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Wastewater for agriculture: A reuse-oriented planning model and its application in peri-urban China

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ABSTRACT

The benefits of Integrated Water Resources Management (IWRM) are widely known but its recommendations remain thinly implemented. Designing wastewater treatment plants for reuse in irrigation is a particularly underutilized IWRM opportunity that could potentially increase agricultural yields, conserve surface water, offset chemical fertilizer demand, and reduce the costs of wastewater treatment by eliminating nutrient removal processes. This paper presents a novel planning model, consisting of a reuse-centric performance assessment and optimization model to help design wastewater treatment plants for reuse in agriculture. The performance assessment and optimization model are described, and their coupled application is demonstrated in the peri-urban district of Pixian, China. Based on the results of the performance assessment, two reuse scenarios are evaluated: wastewater to supplement business as usual (BAU) irrigation, and wastewater to replace BAU irrigation. The results indicate that wastewater supplementation could increase profits by \$20 million (M) annually; alternatively, wastewater replacement could conserve 35 Mm^3 of water in local rivers each year.

1. Introduction

Integrated Water Resources Management (IWRM) was introduced at the UN Conference on Water in 1977 as a process for navigating the complex set of environmental, social, and economic tradeoffs associated with water supply and demand management. IWRM calls for cross-sectoral coordination in water planning, includes wastewater reuse, is widely embraced in the water literature and is reflected in a number of regional and country-wide policies.[1] Its implementation around the globe, however, is limited (Lazarova et al., 2001; Rahaman and Varis, 2005; Ward, 2007): compartmentalized planning remains characteristic of water management. To enable better cross-sectoral coordination we propose a new planning model for wastewater managers. The model reveals the costs, benefits, and opportunities that emerge from coordinating wastewater management with broader water use and allocation objectives.

Wastewater and agriculture are two sectors where the economic and environmental benefits of joint water management have been demonstrated through case studies around the world. It has been shown that the nutrients embodied in wastewater can increase yields as much or more than a combination of tap water and chemical fertilizer (Mohammad and Ayadi, 2005; Lopez et al., 2006; WHO, 2006; Kiziloglu et al., 2007). The reliable access to wastewater irrigation can improve farm productivity in water-constrained systems (Bradford et al., 2003; Huibers and Van Lier, 2005; Raschid-Sally et al., 2005). Diverting wastewater effluent to

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[1] See UN Water's global survey for a comprehensive review of IWRM in 104 participating countries (UN Water, 2008).

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agriculture also reduces the discharge of nutrients to surface waters, may reduce demand for freshwater, and potentially decreases the costs of wastewater treatment by eliminating the need for nutrient removal (Rosenqvist et al., 1997). However, more than 80% of wastewater and fecal sludge generated globally is indiscriminately discharged without treatment (Bos et al., 2004). Aside from unplanned reuse in regions where farmers irrigate with waste-contaminated sources, planned reuse in agriculture is limited in comparison to its potential. Agriculture accounts for 70% of freshwater withdrawals but wastewater-fed irrigation accounts for only 1% of agricultural water use (Jimenez and Asano, 2008; World Water Assessment Program, 2009).

The many benefits of irrigation with treated wastewater do come with certain risks to both human and environmental health. To manage these risks, the World Health Organization (WHO) offers guidelines for implementing safe wastewater reuse in agriculture that include treatment and non-treatment options over the entire chain from cultivation to consumption (WHO, 2006). With user training and effective regulation, both public health and environmental risks can be minimized or avoided. We recognize, however, that institutions to provide training and enforce regulations are currently weak, and will need to be strengthened, in many low-income nations.

This research presents a novel and practical planning model for bridging the wastewater and agriculture sectors to the benefit of both ends. It comprises a reuse-centric irrigation performance assessment coupled with a tractable decision-support model to optimize the impact of supplementing or replacing freshwater for irrigation with wastewater effluent. Most irrigation models in the literature maximize farm profits or water conservation under constrained freshwater supplies (Rao et al., 1990; Liu et al., 1998; Reca et al., 2001; Campos et al., 2003; Kang et al., 2003); few models have been designed to optimize either farm profits or water conservation with the direct reuse of wastewater effluent for irrigation (Amir and Fisher, 1999; Darwish et al., 1999).

The planning model presented here is primarily meant for sanitation planners and is not intended to meet all the demands of comprehensive agricultural planning.[2] Our reuse-centric irrigation performance assessment enables sanitation planners to adopt and implement locally tailored goals of using wastewater effluent for irrigation. Using information from the performance assessment, model users determine the objective function, when and where the effluent is injected into the irrigation system, storage capacity criteria, and whether the effluent will supplement or replace existing irrigation. In the remainder of the paper, we provide a detailed specification of the model, calibrated to the peri-urban district of Pixian, China, and demonstrate its use for designing a wastewater treatment system for reuse in agriculture.

2. Methods and study location

2.1. Assess, simulate, select: 3-step planning model for reuse in agriculture

The reuse-centric irrigation performance assessment comprises only those indicators that would directly be impacted by supplementing or replacing existing irrigation water use with wastewater. Four attributes are considered: agricultural profitability, canal head-tail equity, farmer satisfaction with water quantity, and interaction between regional water resources management objectives and irrigation (Table 1).

As shown in Fig. 1, the performance assessment is used to assess the business as usual (BAU) irrigation system. Insights for improving the BAU regime, as revealed by the performance assessment, are used to shape the alternative reuse simulations generated with the decision-support model. Model users subsequently evaluate the reuse simulations for their impacts on the performance indicators compared to the BAU baseline. Ultimately, tradeoffs among different reuse options are chosen and choices made in the political arena; the model results can be used to select the reuse scenario that best achieves local objectives. This three-step process is an efficient and cost-effective means of producing feasible, regionally tailored joint water management options for sanitation planning and the agricultural sector (Fig. 1). Once a reuse scenario is chosen, a detailed engineering plan can be prepared for the system's implementation.

2.2. Study location

Water shortage and water pollution are both pressing (and related) challenges in China: 400 of the 600 major cities suffer from a water deficit, and 70% of China's rivers and 50% of its

Table 1 – Indicators included in reuse-centric irrigation performance assessment.

