Evaluation of the Jinan City Water Ecological Development Implementation Plan and Recommendations for Improvement

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For more information on this publication, visit www.rand.org/t/RR1682
The Jinan Municipal Water Resources Bureau, with support from the Shandong Provincial Department of Water Resources, asked RAND to evaluate potential effects of demand and climate uncertainties on new investments intended to meet the region’s water resources goals. RAND’s approach uses well-tested methods of decision support, starting with building a shared understanding of the nature of the decision, metrics to evaluate progress toward goals, key uncertainties that drive outcomes, and relevant physical and other relationships within Jinan’s complex water system. The approach also uses visualizations to help policymakers understand the implications of the results, build consensus, and facilitate decision making.

This document describes RAND’s full approach and results, including the development of a mathematical simulation model of the Jinan water system and analysis of the system’s performance under a range of uncertainties about future climate and demand across sectors.

**RAND Infrastructure Resilience and Environmental Policy**

The research reported here was conducted in the RAND Infrastructure Resilience and Environmental Policy program, which performs analyses on urbanization and other stresses. This includes research on infrastructure development; infrastructure financing; energy policy; urban planning and the role of public–private partnerships; transportation policy; climate response, mitigation, and adaptation; environmental sustainability; and water resource management and coastal protection. Program research is supported by government agencies, foundations, and the private sector.

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Summary

In 2012, China’s Ministry of Water Resources designated Shandong Province’s capital of Jinan as the pilot city for National Water Ecological Civilization Development. Jinan has a population of 7,067,900 and covers 8,177 square kilometers, with agricultural and rural lands surrounding an urban core. The Provincial Government of Shandong subsequently approved the Pilot Scheme for Water Ecological Civilization Construction in Jinan City. Its purpose was to help Jinan achieve several goals, including increasing the reliability of its water supply, increasing water use efficiency, improving water quality, improving aquatic ecosystem health, and reducing damage from flooding. By fall 2016, most of the construction under the Pilot Scheme was completed.

Understanding how Jinan’s complex hydrologic system of both surface and groundwater supply sources might perform in the coming decades is particularly important for sustainable economic development in Jinan. In fact, anticipation of future needs beyond the next few years has been standard practice in water resources planning for many years, and China has been a leader in this kind of thinking. This has served the region well, but as the city’s water needs approach—and in some cases exceed—the available supplies, large uncertainties about future conditions become increasingly important. Specifically, the possibility of changes to the region’s climate, coupled with uncertainty in how demand may grow, make it very difficult to predict with precision what investments will be needed in the coming years.

In this spirit, the Jinan Municipal Water Resources Bureau (JWRB), with support from the Shandong Provincial Department of Water Resources (DWR), asked the RAND Corporation to combine qualitative and quantitative methods to assess the possible outcomes of the “Jinan Water Ecological Civilization Development Pilot Implementation Plan (2013–2015)” and provide recommendations for improvement and priorities for long-term investment and management. To support JWRB’s request and its goal of building a scientific and high-quality water management system, RAND developed a technical road map to address the following questions:

- How will future demand and climate conditions challenge Jinan’s system?
- How will JWRB’s Implementation Plan (IP) address future climate and other uncertainties?
- What actions could be taken to reduce vulnerabilities and increase the robustness of Jinan’s system?

Robustness means that the Jinan water system will perform well over a wide range of possible future climate, demand, and other uncertain conditions. This report summarizes RAND’s approach, findings, and recommendations.
**Technical Road Map**

RAND utilized an innovative and scientifically sound approach to analysis that is particularly well suited for considering long-term challenges to the performance of a regional water management system when large uncertainties are present about future condition. In this case, the study considered uncertainties about climate change, fluctuations in demand across sectors throughout the Jinan service area, and the effectiveness of proposed management strategies, particularly related to efficiency improvements and water quality. The approach is called Robust Decision Making (RDM). It can be described as a vulnerability-based framework in contrast to a more traditional “predict-then-act” approach that typically seeks optimal improvements to a system under a limited set of future conditions or scenarios. We thus use climate science, for example, to inform Jinan’s future vulnerabilities to climate change, but we do not use climate model results to predict the future. In previous applications supported by the World Bank, the U.S. Bureau of Reclamation, and other organizations, RDM has been used to help decision makers reach consensus even when they disagree on future expectations, reduce their overconfidence in results based on a limited number of scenarios, manage surprise, and use quantitative analysis in situations when key data are missing or imprecise.

RAND’s technical road map therefore includes the following elements:

- Introduce RDM as an innovative approach to water resources planning under uncertainty.
- Demonstrate the use of a water-balance simulation model of the Jinan water management system with RDM to understand future vulnerabilities.
- Demonstrate how results from an RDM analysis can help identify strategies that may lead to a more robust plan.
- Demonstrate how uncertainties about future climate can be used in analysis of flood frequency.
- Build capacity within JWRB to apply these methods in future work.

