quantity of the river basin. When some districts fail to meet their own reserved emergency water demand, it is necessary to make the demand met through coordination by the scheduling center. $W_{\mathrm{RD}t+1,i}$ in the formula represents the regional reserved development water calculated according to the regional maximum water supply and reserved emergency water demand of agriculture, industry, living, and ecology in the district. When it has a value less than 0, the district is incapable of reserving development water. When it has a value greater than 0, the district is capable of reserving development water. The reserved development water of a river basin is uniformly coordinated by the river basin. After the reserved emergency water demand of all districts in the river basin is met, the total quantity of the remaining water is the confirmed quantity of reserved development water rights in the river basin.

1.2 Allocation model of reserved water-rights options in river basin

Reserved water rights may be in idle during a confirmation period due to no special water demand. In the current market mode of water-rights transaction, the government can only carry out macro-control according to spot price of water-rights transaction, and has no planning capacity for future development of water resources. The demand for water resources reflected by the price generated in option markets is of authenticity and foresightedness. On this basis, in combination with macroeconomic data feedback, the government can guide regional enterprises to adjust scales and directions of their production and operation to conform to the government′s requirements on future macro development and future market allocation of water resources. Thus, the goal of efficient management of water resources in the river basin can be actually realized. Water-rights options have rarely been studied. Therefore, by integrating the existing models of water-rights options [22] and electricity options[23], an allocation model of water-rights options was created based on costs and earnings. Reserved emergency water cannot be reallocated because of its public-welfare attribute of emergency use, which is uniformly controlled by the scheduling center of the river basin. This paper mainly discussed reallocation of reserved development water rights.

1.2.1 Problem generalization

This paper mainly discusses market allocation of reserved development water rights in a river basin. Therefore, we can assume that: A seller is the water-resource scheduling center with reserved water rights in the river basin, and that a buyer is a provincial water-supply company. In the transaction system of water-rights options, the seller of water rights provides transaction contracts of water-rights options. Both the seller and the buyer can obtain symmetrical information, based on which both can judge optimal decisions of each other, and the two sides of the water-rights transaction are neutral in risks. The buyer obtains required water rights in two ways: by executing contracts of water-rights options or through spot transaction of water rights. The demand in the spot market can always be met, and the seller can sell its remaining unexercised water-rights options through the spot water market. The options described in this paper are all buyers' call options [22].

1.2.2 Parameter determination

Required by problem research, this paper defined relevant parameters, as shown in Tab. 2.

Tab. 2 Parameter setting for allocation model of reserved development water-rights options

Parameter	Description	Parameter	Description
D	Demand for water resources in retail market of water-supply company at time T_1	Q	Quantity of options purchased by the water-rights option buyer at time T_0
K	Maximum tradable water in transaction market of river-basin reserved water rights	q_e	Quantity of water-rights options exercised by the buyer at time T_1
p_r	Retail price of sold water resources in retail market of water-supply company	q_s	Quantity of water rights purchased by the buyer in the spot market at time T_1
p_s	Spot price of water rights in water-rights transaction market at time T_1	S	Price of water-rights options, namely premium
β	Fluctuation interval of the principle of fair distribution of reserved water rights	p_e	Exercise price of water-rights option
e	Correlation coefficient between water-resources demand and spot market price		

where p_s is a random variable according to the above assumption. Its probability density function is $f(p_s)$, which ensures that the general assumption obeys uniform distribution in an interval of $[0, Z]$. There is a price transfer mechanism between upstream and downstream markets, $p_r(p_s)$, which means p_r is a variable related to p_s. As the demand in the subordinate market is a function of the retail market price p_r, and p_r is a function of p_s, it is assumed that the demand function for the retail market of the water-rights buyer is $D = K - ep_s$. Specifically, both K and e are constant and greater than 0. The research of this paper focused on allocation of reserved development water rights based on different prices in a "quasi-market" environment. For premiums of water-rights options, Wang's research results on the value of water options were taken for reference [24].

1.2.3 Allocation model of reserved development water-rights options

Based on the above assumption, a buyer's benefit-cost function was constructed. In other words, the profits in the water-rights option market of the provincial water-supply company are maximized. The formulas are as follows

$$\max \prod\nolimits_r = p_r D - (sQ + p_e q_e + p_s q_s) \tag{5}$$

$$s.t \begin{cases} q_s = D - q_e \\ q_e = \min(Q, D)\chi(p_s - p_e) \\ \chi(p_s - p_e) = \begin{cases} 1 & p_s \geqslant p_e \\ 0 & p_s < p_e \end{cases} \\ D \in [0, (\mathrm{GDP}_{t-1,i}/\mathrm{GDP}_{t-1,A}) \times \\ (1+\beta)] \times W_{\mathrm{RD}_{t+1}} \end{cases} \tag{6}$$