Irrigation scheme indicator assessed	Stakeholder tier	Evaluation method
Agricultural profitability and spatial equity		
Yields Temporal distribution Spatial disparity in access	Village and district	Profit maximizing optimization modeling over the individual sub-sections of two irrigation canals
User satisfaction		
Adequacy of water quantity	Farmer households	Pixian-wide farmer interviews[a] ($n = 39$)
Regional water resources management goals \and objectives		
Surface water quality	Municipality	Review of policy documents
Water quantity		Interviews with policy and decision makers[a]

a All interviews and surveys were conducted in Mandarin by the first author, between 2006 and 2008.

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[2] The performance assessment and model are part of a larger planning approach developed by the authors and their colleagues, Design for Service (DFS). DFS is a five-step process for designing reuse-oriented sanitation infrastructure (Murray and Buckley, 2010).

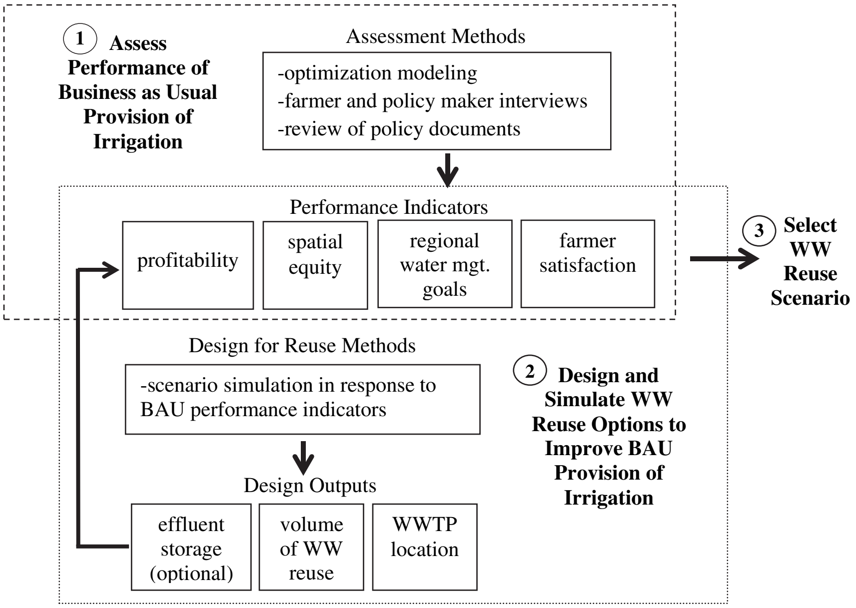

Fig. 1 – Overview of methods and performance indicators comprising the coupled performance assessment and optimization model for designing wastewater treatment systems for reuse in agriculture. The three-step planning model includes (1) a performance assessment of the business as usual provision of irrigation, (2) simulation of various reuse scenarios, and (3) selection of a reuse scheme based on the comparative performance of the reuse scenarios to the baseline performance.

groundwater resources are contaminated (Spooner, 2006; Zhang, 2006). The Chinese government has responded with policies and interventions aimed at expanding wastewater treatment and reuse. China's commitment to improving water management and the urgency of doing so made it a natural research site.

Pixian is a peri-urban district northwest of Chengdu, the capital of Sichuan Province in southwest China. The District has a population of about 490,000 people and is 25% urban. Domestic wastewater production in urban areas is approximately 25,000 m^3/d or 9 Mm^3/yr, all of which was discharged untreated to local surface waters at the time of this research. Expanding wastewater treatment is a priority in Pixian, due in part to water quality mandates in the 11th Five-Year Plan (2006–2010). According to the Chengdu Municipality, Pixian is to achieve a wastewater treatment capacity of 100,000 m^3/d by 2010, and 250,000 m^3/d by 2020 (Chengdu Planning Bureau and Chengdu Water Bureau, 2006). The projected capital costs include nearly \$200/m^3 of treatment capacity to build the activated sludge plants and approximately \$900,000/km of sewer network (ibid.). In terms of agriculture, Pixian has approximately 127,000 farmers on 25,000 ha of cultivated land served by four primary irrigation canals and several secondary canals. Farmers in the Chengdu Municipality are granted 0.8 mu (15 mu = 1 ha); the average rural household farms between 2.4 and 3.2 mu. The Chinese government is concerned about rural livelihoods and is interested in measures that improve agricultural profits and equity along irrigation canals (Huang et al., 2005; Murray, 2007).

Water administration in China, as in many regions of the world, is highly disjointed[3] – a characteristic now seen as a barrier to solving modern water management challenges (Varis and Vakkilainen, 2001). Our BAU performance assessment shows that both Pixian's agricultural sector and the Municipality's water quality objectives would benefit from strategic reuse of wastewater effluent for irrigation; furthermore, it is a China-wide priority to increase wastewater reuse (Chu et al., 2004). Given the investment in wastewater treatment that is planned for Pixian, our planning model has immediate relevance for sanitation expansion in the Chengdu Municipality. By extension it is also useful for sanitation planning in peri-/urban areas around the world that are confronting wastewater treatment and agricultural water resource challenges.

2.3. *Model simulations*

This study considers two of Pixian's four irrigation canals,[4] the Xuyan and Zouma, which were divided into sub-sections according to geopolitical boundaries. Towns that share a border with the canal and draw water off simultaneously were grouped into the same sub-section. Each sub-section of a canal system, designated by its main town and its

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[3] As an interviewee at the Chinese Academy of Sciences in Chengdu said, "Wastewater treatment is planned and managed by people with government background so they're not actively pushing to improve the sustainability of systems. Another problem is that all offices are very segregated – offices don't care about things they're not responsible for even if it could be related to their work. It's getting better though – now there's one office that is supposed to oversee everything."

[4] Our complete study included analyses of Pixian's two other irrigation canals, the Baitiao and Jiangan, and those yielded commensurate results. We discuss only two canals in detail because of space constraints.

Table 2 – Two irrigation river systems in Pixian and characteristics of the regions they serve.

