Unveiling impacts and optimal strategies of water-saving system for integrated water resources management in a water-scarce watershed

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1   **Abstract**

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3   In this study, impacts and optimal strategies of water-saving system are identified through

4   developing a novel stochastic bi-level programming-based water saving and trading

5   simulation model for water resources regulation (SB-WSTM). The link between socio-

6   economic and water resources under uncertain conditions, as well as participation of

7   government water-saving subsidy and water-saving facilities (i.e., sprinkler irrigation, micro-

8   irrigation, low-pressure pipe irrigation) are elaborated. The SB-WSTM is then applied to

9   Dagu River watershed in China with water-scarce characteristics for demonstrating its

10   efficiency. The responses of the water resources system to water-saving facilities and

11   subsidies are disclosed quantitively. Micro-irrigation facility construction is recommended to

12   cope with extremely dry condition; 50% of the subsidy rate combined with 70% of efficient

13   irrigation area is the optimal water-saving scheme based on multi-criterion analysis and

14   should be recommended. Recognizing the effect of water saving, generating efficient water

15   allocation patterns, and taking water-saving strategies are key adaptation means for water

16   system sustainable utilization.

17

18   **Keywords:** Integrated water resources management; Water rights trading; Water-saving

19   irrigation facilities; Water-saving subsidy; Stochastic uncertainties

20   **1. Introduction**

21

22   Constantly changing and evolving economic, technical, political, and environmental factors

23   create new challenges in water management (Shrestha and Wang, 2020; Xiao et al., 2021;

24   Oladosu et al., 2022). In response to these challenges, integrated water resources management

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25   has been central to water governance worldwide, maximizing the potential value of limited

26   water resources (Apostolaki et al., 2019; Zehtabian et al., 2023). Among them, the emergence

27   of water-saving strategy is particularly crucial. The strategy utilizes innovative water-saving

28   techniques to optimize water utilization, and formulates water-saving policy to promote the

29   development of water-saving society (Michaux et al., 2019; Ierna and Mauromicale, 2022).

30

31   In recent years, the agricultural region that employs water-saving irrigation technologies is

32   gradually expanding (Zhang et al., 2019). Reasonable decisions regarding the application of

33   water-saving technologies can increase crop yield on one hand and comprehensively enhance

34   the utilization efficiency of water resources on the other (Chen et al., 2021). This can avoid

35   water wastage and effectively alleviates water-scarce issues. However, the restriction of

36   regional economic factors leads to a significant decline in water-saving social participation

37   (Heiba et al., 2023). High maintenance cost of the measures reduces user's enthusiasm and

38   hinders the widespread adoption (Liu et al., 2022). Therefore, the government provides

39   efficient policies, such as financial subsidy, for supporting the water-saving efforts (Cremades

40   et al., 2015). In summary, water-saving irrigation technologies and government subsidy are

41   two essential considerations in formulating water-saving strategy.

42

43   The evaluation of irrigation technologies' impact and efficacy has emerged as a prominent

44   research topic in the field of water saving (Yang et al., 2020; Zhou et al., 2021; Pronti et al.,

45   2023; Zhao et al., 2023a). Guo et al. (2023) adopted emergy synthesis to assess the input

46   structure of protected vegetable production system, revealing that water-saving technologies

47   and energy-efficient utilization can optimize the emergy input structure in system. Hamidov et

48   al. (2022) found a rebound effect resulting from increased agricultural water use due to

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49 advancements in water-saving technologies, calling for reasonable subsidies. In addition,

50 utility evaluation and impact mechanism of water-saving subsidies have been studied (Jia et

51 al., 2022; Li et al., 2023; Ma et al., 2023). Boudmyxay et al. (2019) employed a dynamic

52 computable general equilibrium model to explore the impact of water-saving subsidy on

53 agricultural production, farmers' welfare and consumption. Cheng et al. (2021) analyzed the

54 impact of water price and water-saving subsidy mechanisms, showing that the related policies

55 can decrease the cultivation of high-water-consuming crops while safeguarding agricultural

56 income and food security. Integrated researches involving water-saving project and policy

57 provide valuable insights for formulating effective water-saving strategies (Yang et al., 2022).

58 Song et al. (2023) took a comprehensive approach to deal with the issue of water resource

59 disorder, energy and grain imbalance by combining water-saving project with policy

60 solutions. Water-saving strategy associated with irrigation technologies and government

61 subsidy is essential for establishing a rational water-saving behavior. Nevertheless, no

62 previous study focuses on integrated impact of water-saving project and policy, as well as

63 optimization of the decision-making related to the efforts.

64

65 Complexity factors exist in integrated water management systems, raising challenges for

66 planning water saving strategies (Gao et al., 2014; Ma et al., 2021; Nematian, 2023; Kanani et

67 al., 2024). For example, surface runoff has stochastic characteristics and causes changes in

68 water supply and demand processes. Besides, water-saving facility construction plan would be

69 inexact associated with uncertainties from surface water supply, and water resource

70 management involves conflicting decisions about water consumption and benefit.

71 Accordingly, mathematical programming approaches were formulated to deal with the

72 complexities represented by probability distributions, imprecise data, and conflicting

3

73   objectives (Haag et al., 2022; Zhu et al., 2023; Wu et al., 2024). Among them, interval two-

74   stage stochastic programming (ITSP) has been widely explored for interpreting combined

75   uncertainties and addressing associated water deficit penalties of violating promised targets in

76   water management cases (Simic, 2016; Yu et al., 2018). Bi-level programming (BP) is

77   capable of solving hierarchical decision-making issues involving conflicting objectives,

78   thereby attaining a balance in the interaction among decision makers regarding system

79   benefits and water consumption levels (Ma et al., 2020). These methods possess their own

80   merits, yet presently, there remains a deficiency in a holistic approach to simultaneously

81   tackle uncertainties and multiple objectives in water saving planning.

82

83   Water rights trading, as a common tool for improving water use efficiency, is widely used in

84   optimizing the water allocation (Xu et al., 2023), adapting to variable water demands (Delorit

85   and Block, 2018), and promoting innovation in water management (Zhang et al.,2021; Chen

86   et al., 2024; Wu et al., 2024). This study provides the first analysis integrating impact of

87   water-saving project and policy, as well as conducts related decision-making simulation

88   planning within water trading framework. A novel stochastic bi-level programming-based

89   water saving and trading simulation model for water resources regulation (SB-WSTM) is

90   proposed to achieve this innovation. SB-WSTM incorporates scenario analysis on water-

91   saving irrigation facility and government subsidy, as well as uncertainty analysis with interval

92   stochastic bi-level programming (ISBP). The established simulation models will be

93   implemented in a real case of Dagu River watershed of China. The objectives include: (i)

94   examining the response of water resources system to water-saving projects and policies under

95   uncertain conditions; (ii) revealing the optimal water-saving scheme taking into account

96   system benefit, water consumption, water-saving amount and water use efficiency.

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2. Methodology

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100 Bi-level programming (BP) is capable of balancing stakeholders to achieve compromise

101 (Sakawa et al., 2000; Ma et al., 2020). Both upper-lower-level functions have their own

102 independent objectives and influence each other. Let $X \in R^{z_1}$ and $Y \in R^{z_2}$ be vectors of

103 decision variables signifying upper-lower-level choices. Let $F_U : R^{z_1} \times R^{z_2} \to R$ and

104 $f_L : R^{z_1} \times R^{z_2} \to R$ represent the upper-lower-level decision makers, respectively.

105 $G_1 : R^{z_1} \times R^{z_2} \to R$ and $g_1 : R^{z_1} \times R^{z_2} \to R$ are decision variables. The BP model can be stated

106 as:

107 $$\underset{X}{Max}\, F_U\left(X,Y\right) \qquad\qquad (1a)$$

108 Subject to:

109 $$G_1\left(X,Y\right) \le 0 \qquad\qquad (1b)$$

110 where:

111 $$Y \in arg\, \underset{Y}{Max}\, f_L\left(X,Y\right) \qquad\qquad (1c)$$

112 Subject to:

113 $$g_1\left(X,Y\right) \le 0 \qquad\qquad (1d)$$

114

115 Although BP is capable of handling the trade-offs among different stakeholders, it has

116 limitations in dealing with stochastic uncertainties in practical integrated water management

117 problems. Interval two-stage stochastic programming (ITSP) provides great flexibility and

118 efficiency in dealing with uncertainties expressed as intervals following the discrete

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119 probability distribution (Ji et al., 2020; Yin et al., 2021). Incorporating ITSP into BP enables

120 the construction of the interval stochastic bi-level programming (ISBP) model as follows (Ma

121 et al., 2020):

122 Upper level:

123 $$\underset{X^{\pm},Y^{\pm}}{Max}\, F_U^{\pm} = C_{T_1}^{\pm} X^{\pm} - \sum_{k=1}^{K} p_k D_{T_2}^{\pm} Y^{\pm} \qquad (2a)$$

124 Subject to:

125 $$A_m^{\pm} X^{\pm} \leq V_m^{\pm},\ m = 1,\ 2,\ ...,\ M \qquad (2b)$$

126 $$B_n^{\pm} X^{\pm} - C_n^{\pm} Y^{\pm} \geq W_k^{\pm},\ n = 1,\ 2,\ ...,\ N;\ k = 1,\ 2,\ ...,\ K \qquad (2c)$$

127 $$x_t^{\pm} \geq 0,\quad x_t^{\pm} \in X^{\pm},\quad t = 1,\ 2,\ ...,\ t_1 \qquad (2d)$$

128 $$y_{tk}^{\pm} \geq 0,\quad y_{tk}^{\pm} \in Y^{\pm},\quad t = 1,\ 2,\ ...,\ t_2;\ k = 1,\ 2,\ ...,\ K \qquad (2e)$$

129 Lower level:

130 $$\underset{X^{\pm},Y^{\pm}}{Max}\, f_L^{\pm} = c_{T_1}^{\pm} X^{\pm} - \sum_{k=1}^{K} p_k d_{T_2}^{\pm} Y^{\pm} \qquad (2f)$$

131 Subject to:

132 $$a_m^{\pm} X^{\pm} \leq v_m^{\pm},\ m = 1,\ 2,\ ...,\ M \qquad (2g)$$

133 $$b_n^{\pm} X^{\pm} - c_n^{\pm} Y^{\pm} \geq w_k^{\pm},\ n = 1,\ 2,\ ...,\ N;\ k = 1,\ 2,\ ...,\ K \qquad (2h)$$

134 $$x_t^{\pm} \geq 0,\quad x_t^{\pm} \in X_t,\quad t = 1,\ 2,\ ...,\ t_1 \qquad (2i)$$

135 $$y_{tk}^{\pm} \geq 0,\quad y_{tk}^{\pm} \in Y_{tk}^{\pm},\quad t = 1,\ 2,\ ...,\ t_2;\ k = 1,\ 2,\ ...,\ K \qquad (2j)$$

136

137 where $A_m \in \left\{ R^{\pm} \right\}^{M \times t_1}$, $B_n \in \left\{ R^{\pm} \right\}^{N \times t_2}$, $B_n \in \left\{ R^{\pm} \right\}^{N \times t_2}$, $B_n \in \left\{ R^{\pm} \right\}^{N \times t_2}$, $V_m \in \left\{ R^{\pm} \right\}^{M \times 1}$,

138 $C_{T_1}^{\pm} \in \left\{ R^{\pm} \right\}^{1 \times t_1}$, $D_{T_2}^{\pm} \in \left\{ R^{\pm} \right\}^{1 \times t_2}$, $a_m^{\pm} \in \left\{ R^{\pm} \right\}^{m \times t_1}$, $b_n^{\pm} \in \left\{ R^{\pm} \right\}^{n \times t_2}$, $b_n^{\pm} \in \left\{ R^{\pm} \right\}^{n \times t_2}$,

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139 $v_m^\pm \in \left\{ R^\pm \right\}^{M \times 1}$, $c_{T_1}^\pm \in \left\{ R^\pm \right\}^{1 \times t_1}$, $d_{T_2}^\pm \in \left\{ R^\pm \right\}^{1 \times t_2}$, $X^\pm \in \left\{ R^\pm \right\}^{t_1 \times 1}$, $Y^\pm \in \left\{ R^\pm \right\}^{t_2 \times 1}$ and $\left\{ R^\pm \right\}$

140 indicate a group of interval parameters and variables; the superscript '±' indicates interval

141 parameters possessing upper-lower limits. $C_{T_1}^\pm$ and $c_{T_1}^\pm$ represent the net gain within period t.

142 $X^\pm$ is a constant target value allocated to stakeholders. p_k is probability value. $D_{T_2}^\pm$ and $d_{T_2}^\pm$

143 indicate the deficit value that fails to reach the actual targets. $Y^\pm$ indicates the decline in net

144 benefit resulting from deficit. $W_m^\pm$ and $w_m^\pm$ respectively indicate the demand quantities of users.

145 $V_m^\pm$ and $v_m^\pm$, as random variables, are indicated as the total available quantities.

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147 An interactive algorithm for ISBP is proposed to gain the compromise solution. Through

148 formula group (3), the upper-level decision can get $f_*^{U\pm} = \left[f_*^{U-}, f_*^{U+} \right]$, $x^{U\pm} = \left[x^{U-}, x^{U+} \right]$,

149 $y^{U\pm} = \left[y^{U-}, y^{U+} \right]$; the lower-level decision can get $f_*^{L\pm} = \left[f_*^{L-}, f_*^{L+} \right]$, $x^{L\pm} = \left[x^{L-}, x^{L+} \right]$,

150 $y^{L\pm} = \left[y^{L-}, y^{L+} \right]$. Because solution $x^{U\pm}$ is constrained by the upper-level decision-making,

151 obtaining the optimal solution in the lower-level is restricted. Existence of tolerance is

152 reasonable and provides a broader feasible range for the lower-level decision-makers to seek

153 the optimal solution. Therefore, permission is given for the solution $x^{U\pm}$ to fluctuate within

154 the range $\left(x^- \in \left[x^{U-} - r_1, \ x^{U-} + r_1 \right], x^+ \in \left[x^{U+} - r_1, \ x^{U+} + r_1 \right] \right)$, where r_1 is maximum

155 tolerance of the upper-level decision maker. $x^{U\pm}$ is the most favorable decision; $x^{U\pm} - r_1$ and

156 $x^{U\pm} + r_1$ are the worst acceptable ones. Concerning the upper-bound, the predilection of

157 decision makers linearly increases within the interval of $\left[x^{U\pm} - r_1, \ x^{U\pm} \right]$ and linearly

158 descends within the interval of $\left[x^{U\pm}, \ x^{U\pm} + r_1 \right]$. As the upper-level indicates an optimization

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159 problem with a maximizing objective, the decision maker would believe that all $f_U^+ \geq f_*^{U+}$ is

160 acceptable and all $f_U^+ < f_U^{+'} = f_U\left(x^{L+}, y^{L+}\right)$ is unacceptable; the lower-level model indicates a

161 minimization problem, the decision maker would believe that the solutions fulfilling

162 $f_L^+ \leq f_*^{L+}$ are acceptable while those fulfilling $f_L^+ > f_L^{+'} = f_L\left(x^{U+}, y^{U+}\right)$ are not. The

163 interactive algorithm is adopted to calculate the upper-bound model, and the formula can be

164 expressed as:

165 $Max = \lambda^+$ $\hspace{6cm}$ (3a)

166 Subject to:

167 $a^- x^+ \leq v^+$ $\hspace{6cm}$ (3b)

168 $b^- x^+ - c^- y^+ \geq w^+$ $\hspace{5cm}$ (3c)

169 $\mu_{x^+}(x^+) \geq \lambda^+ I$ $\hspace{5.5cm}$ (3d)

170 $\mu_{f_U^+}\left[f_U^+(x^+, y^+)\right] \geq \lambda^+$ $\hspace{4.5cm}$ (3e)

171 $\mu_{f_L^+}\left[f_L^+(x^+, y^+)\right] \geq \lambda^+$ $\hspace{4.5cm}$ (3f)

172 $x^+, y^+ \geq 0$ $\hspace{6cm}$ (3g)

173 $\lambda^+ \in [0, 1]$ $\hspace{6cm}$ (3h)

174 where:

175 $\mu_{x^+}(x^+) = \begin{cases} \dfrac{x^+ - (x^{U+} - r_1)}{r_1}, & if \ \ x^{U+} - r_1 \leq x^+ \leq x^{U+} \\[3mm] \dfrac{(x^{U+} + r_1) - x^+}{r_1}, & if \ \ x^{U+} \leq x^+ \leq x^{U+} + r_1 \\[3mm] 0, & if \ \ otherwise \end{cases}$ $\hspace{1.5cm}$ (3i)

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176 $\quad \mu_{f_U^+}\left[f_U^+(x^+,\ y^+)\right]=\begin{cases}1, & if\ \ f_U^+ > f_*^{U+}\\ \dfrac{f_U^+ - f_U^{+'}}{f_*^{U+} - f_U^{+'}}, & if\ \ f_U^{+'} \le f_U^+ \le f_*^+ \\ 0, & if\ \ f_U^+ > f_U^{+'}\end{cases}$ (3j)

177 $\quad \mu_{f_L^+}\left[f_L^+(x^+,\ y^+)\right]=\begin{cases}1, & if\ \ f_L^+ > f_*^{L+}\\ \dfrac{f_L^+ - f_L^{+'}}{f_*^{L+} - f_L^{+'}}, & if\ \ f_L^{+'} \le f_L^+ \le f_*^{L+} \\ 0, & if\ \ f_L^+ > f_U^{+'}\end{cases}$ (3k)

178

179 Among them, formulas (3b) and (3c) are original constraints for ISBP model. $\mu_{x^+}(x^+)$ acts as

180 the membership function among the decision variables. $\mu_{f_U^+}\left[f_U^+(x^+,\ y^+)\right]$ and

181 $\mu_{f_L^+}\left[f_L^+(x^+,\ y^+)\right]$ serve respectively as membership functions of the upper-lower-level

182 model. Subsequently, solutions x_{opt}^+ and y_{opt}^+ can be acquired via formula group (4).

183 Respectively, f_{Uopt}^+ and f_{Lopt}^+ are the values of the objective function for the upper-lower-level

184 model. Analogously, with the computation of $\left(x^{U-},\ y^{U-},\ f_*^{U-}\right)$, $f_L^{-'}=f_L\left(x^{U-},\ y^{U-}\right)$,

185 $\left(x^{L-},\ y^{L-},\ f_*^{L-}\right)$ and $f_U^{-'}=f_U\left(x^{L-},\ y^{L-}\right)$, the solutions of x_{opt}^-, y_{opt}^-, x_{opt}^- and f_{Lopt}^- related to

186 lower-bound of the objective can be attained from the following model:

187 $\quad Max = \lambda^-$ (4a)

188 Subject to:

189 $\quad a^+ x^- \le v^-$ (4b)

190 $\quad b^+ x^- + c^+ y^- \le w^-$ (4c)

191 $\quad \mu_{x^-}(x^-) \ge \lambda^- I$ (4d)

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192 $\quad \mu_{f_U^-}\left[f_U^-(x^-, y^-)\right] \geq \lambda^-$ (4e)

193 $\quad \mu_{f_L^-}\left[f_L^-(x^-, y^-)\right] \geq \lambda^-$ (4f)

194 $\quad x^-, y^- \geq 0$ (4g)

195 $\quad x^- \leq x_{opt}^+$ (4h)

196 $\quad y^- \leq y_{opt}^-$ (4i)

197 $\quad \lambda^- \in [0, 1]$ (4j)

198 where:

199 $\quad \mu_{x^-}(x^-) = \begin{cases} \dfrac{x^- - (x^{U-} - r_1)}{r_1}, & if \ \ x^{U-} - r_1 \leq x^- \leq x^{U-} \\ \dfrac{(x^{U-} + r_1) - x^-}{r_1}, & if \ \ x^{U-} \leq x^- \leq x^{U-} + r_1 \\ 0, & if \ \ \text{otherwise} \end{cases}$ (4k)

200 $\quad \mu_{f_U^-}\left[f_U^-(x^-, y^-)\right] = \begin{cases} 1, & if \ \ f_U^- > f_*^{U-} \\ \dfrac{f_U^- - f_U^{-'}}{f_*^{U-} - f_U^{-'}}, & if \ \ f_U^- \leq f_U^- \leq f_*^{U-} \\ 0, & if \ \ f_U^- > f_U^{-'} \end{cases}$ (4l)

201 $\quad \mu_{f_L^-}\left[f_L^-(x^-, y^-)\right] = \begin{cases} 1, & if \ \ f_L^- > f_*^{L-} \\ \dfrac{f_L^- - f_L^{-'}}{f_*^{L-} - f_L^{-'}}, & if \ \ f_L^{-'} \leq f_L^- \leq f_*^{L-} \\ 0, & if \ \ f_L^- > f_U^{-'} \end{cases}$ (4m)

202

203 Through solving formula groups (3) and (4), solutions for the ISBP model can be obtained

204 (i.e., $x_{opt}^\pm = \left[x_{opt}^-, x_{opt}^+\right]$, $y_{opt}^\pm = \left[y_{opt}^-, y_{opt}^+\right]$, $f_{Uopt}^\pm = \left[f_{Uopt}^-, f_{Uopt}^+\right]$ and $f_{Lopt}^\pm = \left[f_{Lopt}^-, f_{Lopt}^+\right]$).