Where: $\prod_r$ is the profit of the buyer of regional water-rights options; $p_r D$ is the income of the buyer in the subordinate retail market; $(sQ + peq_e + p_s q_s)$ indicates the total costs of the buyer for purchasing water rights in the option market and the spot market. Formula (6) indicates relevant constraints. Specifically, the purchase quantity of water rights in the spot water-rights market is constrained. The quantity of exercised water-rights options is also constrained, and it should not exceed the demand for water rights in the retail market. In addition, the prerequisite for exercising water-rights options is defined, which is that the buyer will choose to exercise options if and only if $p_s \geqslant p_e$. Finally, the fairness constraint is imposed, which is that reserved development water rights cannot be allocated completely according to the market, as relevant transaction is done in a "quasi-market" mode.

Therefore, under the full consideration of fairness, the upper limit of demand for reserved development water in the water-receiving district in the river basin is within the increasing range β of the ratio between GDP of the district and GDP of the river basin in ($t-1$) a, namely the previous year. Based on the above constraints, construction of a coordinated allocation model of reserved development water-rights options in the river basin can be divided into the following four steps.

Step 1: The effects of sport market price and exercise price on quantity of exercised options are analyzed. In the case of $p_s \geqslant p_e$, the buyer of water rights will choose to exercise options to raise profits. In combination with the functional relationship between the buyer′s demand and quantity of exercised options as well as purchase quantity in the spot market, the buyer′s expected return is given by

$$E\prod\nolimits_r = \int_{p_e}^{\infty} \{p_r D - [sQ + p_e \min(Q, D) + p_s [D - \min(Q, D)]]\} f(p_s) \mathrm{d}p_s + \int_0^{p_e} [p_r D - (sQ + p_s D)] f(p_s) \mathrm{d}p_s \tag{7}$$

Step 2: According to the function of water-rights demand in the subordinate retail market of the buyer, the relationship between demand for water resources in the retail market at time T_1 and purchase quantity of water-rights options is established. In an actual situation, the buyer (the provincial water supplier) will not buy more water than the need of users at time T_1. Therefore, following relationship can be given

(1) In the case of $D = K - ep_s > Q$, $q_e = \min(Q, D) = Q$, and $p_s < (K-Q)/e$;

(2) In the case of $D = K - ep_s \leqslant Q$, $q_e = \min(Q, D) = D$, and $p_s \geqslant (K-Q)/e$。

Step 3: According to the relationship of q_e to D and Q and relationship between p_s and p_e shown in Steps 1 and 2, the expected profit functions under different pricing schemes are established as follows

(1) $p_s \geqslant p_e$ and $p_e \geqslant (K-Q)/e$, $p_s \geqslant (K-Q)/e$, $q_e = \min(Q, D) = D$ there is

$$E\prod\nolimits_r = \int_{p_e}^{\infty} \{p_r (K - ep_s) - [sQ + p_e (K - ep_s)]\} f(p_s) \mathrm{d}p_s + \int_0^{p_e} [p_r (K - ep_s) - (sQ + p_s (K - ep_s))] f(p_s) \mathrm{d}p_s \tag{8}$$

By derivation with respect to the variable Q in Formula (8), we have $\frac{\partial E\prod_r}{\partial Q} = -s$. As s is always greater than 0, $-s$ is always less than 0. Thus, the expectation of the water-rights option buyer is a decreasing function of Q [22] that can obtain an extreme value at the boundary. According to the above constraint $q_e = \min(Q, D) = D$, an extreme value can be obtained in the case of $Q = K - ep_e$.

(2) when $p_s > p_e$, $p_e < (K-Q)/e$, and $p_s \in (\frac{K-Q}{e}, \infty)$, there is $p_s > (K-Q)/e$, $\min(Q, D) = D$; $p_e < (K-Q)/e$, when $p_s \in [p_e, \frac{K-Q}{e}]$, there is $\min(Q, D) = Q$。 Therefore, the specific expression of Formula (7) is as follows

$$\begin{aligned} E\prod\nolimits_r = {} & \int_{\frac{K-Q}{e}}^{\infty} \{p_r (K - ep_s) - [sQ + p_e (K - ep_s)]\} f(p_s) \mathrm{d}p_s + \\ & \int_{p_e}^{\frac{K-Q}{e}} \{p_r (K - ep_s) - [sQ + p_e Q + p_s (K - ep_s - Q)]\} f(p_s) \mathrm{d}p_s + \\ & \int_0^{p_e} \{p_r (K - ep_s) - [sQ + p_s (K - ep_s)]\} f(p_s) \mathrm{d}p_s = \\ & \int_0^{\infty} p_r (K - ep_s) f(p_s) \mathrm{d}p_s - \\ & \int_{\frac{K-Q}{e}}^{\infty} [sQ + p_e (K - ep_s)] f(p_s) \mathrm{d}p_s - \\ & \int_{p_e}^{\frac{K-Q}{e}} [sQ + p_e Q + p_s (K - ep_s - Q)] f(p_s) \mathrm{d}p_s - \\ & \int_0^{p_e} [sQ + p_s (K - ep_s)] f(p_s) \mathrm{d}p_s \end{aligned} \tag{9}$$