Sub-section	Town	Cultivated area served[a] (mu[b])	Farmer population	Urban population	Urban wastewater generation (m^3/d)[c]
Xuyan River irrigation system					
1	Tangchang	12,870	17,367	11,005	2.3×10^3
1	Ande	15,970	13,401	6898	1.5×10^3
2	Xinminchang	12,400	5684	18,029	3.8×10^3
3	Sandaoyuan	7970	4438	1749	3.7×10^2
4	Tuanjie	13,030	9866	6462	1.4×10^3
5	Xipu	1880	3599	2044	4.3×10^2
5	Anjing	7430	5960	869	1.85×10^2
Zouma River irrigation system					
1	Huayuan	9970	7383	1874	4.0×10^2
2	Ande	15,970	13,401	6898	1.5×10^2
3	Youai	19,470	15,497	1317	2.8×10^2
4	Pixian center	21,080	9657	59,460	1.3×10^4
4	Deyuan	26,550	8959	678	1.4×10^2
5	Hongguang	13,030	11,528	4070	8.7×10^2
6	Xipu	1880	3599	2044	4.3×10^2

[a] Total cultivated land area is according to the Pixian Agricultural Bureau (PAB) (2007); the area of land served by each irrigation system in a town is an estimation of the fraction of total land served by the system versus others that may flow through the town, based on the geographical proximity of the land to each respective irrigation canal.

[b] 15 mu = 1 hectare.

[c] Assumes per capita water consumption of 0.25 m^3/d and return rate as wastewater (k) 0.85.

surrounding agricultural area, was run as an independent simulation. The difference between water fed into the sub-section and used for irrigation was assumed to be the water availability for the subsequent sub-section; the entire river system is thus modeled as a series of sequential optimizations. Table 2 characterizes both irrigation systems by sub-section, including the number of farmers, cultivated land area served, the size of the urban population, and the volume of wastewater generated.

The baseline model was calibrated to depict the existing agricultural patterns in Pixian. The outputs include the summation of profits from agricultural activities along each system, cropping patterns, and spatial equity with respect to yields and water consumption. Applying the performance assessment to the BAU results exposed two alternative reuse goals: 1) increasing the water available to farmers by supplementing existing irrigation water with wastewater effluent; or 2) decreasing surface water diversion to improve local water quality by replacing existing irrigation with wastewater effluent. We modeled each scenario; the results reveal the extent to which there may be a tradeoff between improving agricultural incomes and improving regional surface water quality.

2.4. *Model data*

Population data are based on 2007 statistics from the Pixian Agricultural Bureau (PAB) (2007) and are disaggregated by rural and urban populations. Pixian's urban settlements are the source of wastewater for the model; we assume a per capita water consumption of 0.25 m^3/d and a return rate as wastewater (k) of 0.85. Total land availability is based on the PAB's statistics for the year 2007. The area of land served by each irrigation system in a town is an estimation of the fraction of total land served by the system versus others that may flow through the town, based on the geographical proximity of the land to each respective irrigation canal. Total water availability in a canal, in 10-day intervals, was estimated based on data from the Dongfeng Channel Irrigation (DCI) office, which manages irrigation allocation for the Chengdu Municipality.[5]

The model consists of 13 crop varieties that are commonly found in Pixian: rice, rapeseed, winter wheat, corn, fall vegetables (average of radish and cabbage), tomato, spring vegetables (average of cucumber, eggplant, hot pepper, and green beans), Chinese cabbage (three different seasons), garlic, green onion, and chuanxiong (a traditional Chinese medicine.) Maximum yields per mu are based on the FAO's geographically sensitive ProdStat model (FAO, 2008). Maximum gross profit per mu is the result of maximum yields multiplied by local retail prices; farmers in Pixian are assumed to be price takers (Table SI1) (China Food and Beverage Net, 2008, (食品商务网, 2008)). A single, lifetime crop yield coefficient (k_y), which describes the relationship between irrigation and crop growth, was used for the sake of model tractability (Table SI1) (Doorenbos and Kassam, 1979).[6] Yields are thus a first approximation, and will tend to underestimate the actual yield because the coefficients used overestimate the impact of irrigation deficit during the early and final stages of the crop cycle (Doorenbos and Kassam, 1979).

Crop water requirements are generated with the FAO's CropWat V4.0 and tailored to Pixian's climate characteristics including monthly rainfall (evenly divided among the 10-day intervals), evapotranspiration rates (ET$_0$), and soil conditions

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[5] See SI for methods and data used to estimate irrigation allocation among canals in Pixian (Tables SI4–SI6).

[6] In a more complex agricultural model, separate yield coefficients can be defined for specific stages in the growth cycle.

(Weather2Travel, 2008; Water Resources Development and Management Unit, 1992). Irrigation efficiency was assumed to be 50%, based on empirical data for flood irrigation (Vickers, 2001). There is likely some recharge of the irrigation canals occurring; however, the quantity and location is completely uncertain and recharge was therefore not included in this model. The conservative estimate of water availability in the canals that this assumption renders is partially counteracted by the generous assumption that farmers do not over-water their crops when water is available (see constraint 3, Equation (5), Section 3).

We generated an irrigation schedule for each crop by entering the planting date and allowing CropWat to determine the harvesting date and crop coefficients. Planting dates were chosen based on surveys conducted in Mandarin throughout the District, and the survey data were also used to confirm that CropWat's harvesting dates approximately coincided with those of the farmers.

The cost of fertilizer for each crop was determined based on surveys of farmers in Pixian and validated by surveying the local retail market for fertilizer. Farmers self-reported the quantity of nitrogen, phosphorus and potassium they added per mu for each crop they planted. The mean application rates were used for the purposes of the model (Table SI3). The total cost of fertilizer per mu for each crop was deducted from the gross profit per crop per mu to give the net profit per mu (P_M).

3. Model specification

The model is written in MS Excel as a quadratic optimization program for allocating a user defined amount of land and water over a choice of crops and/or cultivation seasons, subject to overall resource availability constraints. The model is solved using the Standard GRG nonlinear engine in Frontline's Risk Solver Platform V9.0 for MS Excel. While the model is calibrated to Pixian's crop calendar, crops can easily be added or subtracted and cultivation calendars can be adapted to those of other regions.