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3. Case Study

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3.1 Overview of the study system

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210 Dagu River watershed is positioned between the latitude range of 36°10′ N-37°12′ N and the

211 longitude range of 120°03′ E-120°25′ E (Figure 1). The main stream spans a length of 157

212 km, covering a total area of 4781 km^2 in Qingdao territory (Chen et al., 2024). Dagu River

213 plays a key role as the main water supply in Qingdao, which is one of the northern cities in

214 China facing water scarcity. The interannual variation of the runoff volume is significant. For

215 example, the surface water resource was 1.51×10^9 m^3 in 2020, and increased to 5.95×10^9 m^3

216 in 2021 (Qingdao Water Administration Bureau, 2021). Besides, Qingdao's planting industry

217 irrigation has gradually developed into a water-saving type. In 2018, the city's efficient water-

218 saving irrigation area was 166.7×10^3 hm^2, and in 2019, it was 188.0×10^3 hm^2, of which

219 low-pressure pipe irrigation area is 160.30×10^3 hm^2, sprinkler irrigation area is 11.28×10^3

220 hm^2, and micro-irrigation area is 4.84×10^3 hm^2 (Qingdao water Conservancy Statistical

221 Yearbook 2019).

222 ---------------------------

223 Place Figure 1 here

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225

3.2 Modeling formulation

226

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228 The case study incorporates practical details: (i) The Dagu River is divided into 16 river areas

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229   based on the division of five-level river basin; the river basin is divided into 21 regions

230   according to 4 counties; the model involves users in the regions, among which users are the

231   main water users of the first and second industries in Qingdao, including 21 users of planting

232   industry, livestock, fishery, and 17 users of processing and manufacturing enterprises. (ii)

233   Pollutant content level control considers 5 national and 3 provincial control sections; and

234   treatment capacity of 4 main wastewater treatment plants is considered. The analysis covers 5

235   hydrological year types (Appendix A) and spans 2 planning periods (2024 and 2025). (iii)

236   Dagu River watershed is an important water source of Qingdao City. The modeling effort

237   focuses on promoting economic development while controlling water consumption to ensure

238   sustainability. In this study, a two-level decision-making process is modeled to address

239   economic benefit maximization and water consumption minimization to enhance water use

240   efficiency. (iv) Water-trading system regards users' trading costs and prices, ensuring that the

241   allocation of water rights is commensurate with water consumption by users, so that the

242   trading behavior is in line with the users' interest orientation. (v) For the planting industry, the

243   operating costs, construction costs and water-saving subsidies of main water-saving facilities,

244   such as sprinkler irrigation, micro-irrigation and low-pressure pipe irrigation in Dagu River

245   watershed form part of the water-saving system; in addition, enterprises' calculations involve

246   water-saving potential, costs, and subsidies. The framework of the proposed SB-WSTM is

247   provided in Figure 2. Accordingly, the SB-WSTM can be represented as (the explanations of

248   subscripts, coefficients and decision variables in the simulation planning models are provided

249   in Appendix D):

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251   Place Figure 2 here

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254   Objective function:

255   Upper level:

$$
\begin{aligned}
Maxf_U^{\pm} = &\sum_{t=1}^{T}\sum_{z=1}^{Z}\sum_{a=1}^{A}\left(WQA_{taz}\times BA_{az}^{\pm}\right) - \sum_{t=1}^{T}\sum_{k=1}^{K}\sum_{z=1}^{Z}\sum_{a=1}^{A}\left(p_k\times WLA_{tkaz}^{\pm}\times DA_{az}^{\pm}\right)\\
&-\sum_{t=1}^{T}\sum_{k=1}^{K}\sum_{z=1}^{Z}\sum_{a=1}^{A}\left(p_k\times BWTA_{tkaz}^{\pm}\times TCA_{az}\right)\\
&-\sum_{t=1}^{T}\sum_{k=1}^{K}\sum_{z=1}^{Z}\sum_{a=1}^{1}\left[p_k\times\left(SFRA_{tkaz}^{\pm}+SFBA_{tkaz}^{\pm}\right)\right] + \sum_{t=1}^{T}\sum_{k=1}^{K}\sum_{z=1}^{Z}\sum_{a=1}^{1}\left(p_k\times WSAS_{tkaz}^{\pm}\right)\\
&-\sum_{t=1}^{T}\sum_{k=1}^{K}\sum_{a=1}^{A}\sum_{z=1}^{Z}\left(FAWA_{taz}\times PSGWA_{tkaz}^{\pm}+FAUA_{taz}\times PUGWA_{tkaz}^{\pm}\right)\\
&+\sum_{t=1}^{T}\sum_{i=1}^{I}\left(WQI_{ti}\times BI_i^{\pm}\right) - \sum_{t=1}^{T}\sum_{k=1}^{K}\sum_{i=1}^{I}\left(p_k\times WLI_{tki}^{\pm}\times DI_{zi}^{\pm}\right)\\
&-\sum_{t=1}^{T}\sum_{k=1}^{K}\sum_{i=1}^{I}\left(p_k\times BWTI_{tki}^{\pm}\times TCI_i\right)\\
&-\sum_{t=1}^{T}\sum_{i=1}^{I}SFCI_{ti} + \sum_{t=1}^{T}\sum_{i=1}^{I}WSIS_{ti}\\
&-\sum_{t=1}^{T}\sum_{k=1}^{K}\sum_{z=1}^{Z}\left(FAWI_{ti}\times PSGWI_{tki}^{\pm}+FAUI_{ti}\times PUGWI_{tki}^{\pm}\right)\\
&-\sum_{t=1}^{T}\sum_{k=1}^{K}\sum_{s=1}^{S}\left(p_k\times SDW_{tks}^{\pm}\times SC_{ts}^{\pm}\right)
\end{aligned}
$$

256

257   (5a)

258

259   The upper-level stakeholder is committed to maximizing the benefits derived from Dagu

260   River watershed. This encompasses revenue from objective water, loss from water deficit,

261   water charges, water-saving facilities' operation and construction, subsidies for water-saving

262   costs, water-trading expenditures, and expenses for wastewater treatment.

263

264   Lower level:

13

265 $$Minf_L^\pm = \sum_{t=1}^{T}\sum_{k=1}^{K}\sum_{z=1}^{Z}\sum_{a=1}^{A}\left(p_k \times WPA_{tkaz}^\pm\right) + \sum_{t=1}^{T}\sum_{k=1}^{K}\sum_{i=1}^{I}\left(p_k \times WPI_{tki}^\pm\right) \qquad (5b)$$

266

267 The lower-level stakeholder is committed to minimizing water consumption in Dagu River

268 watershed, involving actual water consumption of all production-oriented.

269

270 Subject to:

271 (1) Water consumption constraints:

272 $$WPA_{tkaz}^\pm = WQA_{taz} - WLA_{tkaz}^\pm - WSA_{tkaz}^\pm \qquad (5c)$$

273 $$WPI_{tki}^\pm = WQI_{ti} - WLI_{tki}^\pm - WSI_{ti} \qquad (5d)$$

274 $$WPA_{tkaz}^\pm = PSGWA_{tkaz}^\pm + PUGWA_{tkaz}^\pm \qquad (5e)$$

275 $$WPI_{tki}^\pm = PSGWI_{tki}^\pm + PUGWI_{tki}^\pm \qquad (5f)$$

276 $$PSGWA_{tkaz}^\pm \leq TWNA_{tkaz}^\pm \qquad (5g)$$

277 $$PSGWI_{tki}^\pm \leq TWNI_{tki}^\pm \qquad (5h)$$

278 $$PUGWA_{tkaz}^\pm \leq UGWA_{tkaz} \qquad (5i)$$

279 $$PUGWI_{tki}^\pm \leq UGWI_{tki} \qquad (5j)$$

280 $$PSA_{tkaz}^\pm = \left(WPA_{tkaz}^\pm + WSA_{tkaz}^\pm\right) \times LWPA_{az}^\pm \qquad (5k)$$

281 $$PSI_{tki}^\pm = \left(WPI_{tki}^\pm + WSI_{ti}\right) \times LWPI_i^\pm \qquad (5l)$$

282 $$QWAmi_{taz} \leq WPA_{tkaz}^\pm + WSA_{tkaz}^\pm \leq QWAma_{taz} \qquad (5m)$$

283 $$QWImi_{ti} \leq WPI_{tki}^\pm + WSI_{ti} \leq WQIma_{ti} \qquad (5n)$$

284

285 Constraints (5c) and (5d) manifest that the actual water is objective water minus the

14

286   combination of water deficit and water saving. Constraints (5e) and (5f) manifest that the

287   actual surface water and groundwater constitute the actual water composition. Constraints

288   (5g) and (5h) manifest that the actual surface water is obliged to satisfy the water rights held.

289   Constraints (5i) and (5j) manifest that the actual groundwater ought to be controlled by the

290   maximum total groundwater intake. Constraints (5k) and (5l) manifest that the actual

291   production scale equals the combination of actual water consumption and saving multiplied

292   by the production scale per unit of water. Constraints (5m) and (5n) manifest that the

293   combination of the actual water consumption and saving should be limited by the peak water

294   demand, and meet the fundamental water demand. Constraints (5m) and (5n) manifest that the

295   combination of actual water consumption and saving remains within the peak water demand

296   and the fundamental water demand.

297

298   (2) Water rights trading constraints:

299   $TWNA_{tkaz}^{\pm} = WNA_{tkaz}^{\pm} + BWTA_{tkaz}^{\pm} - SWTA_{tkaz}^{\pm}$ \hfill (5o)

300   $TWNI_{tki}^{\pm} = WNI_{tki}^{\pm} + BWTI_{tki}^{\pm} - SWTI_{tki}^{\pm}$ \hfill (5p)

301   $QWAmi_{taz} \leq WPA_{tkaz}^{\pm} + WSA_{tkaz}^{\pm} \leq QWAma_{taz}$ \hfill (5q)

302   $TWNI_{tki}^{\pm} + PUGWI_{tki}^{\pm} + WSI_{ti} \leq QWIma_{tzi}$ \hfill (5r)

303   $WNA_{tkaz}^{\pm} \geq SWTA_{tkaz}^{\pm}$ \hfill (5s)

304   $WNI_{tki}^{\pm} \geq SWTI_{tki}^{\pm}$ \hfill (5t)

305   $\sum_{z=1}^{Z}\sum_{a=1}^{A} SWTA_{tkaz}^{\pm} + \sum_{i=1}^{I} SWTI_{tki}^{\pm} = \sum_{z=1}^{Z}\sum_{a=1}^{A} BWTA_{tkaz}^{\pm} + \sum_{i=1}^{I} BWTI_{tki}^{\pm}$ \hfill (5u)

306

307   Constraints (5o) and (5p) manifest that the water rights held are determined by taking into

15

308   account initial water rights and the purchase or sale processes (the calculation of the initial

309   water rights is shown in Appendix B). Constraints (5q) and (5r) manifest that the aggregation

310   of actual groundwater, water rights held and water saving ought to remain within the peak

311   water demand. Constraints (5s) and (5t) manifest that water rights sold should not surpass the

312   initial water rights. Constraint (5u) manifests that the aggregation of water rights sold is equal

313   to the aggregation of water rights purchased.

314

315   (3) Price rule constraint:

$$316 \quad \begin{aligned} & WQA_{tkaz} \times BA_{az}^{\pm} - WLA_{tkaz}^{\pm} \times DA_{az}^{\pm} + SWTA_{tkaz}^{\pm} \times TRA_{az} \\ & - BWTA_{tkaz}^{\pm} \times \left(TCA_{az} + TRA_{az} \right) - SFRA_{tkaz}^{\pm} - SFBA_{taz} \\ & + WSAS_{tkaz}^{\pm} - FAWA_{taz} \times PSGWA_{tkaz}^{\pm} - FAUA_{taz} \times PUGWA_{tkaz}^{\pm} \geq NTGA_{tkaz}^{\pm} \end{aligned} \quad (5\text{v})$$

$$317 \quad \begin{aligned} & WQI_{tki} \times BI_{i}^{\pm} - WLI_{tki}^{\pm} \times DI_{i}^{\pm} + SWTI_{tki}^{\pm} \times TRI_{i} \\ & - BWTI_{tki}^{\pm} \times \left(TCI_{i} + TRI_{i} \right) - SFCI_{ti} + WSIS_{ti} \\ & - FAWI_{ti} \times PSGWI_{tki}^{\pm} - FAUI_{ti} \times PUGWI_{tki}^{\pm} \geq NTGI_{tki}^{\pm} \end{aligned} \quad (5\text{w})$$

318

319   Constraints (5v) and (5w) manifest that the post-trading advantages of the user are at least as

320   much as the pre-trading advantages.

321

322   (4) Wastewater discharge and treatment constraints:

$$323 \quad EPA_{tkaz}^{\pm} = UPEA_{az} \times \left[\left(WPA_{tkaz}^{\pm} + WSA_{tkaz}^{\pm} \right) \times IWPA_{az} \right] \quad (5\text{x})$$

$$324 \quad EPI_{tki}^{\pm} = UPEI_{i} \times \left[\left(WPI_{tki}^{\pm} + WSI_{ti} \right) \times IWPI_{i} \right] \quad (5\text{y})$$

$$325 \quad \sum_{i=16}^{16} DISW_{tki}^{\pm} = \sum_{i=16}^{16} \left[\left(WPI_{tki}^{\pm} + WSI_{ti} \right) \times IWDR_{i} \right] \quad (5\text{z})$$

16

$$SDW_{tks}^{\pm} = \sum_{i=1}^{15} ISS_{si} \times \left[\left(WPI_{tki}^{\pm} + WSI_{ti} \right) \times IWDR_i \right]$$

326
$$+ \sum_{i=17}^{17} ISS_{si} \times \left[\left(WPI_{tki}^{\pm} + WSI_{ti} \right) \times IWDR_i \right] \qquad (5aa)$$

$$+ LSW_{ts}^{\pm} + OSW_{ts}^{\pm} \le MSDW_s^{\pm}$$

327

328 Constraints (5x) and (5y) manifest that the actual pollutant generation is the product of actual

329 production scale and pollutant generation per unit production scale (the pollutants referred to

330 in the constraints regard COD as the object of study). Constraint (5z) manifests that the

331 wastewater directly discharged originates from the combination of the actual water

332 consumption and saving multiplied by the coefficient of drainage. Constraint (5aa) manifests

333 that the capacity of wastewater treatment facility is required to exceed the total of indirect

334 wastewater, domestic wastewater, and other types of wastewater.

335

336 (5) Water balance constraint:

337
$$\sum_{z=1}^{Z} \left\{ ZSW_{wz} \times \left[\sum_{a=1}^{A} TWNA_{tkaz}^{\pm} + \sum_{i=1}^{I} \left(ISZ_{zi} \times TWNI_{tki}^{\pm} \right) \right] \right\} \le SAWR_{tkw}^{\pm} \qquad (5ab)$$

338
$$SAWR_{tkw}^{\pm} = RIBF_{tkw}^{\pm} + \sum_{z=1}^{Z} \left[ZSW_{wz} \times \left(\begin{array}{c} RNF_{tkz} + DIW_{tz} + ORDI_{tkz} \\ -ORDO_{tkz} - OZW_{tz} - REW_{tz} \end{array} \right) \right] \qquad (5ac)$$

339
$$ROBF_{tkv}^{\pm} = \sum_{w=1}^{W} \left(OCR_{wv} \times ROBF_{tkw}^{\pm} \right) \qquad (5ad)$$

340
$$RIBF_{tkw}^{\pm} = \sum_{v=1}^{V} \left(IOCR_{wv} \times ROBF_{tkv}^{\pm} \right) \qquad (5ae)$$

17

$$341 \quad ROBF_{tkw}^{\pm} = RIBF_{tkw}^{\pm} + \sum_{z=1}^{Z} \left\{ ZSW_{wz} \times \begin{bmatrix} RNF_{tkz} + DIW_{tz} + ORDI_{tkz} - ORDO_{tkz} \\ -OZW_{tz} - REW_{tz} \\ -\sum_{a=1}^{A} TWNA_{tkaz}^{\pm} - \sum_{i=1}^{I} \left(ISZ_{zi} \times TWNI_{tki}^{\pm} \right) \\ +DWWP_{z} \times \begin{bmatrix} \sum_{s=1}^{S} \left(SSZ_{zs} \times SDW_{tks}^{\pm} \right) \\ +\sum_{i=16}^{16} \left(ISZ_{zi} \times DISW_{tki}^{\pm} \right) \end{bmatrix} \end{bmatrix} \right\} \quad (5af)$$

342

343 Constraint (5ab) manifests that the water rights held by the river area must not surpass the

344 available water resources of the river area. Constraints (5ac) to (5af) manifest that the water

345 balance of the river region accounts for upstream inflow, natural runoff, exterior diversion,

346 outflow, and the surface water consumption including that by residents and water rights held

347 by users, and other surface water consumption (the calculation of natural runoff is shown in

348 Appendix A).

349

350 (6) Pollutant content level constraints of river monitoring sections:

$$351 \quad CSM_{m} \times MBF_{tkm}^{\pm} \geq OCS_{tkm} + \sum_{z=1}^{Z} ZSM_{mz} \times \left\{ \begin{array}{l} \sum_{a=1}^{A} \left(DPMA_{maz} \times EPA_{tkaz}^{\pm} \right) \\ +\sum_{s=3}^{S} \begin{bmatrix} SSZ_{zs} \times DPMS_{ms} \times \left(1 - UPES_{s} \right) \\ \times \begin{pmatrix} LSW_{ts} \times LSP_{ts} \\ +OSW_{ts} \times OSP_{ts} \end{pmatrix} \end{bmatrix} \\ +\sum_{s=4}^{S} \begin{bmatrix} SSZ_{zs} \times DPMS_{ms} \\ \times \left(1 - UPES_{s} \right) \times \sum_{i=1}^{6} EPI_{tki}^{\pm} \end{bmatrix} \end{array} \right\}$$

352 $\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad$ (5ag)

18

$$353 \qquad MBF_{tkm}^{\pm} = \sum_{w=1}^{W} \left(WSM_{mw} \times ROBF_{tkw}^{\pm} \right) + NRM_{tkm} \qquad\qquad (5ah)$$

354

355 Constraint (5ag) manifests that the pollutant content level at the monitoring section is

356 governed by the stream runoff and pollutant burden (conform to the local standard of surface

357 water quality). Constraint (5ah) manifests that the stream discharge at the monitoring section

358 is fixed by taking into account the upstream inflow (i.e., upstream river region and natural

359 runoff prior to the monitoring section upstream).

360

361 (7) Supply and demand constraints:

$$362 \qquad DWA_{tkaz}^{\pm} = \begin{cases} PSGWA_{tkaz}^{\pm} - WNA_{tkaz}^{\pm} \ , & if \ PSGWA_{tkaz}^{\pm} - WNA_{tkaz}^{\pm} > 0 \\ 0 \ , & if \ PSGWA_{tkaz}^{\pm} - WNA_{tkaz}^{\pm} \leq 0 \end{cases} \qquad (5ai)$$

$$363 \qquad SWA_{tkaz}^{\pm} = \begin{cases} WNA_{tkaz}^{\pm} - PSGWA_{tkaz}^{\pm}, & if \ WNA_{tkaz}^{\pm} - PSGWA_{tkaz}^{\pm} > 0 \\ 0 \ , & if \ WNA_{tkaz}^{\pm} - PSGWA_{tkaz}^{\pm} \leq 0 \end{cases} \qquad (5aj)$$

$$364 \qquad DWI_{tki}^{\pm} = \begin{cases} PSGWI_{tki}^{\pm} - WNI_{tki}^{\pm} \ , & if \ PSGWI_{tki}^{\pm} - WNI_{tki}^{\pm} > 0 \\ 0 \ , & if \ PSGWI_{tki}^{\pm} - WNI_{tki}^{\pm} \leq 0 \end{cases} \qquad (5ak)$$

$$365 \qquad SWI_{tki}^{\pm} = \begin{cases} WNI_{tki}^{\pm} - PSGWI_{tki}^{\pm} \ , & if \ WNI_{tki}^{\pm} - PSGWI_{tki}^{\pm} > 0 \\ 0 \ , & if \ WNI_{tki}^{\pm} - PSGWI_{tki}^{\pm} \leq 0 \end{cases} \qquad (5al)$$

366

367 Constraints (5ai) to (5al) manifest that if the initial water rights transcend the expected surface

368 water consumption, then the water rights can be offered; if the initial water rights fall short of

369 the expected surface water consumption, it implies the demand for water rights.