For Formula (9), the first derivative of Q with respect to p_s is calculated. As p_s obeys uniform distribution in an interval of $[0, Z]$, its probability density function is $f(p_s) = 1/Z$. It is then substituted into the Formula (9) for joint solving of the expression about Q. Finally, the one-unknown quadratic equation of Q with respect to K, e, p_e, Z, and s can be obtained as follows

$$Q^2 + (2ep_e - 2K)Q + (K^2 + p_e^2 e^2 - 2ep_e K) - 2Ze^2 s = 0 \tag{10}$$

Through the root-solving formula, the two roots of Q can be obtained as follows

$$Q_1 = K - ep_e + e\sqrt{2Zs}, Q_2 = K - ep_e - e\sqrt{2Zs} \tag{11}$$

According to the above condition, we have $p_e < (K-Q)/e$, and $e\sqrt{2Zs}$ is always greater than 0. Therefore, the radical expression of the possibly obtained minimum value in Formula (11) is $Q_2 = K - ep_e - e\sqrt{2Zs}$.

Step 4: The expected costs related to the quantity of the water-rights options purchased at time T_0 are established. From the final expression of Formula (9), the former item of the formula is the income of the water-rights option buyer, and the latter deducted items are the buyer's costs. It can be seen that an optimal order quantity is obtained in the case of maximum income and minimum costs. Thus, the specific expression of costs C is given by

$$C=\int_{\frac{K-Q}{e}}^{\infty}[(sQ+p_e(K-ep_s))]f(p_s)\mathrm{d}p_s+\int_{p_e}^{\frac{K-Q}{e}}[(sQ+p_eQ+p_s(K-ep_s-Q))]f(p_s)\mathrm{d}p_s+\int_{0}^{p_e}[sQ+p_s(K-ep_s)]f(p_s)\mathrm{d}p_s \tag{12}$$

By calculation, the expression of C is as follows

$$C=sQ+(K-Q)^3/6Ze^2-p_e(K-Q)^2/2Ze+p_eK-p_eeZ/2-p_e^2Q/2Z \tag{13}$$

In conclusion, the three expressions of Q that can maximize the buyer's expected $E\prod_r$ and minimize the buyer's expected C are as follows

$$\begin{cases}Q_1=0\\Q_2=K-ep_e-e\sqrt{2Zs}\\Q_3=K-ep_e\end{cases} \tag{14}$$

By substituting them into Formula (12) respectively, we can obtain corresponding expressions of expected costs C as follows

$$C_{Q_1}=K^3/(6Ze^2)-p_eK^2/(2eZ)+p_eK-ep_eZ/2 \tag{15}$$

$$C_{Q_2}=-seP_e-ep_eZ/2-p_e^2K/(2Z)+ep_e^3/(6Z)+p_eK+sK-(2se\sqrt{2sZ})/3 \tag{16}$$

$$C_{Q_3}=ep_eZ/2+ep_e^3/(6Z)+sK-sep_e+p_eK-p_e^2K/(2Z) \tag{17}$$

According to the fairness constraint and different price allocation schemes, Q corresponding to the minimum value of expected costs C is the optimal quantity of reserved development water-rights options purchased by the buyer at T_0.

2 Case analysis

2.1 Overview of research area

Empirical research was conducted by focusing on the middle route of the South-to-North Water Transfer Project and its four provinces (or municipalities directly under the Central Government) including Beijing, Tianjin, Hebei, and Henan. On December 12, 2014, the middle route of the South-to-North Water Transfer Project was officially completed. It can mainly solve the problem of water shortage in four provinces (or municipalities directly under the Central Government) including Henan, Hebei, Beijing, and Tianjin. According to the planning of the project construction, an average annual water-transfer capacity of 13 billion m^3 can be realized in the end. The water source of the middle route of the South-to-North Water Transfer Project is located in the Danjiangkou Reservoir in the middle and upper reaches of the Hanjiang River, the largest tributary of the Yangtze River. According to China Statistical Yearbook 2018, the populations of Beijing, Tianjin, Hebei and Henan in 2017 were 21.71 million, 15.57 million, 75.20 million, and 95.59 million, respectively, which totally accounts for 15% of the national population. In 2017, GDP of the four provinces (or municipalities directly under the Central Government) was CNY 2.801 494 trillion, CNY 1.854 919 trillion, CNY 3.401 632 trillion, and CNY 4.452 83 trillion, respectively, which totally accounts for 15.17% of the national GDP.