The quadratic objective function, unlike the more common linear objective function, allows the model to choose the water application rate (from zero up to the amount required for maximum yield) at each time-step (every ten days in this model). The yields are a function of the total amount of water added over the course of the irrigation season. Where water availability during the season varies daily, as in Pixian, this structure is more satisfying than the linear alternative; it allows the model to apply water as a continuous as opposed to a pre-determined step function. Quadratic programs have been used for measuring fertilizer yield response and to model land allocation to different crops. Where the results have been compared to those from other model formulations, they have proven a superior fit to empirical data (Belanger et al., 2000; Hall, 2001). One shortcoming of the quadratic formulation is the tendency of the solver to construe a local optimum – a set of results that satisfy all constraints, and represent a regional peak along the solution frontier – as the overall or global optimum. Sophisticated solvers, like that used for this model, improve the likelihood of finding global optima by using "multistart" and "topographic" search methods (Frontline Systems, 2008). These methods choose several randomly selected starting points between the bounds of the variables in the model, and then look for the optimal solution within each of those clusters, ultimately choosing the best solution among them.

The objective function for each sub-section along the irrigation canal is the sum of the area of each crop planted multiplied by its gross profit[7] per unit area. Based on data collected from Pixian farmers, the objective functions are not strictly profit maximizing. The model assumes that farmers are risk averse, prioritizing a degree of crop diversification over planting the single crop that commands the highest market price (see constraints 5 and 6 below). Based on surveys throughout the region, with very few exceptions, farmers do not have hired help; therefore the cost of labor was not included in the model. Family labor is not a constraint in the model. Among the farmers who planted edible crops (as opposed to ornamentals which are not included here) labor was never mentioned as a constraining factor; this is likely explained by the relatively small land-holdings among rural Chinese households.

$$\sum_{i=0}^{n} A_i P_i \tag{1}$$

where n = total number of crops, from 0 to 13; A_i = area of crop i (mu); P_i = net profit crop i per unit area ($/mu).

Net profit for each crop is subject to total irrigation allocated to the crop over the course of the cultivation season, and the cost of fertilizer, as follows (Doorenbos and Kassam, 1979):

$$P_i = P_M\left[1 - \left[k_y\left(1 - \frac{ET_a}{ET_m}\right)\right]\right] - C_{F,i} \tag{2}$$

where P_M = maximum gross profit with complete irrigation requirements met ($/mu); k_y = crop yield coefficient for total growing period; ET_a = actual effective water supply to crop over growing period, including rain and evapotranspiration (see Table SI2) (m^3/mu); ET_m = required effective water supply to crop over growing period (m^3/mu); $C_{F,i}$ = cost fertilizer for crop i (see Table SI3) ($/mu).

Decision variables include the area of each crop planted and the amount of irrigation water applied to each crop in 10-day increments over its cultivation period. The model consists of 186 decision variables: 13 for land allocation to different crops, and the remainder for water allocation during each crop's cultivation period.

The decision variables and objective function are subject to a number of constraints to reflect the ground reality in Pixian. Our surveys show that farmers balance the goals of crop diversification and high profits. The objective function is constrained by the following:

1. Non-negativity: the area under a given crop must be greater than or equal to zero.

$$A_i \geq 0 \tag{3}$$

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[7] Defined as gross revenues from sales less the costs of cultivation.

2. Total land availability: the sum of the areas planted over all crops at any given time must not exceed the land area. This constraint is evaluated for every 10-day increment such that once a crop is planted it occupies that land area until its designated harvest date.

$$\sum_{i=0}^{n} A_{i,d} \leq A_{T,S} \tag{4}$$

where $A_{i,d}$ = Total land area allocated to crop i per day during 10-day interval d (mu); $A_{T,S}$ = Total land area in sub-section S (mu).

3. Irrigation requirement: the water applied to a given crop during any 10-day interval must be less than or equal to the irrigation requirement to achieve maximum yields.

$$ET_{m,i,d} \geq ET_{a,i,d} \geq 0 \tag{5}$$

where $ET_{m,i,d}$ = irrigation water requirement for crop i per day during 10-day increment d (m^3/mu); $ET_{a,i,d}$ = water applied to crop i per day during d (m^3/mu).

4. Water availability: the water applied to the total cropped area during each 10-day increment must be less than or equal to the water available in the canal during that period.

$$\sum_{i=0}^{n} A_{i,d} ET_{a,i,d} \leq Q_{d,R} \tag{6}$$

where $A_{i,d}$ = area of crop i planted during a given 10-day increment d (mu); $Q_{d,R}$ = quantity of water in irrigation system R during each d (m^3).

In addition, two (mutually exclusive) variants of the crop diversification constraint are modeled:

5. Crop diversification (“3C” scenario): at least three different non-grain crops (out of ten non-grain crops with overlapping cultivation periods), each with a minimum area of 0.1 mu per farmer, must be planted. This constraint prevents the model from allocating all land to the highest grossing crop, and represents the tendency of farmers to spread their risk over several crops. Extensive interviews in Pixian revealed that 0.1 mu is the smallest area of land that a farmer will dedicate to a given crop.

$$A_i \geq 0.1 N_{F,S} \tag{7}$$

and

$$\sum i_{0.1N_{F,S}} \geq 3 \tag{8}$$

where[8] $N_{F,S}$ = number of farmers served within sub-section S; $i_{0.1N_{F,S}}$ = number of crops with area greater than or equal to $0.1N_{F,S}$ mu.

6. Rice, rapeseed, wheat floor constraint (“RRW” scenario): in this variant the model must allocate a minimum land area to each of these staple crops. The minimum allocation is based on actual current cropping statistics from the PAB; the average fraction of land dedicated to these crops in towns across each irrigation system was determined and used as a multiplier. For example, in Xuyan 31% of land is dedicated to rapeseed from mid-September to mid-January. The RRW quota was once enforced in Pixian and remains a legacy cropping pattern with many farmers. This constraint can be relaxed, but including it renders results that are more consistent with observations on the ground.

$$A_{ri} \geq \beta_{ri} A_{T,S} \tag{9}$$

$$A_{ra} \geq \beta_{ra} A_{T,S} \tag{10}$$

$$A_w \geq \beta_w A_{T,S} \tag{11}$$

where A_{ri}, A_{ra}, A_w = area of rice, rapeseed and wheat, respectively; β_{ri}, β_{ra}, β_w = fraction land allocated to rice, rapeseed and wheat, respectively.