370

371 (8) Water-saving regulation constraints:

19

$$372 \quad \sum_{a=1}^{1} SFBA_{tkaz} = \sum_{a=1}^{1} \left(NIPS_{tkaz}SIFC_{az} + NIPM_{tkaz}MIFC_{az} + NIPL_{tkaz}LIFC_{az} \right) \quad (5am)$$

$$373 \quad \sum_{a=1}^{1} SFRA_{tkaz}^{\pm} = \sum_{a=1}^{1} \left(SIA_{tkaz}^{\pm}SIRC_{az} + MIA_{tkaz}^{\pm}MIRC_{az} + LIA_{tkaz}^{\pm}LIRC_{az} \right) \quad (5an)$$

$$374 \quad \sum_{a=1}^{1} WPA_{tkaz}^{\pm} = \sum_{a=1}^{1} \begin{pmatrix} SIA_{tkaz}^{\pm}SICW_{az} + MIA_{tkaz}^{\pm}MICW_{az} \\ +LIA_{tkaz}^{\pm}LICW_{az} + NSA_{tkaz}^{\pm}NSCW_{az} \end{pmatrix} \quad (5ao)$$

$$375 \quad \sum_{a=1}^{1} EFIA_{tkaz}^{\pm} = \sum_{a=1}^{1} \left(SIA_{tkaz}^{\pm} + MIA_{tkaz}^{\pm} + LIA_{tkaz}^{\pm} + NSA_{tkaz}^{\pm} \right) \quad (5ap)$$

$$376 \quad \sum_{a=1}^{1} NSA_{tkaz}^{\pm} = \sum_{a=1}^{1} \left(PNSA_{tkaz}^{\pm} - NIPS_{tkaz} - NIPM_{tkaz} - NIPL_{tkaz} \right) \quad (5aq)$$

$$377 \quad \sum_{a=1}^{1} SIA_{tkaz}^{\pm} = \sum_{a=1}^{1} \left(NIPS_{tkaz} + PIPS_{tkaz}^{\pm} \right) \quad (5ar)$$

$$378 \quad \sum_{a=1}^{1} MIA_{tkaz}^{\pm} = \sum_{a=1}^{1} \left(NIPM_{tkaz} + PIPM_{tkaz}^{\pm} \right) \quad (5as)$$

$$379 \quad \sum_{a=1}^{1} LIA_{tkaz}^{\pm} = \sum_{a=1}^{1} \left(NIPL_{tkaz} + PIPL_{tkaz}^{\pm} \right) \quad (5at)$$

$$380 \quad \sum_{a=1}^{1} SIPW_{tkaz}^{\pm} = \sum_{a=1}^{1} \left(SIA_{tkaz}^{\pm} \times SIRW_{az} \right) \quad (5au)$$

$$381 \quad \sum_{a=1}^{1} MIPW_{tkaz}^{\pm} = \sum_{a=1}^{1} \left(MIA_{tkaz}^{\pm} \times MIRW_{az} \right) \quad (5av)$$

$$382 \quad \sum_{a=1}^{1} LIPW_{tkaz}^{\pm} = \sum_{a=1}^{1} \left(LIA_{tkaz}^{\pm} \times LIRW_{az} \right) \quad (5aw)$$

$$383 \quad \sum_{a=1}^{1} WSA_{tkaz}^{\pm} = \sum_{a=1}^{1} \left(SIPW_{tkaz}^{\pm} + MIPW_{tkaz}^{\pm} + LIPW_{tkaz}^{\pm} \right) \quad (5ax)$$

$$384 \quad \sum_{a=1}^{1} \left(\sigma_a \times EFIA_{tkaz}^{\pm} \right) = \sum_{a=1}^{1} \left(SIA_{tkaz}^{\pm} + MIA_{tkaz}^{\pm} + LIA_{tkaz}^{\pm} \right) \quad (5ay)$$

20

$$385 \quad WSI_{ti} = TIOV_i \times \left(PTVW_i - TIVW_i \right) + CICW_i \times \frac{\eta_p - \eta_c}{1 - \eta_p} \qquad (5az)$$

$$386 \quad SFCI_{ti} = USFC_i \times WSI_{ti} \qquad (5ba)$$

$$387 \quad \sum_{a=1}^{1} WSAS_{tkaz}^{\pm} = \sum_{a=1}^{1} \left[\varphi_a \times \left(SFRA_{tkaz}^{\pm} + SFBA_{tkaz} \right) \right] \qquad (5bb)$$

$$388 \quad WSIS_{ti} = \varphi_i \times SFCI_{ti} \qquad (5be)$$

389

390 Constraint (5am) manifests that the water-saving construction cost is the unit area

391 construction cost multiplied by total areas of three efficient irrigation facilities. Constraint

392 (5an) manifests that the water-saving operating cost is equivalent to the sum of operating cost

393 per unit area multiplied by the total area of three efficient irrigation facilities. Constraint (5ao)

394 manifests the actual water consumption is equal to the product of the sum of the areas of three

395 efficient irrigation facilities, and non-water-saving irrigation and the corresponding water

396 consumption per unit area. Constraint (5ap) manifests that the non-water-saving irrigation

397 area is original non-water-saving irrigation area minus total newly added irrigation areas of

398 three efficient irrigation facilities. Constraints (5aq) to (5at) manifest that the actual

399 sprinkling, micro-irrigation, and low-pressure pipe irrigation areas amount to the combination

400 of the original irrigation area and the newly added irrigation area. Constraints (5au) to (5ax)

401 manifest that the water-saving amount is equivalent to the sum of three actual efficient

402 irrigation facilities multiplied by the corresponding Water saving per unit area. Constraint

403 (5ay) manifests that the proportion of irrigation area allocated to three efficient irrigations.

404 Constraint (5az) is manifested as the computing process of the water-saving potential of

405 enterprises. Constraint (5ba) manifests that the water-saving cost of the enterprise is obtained

406 by multiplying the water saving by the unit saving cost. Constraints (5bb) and (5be) manifest

21

407   the water-saving subsidy for planting industry and enterprises from the government.

408

409   *3.3 Scenario design and data collection*

410

411   The 14th Five-Year Plan for Water Saving and Unconventional Water Use in Qingdao city

412   (compiled by Qingdao Water Administration Bureau, 2021) provides crucial guidelines for

413   the further advancement of efficient water-saving irrigation project and the improvement of

414   precise subsidy and incentive for agricultural water use in Qingdao. This "Plan" aims to refine

415   Qingdao's water-saving activities plan to address the predicament of water scarcity.

416   Therefore, to align with the refinement of water-saving activity planning, this study designed

417   five scenarios of efficient water-saving irrigation area ratios and five scenarios of water-

418   saving subsidy policy to examine the impact of different water-saving schemes on the water

419   rights trading market under conditions of water scarcity (details are described in Table 1). The

420   ratios of efficient water-saving irrigation area are set according to 2025 planning targets.

421   Agricultural users are free to choose efficient water-saving irrigation methods (as described

422   by constraint condition 5ay). Water-saving subsidy policy aims to examine the applicability

423   of national policy at the local level and the impact of water-saving policy on Qingdao's water

424   rights trading (as described by constraint conditions 5bb and 5be).

425   --------------------------

426   Place Table 1 here

427   --------------------------

428

429   The study relies on data from reliable and valid sources, including statistical yearbooks, water

430   resource bulletins, published papers, and expert consultations. Flow data of Nancun

22

431   hydrologic station from 1998 to 2011 are collected for calibration of hydrological simulation.

432   Meteorological data employed are gathered from China Meteorological Data Service Center

433   (encompassing daily rainfall data along with highest and lowest temperatures). A digital

434   elevation model (DEM) comes from geospatial data cloud site of the Computer Network

435   Information Center of the Chinese Academy of Sciences (http://www.gscloud.cn), which is

436   applied to obtain the physical characteristics, flow direction and hydrological network. The

437   Data Center for Resources and Environmental Sciences, Chinese Academy of Sciences

438   provided land use data sets (http://www.resdc.cn). The Soil and Terrain Database obtained a

439   soil map of 1:1 million. The Water Resources Bulletin obtains water demand and supply data,

440   in addition, based on the Water Conservancy Statistical Yearbook, the area data of three

441   efficient irrigation facilities (i.e., sprinkling, micro-irrigation, and low-pressure pipe

442   irrigation) are acquired. Enterprise wastewater data and agricultural wastewater data are

443   derived from the Key Pollution Source Data Release System of the Department of Ecology

444   and Environment of Shandong Province and the Bulletin of the Second National Pollution

445   Source Census of Qingdao City, respectively (Qingdao Municipal Bureau of Ecology and

446   Environment, 2020).

447

448   **4. Results and Discussion**

449

450   *4.1 Initial water right allocation*

451

452   Figure 3 illustrates initial water rights under water-saving scenarios among hydrological year

453   types. The volume of available water resources is commensurate with that of total initial water

454   rights. The results indicate that the total initial water rights in wet years ($k = 4$ and 5) would

23

455   increase compared to dry years (k = 1 and 2). For example, under Scenario S1, total initial

456   water rights in wet years would increase by [18.08, 20.81]% compared to dry years in 2025.

457   This is due to higher surface available water resource in wet years. Besides, the results show

458   that, compared with non-subsidy scenarios (S1-S5), total initial water rights under full water-

459   saving subsidy (S21-S25) would decrease. For example, under 70% efficient water-saving

460   irrigation area, total initial water rights would decrease by [4.16, 4.29]%, i.e., [3.18, 3.30] $\times$

461   10^6 m^3. This is because the costs incurred by operation and construction of water-saving

462   irrigation technologies are offset under full subsidy, bringing about the tendency to adopt

463   irrigation technology with higher water-saving capacity (as shown in Figure 7), leading to a

464   decrease in surface water consumption for planting industry. From the results, with the

465   increase of efficient water-saving irrigation area, the total initial rights would decrease. For

466   example, the total rights under S25 would decrease by [6.97, 8.15]%, i.e. [55.06, 65.34] $\times$ 10^6

467   m^3, compared to S21. This is because the increase in efficient water-saving irrigation area

468   leads to a decrease in water consumption of planting industry users. In addition, with the

469   increase of efficient water-saving irrigation area, the initial water rights amount for planting

470   industry would decrease, while those for enterprise would increase.

471   --------------------------

472   Place Figure 3 here

473   --------------------------

474

475   *4.2 Water rights trading process*

476

477   Figure 4 illustrates water rights trading amount under water-saving scenarios among

478   hydrological year types (PL: planting industry; LI: livestock; FI: fishery; EN: enterprise). The

479　results indicate that water trading mainly occurs in special dry years ($k = 1$), where enterprises

480　are buyers, and agriculture (including planting industry, livestock, and fishery) are sellers.

481　Notably, agriculture, especially planting industry, is the main seller, accounting for [66.36,

482　71.54]% of total sales on average. This is because the benefits per unit water consumption of

483　enterprises is higher than that of agriculture, and planting industry has a larger water basis, so

484　water rights tend to flow to high-efficiency enterprises (Ma et al., 2020; Browne and Ji, 2023;

485　Chen et al., 2024). Besides, the results show that, compared to non-subsidy scenarios (S1-S5),

486　the trading amount under full water-saving subsidy (S21-S25) would decrease by [11.60,

487　14.75]% on average, i.e., [308.02, 455.64] $\times$ 10^3 m^3. This arises from the fact that water-

488　saving subsidy would decrease enterprises' actual surface water consumption, as shown in

489　Figure 5. And enterprises' demand for water rights would decrease by [12.63, 13.27]%. In

490　detail, from the results in Figure 5, compared to non-subsidy scenarios, enterprises' actual

491　surface water consumption under full subsidy would decrease by [371.60, 392.28] $\times$ 10^3 m^3,

492　and the actual groundwater consumption would increase by [401.64, 498.02] $\times$ 10^3 m^3. This is

493　because under scenarios with subsidy, enterprises would utilize more groundwater with higher

494　water price to substitute for surface water. Surface water with lower price tends to flow to

495　industries without subsidy such as fisheries, whose actual surface water use would increase by

496　[382.86, 502.99] $\times$ 10^3 m^3. These results imply that water saving subsidy alters enterprises'

497　water consumption structure of surface water and groundwater, thereby impacts supply and

498　demand dynamics and water trading processes. The results also show that with the increase of

499　efficient water-saving irrigation area, the water trading amount would increase. For example,

500　compared to S1, water trading amount under S5 would increases by [41.43, 67.02]%, i.e.,

501　[952.93, 1173.66] $\times$ 10^3 m^3. This is because the expansion of efficient irrigation area would

502　raise planting industry's water-saving amount and reduce surface water consumption.

25

503   Therefore, planting industry's water right supply would nearly double, enlarging the water

504   trading market scale. The aforementioned analysis implies that water-saving users transfer

505   surplus water rights to high-return users, gaining water-saving benefits; and high-return users

506   pay for the water rights, thereby stimulating the intrinsic motivation of users to save water.

507   ----------------------------------

508   Place Figures 4 and 5 here

509   ----------------------------------

510

511   *4.3 Water resources allocation*

512

513   Figure 6 illustrates surface and underground water consumption of multiple industries under

514   water-saving schemes among hydrological year types. The results indicate that, compared to

515   dry years, surface water consumption under wet years would increase, while the groundwater

516   consumption would decrease. For example, in wet years under S1, the planting industry of

517   surface water consumption would increase by [18.93, 22.09]% compared to dry years, while

518   the groundwater consumption would decrease to 0. This results from the fact that groundwater

519   price is higher than price of surface water that is abundant in wet years. In addition, the results

520   show that the total surface water consumption under full water-saving subsidy (S21-S25)

521   would decrease by $[1.58, 2.41] \times 10^6$ m^3 on average compared with non-subsidy scenarios

522   (S1-S5). This is because the water-saving amount under full water saving subsidy is [6.52,

523   10.16]% more than that without subsidy. The results also show that the consumption of

524   surface water by planting industry would decrease as the area of efficient water-saving

525   irrigation increases. For example, the consumption of surface water by planting industry

526   under S5 is [5.68, 5.76]% less than that under S1, i.e., $[3.35, 3.39] \times 10^6$ m^3. This is because

26

527   the increase of efficient water-saving irrigation area leads to an increase in water-saving

528   amount by planting industry (Pinto et al., 2023). For example, the water-saving amount under

529   70% efficient water-saving irrigation area (S5, S10, S15, S20 and S25) is increased by [19.16,

530   19.60] on average, i.e., [4.00, 4.05] $\times 10^6$ m^3, compared to 60% efficient water-saving

531   irrigation area (S1, S6, S11, S16 and S21).

532   --------------------------

533   Place Figure 6 here

534   --------------------------

535

536   *4.4 Water-saving facilities construction*

537

538   Figure 7 illustrates construction area of three facilities among hydrological year types (NIPS:

539   sprinkler construction area; NIPM: micro-irrigation construction area; NIPL: low-pressure

540   pipe construction area). The results indicate that, in special dry years ($k = 1$), micro-irrigation

541   is the predominant type of efficient water-saving irrigation facility construction, accounting

542   for [91.58, 92.44]% of total construction area on average. For other hydrological years, the

543   predominant type of facility construction is low-pressure pipe. It accounts for [80.00, 88.78]%

544   for $k = 2$, [80.00, 88.78]% for $k = 3$, [80.16, 92.91]% for $k = 4$, and [87.39, 93.77]% for $k = 5$

545   on average, respectively. This is because the water-saving ability of micro-irrigation is nearly

546   twice that of low-pressure pipe irrigation; but the water-saving cost of micro-irrigation is

547   high. Thus, micro-irrigation technology is more applicable during special dry years. Low-

548   pressure pipe irrigation with lower cost would be adopted when surface water resources is

549   increased. Besides, the results show that the micro-irrigation facility construction area under

550   full water-saving subsidy would increase by nearly 7 times compared to non-subsidy

27

551   scenarios. This is because water-saving subsidy alleviates the cost; users would be more

552   inclined to choose irrigation facility with high water-saving capabilities. The result implies

553   that with suitable water-saving subsidy, the agricultural sector will progressively lean towards

554   utilizing irrigation systems with greater water-saving capacities, such as micro-irrigation,

555   fostering high-quality water-saving advancements in the region (Zhao et al., 2023b). The

556   results also show that the increase of low-pressure pipe irrigation area is the largest with the

557   construction of efficient water-saving irrigation facility (Figure 7 (a)-(e)). For example, under

558   70% efficient water-saving irrigation area (i.e., S5, S10, S15, S20 and S25), construction area

559   for water-saving facility would be $[12.67, 13.30] \times 10^3 \, \text{hm}^2$ for low-pressure pipe irrigation on

560   average, $[3.85, 4.04] \times 10^3 \, \text{hm}^2$ for micro-irrigation, and $[0.12, 0.56] \times 10^3 \, \text{hm}^2$ for sprinkler

561   irrigation. This is because low-pressure pipe irrigation facility has lowest construction cost.

562   ----------------------------

563   Place Figure 7 here

564   ----------------------------

565

566   *4.5 Bi-objective function values*

567

568   Figure 8 illustrates system benefits and total actual water consumption under water-saving

569   schemes. The results indicate that system benefits and water consumption are higher in wet

570   years than those in dry years. For example, under S1, the system benefits in wet years would

571   be improved by [5.25, 6.41]% on average, and the total water consumption would be

572   improved by [4.54, 5.89]%, compared to dry years. In addition, the results show that, with the

573   rise of water-saving subsidy, the system benefits would be increased, and the total water

574   consumption would decrease. For example, compared to non-subsidy scenarios, the system

28

575   benefit under full subsidy would increase by $[157.24, 172.76] \times 10^6$ RMB¥, and the total

576   water consumption would decrease by $[1.38, 2.27] \times 10^6 \, m^3$ on average. This is because the

577   subsidy makes up for the cost of water saving, and planting industry tends to invest in micro-

578   irrigation water-saving facility (see Figure 7), leading to increased water-saving amount and

579   reduced total water consumption (Li et al., 2023). The findings also indicate that, with the

580   increase in efficient irrigation area, the total water consumption would decrease. For example,

581   compared to 60% of the irrigation area, the total water consumption under 75% would

582   decrease by $[4.97, 5.12]\%$ on average, i.e., $[3.86, 3.97] \times 10^6 \, m^3$. This is because, as the

583   planting industry increase the area of efficient water-saving irrigation, water-savings amount

584   would increase, consequently decreasing total water consumption.

585   ---------------------------

586   Place Figure 8 here

587   ---------------------------

588

589   *4.6 Optimal water saving scheme*

590

591   The optimal water-saving scheme is ascertained relying on Technique for Order Preference by

592   Similarity to an Ideal Solution (TOPSIS) (Shih et al., 2007; Ghazali et al., 2018; Wang et al.,

593   2022). This study comprehensively considers the system benefits (deduction of water-saving

594   subsidy), water consumption, water-saving amount, and water use efficiency to evaluate the

595   performance of multiple water saving scenarios. The evaluation results are presented in Table

596   2, regarding the results, the largest Euclidean distance is 0.7936 (S15), succeeded by 0.7842

597   (S5) and 0.7402 (S10). It indicates that S15 that corresponds to 50% of the subsidy rate and

598   70% of efficient irrigation area is the optimal water-saving scenario under SB-WSTM. Table

29

599   3 presents the optimal decisions under optimal water saving scheme. The results can be

600   displayed as follows: (a) The actual production scales of planting industry in Pingdu county is

601   the largest among all counties in each year. The production scales would respectively be

602   [148.81, 150.31] × 10^3 ha/year (Pingdu), [127.85, 129.15] × 10^3 ha/year (Laixi), [104.28,

603   105.34] × 10^3 ha/year (Jiaozhou) and [81.17, 81.99] × 10^3 ha/year (Jimo). (b) The agricultural

604   water consumption of Laixi county is the largest. The agricultural water consumption would

605   respectively be [35.75, 35.94] × 10^6 m^3/year in Laixi, [19.65, 19.97] × 10^6 m^3/year in Pingdu,

606   [7.26, 7.26] × 10^6 m^3/year in Jimo and [15.85, 15.87] × 10^6 m^3/year in Jiaozhou. Table 4

607   presents the optimal water-saving scheme. The results show that: (a) The main water-saving

608   facility of each county is, with an area of [43.62, 44.43] × 10^3 ha/year in Laixi, [14.40, 14,42]

609   × 10^3 ha in Jiaozhou, [12.98, 13.52] × 10^3 ha/year in Pingdu and [6.95, 6.96] × 10^3 ha/year in

610   Jimo. (b) The area of each water-saving facility in the main county is listed as follows: the

611   area of sprinkler irrigation facility in Jiaozhou is [1.92, 1.97] × 10^3 ha/year, the area of micro-

612   irrigation facility in Laixi is [1.99, 1.99] × 10^3 ha/year, the area of low-pressure pipe irrigation

613   facility in Laixi is [43.62, 44.43] × 10^3 ha/year. (c) The main hydrological year type of water-

614   saving facility in each county is listed as follows: the construction area of Laixi is [13.68,

615   14.56] × 10^3 ha/year, the construction area of Pingdu is [5.91, 7.16] × 10^3 ha/year, the

616   construction area of Jimo is [1.32, 1.32] × 10^3 ha/year, and the construction area of Jiaozhou

617   is [4.43, 4.61] × 10^3 ha/year under special dry year. (d) The water-saving subsidy for Laixi

618   county is the largest. The subsidy would be [165.40, 171.30] × 10^6 RMB/year (Laixi), [6.66,

619   13.86] × 10^6 RMB/year (Pingdu), [0.99, 1.05] × 10^6 RMB/year (Jimo) and [2.16, 3.00] × 10^6

620   RMB/year (Jiaozhou), respectively. (e) The main hydrological year type of water-saving

621   subsidy in each county is listed as follows: the subsidy of Laixi is [209.57, 222.67] × 10^6

622   RMB/year, the subsidy of Pingdu is [13.92, 21.57] × 10^6 RMB/year, the subsidy of Jimo is

30

623   [0.49, 0.49] × 10^6 RMB/year, and the subsidy of Jiaozhou is [1.14, 4.52] × 10^6 RMB/year

624   under special dry year.