2.2 Data sources

Data sources included *China Statistical Yearbooks* of 15 years from 2004 to 2018, *Statistical Yearbooks* of various provinces from 2004 to 2018, *the China Water Resources Bulletin* (2017), the official website of the South-to-North Water Transfer Project (http://www.nsbd.gov.cn/), and the official website of Beijing Water Authority (http://www.bjwater.gov.cn/). Specifically, the typical reference datum for formulating price-allocation schemes of reserved development water rights in the river basin where the middle route of the South-to-North Water Transfer Project is located is as follows: non-household water price in Beijing's retail market is CNY 9/m^3. It comes from the [2018] No. 115 document issued by Beijing Municipal Commission of Development and Reform, and published by Beijing Water Authority on January 22, 2018.

2.3　Analysis and discussion

2.3.1　Confirmation of reserved water rights in river basin

2.3.1.1　Prediction of ecological water demand in river basin

Based on confirmation paths of ARIMA models, on the premise of minimizing effects of auto-regression, difference, and moving average on data, 27 ARIMA models were used to analyze ecological water demand in the river basin where the middle-route project is located. Finally, the ARIMA (2, 3, 1) model was selected, with $R^2 = 0.742$. Moreover, the model is of high reliability, with no outlier. Figs. 1 and 2 show the ecological water demand in the river basin predicted based on the moving average algorithm and the ARIMA prediction model, respectively.

According to Fig. 1 and 2, the ecological water demand in 2018 predicted by the moving-average model is 3.607 billion m^3, with a downward trend, while that predicted by the ARIMA model is 5.907 billion m^3, with an upward trend. By comparison, it can be seen that the latter prediction result is more in line with the changing trend of ecological water demand in the river basin under the regulation of national policies. Fig. 3 shows historical fitting data of the ARIMA model.

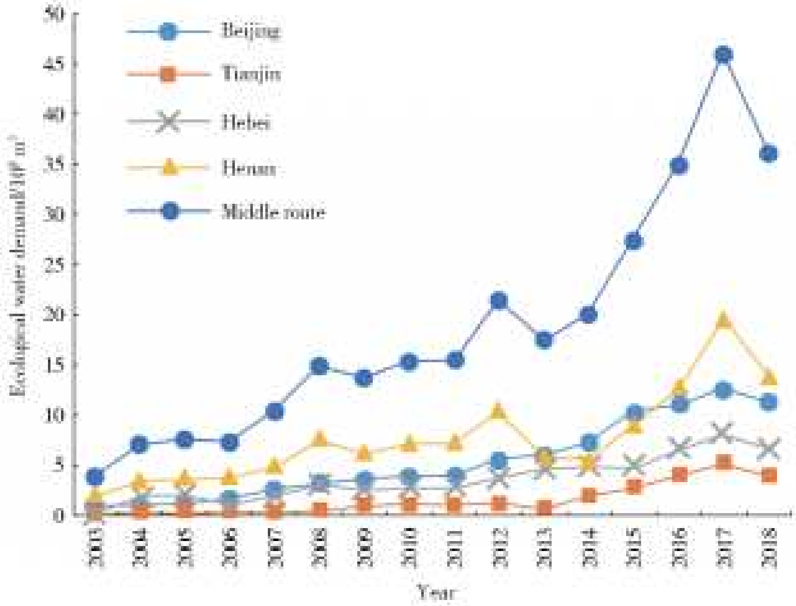

Fig. 1　Prediction of watershed ecological water demand depend on moving average model in 2018

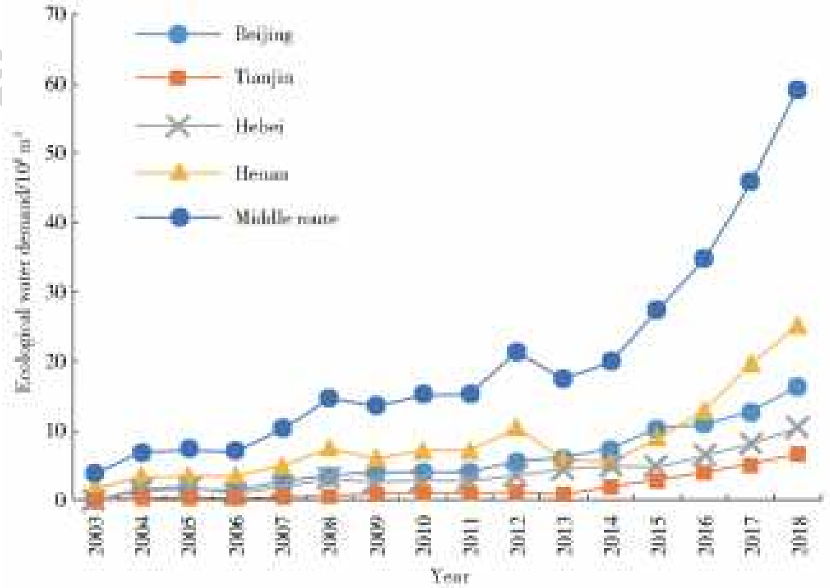

Fig. 2　Prediction of watershed ecological water demand depend on ARIMA model in 2018