4. Results: BAU irrigation assessment

4.1. *Profitability and spatial equity*

The baseline model run confirmed common refrains among surveyed farmers such as, “there’s never enough water in the canals because of the upstream users,” and “my yields would increase 30 or 40% if I had enough water.” Indeed, irrigation water is insufficient for farmers to achieve full potential profits from the crops they plant, and decreases in profitability showed a head to tail location effect[9] (Fig. 2, Tables 3 and 4). For some crops, such as green onions and rice, enough water is available at the head of the canal for farmers to reap the full yield, but yields decrease at the tail (Fig. 2). For crops that are grown outside of the irrigation season, such as wheat, even at the head of the canals there is only enough water for a fraction of the potential profit, and that fraction continues to decrease with each subsequent sub-section (Fig. 2). The baseline model closely replicates actual crop patterns and yields in Pixian as reported by the PAB and found through our own surveys (Pixian Agricultural Bureau, 2007).

The RRW and 3C scenarios exhibit similar trends; however, potential profit is nearly double under the 3C constraints because the model replaced low value staple crops with the more profitable fall vegetables, green onions, and garlic. Under the RRW conditions, profits along the Xuyan canal were constant for the first two sub-sections and dropped by 19% between the second and final sub-sections. The corresponding drop under the 3C condition is about 12% (Table 3). The smaller drop can be explained by the 3C model opting not to cultivate rice, the most water intensive crop, thus causing less water stress on the system as a whole. Along the Zouma, profits under RRW were constant for the first three sub-sections but declined by 14% over the next three; profits in the 3C scenario decreased by 12% over the system (Table 4). The model assumes away the tendency of many farmers to over-irrigate

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[8] Sub-sections are the smallest unit of analysis, so farmers are not individually differentiated in the model.

[9] Locational asymmetry is a common phenomenon along irrigation systems, see Chambers (1980), Chakravorty et al. (1995), Ray and Williams (1999).

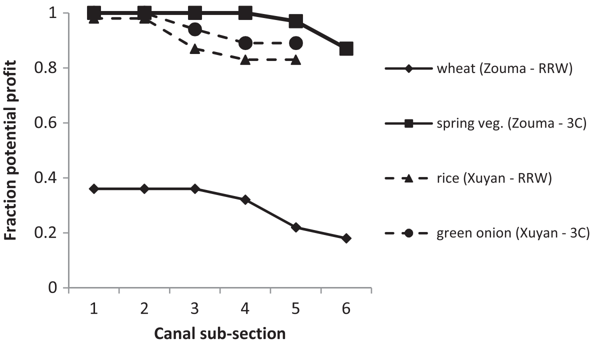

Fig. 2 – Fraction of potential profit earned for various crops grown along the Xuyan and Zouma canals.

their crops when they can; thus it underestimates the actual profit declines for both the RRW and 3C scenarios.

4.2. *Regional water management goals and objectives*

Despite the irrigation water shortage reported by farmers and revealed by the model, regional water management objectives would suggest that too much is currently extracted from local surface waters. ''Water resources in the city would be okay but too much is diverted to agriculture,'' according to the Vice Director of the Chengdu Environmental Protection Bureau. In response to the water quality guidelines in the 11th Five-Year Plan, the provincial government has required that two major rivers in the Chengdu Municipality, the Fu (fed by the Xuyan) and the Tuo (fed by the Zouma), achieve Class III[10] water quality standards by 2010. As of 2007, each river had sections that measured Class IV, V, and worse than V (Chengdu Environmental Protection Bureau, 2006). The government has concluded that they need to reduce the influx of pollutants and increase the flow of water in the rivers to restore their ecological health (Chengdu Water Bureau and Chengdu Planning Bureau, 2006). Thus, two distinct wastewater effluent reuse schemes warranted evaluation: one designed to supplement and the other to replace existing irrigation water. These scenarios are presented below, showing how each one would impact agricultural profitability, spatial equity, regional water management goals, and farmer satisfaction. The sensitivity of the model results to changes in several inputs, including wastewater availability and crop prices, was tested; selected results are presented in the Supplementary Information (Tables SI8, SI9).

5. Results: wastewater reuse simulations

5.1. *Agricultural profitability and spatial equity*

5.1.1. *Wastewater reuse to supplement existing irrigation*

Using urban wastewater to supplement the existing irrigation regimes had similar impacts on the two river systems, but the impacts varied depending upon the cultivation constraints. Under the RRW scenario, supplementing the canals with wastewater reduced the decline in profit per area from the head to tail of the Xuyan system from 19% to 2%, and reduced the standard deviation among the sub-sections from 28 to 7 (Table 3). Under the 3C scenario, supplementing the Xuyan with wastewater had a substantial impact on the lower reaches; from the second through fifth sub-section, the increase over the baseline scenarios went from 3 to 18% (Table 3). Under the more conservative RRW scenario, wastewater supplementation would add approximately $9.1 M annually in profits to the irrigation system, an increase of 12% over the baseline. This added profit would more than cover the cost of building new wastewater treatment plants (see Section 2.2), with the capacity to serve existing demand (a 10,000 m^3/d plant would cost $2 M), plus over 8 km of sewer pipes.

Along the Zouma canal, wastewater injection at subsection 2 was minimal and only apparent for the 3C scenario (Table 4). Wastewater made available in sub-sections 4 and 5 increased profits per area by up to nearly 15% and reduced standard deviation in profits among sub-sections from 24 to 8 and 56 to 39 in the RRW and 3C scenarios, respectively (Table 4). Assuming the economically conservative RRW constraints, supplementing the system with wastewater could add $12.5 M in profits to the irrigation system. As with the Xuyan, this could more than cover the costs of wastewater treatment infrastructure, and those costs may potentially decrease if nutrient removal were no longer a priority. Wastewater, strategically injected, could serve as a significant source of funding for debt service or on-going operation and maintenance (O&M) of wastewater treatment plants. Introducing a revenue stream from the end users of wastewater effluent would decrease the burden on governments and households to fully cover the costs of sanitation.[11]

5.1.2. *Wastewater reuse to replace existing irrigation scheme*

The wastewater replacement simulations revealed opportunities to offset a non-trivial amount of surface water for irrigation with the use of wastewater effluent, thus contributing to surface water conservation, ecosystem health, and Pixian's water quality goals. These simulations were run with and without storage facilities for the wastewater. Allowing storage substantially increased potential profits by better aligning water availability with seasonal demand for irrigation, and increased the amount of surface water that could be offset.