625   ----------------------------------

626   Place Tables 2, 3 and 4 here

627   ----------------------------------

628

629   **5. Conclusions**

630

631   This study proposes a novel stochastic bi-level programming-based water saving and trading

632   simulation model for water resources regulation (SB-WSTM) in a water-scarce watershed.

633   SB-WSTM incorporates scenario analysis on water-saving irrigation facility and government

634   subsidy, as well as uncertainty analysis with interval stochastic bi-level programming (ISBP)

635   within a water trading market framework. The SB-WSTM has superiority in: (i) disclosing the

636   response of water resources system to water-saving facilities and subsidies; (ii) obtaining the

637   optimal water saving and water resources regulation schemes considering water system

638   functions.

639

640   The SB-WSTM is applied in a water-scarce watershed, Dagu River watershed of China.

641   Several findings can be disclosed: (i) As surface water resources increase, total initial water

642   rights, surface water and total water consumption, and system benefits would rise accordingly,

643   accompanied with a decrease in groundwater consumption. Besides, water rights trading

644   process mainly occurs during special dry years. (ii) Micro-irrigation, which is given priority in

645   special dry years because of its efficient water-saving ability, accounting for [91.58, 92.44]%

646   of total construction area. Low-pressure pipe irrigation is more favored in other hydrological

<div align="center">31</div>

647   year types because of the lower construction costs, accounting for more than 80%. To cope

648   with extremely dry years that may damage food security and ecological red line in Dagu River

649   watershed, it is recommended to increase the promotion and investment of micro-irrigation

650   facility. (iii) Water-saving subsidy would decrease total water rights and surface water

651   consumption, while increasing system benefit. In addition, water-saving subsidy would

652   change users' water consumption structure, decreasing the proportion of surface water

653   consumption for enterprises; full water-saving subsidy leads to a decrease in water right

654   demand by [12.63, 13.27]% compared with non-subsidy scenarios, which would reduce water

655   trading amount by [11.60, 14.75]%. And full water-saving subsidy would increase the

656   construction area of micro-irrigation facility by nearly 7 times. (iv) The increase of water-

657   saving irrigation area would decrease total water rights and the consumption of surface water

658   by planting industry, consequently increasing water rights allocation to enterprises.

659   Furthermore, this expansion would transfer surplus water rights to high-return users and raise

660   the amount of water right supply, thereby stimulating the intrinsic motivation to save water.

661   (v) Based on comprehensive evaluation for system benefits (deduction of water-saving

662   subsidy), water consumption, water-saving amount, and water use efficiency, the scenario that

663   entails 50% of the subsidy rate combined with 70% of efficient irrigation area emerges as the

664   optimal water-saving scheme.

665

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667

32

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862 **List of Table Captions**

863 Table 1 Design of water-saving schemes

864 Table 2 TOPSIS analysis results of different water-saving scenarios

865 Table 3 Production and water consumption decision scheme under optimal water saving

866   scheme

867 Table 4 Water-saving irrigation facility areas and subsidy decision scheme under optimal

868   water saving scheme

870 Table 1 Design of water-saving schemes

Scenario	High-efficient water-saving irrigation area rate (%)	Water-saving costs subsidy rate (%)
S1	60.0	0
S2	62.5	0
S3	65.0	0
S4	67.5	0
S5	70.0	0
S6	60.0	25
S7	62.5	25
S8	65.0	25
S9	67.5	25
S10	70.0	25
S11	60.0	50
S12	62.5	50
S13	65.0	50
S14	67.5	50
S15	70.0	50
S16	60.0	75
S17	62.5	75
S18	65.0	75
S19	67.5	75
S20	70.0	75
S21	60.0	100
S22	62.5	100
S23	65.0	100
S24	67.5	100
S25	70.0	100

872   Table 2 TOPSIS analysis results of different water-saving scenarios

Scenario	Maximum Euclidean distance
S1	0.5319
S2	0.6221
S3	0.6589
S4	0.6833
S5	0.7843
S6	0.5585
S7	0.6375
S8	0.6787
S9	0.6630
S10	0.7402
S11	0.4922
S12	0.5929
S13	0.5593
S14	0.7210
S15	0.7936
S16	0.5059
S17	0.5246
S18	0.6579
S19	0.6399
S20	0.6835
S21	0.3507
S22	0.2806
S23	0.3624
S24	0.3255
S25	0.3572

874 Table 3 Production and water consumption decision scheme under optimal water saving scheme

Decisions	Hydrological year type	Laixi	Pingdu	Jimo	Jiaozhou
Objective production scales of planting industry (10^3 ha)	\	[128.95, 130.26]	[148.82, 150.31]	[81.17, 81.99]	[104.29, 105.34]
Objective production scales of livestock industry (10^6 head)	\	[1.93, 1.95]	[0.80, 0.81]	[0.83, 0.84]	[1.63, 1.64]
Objective production scales of fishery industry (10^3 ha)	\	[0.97, 0.98]	[0.22, 0.22]	[0.24, 0.24]	[1.07, 1.08]
Actual agricultural water consumption (10^6 m^3)	Special dry year	[31.12, 32.08]	[17.90, 19.15]	[6.96, 6.97]	[15.49, 15.67]
	Dry year	[35.86, 36.22]	[19.69, 20.25]	[7.16, 7.16]	[15.90, 15.90]
	Normal year	[36.43, 36.80]	[19.69, 20.25]	[7.30, 7.31]	[15.90, 15.90]
	Wet year	[36.43, 36.78]	[19.76, 20.29]	[7.39, 7.39]	[15.90, 15.90]
	Special wet year	[36.43, 36.78]	[19.76, 20.29]	[7.39, 7.39]	[15.90, 15.90]
	Expected value	[35.75, 35.94]	[19.65, 19.97]	[7.26, 7.26]	[15.85, 15.87]
Actual irrigation water consumption of planting industry (10^6 m^3)	Special dry year	[19.15, 20.03]	[14.00, 15.26]	[6.03, 6.03]	[12.76, 12.95]
	Dry year	[23.16, 23.53]	[15.61, 16.16]	[6.03, 6.03]	[12.95, 12.95]
	Normal year	[23.16, 23.53]	[15.61, 16.16]	[6.03, 6.03]	[12.95, 12.95]
	Wet year	[23.16, 23.51]	[15.64, 16.16]	[6.02, 6.03]	[12.95, 12.95]
	Special wet year	[23.16, 23.51]	[15.64, 16.16]	[6.02, 6.03]	[12.95, 12.95]
	Expected value	[22.77, 22.97]	[15.58, 15.89]	[6.02, 6.03]	[12.93, 12.95]

44

876   Table 4 Water-saving irrigation facility areas and subsidy decision scheme under optimal water saving scheme

Decisions	Hydrological year type	Laixi	Pingdu	Jimo	Jiaozhou
Sprinkler irrigation facility area (10^3 ha)	Special dry year	[1.31, 1.50]	[0.29, 1.48]	[0.43, 0.43]	[1.92, 2.32]
	Special wet year	1.39	0.29	0.43	1.92
	Expected value	[1.39, 1.41]	[0.29, 0.44]	[0.43, 0.43]	[1.92, 1.97]
Micro-irrigation facility area (10^3 ha)	Special dry year	[11.41, 11.41]	[0.011, 0.24]	[0.21, 0.21]	[0.24, 0.24]
	Special wet year	0.65	0.011	0.21	0.24
	Expected value	[1.99, 1.99]	[0.011, 0.040]	[0.21, 0.21]	[0.24, 0.24]
Low-pressure pipe irrigation facility area (10^3 ha)	Special dry year	[27.96, 31.08]	[12.50, 17.78]	[6.95, 6.95]	[14.41, 14,58]
	Special wet year	[45.44, 46.78]	[12.30, 13.62]	[6.94, 6.97]	[14.40, 14,40]
	Expected value	[43.62, 44.43]	[12.98, 13.52]	[6.95, 6.96]	[14.40, 14,42]
Water-saving subsidy (10^6 RMB)	Special dry year	[419.13, 445.33]	[27.83, 43.14]	[0.99, 0.99]	[2.29, 9.04]
	Special wet year	[125.67, 135.89]	[1.45, 11.50]	[0.99, 1.16]	[2.14, 2.14]
	Expected value	[165.40, 171.30]	[6.66, 13.86]	[0.99, 1.05]	[2.16, 3.00]

45

878 **List of Figure Captions**

879 Figure 1 The geographical location and division of Dagu River watershed (the explanation of

880   the river reach is seen in Appendix D)

881 Figure 2 Framework of the SB-WSTM

882 Figure 3 The quantity of initial water rights in five hydrological year types under 25 water-

883   saving scenarios ($k = 1, 2, 3, 4, 5$ represent special dry year, dry year, normal year,

884   wet year and special wet year, respectively)

885 Figure 4 Water rights trading in five hydrological year types under water-saving scenarios

886   (PL: planting industry; LI: livestock; FI: fishery; EN: enterprise)

887 Figure 5 Actual surface and underground water consumption and initial water rights of

888   different industries in special dry year

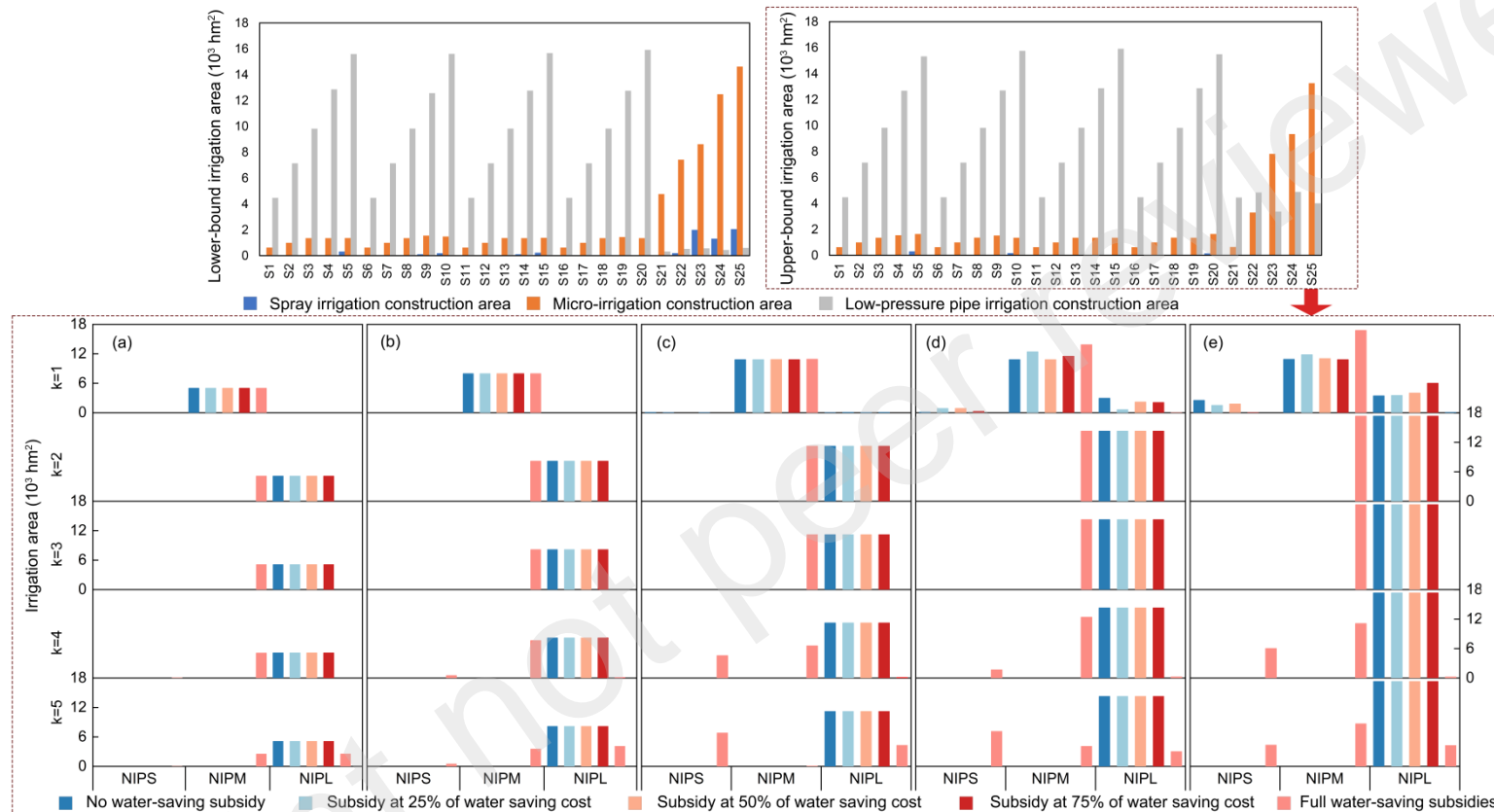889 Figure 6 Surface and underground water consumption of multiple industries in five

890   hydrological year types under water-saving scenarios

891 Figure 7 The construction area of different water-saving facilities for planting industry in five

892   hydrological year types under water-saving scenarios (NIPS: sprinkler construction

893   area; NIPM: micro-irrigation construction area; NIPL: low-pressure pipe

894   construction area; (a): 60% of the efficient water-saving irrigation area; (b): 62.5% of

895   the efficient water-saving irrigation area; (c): 65% of the efficient water-saving

896   irrigation area; (d): 67.5% of the efficient water-saving irrigation area; (e): 70% of

897   the efficient water-saving irrigation area)

898 Figure 8 System benefits and total actual water consumption under five hydrological year

899   types under water-saving scenarios
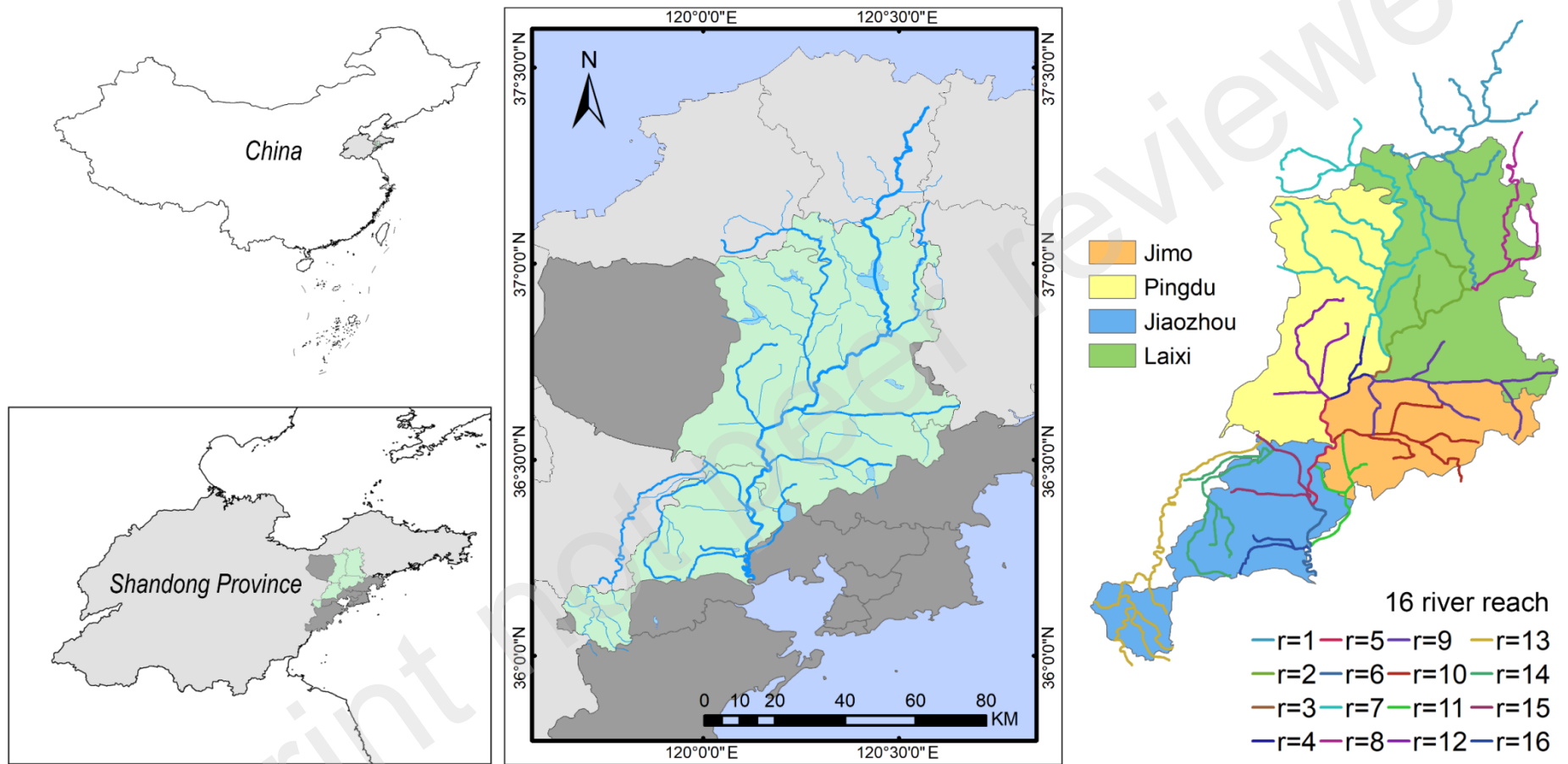
46