As can be seen from Fig. 3, fitting of the model tends to be improved with the passage of time. The fitting produced greater deviations in 2007, 2009, 2013, and 2015. According to the analysis, currently available data of ecological water demand in China started in 2003, so there have been only data of 15 a up to 2018. Third-order difference will affect earlier-stage data to a certain extent, resulting in a low fitting degree of data prediction in 2007. Compared with other years, 2009 witnessed a sharper change in the weather: the national average annual precipitation was 573.3 mm, which was the lowest since 1987; the average annual temperature was 9.9° a, which was the fourth highest since 1951. With the significant decrease in rainfall, ecological water demand in the river basin had to be restricted on the premise of ensuring agricultural production and household water consumption. In addition, the obvious temperature rise accelerated water evapotranspiration. Therefore, the observed value in that year was lower than the fitted one. In 2012, the State Council issued the No. 3 document *Opinions on Implementation of the Strictest Water Resources Management System*. The document clearly defines "three red lines" and "four regulations", which restrained the total ecological water consumption in 2013 to a certain extent. In 2015, the CPC Central Committee and the State Council issued *General Plan for the Reform of Ecological Civilization System*, which paid unprecedented attention to ecological construction in terms of policies and systems. Therefore, ecological water consumption in that year surges compared with that in previous years. The four data with greater deviations of fitting degree provide excellent case for studying possible effects of data quantity, natural weather conditions, and policy directions on ecological water consumption. This provides a basis for more accurate prediction of ecological water consumption in a later stage.

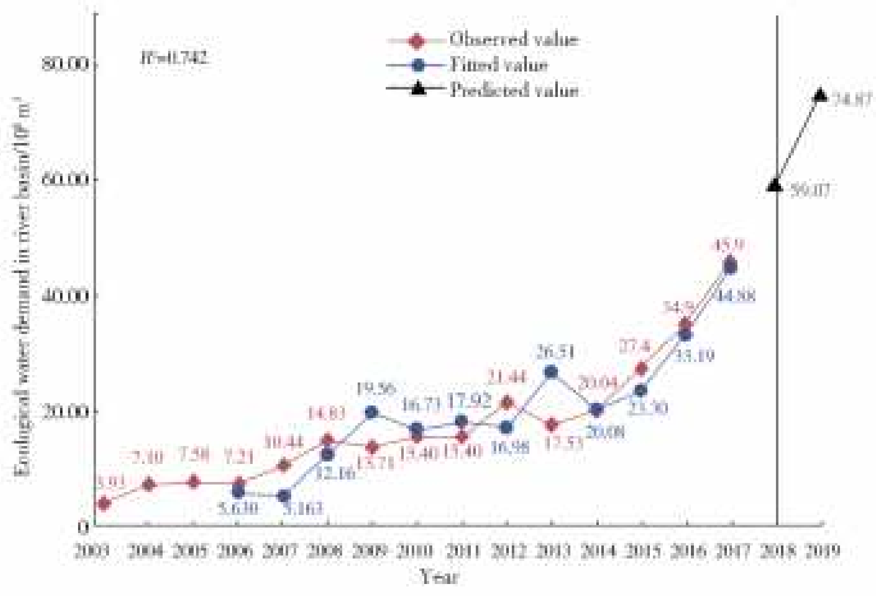

Fig. 3 ARIMA(2,3,1) historical data fit

2.3.1.2 Prediction of regional production, living, and ecological water demand

Prediction was conducted based on Formulas (2) and (3), as well as the ARIMA (2,3,1) prediction model of ecological water demand in the river basin where the middle-route project is located. Fig. 4 shows the production, living, and ecological water demand in the middle-route project and its four water-receiving districts.

From Fig. 4, different kinds of water demand in the four different water-receiving districts of the middle-route project are quite different. Total water demand of Beijing, Tianjin, Hebei, and Henan is 4.374 billion, 2.939 billion, 18.768 billion, and 23.961 billion m^3, respectively. Total agricultural water demand is the greatest. Specifically, agricultural water demand of Hebei Province and Henan Province is more than the sum of the other three kinds of water demand. In addition, the agricultural water demand of Hebei Province is even twice the other three kinds of water demand. Sequences of industrial and living water demand of different districts in the total water-demand structure will be slightly different according to different population and industrial structure. The water-use structure of Beijing is quite different from that of the other three water-receiving districts, with small proportions of agricultural and industrial water demand. This is closely related to strict implementation of ecological protection policies and relocation of industrial enterprises in Beijing in the recent two years.