Along the Xuyan system, replacing surface water diversion with wastewater effluent can offset 17 Mm^3 of freshwater per year (Table 5). This amounts to nearly two-thirds of the initial water volume in the Xuyan system for Pixian, and would serve over 45,000 mu of land. Wastewater can serve all of Tangchang (in sub-section 1), Xinminchang (sub-section 2), and Xipu (in sub-section 5), as well as a substantial fraction of land in Ande (in sub-section 1) and Tuanjie (sub-section 4), without reducing farmers' profits by more than 10% under the RRW or 3C scenarios. The spatial equity along the canal would not

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[10] Surface water quality in China is measured on a scale from Class I to V, Class I being the best. See Table SI7.

[11] This option may have more traction outside of China given that in 2006 the Chinese government eliminated a 2600-year-old agricultural tax in an effort to narrow the gap between urban and rural incomes.

Table 3 – Comparison of profits earned from existing Xuyan irrigation system and that system supplemented with wastewater effluent. Wastewater is injected into each sub-section where 1 = head, 5 = tail. The impact of wastewater is greater for the RRW scenario; in both scenarios the standard deviation among towns is substantially decreased.

Sub-section	Baseline scenario			Wastewater supplement			
	Land (mu)	RRW[a] ($/mu)[b]	3C[c] ($/mu)	RRW ($/mu)	Δ from base (%)	3C ($/mu)	Δ from base (%)
1	28,740	327	802	334	+2	803	0
2	12,400	326	804	342	+5	831	+3
3	7970	308	766	331	+7	808	+5
4	13,030	281	711	327	+14	811	+12
5	9320	265	710	323	+18	806	+12
% change top to bottom		−19	−13	−2		+1	
Standard deviation		28	46	7		11	
Total additional profit to irrigation system (M$)				9.1		16.1	

[a] RRW = rice, rapeseed and wheat floor constraint. The minimum cropping requirement is equal to 0.74, 0.31, 0.35 total cultivated land in a town, respectively. The constraints are based on actual data from the towns.

[b] Conversion rate assumes 7 Chinese Yuan/$.

[c] 3C = minimum three non-grain crops must been planted, each with a minimum area equivalent to 0.1 mu per farmer served by the irrigation system.

improve with this scenario, as the standard deviation in profits would remain unchanged over the baseline situation (Tables 3 and 5). If farmers follow the RRW scenario, their profits may increase slightly (Table 5). The effluent storage requirement for this level of freshwater conservation ranges from approximately 0.14 to 0.65 Mm^3 for each town (Table 5). Under the existing irrigation scheme farmers already experience suboptimal yields due to water shortage (Fig. 2); thus Pixian decision makers must weigh the tradeoff between further profit loss to farmers and freshwater savings, and leverage wastewater reuse accordingly.

Along the Zouma canal, using wastewater generated in Ande and Pixian to irrigate fractions of land in those towns, as well as the downstream town Hongguang, there is potential to offset 19 Mm^3 of surface water diversion annually. This is 40% of the initial volume of water in the Zouma canals in Pixian (Table 6). In Ande, eliminating surface water for irrigation across 50% of the land area served by the Zouma may cause an 8% drop in profits (Table 6). However, this profit loss does not account for the potential decrease in fertilizer requirements. Conversely, serving 50% of Pixian's cultivated land and 100% of the land in Hongguang with wastewater effluent in place of

Table 4 – Comparison of profits earned from existing Zouma irrigation system and that system supplemented with wastewater effluent. Sub-section 1 = head, 6 = tail and wastewater is injected into sub-sections 2, 4 and 5 (in bold). The injection of wastewater largely eliminates the downstream location effect, and decreases the standard deviation among the towns.

Sub-section	Baseline scenario			Wastewater supplement			
	Land (mu)	RRW[a] ($/mu)[b]	3C[c] ($/mu)	RRW ($/mu)	⊿ from base (%)	3C ($/mu)	Δ from base (%)
1	9970	328	802	328	0	802	0
2	**15,980**	**328**	**802**	**334**	**+2**	**809**	**+1**
3	19,470	328	707	328	0	734	+4
4	**47,640**	**319**	**674**	**342**	**+7**	**782**	**+14**
5	**26,060**	**281**	**692**	**324**	**+13**	**712**	**+3**
6	1880	279	709	321	+13	799	+11
% change top to bottom		−14	−12	−1			
Standard deviation		24	56	8		39	
Total additional profit to irrigation system (M$)				12.5		24.8	

[a] RRW = rice, rapeseed and wheat floor constraint. The minimum cropping requirement is equal to 0.74, 0.22, 0.28 total cultivated land in a town, respectively. The constraints are based on actual data from the towns.

[b] Conversion rate assumes 7 Chinese Yuan/$.

[c] 3C = minimum three non-grain crops must been planted, each with a minimum area equivalent to 0.1 mu per farmer served by the irrigation system.

Table 5 – Towns along Xuyan irrigation system, shown from head to tail, with potential for wastewater reuse to replace surface water diversion for irrigation. Between 60 and 100% of the irrigated land in five towns served by the Xuyan system could be served by wastewater effluent (with storage) with a corresponding impact on profits between −8 and +1%.

Town	WW production (m^3/d)	Baseline cultivated land served (mu)	Cultivated land served by WW (mu)	RRW const. ($/mu)[a]	Δ from baseline profit (%)	3C const. ($/mu)	Δ from base profit (%)	Effluent storage req. (m^3; mu (with 10 m reservoir depth))
Tangchg.	2.34×10^3	12,770	12,770	312	−4	697	−8	2.34×10^5; 35
Ande	1.47×10^3	15,980	8000	315	−4	731	−9	1.85×10^5; 28
Xinmin.	3.83×10^3	12,400	12,400	327	+1	778	−3	6.5×10^5; 98
Tuanjie	1.37×10^3	13,030	12,000	270	−2	653	−8	1.4×10^5; 21
Xipu	4.34×10^2	1880	3000[b]	334	+4	690	−3	0
Std. deviation				24		47		
Total land offset (mu)					48,170			
Total water offset (m^3/yr)					1.7×10^7 (64% of baseline volume)			

a Conversion rate assumes 7 Chinese Yuan/$.

b Xipu has a total of 5640 mu cultivated land served by three irrigation systems; urban wastewater would offset approximately two-thirds of the total irrigated land.

surface water could increase farmers' profits by 16% (Table 6). This scheme would substantially improve spatial equity along the canal, reducing the standard deviation among the towns for the RRW and 3C scenarios (Table 4 and 6). If farmers behave as predicted by the model, wastewater reuse would not require any storage in Pixian and would require 0.17 and 0.28 Mm^3 of capacity in Ande and Hongguang, respectively (Table 6).