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47
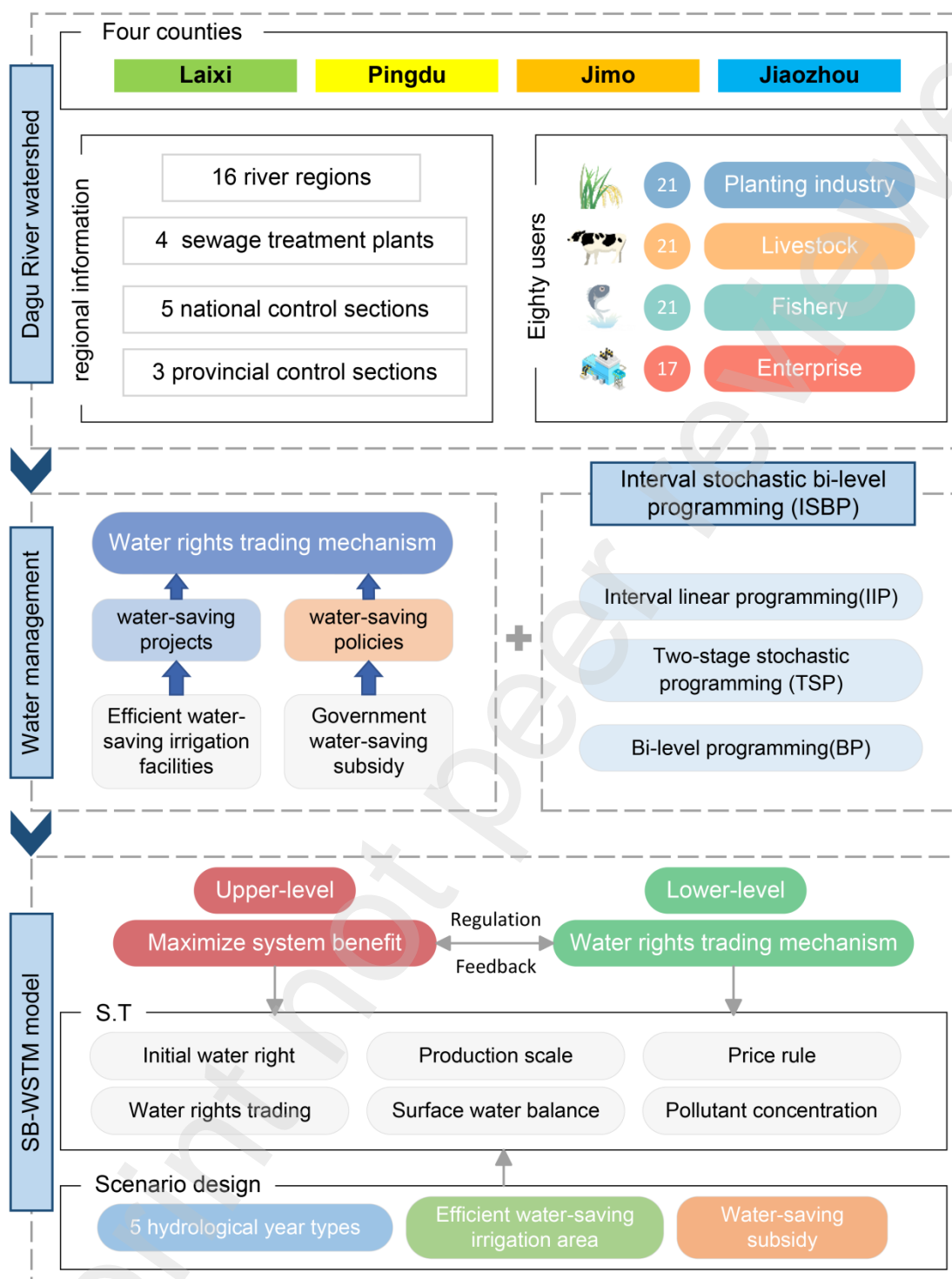
902 Figure 2 Framework of the SB-WSTM
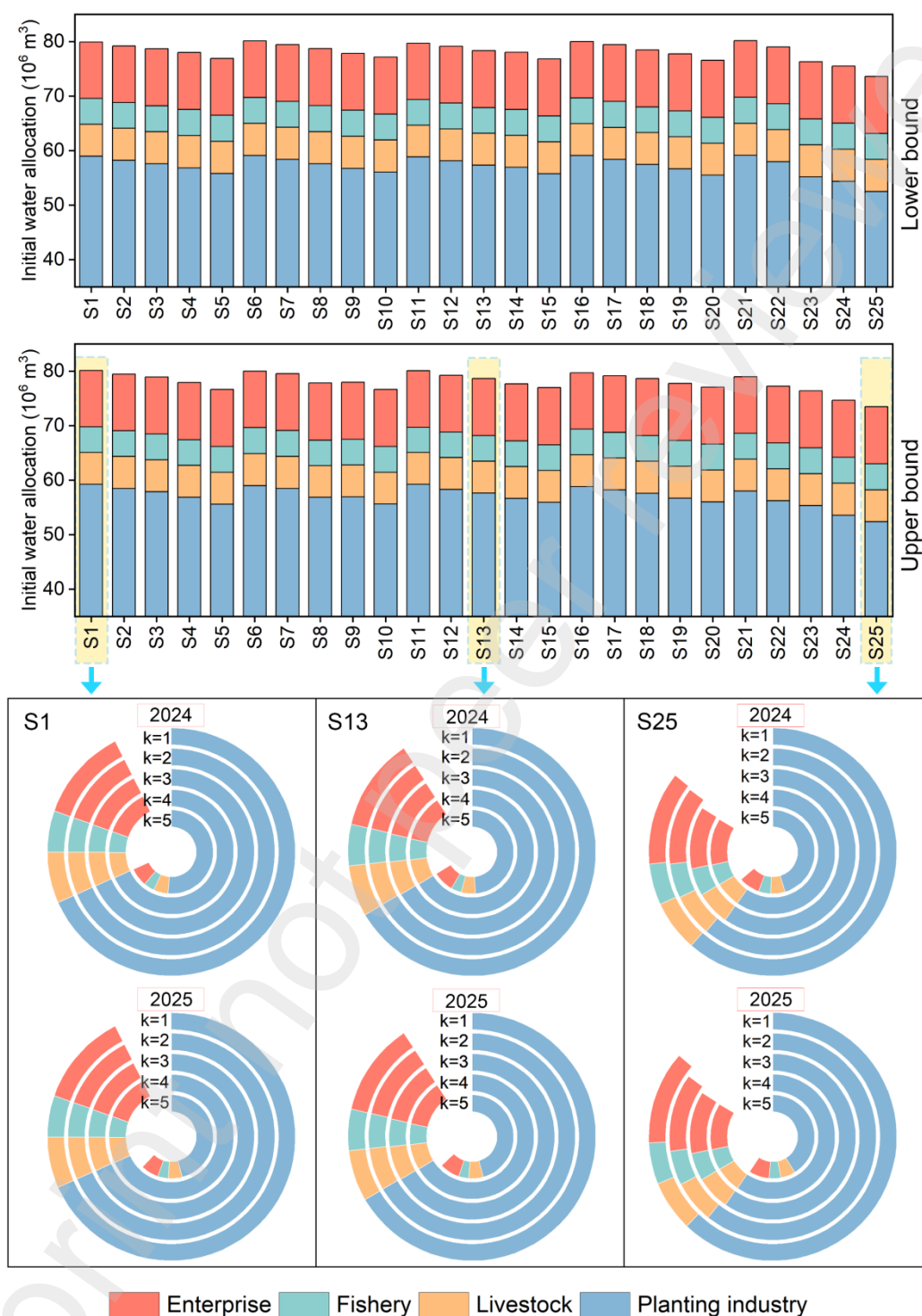
903

Figure 3 The quantity of initial water rights in five hydrological year types under 25 water-

saving scenarios (k = 1, 2, 3, 4, 5 represent special dry year, dry year, normal year, wet year

and special wet year, respectively)

49
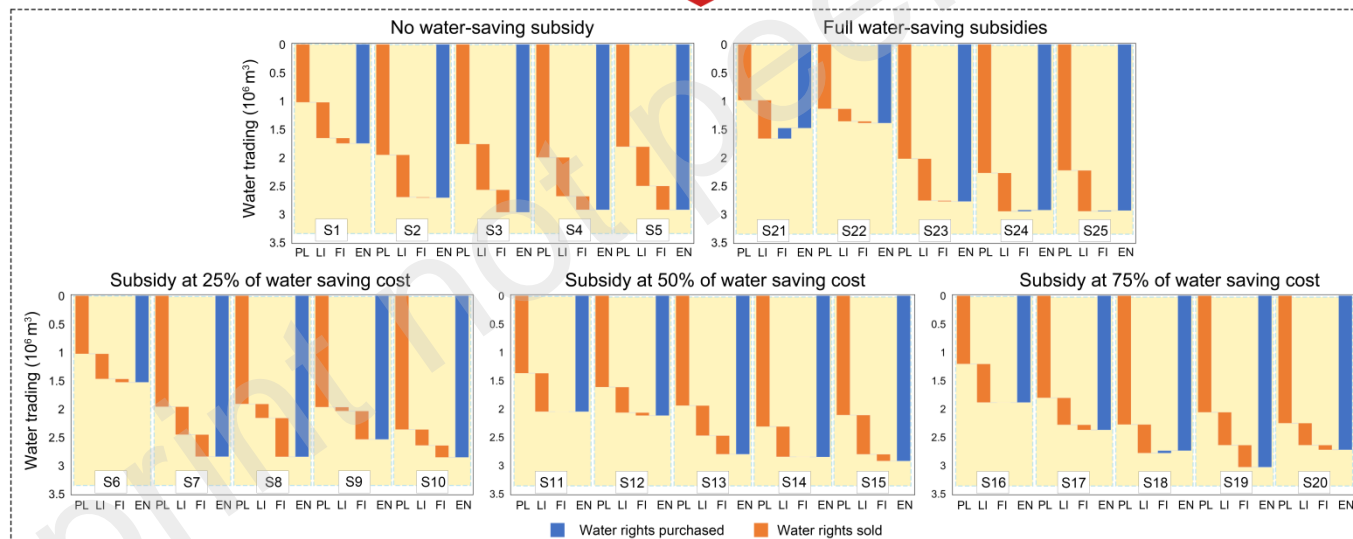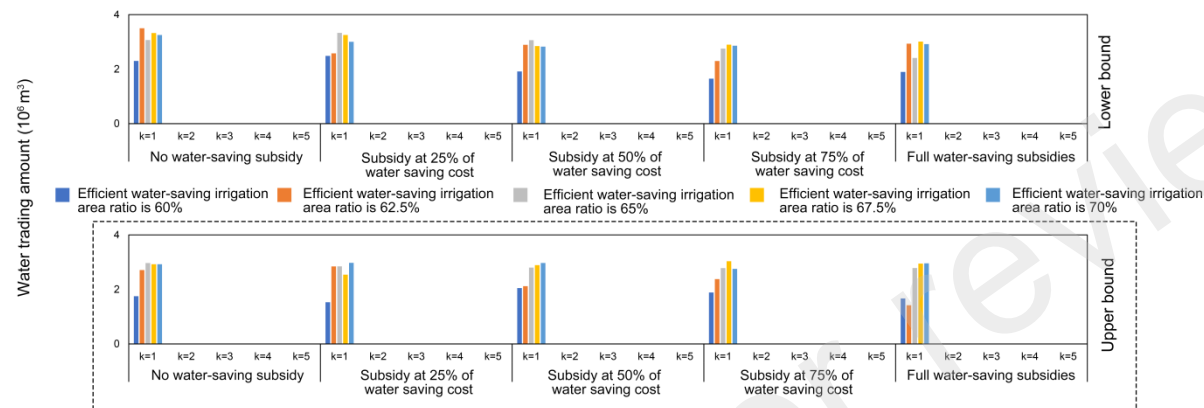
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908 enterprise)

50
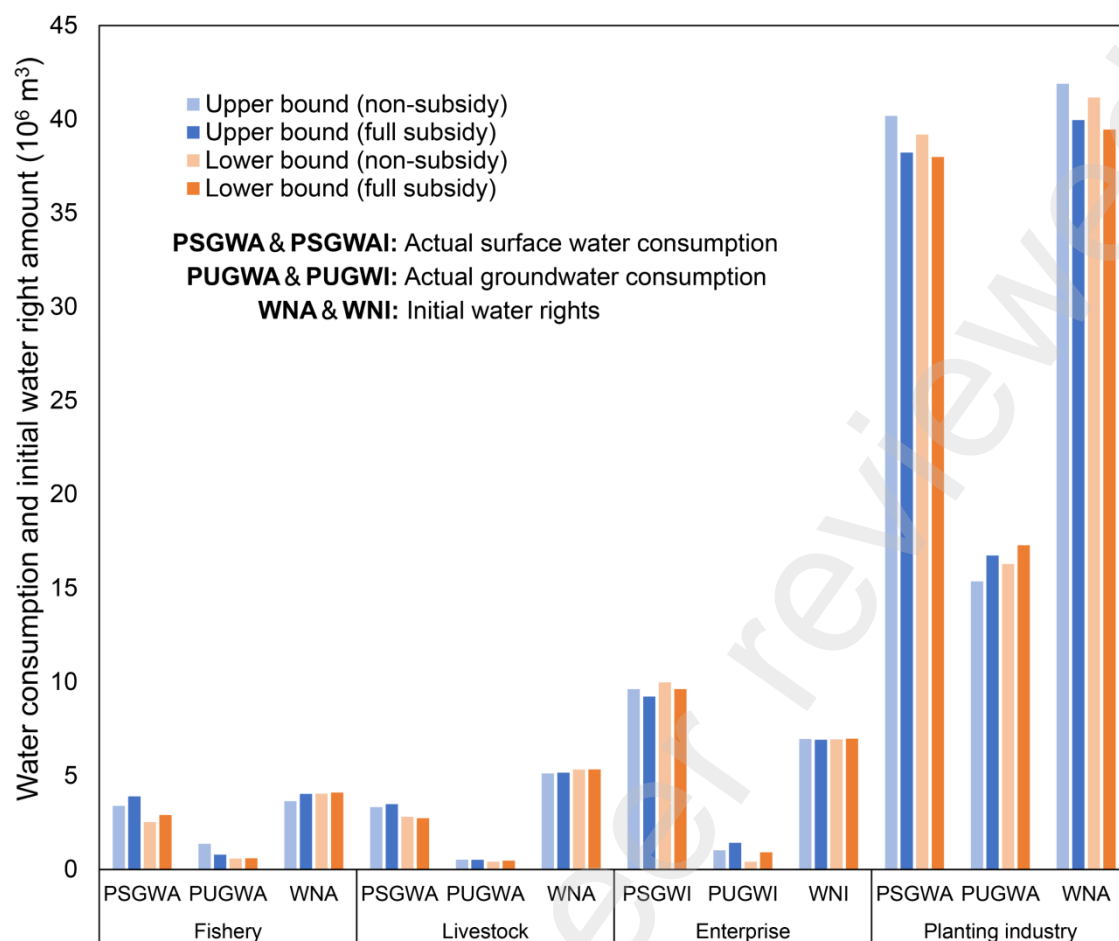
909 Figure 5 Actual surface and underground water consumption and initial water rights of

910 different industries in special dry year
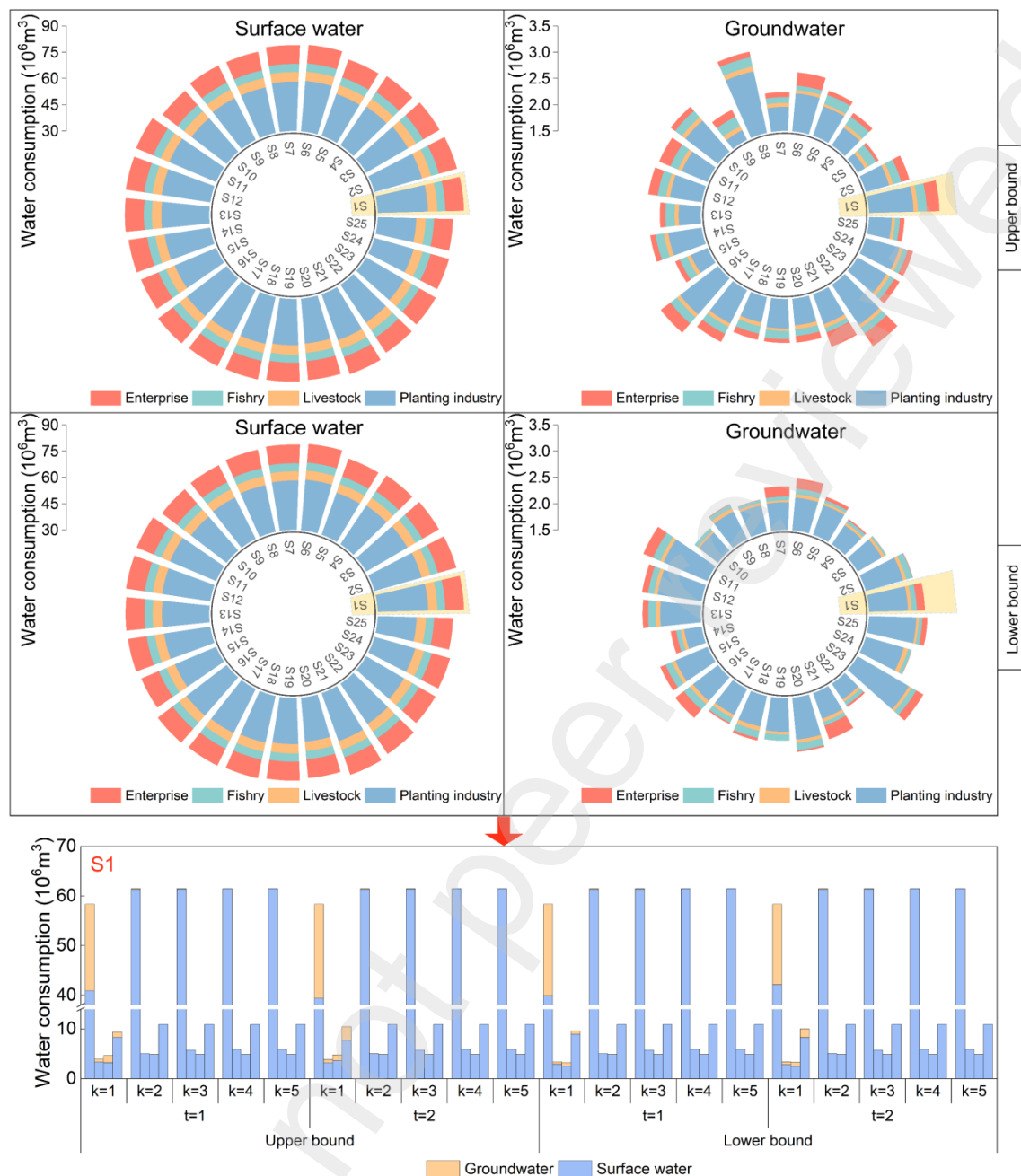
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912   hydrological year types under water-saving scenarios

913 Figure 7 The construction area of different water-saving facility for planting industry in five hydrological year types under water-saving

914 scenarios (NIPS: sprinkler construction area; NIPM: micro-irrigation construction area; NIPL: low-pressure pipe construction area; (a): 60% of

915 the efficient water-saving irrigation area; (b): 62.5% of the efficient water-saving irrigation area; (c): 65% of the efficient water-saving irrigation

916 area; (d): 67.5% of the efficient water-saving irrigation area; (e): 70% of the efficient water-saving irrigation area)
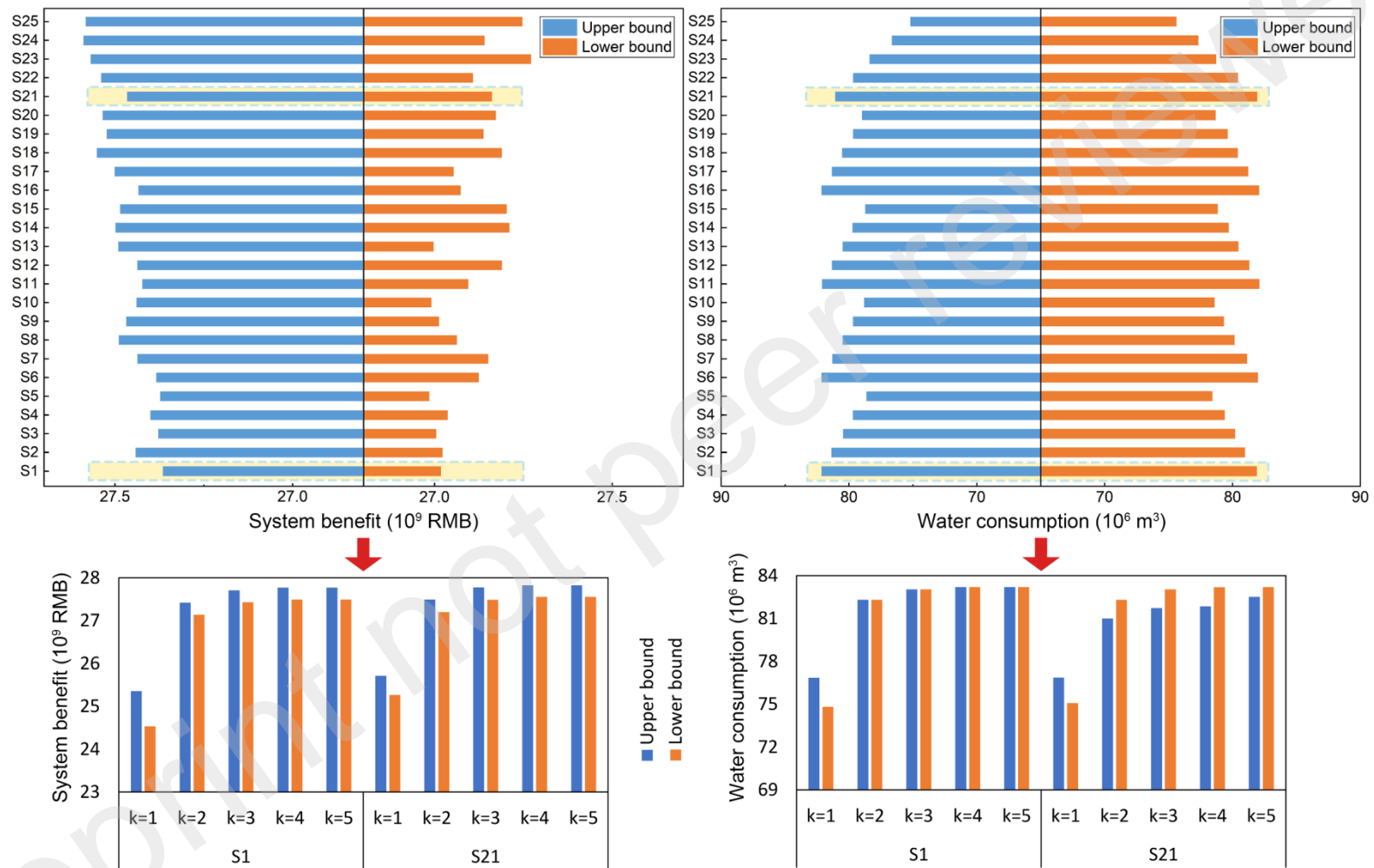
54

917

Figure 8 System benefits and total actual water consumption under five hydrological year types under water-saving scenarios

55

919 **Appendix A. Reconstruction of natural runoff with SWAT**

920

921 *A.1 Methodology*

922

923 SWAT is a semi-distributed physical model capable of predicting the impact of water

924 management, agriculture chemical yield, and sediment in the large watershed on different

925 timescales (Neitsch et al., 2009; Aloui et al., 2023). The model predicts surface runoff based

926 on a water balance equation (Zhang et al., 2016):

$$SW = SW_0 + \sum_{i=1}^{t}(R_i - Q_{surf,i} - E_{a,i} - w_{seep,i} - Q_{gw,i}) \tag{A.1}$$

928

929 where SW and SW_0 are the respective final and initial soil water contents at time t,

930 respectively; R_i is the precipitation on the i day, $Q_{surf,i}$ is the surface runoff on the i day (mm

931 H_2O), $E_{a,i}$ is the evaporation on the i day, $w_{seep,i}$ is the infiltration from the soil layer to the

932 vadose zone on the i day, $Q_{gw,i}$ is the return flow on the i day.