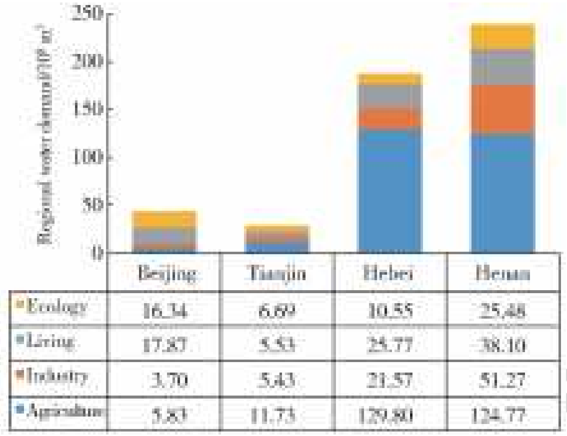

Fig. 4 The demand in forecast year of agricultural, industrial, living, and ecological water in middle route basin

Among the four water-receiving districts of the middlet-route project, Beijing has a high proportion of ecological water demand nationally, and its predicted ecological water demand in 2018 was 1.634 billion m^3, almost the same as its living water demand. By comparison, Tianjin has a lower proportion of ecological water demand. In addition, Henan Province has the greatest ecological water demand among the four water-receiving districts. By comparison with corresponding data in 2017, it is found that ecological water demand of the river basin where the middle-route project is located was increased greatly as a whole. Beijing is taken as an example for explanation. Before the issue of *General Plan for Reform of Ecological Civilization System*, Beijing′s ecological water demand in 2014 was 725 million m^3, while its predicted ecological water demand in 2018 was 1.634 billion m^3. The increasing range was 125%, and the average annual growth rate was up to 31%. Thus, it can be seen that ecological water demand is greatly affected by policies.

2.3.1.3 Confirmation of reserved water rights in river basin

Reserved emergency water and reserved development water in the river basin were confirmed according to Formulas (3) and (4). Tab. 3 lists relevant results.

Tab. 3 Reserved water rights in the middle route project in 2018

Unit: 10^8 m^3

District	Reserved water	Reserved emergency water	Reserved development water	Reserved development water in river basin
Beijing	10.23	7.29	2.94	—
Tianjin	−4.29	4.90	−9.19	—
Hebei	7.58	31.28	−23.70	—
Henan	147.29	39.94	107.35	—
Middle route	160.80	83.40	77.39	77.39

According to Tab. 3, Henan Province has the most reserved water, and its contribution to the total reserved water in the river basin reaches 91.6%. Tianjin lacks water severely, and it loses the ability to reserve water. Moreover, Hebei Province can only meet a small part of its reserved emergency water demand. Henan has the most reserved emergency water of 3.994 billion m^3, which is close to the regional living-water consumption in that year. Tianjin has reserved emergency water of 490 million m^3, which is the least among the four water-receiving districts of the middle-route project. Beijing has reserved emergency water of 729 million m^3, which is 1/2 of the ecological water demand in that year. Reserved emergency water is the water reserved to deal with unknowable water demand in a river basin, and when it fails to satisfy the demand, coordination must be done in the river basin. This is consistent with the suggestion that reserved water rights should be uniformly allocated across river basins proposed by Wang et al.[1] in the construction of water-rights systems in China. Reserved emergency water requires high response efficiency. If this part of water is stored in Danjiangkou reservoir, in case of an emergency in Beijing, it normally takes 15 days to finish water transfer. Starting and transportation of the large-scale water transfer project take a relatively long time, but the emergency requires efficient response and controllability. With the above consideration, Danjiangkou reservoir is not suitable. Therefore, on the premise of unified management in the river basin, a risk response procedure should be established in the basin scheduling center for reserved emergency water and to store the water nearby for convenient transfer in order to achieve efficient management.

According to the analysis, reserved development water in Beijing is also very little, but that in Henan Province is relatively abundant. The reason is found through further comparison of supply and demand of three years in the water-receiving districts in the middle-route river basin, as shown in Fig. 5.