5.1.3. *Water use patterns with existing conditions and alternative reuse scenarios*

Under the wastewater supplementation scenario, the model retained existing temporal irrigation patterns but applied more water on any given date (Fig. 3). Conversely, the wastewater replacement scenario affords less water per area at a given time but water is available year-round; thus enabling an additional peak irrigation period when water would otherwise be unavailable (Fig. 3). Where the climate is conducive to year-round agriculture, making water available outside of the peak irrigation season enables farmers to smooth their risk as well as their earnings over the course of the year.

5.2. *Regional water management goals and objectives*

The scenarios in which wastewater effluent supplements existing irrigation could have a debilitating effect on local surface water quality by decreasing the flow of water within the Pixian reaches; the rivers currently receive untreated wastewater. Conversely, the scenarios in which wastewater effluent replaces surface water diversions are compatible with regional water management objectives, as long as the irrigation water that is offset is conserved in the local rivers and not diverted for another purpose. The modeled wastewater reuse scheme along the Xuyan irrigation canal would facilitate an increase in flow in the Fu River from 0.2 to 6.3 m^3/s, with an average increase of about 1.1 m^3/s (Fig. 4). Implementing the modeled reuse scheme along the Zouma irrigation canal would facilitate a flow increase in the Tuo River ranging from 0.2 to 7.1 m^3/s,[12] (Fig. 4).

6. Discussion

The planning model results reveal many options for designing wastewater reuse schemes, each with different impacts on agricultural profitability, spatial equity, regional water management goals, and farmer satisfaction (Table 7). For some scenarios, there is a tradeoff between improved profitability and spatial equity in agriculture versus broader regional water quality goals (Table 7).

6.1. *Prioritizing agricultural profitability and spatial equity*

In 2006, the State Council published a document on the "Building of a New Socialist Countryside" that began a shift away from policies that burden rural inhabitants to policies that subsidize their livelihoods, such as eliminating taxes and cultivation quotas (OECD, 2006; Huang et al., 2007). If improving local livelihoods is a priority of the Pixian government, supplementing the existing Xuyan irrigation scheme would yield the greatest percentage increase in farmer profits over the BAU scenario (see Table 3). Thus, the Xuyan system appears to be a wise pilot location for wastewater reuse as supplemental supply; it would enhance farm livelihoods without exacerbating the earning differential among farmers in the district as a whole.[13] As indicated in Table 7, the decision to supplement existing irrigation with wastewater effluent will detract from regional water management goals. A reuse scheme that supplements rather than substitutes one source of water for

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[12] Additional water conservation measures may still be required to achieve the desired water quality.

[13] A course topographic analysis shows a gradual decline in elevation from northwestern to southeastern Pixian. Prior to pursuing this (or any) reuse option, it is important to conduct a detailed analysis of the costs and feasibility of conveying the wastewater to the fields.

Table 6 – Towns along Zouma irrigation system, shown from head to tail, with potential for wastewater reuse to replace surface water diversion for irrigation. Between 50 and 100% of the irrigated land in three towns served by the Zouma River system could be served by wastewater effluent with a corresponding impact on profits between −3 and +16%.

Town	WW production (m^3/d)	Baseline cultivated land served (mu)	Cultivated land served by WW (mu)	RRW const. ($/mu)[a]	Δ from base profit (%)	3C const. ($/mu)	Δ from baseline profit (%)	Effluent storage req. (m^3; mu (with 10 m reservoir depth))
Ande	1.47×10^3	15,980	8000	318	−3	736	−8	1.7×10^5; 26
Pixian	1.26×10^4	21,080	10,540	334	+16	698	+2	0
Hongguang	WW from Pixian	26,060	26,060	334	+16	698	+2	2.8×10^5; 41
Xipu	4.34×10^2	1880	3000[b]	334	+4	690	−3	0
Standard deviation[c]				6		41		
Total land offset (mu)					47,600			
Total water offset (m^3/yr)					1.9×10^7 (40% of baseline volume)			

a Conversion rate assumes 7 Chinese Yuan/$.

b Xipu has a total of 5640 mu cultivated land served by three irrigation systems; urban wastewater would offset approximately two-thirds of the total irrigated land.

c Calculated among all towns (sub-sections) including those where wastewater is not used to replace existing irrigation water.

another must be recognized as a reallocation of water and not the creation of an additional supply.

6.2. *Prioritizing regional water management goals and objectives*

The Pixian government may prioritize regional water management objectives rather than higher agricultural profits. This would suggest capitalizing on wastewater reuse as a means of offsetting surface water irrigation. If the schemes were to be implemented as modeled, a slightly greater water savings is possible in the Zouma. Counter to expectations, the model simulations show that wastewater replacement with storage in the Zouma would not only conserve surface water, it would increase farmers' profits over the BAU scenario by increasing the total water availability over the course of the year, thus enabling an additional peak irrigation period (Table 6).

It is unlikely that the modeled schemes could be implemented in their entirety at once. The model results show that, along the Zouma, the construction of one treatment plant and conveyance system in the core of Pixian would reap most of the potential surface water offset that is available over the canal as a whole. As shown in Table 6, wastewater generated in Pixian's core could serve half of Pixian township's and all of Hongguang's agricultural land. This single wastewater treatment and reuse project would facilitate conservation of nearly 80% of the total potential surface water offset for the Zouma River.

6.3. *Applicability and limits of the model*

The planning model developed here is designed to provide an accessible means for sanitation planners to evaluate the impacts that wastewater reuse would have on local agriculture and regional water management. It can inform and guide the design of sanitation systems that serve local economies and simultaneously achieve the environmental and health benefits of improved sanitation. Some components of the decision-support model may require modification for applications in other regions.