933

934 Due to influence of human activities, the measured runoff cannot fully reflect the law of river

935 runoff. It is necessary to carry out runoff reduction investigation and analysis calculation, and

936 restore the measured annual runoff series to the natural annual runoff series. In this study, the

937 runoff component investigation method is used to reconstruct the natural runoff of Dagu River

938 watershed (Loboda et al., 2005). The water balance equation based on the annual runoff

939 reduction calculation is:

940 $$W_{nr} = W_m + W_c + W_i + W_{flf} + W_{td} \pm W_{rf} \pm W_{re} \pm W_d \pm W_{fd} \pm W_o \tag{A.2}$$

941

56

942   where W_{nr} is the natural runoff (10^6 m^3/a); W_m is the measured runoff; W_c is the net water

943   consumption of surface water for agricultural irrigation (10^6 m^3/a); W_i represents the net water

944   consumption of industrial surface water (10^6 m^3/a); W_{flf} is the net water consumption of

945   surface water in forest and fishery (10^6 m^3/a); W_{td} is the net water consumption of urban

946   domestic water (10^6 m^3/a); W_{rf} is the reservoir storage variable (10^6 m^3/a); W_{re} denotes the

947   difference between reservoir water surface evaporation and land surface evapotranspiration

948   response (10^6 m^3/a); W_d is the quantity of water diversion across the watershed (10^6 m^3/a); W_{fd}

949   is the quantity of flood diversion in the river (10^6 m^3/a); W_o denotes other runoff (10^6 m^3/a).

950

951   *A.2 Results*

952

953   Figure A1 displays the streamflow simulation results of Dagu River watershed based on the

954   SWAT model. The Nash-Sutcliffe Efficiency (NSE) value is 0.58, indicating satisfactory

955   simulation of surface runoff. The natural runoff of Dagu River watershed is then

956   reconstructed utilizing water balance equation based on the process of water consumption,

957   drainage, water diversion, and predicted streamflow. Statistical analysis of multi-year natural

958   runoff is conducted to provide random inputs for model. Pearson type III distribution is used

959   to fit the probability density function. Figure A2 and Table A1 provide the hydrological

960   frequency and probability of natural runoff, which are used to provide SCWM-WT with

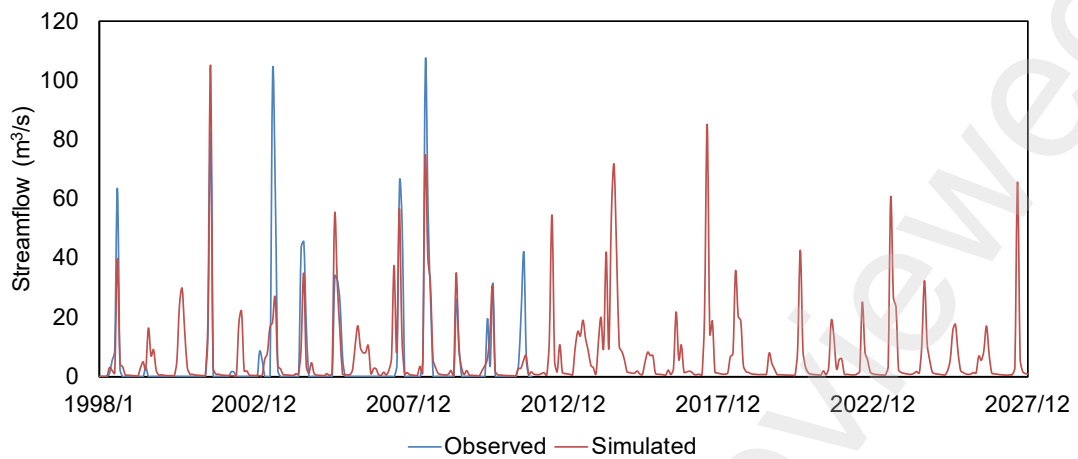961   surface water resources amount which is of randomness.

962

963 Figure A1 The observed and simulated surface runoff in Nancun hydrological station
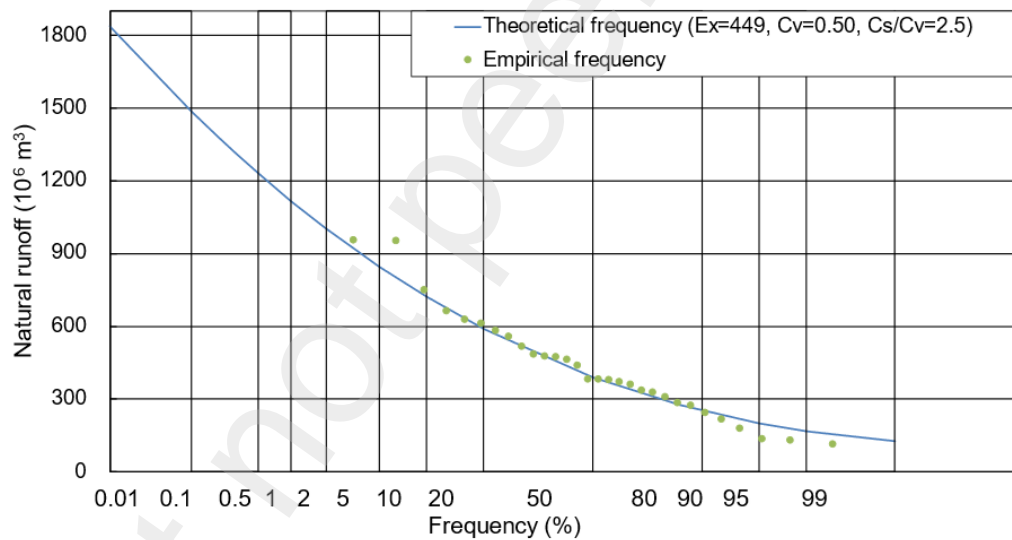
964

965

966 Figure A2 Natural runoff frequency curve diagram

967

968 Table A1 Natural runoff and its distribution probability under different hydrological year type

Hydrological year type	Special dry	Dry	Normal	Wet	Special wet
Natural runoff (10^6 m^3)	173.44	273.83	390.85	551.91	852.57
Distribution probability (%)	0.125	0.25	0.25	0.25	0.125

969

58

970

971 **Appendix B. Initial water rights model**

972

973 Objective function:

974 $$Max\, f = \sum_{t=1}^{T}\sum_{k=1}^{K}\left(p_k \times HD_{tk}^{\pm} \right) \qquad (B.1)$$

975

976 The objective function is to maximize harmonious degree.

977 Subject to:

978 (1) Harmonious degree.

979 $$HD_{tk}^{\pm} \leq HDP_{tk}^{\pm} \qquad (B.2)$$

980 $$HD_{tk}^{\pm} \leq HDW_{tk}^{\pm} \qquad (B.3)$$

981 $$HD_{tk}^{\pm} \leq HDE_{tk}^{\pm} \qquad (B.4)$$

982

983 Constraints (B.2) to (B.4) reflect that the harmonious degree should not harmonious degree

984 about current situation; the harmonious degree should not exceed harmonious degree about

985 current situation.

986

987 (2) The principle of fairness.

988 $$\frac{\left\{ \begin{array}{l} \sum_{z=1}^{Z}\left[ZSD_{dz} \times \sum_{a=1}^{A}\left(WNA_{tkaz}^{\pm} + WSA_{tkaz}^{\pm} \right) \right] \\ + \sum_{z=1}^{Z}\left[ZSD_{dz} \times \sum_{i=1}^{I} ISZ_{zi} \times \left(WNI_{tki}^{\pm} + WSI_{ti}^{\pm} \right) \right] \end{array} \right\} \div POP_{td}}{PCWT_{td}} \geq HDP_{tk}^{\pm} \qquad (B.5)$$

59

989 $$PCWT_{td} = \left[\sum_{z=1}^{Z} \sum_{a=1}^{A} QWAma_{taz} + \sum_{i=1}^{I} QWIma_{ti} \right] \div \sum_{d=1}^{D} POP_{td} \qquad \text{(B.6)}$$

990

991 Constraint (B.5) reflects that the ratio of the sum of the initial water rights allocated to each

992 user before water saving and the water saving amount of water saving users to the per capita

993 water consumption. Constraint (B.6) reflects that the ratio of current total water consumption

994 to population.

995

996 (3) The principle of status quo.

997 $$\frac{WNA_{tkaz}^{\pm} + WSA_{tkaz}^{\pm}}{QWAma_{taz}} \geq HDW_{tk}^{\pm} \qquad \text{(B.7)}$$

998 $$\frac{WNI_{tki}^{\pm} + WSI_{ti}^{\pm}}{QWIma_{ti}} \geq HDW_{tk}^{\pm} \qquad \text{(B.8)}$$

999

1000 Constraints (B.7) and (B.8) reflect that the proportion of the sum of the initial water rights

1001 allocated to each user before water saving and the sum of the water saving amount of water

1002 saving users to the maximum water consumption that can be achieved by the current situation.

1003

1004 (4) The principle of maximum benefit.

60

$$\left\{ \begin{array}{l} \displaystyle\sum_{t=1}^{T}\sum_{z=1}^{Z}\sum_{a=1}^{A}\left(WQA_{taz}\times BA_{az}^{\pm}\right)-\sum_{t=1}^{T}\sum_{k=1}^{K}\sum_{z=1}^{Z}\sum_{a=1}^{A}\left(p_{k}\times WLA_{tkaz}^{\pm}\times DA_{az}^{\pm}\right) \\[4mm] \displaystyle-\sum_{t=1}^{T}\sum_{k=1}^{K}\sum_{z=1}^{Z}\sum_{a=1}^{1}\left[p_{k}\times\left(SFRA_{tkaz}^{\pm}+SFBA_{tkaz}\right)\right] \\[4mm] \displaystyle+\sum_{t=1}^{T}\sum_{k=1}^{K}\sum_{z=1}^{Z}\sum_{a=1}^{1}\left(p_{k}\times WSAS_{tkaz}^{\pm}\right) \\[4mm] \displaystyle-\sum_{t=1}^{T}\sum_{k=1}^{K}\sum_{a=1}^{A}\sum_{z=1}^{Z}\left(FAWA_{taz}\times PSGWA_{tkaz}^{\pm}+FAUA_{taz}\times PUGWA_{tkaz}^{\pm}\right) \\[4mm] \displaystyle+\sum_{t=1}^{T}\sum_{i=1}^{I}\left(WQI_{ti}\times BI_{i}^{\pm}\right)-\sum_{t=1}^{T}\sum_{k=1}^{K}\sum_{i=1}^{I}\left(p_{k}\times WLI_{tki}^{\pm}\times DI_{zi}^{\pm}\right) \\[4mm] \displaystyle-\sum_{t=1}^{T}\sum_{i=1}^{I}SFCI_{ti}+\sum_{t=1}^{T}\sum_{i=1}^{I}WSIS_{ti} \\[4mm] \displaystyle-\sum_{t=1}^{T}\sum_{k=1}^{K}\sum_{z=1}^{Z}\left(FAWI_{ti}\times PSGWI_{tki}^{\pm}+FAUI_{ti}\times PUGWI_{tki}^{\pm}\right) \\[4mm] \displaystyle-\sum_{t=1}^{T}\sum_{k=1}^{K}\sum_{s=1}^{S}\left(p_{k}\times SDW_{tks}^{\pm}\times SC_{ts}^{\pm}\right) \end{array} \right\} \Big/ FMAX_{tk}^{\pm} \ge HDE_{tk}^{\pm} \quad \text{(B.9)}$$

Constraint (B.9) reflects that ratio of system benefit of water saving participation to maximum

system benefit under different planning periods and hydrological year types (the calculation

of maximum system benefit is shown in constraint C.2 in Appendix C).

(5) Water consumption constraints:

$$WPA_{tkaz}^{\pm}=WQA_{taz}-WLA_{tkaz}^{\pm}-WSA_{tkaz}^{\pm} \qquad \text{(B.10)}$$

$$WPI_{tki}^{\pm}=WQI_{ti}-WLI_{tki}^{\pm}-WSI_{ti} \qquad \text{(B.11)}$$

$$WPA_{tkaz}^{\pm}=PSGWA_{tkaz}^{\pm}+PUGWA_{tkaz}^{\pm} \qquad \text{(B.12)}$$

$$WPI_{tki}^{\pm}=PSGWI_{tki}^{\pm}+PUGWI_{tki}^{\pm} \qquad \text{(B.13)}$$

$$PSGWA_{tkaz}^{\pm}\le WNA_{tkaz}^{\pm} \qquad \text{(B.14)}$$

$$PSGWI_{tki}^{\pm}\le WNI_{tki}^{\pm} \qquad \text{(B.15)}$$

61

1018 $$PUGWA_{tkaz}^{\pm} \leq UGWA_{tkaz}$$ (B.16)

1019 $$PUGWI_{tki}^{\pm} \leq UGWI_{tki}$$ (B.17)

1020 $$PSA_{tkaz}^{\pm} = \left(WPA_{tkaz}^{\pm} + WSA_{tkaz}^{\pm}\right) \times LWPA_{az}^{\pm}$$ (B.18)

1021 $$PSI_{tki}^{\pm} = \left(WPI_{tki}^{\pm} + WSI_{ti}\right) \times LWPI_{i}^{\pm}$$ (B.19)

1022 $$QWAmi_{taz} \leq WPA_{tkaz}^{\pm} + WSA_{tkaz}^{\pm} \leq QWAma_{taz}$$ (B.20)

1023 $$QWImi_{ti} \leq WPI_{tki}^{\pm} + WSI_{ti} \leq WQIma_{ti}$$ (B.21)

1024

1025 (6) Initial water rights constraint:

1026 $$WNA_{tkaz}^{\pm} + PUGWA_{tkaz}^{\pm} + WSA_{tkaz}^{\pm} \leq QWAma_{taz}$$ (B.22)

1027 $$WNI_{tki}^{\pm} + PUGWI_{tki}^{\pm} + WSI_{ti} \leq QWIma_{tzi}$$ (B.23)

1028

1029 (7) Price rule constraint：

1030 $$WQA_{tkaz} \times BA_{az}^{\pm} - WLA_{tkaz}^{\pm} \times DA_{az}^{\pm} - SFRA_{tkaz}^{\pm} - SFBA_{taz} + WSAS_{tkaz}^{\pm}$$
$$-FAWA_{taz} \times PSGWA_{tkaz}^{\pm} - FAUA_{taz} \times PUGWA_{tkaz}^{\pm} = NTGA_{tkaz}^{\pm}$$ (B.24)

1031 $$WQI_{tki} \times BI_{i}^{\pm} - WLI_{tki}^{\pm} \times DI_{i}^{\pm} - SFCI_{ti} + WSIS_{ti}$$
$$-FAWI_{ti} \times PSGWI_{tki}^{\pm} - FAUI_{ti} \times PUGWI_{tki}^{\pm} = NTGI_{tki}^{\pm}$$ (B.25)

1032

1033 (8) Wastewater discharge and treatment constraints:

1034 $$EPA_{tkaz}^{\pm} = UPEA_{az} \times \left[\left(WPA_{tkaz}^{\pm} + WSA_{tkaz}^{\pm}\right) \times IWPA_{az}\right]$$ (B.26)

1035 $$EPI_{tki}^{\pm} = UPEI_{i} \times \left[\left(WPI_{tki}^{\pm} + WSI_{ti}\right) \times IWPI_{i}\right]$$ (B.27)

1036 $$\sum_{i=16}^{16} DISW_{tki}^{\pm} = \sum_{i=16}^{16} \left[\left(WPI_{tki}^{\pm} + WSI_{ti}\right) \times IWDR_{i}\right]$$ (B.28)

62

$$SDW_{tks}^{\pm} = \sum_{i=1}^{15} ISS_{si} \times \left[\left(WPI_{tki}^{\pm} + WSI_{ti} \right) \times IWDR_i \right]$$

1037
$$+ \sum_{i=17}^{17} ISS_{si} \times \left[\left(WPI_{tki}^{\pm} + WSI_{ti} \right) \times IWDR_i \right] \tag{B.29}$$

$$+ LSW_{ts}^{\pm} + OSW_{ts}^{\pm} \leq MSDW_s^{\pm}$$

1038

1039   (9) Surface water balance constraint:

1040
$$\sum_{z=1}^{Z} \left\{ ZSW_{wz} \times \left[\sum_{a=1}^{A} WNA_{tkaz}^{\pm} + \sum_{i=1}^{I} \left(ISZ_{zi} \times WNI_{tki}^{\pm} \right) \right] \right\} \leq SAWR_{tkw}^{\pm} \tag{B.30}$$

1041
$$SAWR_{tkw}^{\pm} = RIBF_{tkw}^{\pm} + \sum_{z=1}^{Z} \left[ZSW_{wz} \times \begin{pmatrix} RNF_{tkz} + DIW_{tz} + ORDI_{tkz} \\ -ORDO_{tkz} - OZW_{tz} - REW_{tz} \end{pmatrix} \right] \tag{B.31}$$

1042
$$ROBF_{tkv}^{\pm} = \sum_{w=1}^{W} \left(OCR_{wv} \times ROBF_{tkw}^{\pm} \right) \tag{B.32}$$

1043
$$RIBF_{tkw}^{\pm} = \sum_{v=1}^{V} \left(IOCR_{wv} \times ROBF_{tkv}^{\pm} \right) \tag{B.33}$$

1044
$$ROBF_{tkw}^{\pm} = RIBF_{tkw}^{\pm} + \sum_{z=1}^{Z} \left\{ ZSW_{wz} \times \begin{bmatrix} RNF_{tkz} + DIW_{tz} + ORDI_{tkz} - ORDO_{tkz} \\ -OZW_{tz} - REW_{tz} \\ -\sum_{a=1}^{A} TWNA_{tkaz}^{\pm} - \sum_{i=1}^{I} \left(ISZ_{zi} \times TWNI_{tki}^{\pm} \right) \\ +DWWP_z \times \begin{bmatrix} \sum_{s=1}^{S} \left(SSZ_{zs} \times SDW_{tks}^{\pm} \right) \\ +\sum_{i=16}^{16} \left(ISZ_{zi} \times DISW_{tki}^{\pm} \right) \end{bmatrix} \end{bmatrix} \right\} \tag{B.34}$$

1045

1046   (10) Pollutant content level constraints of river monitoring sections:

63

$$1047 \quad CSM_m \times MBF_{tkm}^{\pm} \geq \sum_{z=1}^{Z} ZSM_{mz} \times \left\{ \begin{array}{l} \sum_{a=1}^{A} \left(DPMA_{maz} \times EPA_{tkaz}^{\pm} \right) \\ + \sum_{s=3}^{S} \left[\begin{array}{l} SSZ_{zs} \times DPMS_{ms} \times \left(1 - UPES_s \right) \\ \times \left(\begin{array}{l} LSW_{ts} \times LSP_{ts} \\ + OSW_{ts} \times OSP_{ts} \end{array} \right) \end{array} \right] \\ + \sum_{s=4}^{S} \left[\begin{array}{l} SSZ_{zs} \times DPMS_{ms} \\ \times \left(1 - UPES_s \right) \times \sum_{i=1}^{6} EPI_{tki}^{\pm} \end{array} \right] \end{array} \right\} \quad (B.35)$$

$$1048 \quad MBF_{tkm}^{\pm} = \sum_{w=1}^{W} \left(WSM_{mw} \times ROBF_{tkw}^{\pm} \right) + NRM_{tkm} \quad (B.36)$$