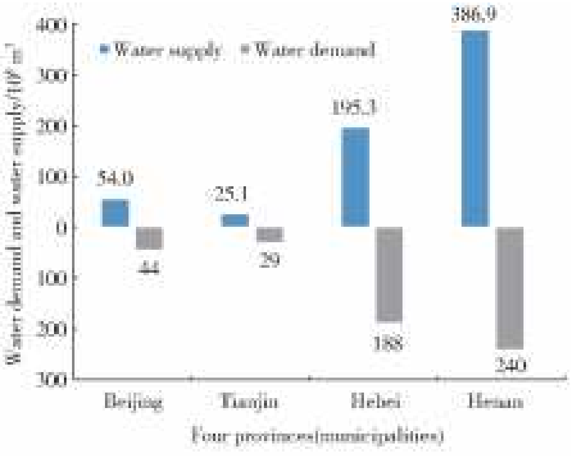

Fig. 5 Comparison of five-year average water supply and demand in South-to-North Water Transfer Middle Route

As shown by the comparison, the Beijing-Tianjin-Hebei region is a typical resource-dependent water-deficient region. Relying on its own leading technology, Beijing realized an average annual supply of 1 billion m^3 reclaimed water in the past three years. This barely leads to a surplus of water on the premise of meeting production and living water demand. By contrast, Tianjin and Hebei Province are currently in the situation where their available water supply cannot meet or can narrowly meet normal production, living, and ecological water demand. Therefore, they have poor capacity to provide reserved emergency water and reserved development water for themselves, and they need unified coordination by the scheduling center of the river basin. According to the conclusion of the above comparative analysis, reserved development water is relatively abundant in the river basin. It can be coordinated through efficient market allocation schemes of water-rights options to solve the problem that some districts are incapable of preparing their own reserved development water. In the following section, efficient allocation of reserved development water rights in the river basin will be analyzed and discussed based on the water-rights option model.

2.3.2 Analysis on market allocation of reserved development water rights

Based on the market allocation model of water-rights options, this paper analyzed the feasible market allocation of reserved development water rights in Beijing. Based on the assumptions in the model, the basic situations were defined as follows: (1) the seller of water-rights options was the water-resource scheduling center of the river basin where the middle-route project is located, and the buyer was the Beijing water-supply company. (2) The maximum reserved development water right that can be invested in the water-rights market by the water-resource scheduling center of the river basin was K=7.739 billion m^3. (3) The coefficient of the buyer′s market demand related to spot market price was e=400 million m^3/CNY. (4) According to the latest guiding price of CNY 9/m^3 for non-household water use and CNY 5/m^3 for household water use, announced by the Beijing Water Authority on January 22, 2018, for the maximum range of spot market price, Z= CNY 18/m^3. (5) This paper focused on effects of different option price strategies on reserved development water rights in a "quasi-market" environment. Therefore, based on the previous research results from Wang et al.[24] regarding value of water-rights options, it was assumed that the price of options, namely, the premium s=CNY 1/m^3. (6) Under the GDP-based fairness principle, according to experts′ suggestions, the increasing range of β=15% was reasonable and in line with economic development. Thus, the demand proportion of reserved development water rights in Beijing in 2018 was in an interval of [0, 25.75%], and the demand quantity was in an interval of [0, 1.993] billion m^3. (7) According to the demand price function of the buyer′s subordinate market related to the spot market, $p_s \in$ CNY [14.37, 18.00]/m^3 was obtained.

2.3.2.1 Analysis of sensitivity of purchase quantity of water-right options to their exercise price

From Fig. 6, conclusions can be made as follows: (1) with the continuous increase in exercise price, purchase quantity of water-rights options at T_0 continues to decline; when the exercise price of water rights is CNY 13.35/m^3, the purchase quantity of water-rights options is 0. (2) At an exercise-price interval of CNY [8.5, 13.35]/m^3, the buyer of water-rights option achieves minimum costs by selecting option purchase quantity of the second case. However, when the exercise price exceeds CNY 13.35/m^3, the buyer of water-rights options achieves minimum costs by selecting the first scheme, namely purchasing no water-rights options. (3) On the basis of the non-household water price of CNY 9/m^3 announced by the Water Authority at present, when exercise price changes below the retail-market price, costs are highly sensitive, and the price sensitivity coefficient shows an obvious step downward trend. In the case of exercise price increasing between CNY 8.5/m^3 and 9/m^3 at a unit rate of α, the purchase cost of the water-rights buyer will grow by 800α million CNY. In the case of exercise price increasing between CNY 9/m^3 and 10/m^3 at the unit rate, the purchase cost of the water-rights buyer will go up by 600α to 700α million CNY. In the case of exercise price increasing between CNY 10/m^3 and 12/m^3 at the unit rate, the purchase cost of the water-rights buyer will mount up by 200 α to 400 α million CNY.