Crop choices and calendars must be site-specific. This version of the model is based on the crops currently grown in Pixian. The model is not equipped to show if or to what extent farmers might shift to entirely new crops that only become profitable with the introduction of wastewater. If a shift occurs, the injected wastewater may not reach as many farmers as currently predicted by the model, and therefore may not have the effect on spatial equity that the results indicate. If farmers grow crops that require extended irrigation, but which do not consume more water overall, it need not undermine spatial equity. Given data availability, the model can easily be modified

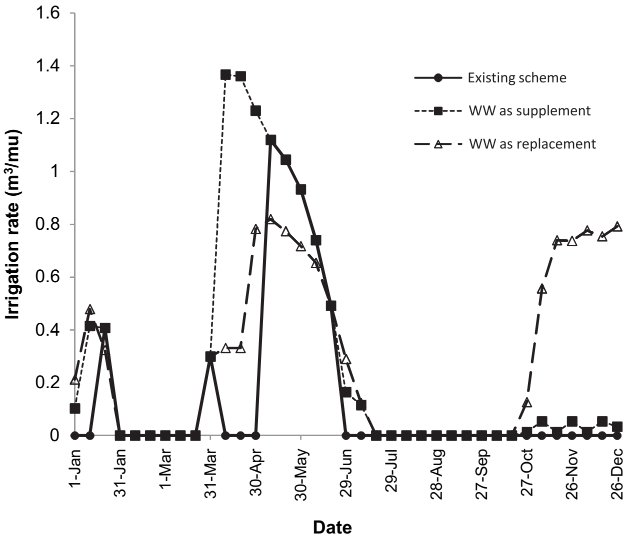

Fig. 3 – Irrigation patterns for Hongguang (sub-section 5) in the Zouma irrigation system under three model scenarios: existing, existing supplemented with wastewater effluent, existing replaced by wastewater effluent. The model evaluates water use and availability over a 1-year period and the resultant trends are a function of the strict crop calendars that comprise the model, and water storage decisions made by the model under the "wastewater as replacement" scenario.

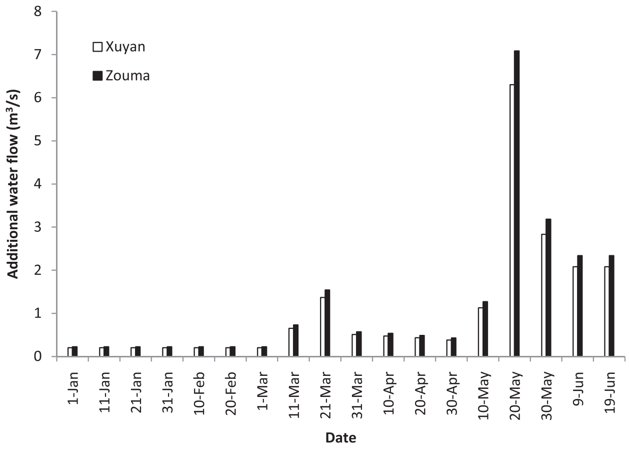

Fig. 4 – Daily additional water flow (in 10-day intervals) that could be achieved in the Fu and Tuo Rivers as a result of conserved water diversion from the Xuyan and Zouma Rivers, respectively, if wastewater effluent were to replace surface water for irrigation. No water is diverted for irrigation between June 29th and December 31st.

to include additional crops that are not feasible to grow now but may become feasible with more water.

The absence of a labor constraint is a simplification of the model that was justified in the context of Pixian, where water is more likely than labor to be the limiting factor in terms of cultivation choices. It is a simplification that is likely transferable throughout much of China, given the small landholdings of rural Chinese households. In regions with larger farms, the cost of, and access to, labor could become a binding constraint, and thus should be included in the model.

7. Conclusions and Recommendations

Planning models such as the one developed here offer a practical process for designing sanitation systems for reuse. Simple models, which clearly reveal the costs and opportunities associated with reuse, and that are easy to understand and adapt, have potential to take IWRM to scale.

Table 7 – Impact of modeled reuse scenarios on four performance indicators. A "+" represents a positive impact; "−" represents a negative impact; "o" represents no expected impact; and +/− represents potential mixed impacts. Canals are ranked within each reuse scenario; "++" is the most positive, "− −" is the most negative.

	Profitability	Spatial equity	Regional water management goals	User (farmer) satisfaction
Wastewater supplementation				
Xuyan canal	++	++	−	+/−
Zouma canal	+	+	−	+/−
Wastewater replacement				
Xuyan canal	o	+	+	+/−
Zouma canal	+	++	++	+/−

This paper developed the first hybrid performance assessment – decision-support model for the optimal reuse of wastewater for irrigation. The coupled performance assessment and optimization model revealed tradeoffs and benefits associated with implementing agricultural reuse in Pixian. Using wastewater effluent for irrigation could add more than $20 M in additional profits for farmers within the Xuyan and Zouma irrigation systems, or conserve over 35 Mm^3 of surface water in local rivers every year. These benefits would never be realized or captured under planning processes that favor conventional, disposal-oriented wastewater treatment schemes. Furthermore, the application of this model is in direct pursuit of policy goals of the Chinese government. In addition to the wastewater treatment expansion goals of the 11th Five-Year Plan, the People's Republic of China Water Law amended in 2002 embraces the IWRM concept and specifically promotes wastewater reuse (National People's Congress, 2002).

The scarcity of funds to support the on-going O&M of wastewater treatment plants is a major barrier to the expansion of sanitation facilities in China and elsewhere. Designing facilities for reuse in agriculture is one way to harness the resource value of wastewater, and part of that value can be captured in the form of "end-user" fees to the treatment plant in order to help finance its operation. Beyond Pixian and beyond China, there is enormous opportunity for incorporating tools and techniques that are traditionally affiliated with the agricultural sector into sanitation planning processes. The use of such methods and tools by sanitation experts and decision makers can help to realize the objectives of IWRM, particularly between the natural allies that are the wastewater and agricultural sectors.

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Appendix.
Supplementary material

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.watres.2009.11.028.

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