1049

1050   (11) Water-saving rule constraints：

$$1051 \quad \sum_{a=1}^{1} SFBA_{tkaz} = \sum_{a=1}^{1} \left(NIPS_{tkaz} SIFC_{az} + NIPM_{tkaz} MIFC_{az} + NIPL_{tkaz} LIFC_{az} \right) \quad (B.37)$$

$$1052 \quad \sum_{a=1}^{1} SFRA_{tkaz}^{\pm} = \sum_{a=1}^{1} \left(SIA_{tkaz}^{\pm} SIRC_{az} + MIA_{tkaz}^{\pm} MIRC_{az} + LIA_{tkaz}^{\pm} LIRC_{az} \right) \quad (B.38)$$

$$1053 \quad \sum_{a=1}^{1} WPA_{tkaz}^{\pm} = \sum_{a=1}^{1} \left(\begin{array}{l} SIA_{tkaz}^{\pm} SICW_{az} + MIA_{tkaz}^{\pm} MICW_{az} \\ + LIA_{tkaz}^{\pm} LICW_{az} + NSA_{tkaz}^{\pm} NSCW_{az} \end{array} \right) \quad (B.39)$$

$$1054 \quad \sum_{a=1}^{1} EFIA_{tkaz}^{\pm} = \sum_{a=1}^{1} \left(SIA_{tkaz}^{\pm} + MIA_{tkaz}^{\pm} + LIA_{tkaz}^{\pm} + NSA_{tkaz}^{\pm} \right) \quad (B.40)$$

$$1055 \quad \sum_{a=1}^{1} NSA_{tkaz}^{\pm} = \sum_{a=1}^{1} \left(PNSA_{tkaz}^{\pm} - NIPS_{tkaz} - NIPM_{tkaz} - NIPL_{tkaz} \right) \quad (B.41)$$

$$1056 \quad \sum_{a=1}^{1} SIA_{tkaz}^{\pm} = \sum_{a=1}^{1} \left(NIPS_{tkaz} + PIPS_{tkaz}^{\pm} \right) \quad (B.42)$$

$$1057 \quad \sum_{a=1}^{1} MIA_{tkaz}^{\pm} = \sum_{a=1}^{1} \left(NIPM_{tkaz} + PIPM_{tkaz}^{\pm} \right) \quad (B.43)$$

64

$$1058 \quad \sum_{a=1}^{1} LIA_{tkaz}^{\pm} = \sum_{a=1}^{1} \left(NIPL_{tkaz} + PIPL_{tkaz}^{\pm} \right) \tag{B.44}$$

$$1059 \quad \sum_{a=1}^{1} SIPW_{tkaz}^{\pm} = \sum_{a=1}^{1} \left(SIA_{tkaz}^{\pm} \times SIRW_{az} \right) \tag{B.45}$$

$$1060 \quad \sum_{a=1}^{1} MIPW_{tkaz}^{\pm} = \sum_{a=1}^{1} \left(MIA_{tkaz}^{\pm} \times MIRW_{az} \right) \tag{B.46}$$

$$1061 \quad \sum_{a=1}^{1} LIPW_{tkaz}^{\pm} = \sum_{a=1}^{1} \left(LIA_{tkaz}^{\pm} \times LIRW_{az} \right) \tag{B.47}$$

$$1062 \quad \sum_{a=1}^{1} WSA_{tkaz}^{\pm} = \sum_{a=1}^{1} \left(SIPW_{tkaz}^{\pm} + MIPW_{tkaz}^{\pm} + LIPW_{tkaz}^{\pm} \right) \tag{B.48}$$

$$1063 \quad \sum_{a=1}^{1} \left(\sigma_a \times EFIA_{tkaz}^{\pm} \right) = \sum_{a=1}^{1} \left(SIA_{tkaz}^{\pm} + MIA_{tkaz}^{\pm} + LIA_{tkaz}^{\pm} \right) \tag{B.49}$$

$$1064 \quad WSI_{ti} = TIOV \times \left(PTVW_i - TIVW_i \right) + CICW_i \times \frac{\eta_p - \eta_c}{1 - \eta_p} \tag{B.50}$$

$$1065 \quad SFCI_{ti} = USFC_i \times WSI_{ti} \tag{B.51}$$

$$1066 \quad \sum_{a=1}^{1} WSAS_{tkaz}^{\pm} = \sum_{a=1}^{1} \left[\varphi_a \times \left(SFRA_{tkaz}^{\pm} + SFBA_{tkaz} \right) \right] \tag{B.52}$$

$$1067 \quad WSIS_{ti} = \varphi_i \times SFCI_{ti} \tag{B.53}$$

1068

1069 Appendix C. Maximum benefit for initial water rights:

1070

1071 Objective function:

$$Maxf_U^\pm = \sum_{t=1}^{T}\sum_{z=1}^{Z}\sum_{a=1}^{A}\left(WQA_{taz}\times BA_{az}^\pm\right) - \sum_{t=1}^{T}\sum_{k=1}^{K}\sum_{z=1}^{Z}\sum_{a=1}^{A}\left(p_k\times WLA_{tkaz}^\pm\times DA_{az}^\pm\right)$$

$$-\sum_{t=1}^{T}\sum_{k=1}^{K}\sum_{z=1}^{Z}\sum_{a=1}^{1}\left[p_k\times\left(SFRA_{tkaz}^\pm + SFBA_{tkaz}\right)\right]$$

$$-\sum_{t=1}^{T}\sum_{k=1}^{K}\sum_{a=1}^{A}\sum_{z=1}^{Z}\left(FAWA_{taz}\times PSGWA_{tkaz}^\pm + FAUA_{taz}\times PUGWA_{tkaz}^\pm\right)$$

$$+\sum_{t=1}^{T}\sum_{i=1}^{I}\left(WQI_{ti}\times BI_{i}^\pm\right) - \sum_{t=1}^{T}\sum_{k=1}^{K}\sum_{i=1}^{I}\left(p_k\times WLI_{tki}^\pm\times DI_{zi}^\pm\right) \qquad\qquad \text{(C.1)}$$

$$-\sum_{t=1}^{T}\sum_{i=1}^{I}SFCI_{ti} + \sum_{t=1}^{T}\sum_{i=1}^{I}WSIS_{ti}$$

$$-\sum_{t=1}^{T}\sum_{k=1}^{K}\sum_{z=1}^{Z}\left(FAWI_{ti}\times PSGWI_{tki}^\pm + FAUI_{ti}\times PUGWI_{tki}^\pm\right)$$

$$-\sum_{t=1}^{T}\sum_{k=1}^{K}\sum_{s=1}^{S}\left(p_k\times SDW_{tks}^\pm\times SC_{ts}^\pm\right)$$

1073

1074   Subject to:

1075   (1) Constraints for obtain the maximum value of system benefit under different planning

1076   periods and hydrological year type.

$$FMAX_{tk}^\pm = \sum_{z=1}^{Z}\sum_{a=1}^{A}\left(WQA_{taz}\times BA_{az}^\pm\right) - \sum_{z=1}^{Z}\sum_{a=1}^{A}\left(WLA_{tkaz}^\pm\times DA_{az}^\pm\right)$$

$$-\sum_{z=1}^{Z}\sum_{a=1}^{1}\left(SFRA_{tkaz}^\pm + SFBA_{tkaz}\right) + \sum_{z=1}^{Z}\sum_{a=1}^{1}WSAS_{tkaz}^\pm$$

$$-\sum_{a=1}^{A}\sum_{z=1}^{Z}\left(FAWA_{taz}\times PSGWA_{tkaz}^\pm + FAUA_{taz}\times PUGWA_{tkaz}^\pm\right)$$

$$+\sum_{i=1}^{I}\left(WQI_{ti}\times BI_{i}^\pm\right) - \sum_{i=1}^{I}\left(WLI_{tki}^\pm\times DI_{zi}^\pm\right) \qquad\qquad \text{(C.2)}$$

$$-\sum_{i=1}^{I}SFCI_{ti} + \sum_{i=1}^{I}WSIS_{ti} - \sum_{z=1}^{Z}\left(FAWI_{ti}\times PSGWI_{tki}^\pm + FAUI_{ti}\times PUGWI_{tki}^\pm\right)$$

$$-\sum_{s=1}^{S}\left(SDW_{tks}^\pm\times SC_{ts}^\pm\right)$$

1078

1079   (3) Water consumption constraints:

66

1080 $$WPA_{tkaz}^{\pm} = WQA_{taz} - WLA_{tkaz}^{\pm} - WSA_{tkaz}^{\pm}$$ (C.3)

1081 $$WPI_{tki}^{\pm} = WQI_{ti} - WLI_{tki}^{\pm} - WSI_{ti}$$ (C.4)

1082 $$WPA_{tkaz}^{\pm} = PSGWA_{tkaz}^{\pm} + PUGWA_{tkaz}^{\pm}$$ (C.5)

1083 $$WPI_{tki}^{\pm} = PSGWI_{tki}^{\pm} + PUGWI_{tki}^{\pm}$$ (C.6)

1084 $$PSGWA_{tkaz}^{\pm} \leq WNA_{tkaz}^{\pm}$$ (C.7)

1085 $$PSGWI_{tki}^{\pm} \leq WNI_{tki}^{\pm}$$ (C.8)

1086 $$PUGWA_{tkaz}^{\pm} \leq UGWA_{tkaz}$$ (C.9)

1087 $$PUGWI_{tki}^{\pm} \leq UGWI_{tki}$$ (C.10)

1088 $$PSA_{tkaz}^{\pm} = \left(WPA_{tkaz}^{\pm} + WSA_{tkaz}^{\pm} \right) \times LWPA_{az}^{\pm}$$ (C.11)

1089 $$PSI_{tki}^{\pm} = \left(WPI_{tki}^{\pm} + WSI_{ti} \right) \times LWPI_{i}^{\pm}$$ (C.12)

1090 $$QWAmi_{taz} \leq WPA_{tkaz}^{\pm} + WSA_{tkaz}^{\pm} \leq QWAma_{taz}$$ (C.13)

1091 $$QWImi_{ti} \leq WPI_{tki}^{\pm} + WSI_{ti} \leq WQIma_{ti}$$ (C.14)

1092

1093 (4) Initial water rights constraint:

1094 $$WNA_{tkaz}^{\pm} + PUGWA_{tkaz}^{\pm} + WSA_{tkaz}^{\pm} \leq QWAma_{taz}$$ (C.15)

1095 $$WNI_{tki}^{\pm} + PUGWI_{tki}^{\pm} + WSI_{tki}^{\pm} \leq QWIma_{tzi}$$ (C.16)

1096

1097 (5) Wastewater discharge and treatment constraints:

1098 $$EPA_{tkaz}^{\pm} = UPEA_{az} \times \left[\left(WPA_{tkaz}^{\pm} + WSA_{tkaz}^{\pm} \right) \times IWPA_{az} \right]$$ (C.17)

1099 $$EPI_{tki}^{\pm} = UPEI_{i} \times \left[\left(WPI_{tki}^{\pm} + WSI_{ti} \right) \times IWPI_{i} \right]$$ (C.18)

67

$$1100 \qquad \sum_{i=16}^{16} DISW_{tki}^{\pm} = \sum_{i=16}^{16} \left[\left(WPI_{tki}^{\pm} + WSI_{ti} \right) \times IWDR_i \right] \qquad \text{(C.19)}$$

$$1101 \qquad \begin{aligned} SDW_{tks}^{\pm} &= \sum_{i=1}^{15} ISS_{si} \times \left[\left(WPI_{tki}^{\pm} + WSI_{ti} \right) \times IWDR_i \right] \\ &+ \sum_{i=17}^{17} ISS_{si} \times \left[\left(WPI_{tki}^{\pm} + WSI_{ti} \right) \times IWDR_i \right] \\ &+ LSW_{ts}^{\pm} + OSW_{ts}^{\pm} \le MSDW_s^{\pm} \end{aligned} \qquad \text{(C.20)}$$

1102

1103   (6) Surface water balance constraint:

$$1104 \qquad \sum_{z=1}^{Z} \left\{ ZSW_{wz} \times \left[\sum_{a=1}^{A} WNA_{tkaz}^{\pm} + \sum_{i=1}^{I} \left(ISZ_{zi} \times WNI_{tki}^{\pm} \right) \right] \right\} \le SAWR_{tkw}^{\pm} \qquad \text{(C.21)}$$

$$1105 \qquad SAWR_{tkw}^{\pm} = RIBF_{tkw}^{\pm} + \sum_{z=1}^{Z} \left[ZSW_{wz} \times \left(\begin{array}{c} RNF_{tkz} + DIW_{tz} + ORDI_{tkz} \\ -ORDO_{tkz} - OZW_{tz} - REW_{tz} \end{array} \right) \right] \qquad \text{(C.22)}$$

$$1106 \qquad ROBF_{tkv}^{\pm} = \sum_{w=1}^{W} \left(OCR_{wv} \times ROBF_{tkw}^{\pm} \right) \qquad \text{(C.23)}$$

$$1107 \qquad RIBF_{tkw}^{\pm} = \sum_{v=1}^{V} \left(IOCR_{wv} \times ROBF_{tkv}^{\pm} \right) \qquad \text{(C.24)}$$

$$1108 \qquad ROBF_{tkw}^{\pm} = RIBF_{tkw}^{\pm} + \sum_{z=1}^{Z} \left\{ ZSW_{wz} \times \left[\begin{array}{c} RNF_{tkz} + DIW_{tz} + ORDI_{tkz} - ORDO_{tkz} \\ -OZW_{tz} - REW_{tz} \\ -\sum_{a=1}^{A} TWNA_{tkaz}^{\pm} - \sum_{i=1}^{I} \left(ISZ_{zi} \times TWNI_{tki}^{\pm} \right) \\ +DWWP_z \times \left[\begin{array}{c} \sum_{s=1}^{S} \left(SSZ_{zs} \times SDW_{tks}^{\pm} \right) \\ +\sum_{i=16}^{16} \left(ISZ_{zi} \times DISW_{tki}^{\pm} \right) \end{array} \right] \end{array} \right] \right\} \qquad \text{(C.25)}$$

1109

1110   (7) Pollutant content level constraints of river monitoring sections:

68

$$1111 \quad CSM_m \times MBF_{tkm}^{\pm} \geq OCS_{tkm} + \sum_{z=1}^{Z} ZSM_{mz} \times \left\{ \begin{array}{l} \sum_{a=1}^{A}\left(DPMA_{maz} \times EPA_{tkaz}^{\pm}\right) \\ + \sum_{s=3}^{S}\left[\begin{array}{l} SSZ_{zs} \times DPMS_{ms} \times \left(1-UPES_s\right) \\ \times \left(\begin{array}{l} LSW_{ts} \times LSP_{ts} \\ +OSW_{ts} \times OSP_{ts} \end{array} \right) \end{array} \right] \\ + \sum_{s=4}^{S}\left[\begin{array}{l} SSZ_{zs} \times DPMS_{ms} \\ \times \left(1-UPES_s\right) \times \sum_{i=1}^{6} EPI_{tki}^{\pm} \end{array} \right] \end{array} \right\}$$

1112 $\hspace{10cm}$ (C.26)

$$1113 \quad MBF_{tkm}^{\pm} = \sum_{w=1}^{W}\left(WSM_{mw} \times ROBF_{tkw}^{\pm}\right) + NRM_{tkm} \hspace{2cm} \text{(C.27)}$$

1114

1115 (8) Water-saving rule constraints：

$$1116 \quad \sum_{a=1}^{1} SFBA_{tkaz} = \sum_{a=1}^{1}\left(NIPS_{tkaz} SIFC_{az} + NIPM_{tkaz} MIFC_{az} + NIPL_{tkaz} LIFC_{az}\right) \hspace{1cm} \text{(B.37)}$$

$$1117 \quad \sum_{a=1}^{1} SFRA_{tkaz}^{\pm} = \sum_{a=1}^{1}\left(SIA_{tkaz}^{\pm} SIRC_{az} + MIA_{tkaz}^{\pm} MIRC_{az} + LIA_{tkaz}^{\pm} LIRC_{az}\right) \hspace{1cm} \text{(B.38)}$$

$$1118 \quad \sum_{a=1}^{1} WPA_{tkaz}^{\pm} = \sum_{a=1}^{1}\left(\begin{array}{l} SIA_{tkaz}^{\pm} SICW_{az} + MIA_{tkaz}^{\pm} MICW_{az} \\ + LIA_{tkaz}^{\pm} LICW_{az} + NSA_{tkaz}^{\pm} NSCW_{az} \end{array} \right) \hspace{1cm} \text{(B.39)}$$

$$1119 \quad \sum_{a=1}^{1} EFIA_{tkaz}^{\pm} = \sum_{a=1}^{1}\left(SIA_{tkaz}^{\pm} + MIA_{tkaz}^{\pm} + LIA_{tkaz}^{\pm} + NSA_{tkaz}^{\pm}\right) \hspace{1cm} \text{(B.40)}$$

$$1120 \quad \sum_{a=1}^{1} NSA_{tkaz}^{\pm} = \sum_{a=1}^{1}\left(PNSA_{tkaz}^{\pm} - NIPS_{tkaz} - NIPM_{tkaz} - NIPL_{tkaz}\right) \hspace{1cm} \text{(B.41)}$$

$$1121 \quad \sum_{a=1}^{1} SIA_{tkaz}^{\pm} = \sum_{a=1}^{1}\left(NIPS_{tkaz} + PIPS_{tkaz}^{\pm}\right) \hspace{1cm} \text{(B.42)}$$

$$1122 \quad \sum_{a=1}^{1} MIA_{tkaz}^{\pm} = \sum_{a=1}^{1}\left(NIPM_{tkaz} + PIPM_{tkaz}^{\pm}\right) \hspace{1cm} \text{(B.43)}$$

69

1123 $$\sum_{a=1}^{1} LIA_{tkaz}^{\pm} = \sum_{a=1}^{1} \left(NIPL_{tkaz} + PIPL_{tkaz}^{\pm} \right)$$ (B.44)

1124 $$\sum_{a=1}^{1} SIPW_{tkaz}^{\pm} = \sum_{a=1}^{1} \left(SIA_{tkaz}^{\pm} \times SIRW_{az} \right)$$ (B.45)

1125 $$\sum_{a=1}^{1} MIPW_{tkaz}^{\pm} = \sum_{a=1}^{1} \left(MIA_{tkaz}^{\pm} \times MIRW_{az} \right)$$ (B.46)

1126 $$\sum_{a=1}^{1} LIPW_{tkaz}^{\pm} = \sum_{a=1}^{1} \left(LIA_{tkaz}^{\pm} \times LIRW_{az} \right)$$ (B.47)

1127 $$\sum_{a=1}^{1} WSA_{tkaz}^{\pm} = \sum_{a=1}^{1} \left(SIPW_{tkaz}^{\pm} + MIPW_{tkaz}^{\pm} + LIPW_{tkaz}^{\pm} \right)$$ (B.48)

1128 $$\sum_{a=1}^{1} \left(\sigma_a \times EFIA_{tkaz}^{\pm} \right) = \sum_{a=1}^{1} \left(SIA_{tkaz}^{\pm} + MIA_{tkaz}^{\pm} + LIA_{tkaz}^{\pm} \right)$$ (B.49)

1129 $$WSI_{ti} = TIOV \times \left(PTVW_i - TIVW_i \right) + CICW_i \times \frac{\eta_p - \eta_c}{1 - \eta_p}$$ (B.50)

1130 $$SFCI_{ti} = USFC_i \times WSI_{ti}$$ (B.51)

1131 $$\sum_{a=1}^{1} WSAS_{tkaz}^{\pm} = \sum_{a=1}^{1} \left[\varphi_a \times \left(SFRA_{tkaz}^{\pm} + SFBA_{tkaz} \right) \right]$$ (B.52)

1132 $$WSIS_{ti} = \varphi_i \times SFCI_{ti}$$ (B.53)

1133 **Appendix D. Nomenclature**

1134

1135 Subscripts:

1136 a types of agriculture with a= 1, 2, 3 for planting industry, livestock, fishery.

1137 d type of county with d = 1, 2, 3, 4 for Laixi, Pingdu, Jiaozhou, Jimo.

1138 i type of enterprise with i= 1, 2, …, 17 for Haoda (HD), Xinxiwang (XXW),

1139   Nongxin (NX), Fuji (FJ), Donglin (DL), Ouliyou (OLY), Xijie (XJ), Aikang (AK),

70

1140		Jiulian (JL), Fenhuang (FH), Dahan (DH), Qili (QL), Yongchang (YC), Hansheng
1141		(HS), WanfuT (WFT), WanfuS (WFS, enterprise directly discharging pollutants),
1142		Naikesen (NKS).
1143	k	hydrological year type with k = 1, 2, 3, 4, 5 for special dry year, dry year, normal
1144		year, wet year and special wet year.
1145	m	type of monitoring section with m = 1, 2, …, 8 for Malian village, Zaochao village,
1146		Jiangjia village, Houshawan village, Yifeng dam, Qingping highway bridge,
1147		Mawan bridge, Xiela bridge.
1148	s	type of wastewater treatment plant with s = 1, 2, 3, 4 for Laixi wastewater treatment
1149		plant (in Zhu River region), Laixi wastewater treatment plant (in Wugu River
1150		region), Pingdu wastewater treatment plant, Jiaozhou wastewater treatment plant.
1151	t	type of planning period with t = 1, 2 for the first planning period (2024 years), the
1152		second planning period (2025 years).
1153	w	type of river region with w = 1, 2, …, 16 for River region from beginning of Dagu
1154		River in Qingdao to confluence point of Zhu River (wDZ), River region from
1155		confluence point of Zhu River to confluence point of Xiaogu River (wZX), River
1156		region from confluence point of Xiaogu River to confluence point of Wugu River
1157		(wXW), River region from confluence point of Wugu River to confluence point of
1158		Luoyao River (wWL), River region from confluence point of Luoyao River to
1159		confluence point of Nanjiaolai River (wLN), River region from confluence point of
1160		Nanjiaolai River to entrance to the sea (wJH), Xiaogu River region in Qingdao city
1161		(wXG), Zhu River region in Qingdao city (wZR), Wugu River region (wWG),
1162		Liuhao River region (wLH), Taoyuan River region (wTY), Luoyao River region
1163		(wLY), Jiao River region in Qingdao city (wJR), Moshui River region in Qingdao

<div align="center">71</div>

1164   city (wMS), Nanjiaolai River mainstream river region in Qingdao city (wNJ),

1165   Yunxi River region (wYX).

1166 v type of river region with v =1, 2, …, 16 for wDZ, wZX, wXW, wWL, wLN, wJH,

1167   wXG, wZR, wWG, wLH, wTY, wLY, wJR, wMS, wNJ, wYX.