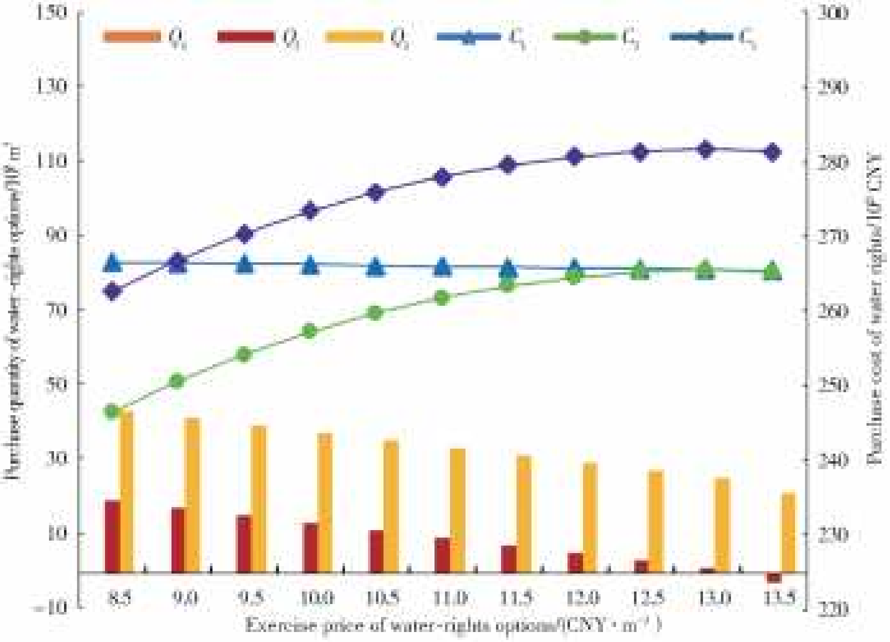

Fig. 6　Analysis of sensitivity of purchase quantity of water-right options to their exercise price

2.3.2.2 Analysis of allocation schemes of exercise price and spot market price of water-rights options

Scheme 1: It is assumed that spot market price of water rights at T_1 is CNY 15/m^3. In the case of $p_s = 15$ CNY/m^3, according to the price demand function of the subordinate market, we have $D =$ 1.739 billion m^3. The option purchase quantity corresponding to $p_e \in$ CNY [8.5, 9]/m^3 exceeds the possible demand in the subordinate market. The buyer of water-rights options will choose to exercise options and all the demand for water rights can be met by exercising water-rights options. The option purchase quantity corresponding to the price range of CNY [9, 13.35]/m^3 is less than the market demand. Thus, when the Beijing water-supply company chooses to exercise options, it will buy water rights in the spot market for unmet demand at the same time.

Scheme 2: It is assumed that spot market price of water rights at T_1 is 18 yuan/m^3. In the case of $p_s=$ CNY 18/m^3, according to the price demand function of the subordinate market, we have $D=$ 539 million m^3. The option purchase quantity corresponding to $p_e\in$ CNY [8.5,12]/m^3 exceeds the possible demand in the subordinate market. The buyer of water-rights options will choose to exercise options and all the demand for water rights can be met by exercising water-rights options. The option purchase quantity corresponding to the price range of CNY [12,13.35]/m^3 is less than the market demand. Thus, when the Beijing water-supply company chooses to exercise options, it will buy water rights in the spot market for unmet demand at the same time.

In conclusion, p_s can directly reflect current situations of water supply in the river basin. In the case of water supply in shortage, spot market price is higher, while in the case of the water supply in surplus, the spot market price is lower. The scheduling center of the river basin can carry out comprehensive analysis according to the demand for reserved development water rights in the forecast year. On this basis, a price-allocation scheme with lower p_e can be set in the case of less expected demand to encourage water-demanding provinces in the river basin to enhance the demand for reserved development water rights. On the other hand, a price-allocation scheme with higher p_e can be set in the case of more expected demand, to reduce supply of reserved development water rights in the river basin. This will finally realize efficient allocation of reserved development water rights between both supply and demand sides in the river basin.

Noteworthily, the price-allocation schemes in this paper are established based on stable p_s at T_1, as well as no fluctuation in the price correlation coefficient e which is greatly affected by politics, economy, and environment. Greater fluctuations in p_s and e will greatly affect price-allocation schemes of water-rights options, thus hindering efficient utilization of reserved development water rights in the river basin. Therefore, it is necessary to further explore specific influencing factors of spot market price and price correlation coefficient in future research.

3　Conclusions and suggestions

(1) Ecological water demand is greatly affected by basic data quantity, natural climate changes, and national macro policies. The national department of water-resource allocation needs to fully consider ecological water demand, formulate water-saving incentive policies, and apply saved water to ecological sustainable development.

(2) Tianjin and Hebei Province are incapable of reserving development water in the condition of existing available water resources. Great efforts should be made to develop Beijing-Tianjin-Hebei integration to realize unified coordination of resources in the river basin. In addition, during the consideration of fairness, appropriate preferential policies should be given to districts with efficient water conservation to encourage the use of reclaimed water in the districts.

(3) With the continuous increase in exercise price of water-rights options, regional demand for water-rights options and sensitivity to unit-price variation decrease. The scheduling center of the river basin can flexibly regulate regional demand for reserved development water through price schemes, based on comprehensive risk analysis of reserved development water rights.

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