1168 r type of river reach with r =1, 2, …, 16 for River reach from beginning of Dagu

1169   River in Qingdao to confluence point of Zhu River, River reach from confluence

1170   point of Zhu River to confluence point of Xiaogu River, River reach from

1171   confluence point of Xiaogu River to confluence point of Wugu River, River reach

1172   from confluence point of Wugu River to confluence point of Luoyao River, River

1173   reach from confluence point of Luoyao River to confluence point of Nanjiaolai

1174   River, River reach from confluence point of Nanjiaolai River to entrance to the sea

1175   (wJH), Xiaogu River reach in Qingdao city, Zhu River reach in Qingdao city

1176   (wZR), Wugu River reach, Liuhao River reach (wLH), Taoyuan River reach (wTY),

1177   Luoyao River reach (wLY), Jiao River reach in Qingdao city (wJR), Moshui River

1178   reach in Qingdao city (wMS), Nanjiaolai River mainstream River reach in Qingdao

1179   city (wNJ), Yunxi River reach.

1180 z type of area with z =1, 2, …, 21 for Laixi county in river region from beginning of

1181   Dagu River in Qingdao to confluence point of Zhu River (DZ), Laixi county in river

1182   region from confluence point of Zhu River to confluence point of Xiaogu River

1183   (ZX), Laixi county in river region from confluence point of Xiaogu River to

1184   confluence point of Wugu River (LXW), Pingdu county in river region from

1185   confluence point of Xiaogu River to confluence point of Wugu River (PXW), Jimo

1186   county in river region from confluence point of Wugu River to confluence point of

1187   Luoyao River (JWL), Pingdu county in river region from confluence point of Wugu

72

1188   River to confluence point of Luoyao River (PWL), Jimo county in river region from

1189   confluence point of Luoyao River to confluence point of Nanjiaolai River (LN),

1190   Jiaozhou county in river region from confluence point of Nanjiaolai River to

1191   entrance to the sea (JH), Laixi county in Xiaogu River region (LXG), Pingdu

1192   county in Xiaogu River region (PXG), Laixi county in Zhu River region (ZR), Laixi

1193   county in Wugu River region (LWG), Jimo county in Wugu River region (JWG),

1194   Jimo county in Liuhao River region (LH), Jimo county in Taoyuan River region

1195   (TY), Pingdu county in Luoyao River region (LY), Jiaozhou county in Jiao River

1196   region (JR), Jiaozhou county in Moshui River region in Qingdao city (MS),

1197   Jiaozhou county in Nanjiaolai River mainstream river region in Qingdao city (PNJ),

1198   Pingdu county in Nanjiaolai River mainstream river region in Qingdao city (JNJ),

1199   Jiaozhou county in Yunxi River region (YX).

1200

1201   Coefficients:

1202 $BA_{az}^{\pm}$ net benefit of unit target water consumption of agricultural user a in area z

1203   (RMB¥/m^3).

1204 $BI_i^{\pm}$ net benefit of unit target water consumption of enterprise users i (RMB¥/m^3).

1205 $DA_{az}^{\pm}$ cost per unit of water deficit of agricultural user a in area z (RMB¥/m^3).

1206 $DI_{zi}^{\pm}$ cost per unit of water deficit of enterprise users i (RMB¥/m^3).

1207 p_k probability for occurrence of scenario in hydrological year type k.

1208 TCA_{az} management cost for water trading of agricultural user a in area z

1209   (RMB¥/m^3).

73

1210	TCI_i	management cost for water trading of enterprise users i (RMB¥/m^3).
1211	TRA_{az}	price of water rights of agricultural user a in area z (RMB¥/m^3).
1212	TRI_i	price of water rights of enterprise users i (RMB¥/m^3).
1213	$FAWA_{taz}$	cost per unit of surface water used of agricultural user a in area z in planning
1214		period l (RMB¥/m^3).
1215	$FAUA_{taz}$	cost per unit of groundwater used of agricultural user a in area z in planning
1216		period l (RMB¥/m^3).
1217	$FAWI_{ti}$	cost per unit of surface water used of enterprise users i in planning period l
1218		(RMB¥/m^3).
1219	$FAUI_{ti}$	cost per unit of groundwater used of enterprise users i in planning period l
1220		(RMB¥/m^3).
1221	$SC_{ts}^{\pm}$	the operating cost of unit wastewater volume in wastewater treatment plant s
1222		(RMB¥/m^3).
1223	$UGWA_{tkaz}$	the maximum total quantity of groundwater intake in the control range of the
1224		total quantity of groundwater intake of agricultural user a in area z in
1225		hydrological year type k in planning period l (10^4 m^3).
1226	$UGWI_{tki}$	the maximum total quantity of groundwater intake in the control range of the
1227		total quantity of groundwater intake of enterprise users i in hydrological year
1228		type k in planning period l (10^4 m^3).
1229	$LWPA_{az}^{\pm}$	production scale of unit water consumption of agricultural user a in area z
1230		(ha/10^4m^3 (planting industry), head/ m^3 (livestock), ha/10^4m^3 (fishery))

74

1231	$LWPI_i^{\pm}$	production scale of unit water consumption of enterprise users i (m³/m³).
1232	$QWAmi_{taz}$	the minimum water requirement of agricultural user a in area z in planning
1233		period l (10^4 m³).
1234	$QWAma_{taz}$	the maximum water requirement of agricultural user a in area z in planning
1235		period l (10^4 m³).
1236	$QWImi_{ti}$	the minimum production scale of enterprise users i in planning period l (10^4
1237		m³).
1238	$WQIma_{ti}$	the maximum production scale of enterprise users i in planning period l (10^4
1239		m³).
1240	$IWDR_i$	drainage rate of enterprise users i (m³/m³)
1241	$UPEA_{az}^{\pm}$	COD emission per unit production scale of agricultural user a in area z
1242		(ton/ha (planting industry), ton/ head (livestock), ton/ha (fishery)).
1243	$UPEI_i$	COD emission per unit production scale of enterprise users i (ton/10^4m³).
1244	LSP_{ts}	COD concertation of domestic wastewater treated by wastewater treatment
1245		plant s (ton/10^4 m³).
1246	OSP_{ts}	COD concertation of other wastewater treated by wastewater treatment plant s
1247		(ton/10^4 m³).
1248	$DPMA_{maz}$	influence of pollutant emission of agricultural user a in area z on monitoring
1249		section m (ton/ton).
1250	$DPMS_{ms}$	influence of pollutant emission of wastewater treatment plant s on monitoring
1251		section m (ton/ton).

75

1252	CSM_m	surface water quality standards of monitoring section m (ton/10^4 m³).
1253	OCS_{tkm}	the quantity of pollutants outside the city to monitoring section m in
1254		hydrological year type k in planning period l (ton).
1255	NRM_{tkm}	natural runoff from upstream river regions to monitoring section m in
1256		hydrological year type k in planning period l (10^4 m³).
1257	$LSW_{ts}^{\pm}$	domestic wastewater treated by wastewater treatment plant s in planning
1258		period l (10^4 m³).
1259	$OSW_{ts}^{\pm}$	other wastewater treated by wastewater treatment plant s in planning period l
1260		(10^4 m³).
1261	$MSDW_s^{\pm}$	the maximum wastewater treatment of wastewater treatment plant s (10^4 m³).
1262	$UPES_s$	pollutant treatment rate of wastewater treatment plant s (ton/ton).
1263	RNF_{tkz}	natural runoff of river region w in area z in hydrological year type k in
1264		planning period l (10^4 m³).
1265	$DWWP_z$	area z is allowed to discharge wastewater, $z = 1$ is dischargeable, $z = 0$ is not
1266		dischargeable.
1267	DIW_{tz}	inter-watershed diverted surface water resources in area z in planning period l
1268		(10^4 m³).
1269	$ORDI_{tkz}$	surface water resources from diversion of water within the watershed in in area
1270		z in hydrological year type k in planning period l (10^4 m³).
1271	$ORDO_{tkz}$	water transferred of area z in hydrological year type k in planning period l
1272		(10^4 m³).

76

1273 OZW_{tz} surface water resources used for the other in area z in planning period l (10^4

1274 m^3).

1275 REW_{tz} basic ecological runoff of area z in planning period l ($10^4\,m^3$).

1276 SSZ_{zs} the corresponding relationship between wastewater treatment plant s and area

1277 z. If the wastewater treatment plant s is in area z, $SSZ_{zs} = 1$; Conversely

1278 $SSZ_{zs} = 0$.

1279 ISZ_{zi} the corresponding relationship between enterprise users i and area z. If the

1280   enterprise users i is in area z, $ISZ_{zi} = 1$; Conversely $ISZ_{zi} = 0$.

1281 ZSW_{wz} the corresponding relationship between area z and river region w. If the area

1282 z is in river region w, $ZSW_{wz} = 1$; Conversely $ZSW_{wz} = 0$.

1283 OCR_{wv} coefficient that determines whether river region w is river region v. If river

1284   region w is river region v, $OCR_{wv} = 1$; If river region w is not river region

1285 w, $OCR_{wv} = 0$

1286 $IOCR_{wv}$ coefficient that determines whether river region w is upstream of river region

1287 v and next to river region w. If river region w is upstream of river region v

1288   and next to river region w, $IOCR_{wv} = 1$; If river region w is not upstream of

1289   river region v or next to river region w, $IOCR_{wv} = 0$.

1290 ZSM_{mz} the corresponding relationship between area z and monitoring section m. the

1291   monitoring section m above the area z, $ZSM_{mz} = 1$; Conversely $ZSM_{mz} = 0$.

1292 WSM_{mw} the corresponding relationship between river region w and monitoring section

77

1293 m. the monitoring section m above the river region w, $WSM_{mw} = 1$;

1294   Conversely $WSM_{mw} = 0$.

1295 $SIFC_{az}$ construction cost per unit area of sprinkler irrigation water-saving facility in

1296   area z (10^4 RMB¥/ha).

1297 $MIFC_{az}$ construction cost per unit area of micro-irrigation water-saving facility in area

1298 z (10^4 RMB¥/ha).

1299 $LIFC_{az}$ construction cost per unit area of low-pressure pipe irrigation water-saving

1300   facility in area z (10^4 RMB¥/ha).

1301 $SIRC_{az}$ operating cost per unit area of sprinkler irrigation water-saving facility in area

1302 z (10^4 RMB¥/ha).

1303 $MIRC_{az}$ operating cost per unit area of micro-irrigation water-saving facility in area z

1304   (10^4 RMB¥/ha).

1305 $LIRC_{az}$ operating cost per unit area of low-pressure pipe irrigation water-saving

1306   facility in area z (10^4 RMB¥/ha).

1307 $SICW_{az}$ water consumption per unit area based on sprinkler irrigation water-saving

1308   facility in area z (10^4 m^3/ha).

1309 $MICW_{az}$ water consumption per unit area based on micro-irrigation water-saving facility

1310   in area z (10^4 m^3/ha).

1311 $LICW_{az}$ water consumption per unit area based on low-pressure pipe irrigation water-

1312   saving facility in area z (10^4 m^3/ha).

1313 $NSCW_{az}$ water consumption per unit area under non-water saving in area z (10^4 m^3/ha).

1314	$PNSA_{tkaz}$	the original total irrigation area under area z in hydrological year type k in
1315		planning period l (ha).
1316	$PIPS_{tkaz}$	the original irrigation area based on sprinkler irrigation water-saving facility
1317		under area z in hydrological year type k in planning period l (ha).
1318	$NIPS_{tkaz}$	new added irrigation area based on sprinkler irrigation water-saving facility
1319		under area z in hydrological year type k in planning period l (ha).
1320	$PIPM_{tkaz}$	the original irrigation area based on micro-irrigation water-saving facility
1321		under area z in hydrological year type k in planning period l (ha).
1322	$NIPM_{tkaz}$	new added irrigation area based on micro-irrigation water-saving facility under
1323		area z in hydrological year type k in planning period l (ha).
1324	$PIPL_{tkaz}$	he original irrigation area based on low-pressure pipe irrigation water-saving
1325		facility under area z in hydrological year type k in planning period l (ha).
1326	$NIPL_{tkaz}$	new added irrigation area based on low-pressure pipe irrigation water-saving
1327		facility under area z in hydrological year type k in planning period l (ha).
1328	$SIRW_{az}$	water saving per unit area based on sprinkler irrigation water saving facility in
1329		area z ($10^4\,\mathrm{m}^3$/ha).
1330	$MIRW_{az}$	water saving per unit area based on micro-irrigation water saving facility in
1331		area z ($10^4\,\mathrm{m}^3$/ha).
1332	$LIRW_{az}$	water saving per unit area based on low-pressure pipe irrigation water saving
1333		facility in area z ($10^4\,\mathrm{m}^3$/ha).
1334	$EFIA_{tkaz}^{\pm}$	total irrigation area of agricultural user a in area z in hydrological year type

79

1335		k in planning period l (ha).
1336	$USFC_i$	process cost of enterprise i unit water saving (RMB¥/ m³).
1337	$TIOV_i$	enterprise i current annual value added (10^4 RMB¥).
1338	$PTVW_i$	the water consumption of ten-thousand-yuan industrial added value under the
1339		current situation of enterprise i (m³).
1340	$TIVW_i$	the water consumption of ten-thousand-yuan industrial added value under the
1341		planning index of enterprise i (m³).
1342	$CICW_i$	enterprise i current water consumption (10^4 m³)
1343	η_p	industrial water reuse rate under the planning index of enterprise i (%).
1344	η_c	industrial water reuse rate under the current situation of enterprise ii (%).
1345	φ_a	planting industry water-saving subsidy rate (%).
1346	φ_i	enterprise water-saving subsidy rate (%).
1347		
1348	Decision variables:	
1349	WQA_{taz}	objective water consumption of agricultural user a in area z in planning
1350		period l (10^4 m³)
1351	WQI_{ti}	objective water consumption of enterprise i in planning period l (10^4 m³)
1352	$WLA_{tkaz}^{\pm}$	water deficit of agricultural user a in area z in hydrological year type k in
1353		planning period l (10^4 m³).
1354	$WLI_{ti}^{\pm}$	water deficit of enterprise i in planning period l (10^4 m³).

1355	$BWTA_{tkaz}^{\pm}$	purchase for water rights from other users of agricultural user a in area z in
1356		hydrological year type k in planning period l $(10^4\,\text{m}^3)$.
1357	$SWTA_{tkaz}^{\pm}$	sale for water rights to other users of agricultural user a in area z in
1358		hydrological year type k in planning period l $(10^4\,\text{m}^3)$.
1359	$BWTI_{tki}^{\pm}$	purchase for water rights from other users of enterprise i in hydrological year
1360		type k in planning period l $(10^4\,\text{m}^3)$.
1361	$SWTI_{tki}^{\pm}$	sale for water rights to other users of enterprise i in hydrological year type k
1362		in planning period l $(10^4\,\text{m}^3)$.
1363	$SFRA_{tkaz}^{\pm}$	operating costs of agricultural user a using water-saving facility in area z in
1364		hydrological year type k in planning period l $(10^4\,\text{RMB¥})$.
1365	$SFCI_{ti}$	water-saving process cost of enterprise i in planning period l $(10^4\,\text{RMB¥})$.
1366	$SFBA_{tkaz}$	construction costs of agricultural user a using water-saving facility in area z
1367		in hydrological year type k in planning period l $(10^4\,\text{RMB¥})$.
1368	$WSAS_{tkaz}^{\pm}$	government water-saving subsidy of agricultural user a in area z in
1369		hydrological year type k in planning period l $(10^4\,\text{RMB¥})$.
1370	$WSIS_{ti}$	government water-saving subsidy of enterprise i in planning period l $(10^4$
1371		RMB¥).
1372	$PSGWA_{tkaz}^{\pm}$	actual surface water consumption of agricultural user a in area z in
1373		hydrological year type k in planning period l $(10^4\,\text{m}^3)$.
1374	$PSGWI_{tki}^{\pm}$	actual surface water consumption of enterprise i in hydrological year type k in
1375		planning period l (10^4m^3).

81

1376	$PUGWA_{tkaz}^{\pm}$	actual groundwater consumption of agricultural user a in area z in
1377		hydrological year type k in planning period l ($10^4\,\mathrm{m}^3$).
1378	$PUGWI_{tki}^{\pm}$	actual groundwater consumption of enterprise i in hydrological year type k in
1379		planning period l ($10^4\,\mathrm{m}^3$).
1380	$SDW_{tks}^{\pm}$	wastewater treatment of wastewater treatment plant s in hydrological year
1381		type k in planning period l ($10^4\,\mathrm{m}^3$)
1382	$WPA_{tkaz}^{\pm}$	actual water consumption of agricultural user a in area z in hydrological year
1383		type k in planning period l ($10^4\,\mathrm{m}^3$)
1384	$WPI_{tki}^{\pm}$	actual water consumption of enterprise i in hydrological year type k in
1385		planning period l ($10^4\,\mathrm{m}^3$)
1386	$WSA_{tkaz}^{\pm}$	water-saving amount of agricultural user a in area z in hydrological year type
1387		k in planning period l ($10^4\,\mathrm{m}^3$)
1388	WSI_{tki}	water-saving amount of enterprise i in hydrological year type k in planning
1389		period l ($10^4\,\mathrm{m}^3$)
1390	$TWNA_{tkaz}^{\pm}$	water rights after trading of agricultural user a in area z in hydrological year
1391		type k in planning period l ($10^4\,\mathrm{m}^3$).
1392	$TWNI_{tki}^{\pm}$	water rights after trading of enterprise i in hydrological year type k in
1393		planning period l ($10^4\,\mathrm{m}^3$).
1394	$PSA_{tkaz}^{\pm}$	actual production scale of agricultural user a in area z in hydrological year
1395		type k in planning period l ($10^4\,\mathrm{m}^3$).

1396	$PSI_{tki}^{\pm}$	actual production scale of enterprise i in hydrological year type k in planning
1397		period l ($10^4\,\mathrm{m}^3$).
1398	$DISW_{tki}^{\pm}$	actual wastewater emission of enterprise indirectly discharging pollutants i in
1399		hydrological year type k in planning period l ($10^4\,\mathrm{m}^3$).
1400	$SAWR_{tkw}^{\pm}$	available surface water resources of river region w in hydrological year type
1401		k in planning period l ($10^4\,\mathrm{m}^3$).
1402	$RIBF_{tkw}^{\pm}$	inbound runoff of river region w in hydrological year type k in planning
1403		period l ($10^4\,\mathrm{m}^3$).
1404	$ROBF_{tkw}^{\pm}$	outbound runoff of river region w in hydrological year type k in planning
1405		period l ($10^4\,\mathrm{m}^3$).
1406	$ROBF_{tkv}^{\pm}$	outbound runoff of river region v in hydrological year type k in planning
1407		period l ($10^4\,\mathrm{m}^3$).
1408	$MBF_{tkm}^{\pm}$	streamflow of monitoring section m in hydrological year type k in planning
1409		period l ($10^4\,\mathrm{m}^3$).
1410	$SIA_{tkaz}^{\pm}$	irrigation area based on sprinkler irrigation water-saving facility of agricultural
1411		user a in area z in hydrological year type k in planning period l (ha).
1412	MIA_{tkaz}	irrigation area based on micro-irrigation water-saving facility of agricultural
1413		user a in area z in hydrological year type k in planning period l (ha).
1414	LIA_{tkaz}	irrigation area based on low-pressure pipeline irrigation water-saving facility
1415		of agricultural user a in area z in hydrological year type k in planning period
1416		l (ha).

1417 $NSA_{tkaz}^{\pm}$ irrigation area based on non-water-saving of agricultural user a in area z in

1418   hydrological year type k in planning period l (ha).

1419 $PCWT_{td}$ per capita water consumption in planning period l (m^3/capita).

1420 $HDP_{tk}^{\pm}$ harmonious degree about population in hydrological year type k in planning

1421   period l.

1422 $HDW_{tk}^{\pm}$ harmonious degree about water consumption status of users in hydrological

1423   year type k in planning period l.

1424 $HDF_{tk}^{\pm}$ harmonious degree about system benefit in hydrological year type k in

1425   planning period l.