With respect to capacity building, RAND built and ran a simulation model and then transferred it to JWRB for future use, built and demonstrated use of a decision support tool and then transferred that to JWRB for future use, trained JWRB staff to use the model and tool, and identified priorities for future data collection and analysis.

It should be noted that our focus was on introducing Jinan to a new and innovative approach to analysis of future water needs. Beyond the development of the Jinan Water Evaluation and Planning (WEAP) software model that could be refined and further improved in the future, JWRB and RAND agreed at the outset of the project that other hydrologic systems modeling was not feasible because of lack of sufficient data of good quality and lack of time.

**Robust Decision Making**

RDM is an approach to long-term planning when the future is deeply uncertain. RDM was developed at RAND to identify strategies for complex systems that perform well under a wide range of possible future conditions. Traditional engineering design methods are not appropriate in the presence of “deep” uncertainties, such as global climate change and future demand, as is the case across sectors and districts in Jinan. Deep uncertainty exists when there is no
justifiable basis for selecting a probability distribution to describe a physical process and, consequently, no justifiable basis for using probabilities to predict future outcomes. It is possible, however, to establish a basis for bounding the range of uncertainty for a given process, such as expected changes in annual precipitation or temperature, and then exploring the performance of a water system across that range to identify circumstances when the system may not be able to meet future demand. We call the process of exploring the performance of a system over a wide range of possible future conditions a vulnerability assessment.

In this particular application of RDM, we followed a simple linear approach, shown in Figure S.1. In more extensive studies, we represent RDM as an iterative process with feedbacks to earlier steps.

An example helps to explain the difference between RDM and more-traditional engineering analysis. Suppose a new reservoir is to be built to increase storage in the Jinan system. How large should the reservoir be, how should it be operated, and what is the basis for these decisions? In a traditional analysis, planners and engineers might typically use one estimate of projected demand along with historical data on climate fluctuations to make a determination about the optimal additional storage and operating rules required to meet the assumed level of future demand. They would then most likely conduct a sensitivity analysis by varying the level of assumed future demand and add a “margin of safety” factor to reduce the risk of failure.

In contrast, RDM takes advantage of inexpensive computing power to consider many different futures and a large number of potential strategies. Planners using RDM would simulate system operations to determine which climate and demand conditions cause shortages in the current system (the vulnerability analysis), then identify several different reservoir sizes and operational strategies, simulate operations, and determine the extent to which shortages would be reduced under the different potential sizes and strategies. Finally, decision makers would choose a design storage capacity that does best under a wider, but still plausible, range of future conditions.

Figure S.2 shows the implications of these two different approaches. In this hypothetical example, the vertical axis represents unmet demand in the system as a whole. The hori-
Horizontal axis represents different assumptions about how aggregate demand may change in the future relative to current demand. (Another example could have shown the horizontal axis as changes in precipitation relative to historical averages.) A value of zero means that demand in the future, say in 2030, is the same as demand in the present. The blue line represents the performance of the current system. The red line represents the performance of a proposed reservoir whose design storage capacity (X) was determined by a traditional method that sought to optimize reservoir capacity based on an assumption that future climate conditions would be the same as historical ones. The traditional method does very well under the assumption that demand in the future will be less than demand in the present, for example, as a consequence of efficiency measures. However, its performance would not be satisfactory if demand did not decline as expected and instead turned out to increase in the future.

In contrast, the green line shows the performance of the system with a reservoir with the same capacity as before but, in this case, additional investments in interconnections or changes in operations throughout the system are considered. The performance of this option is better under a wider range of demand conditions and may be more appealing to decision makers as a way to minimize future risk.

**Define Scope of Analysis**

In a series of workshops with the JWRB team, RAND used a structured decision-framing approach to gain consensus on goals and metrics, key uncertainties that might bear on future outcomes, strategies for improving the performance of the system over the long term, and the mathematical models to represent Jinan’s water management system. These are the essential building blocks of RDM.
Table S.1 summarizes the essential features of the decision analysis for Jinan.

**Key Uncertainties**

We developed a large set of futures to reflecting uncertainty in demand, climate conditions, allocation of Yellow River resources, and initial groundwater storage levels, as shown in the upper left box of Table S.1. These were uncertain factors that we hypothesize to be most critical but also within our capability to model at this time.

To capture uncertainties in future demand across residential, industrial, and agricultural sectors in the seven districts, we identified three demand projections representing low, medium, and high aggregate growth in demand. Most of these projections were provided to us by JWRB. On request by JWRB, the High Demand projection for the residential sector corresponds to water use rates for New York City.

To generate future climate projections, we first developed one based on historical data provided to us by JWRB (see Appendix A), which we refer to as the Historical Climate projection. We drew on 34 unique general circulation (climate) models developed in research laboratories throughout the world to generate 106 projections of precipitation and temperature to 2050. These projections are based on different emissions scenarios that can then be used to estimate changes in river flows, groundwater recharge, and irrigation demand across a range of climate model simulations. We then chose a subset of 26 climate projections (defined by model and emissions scenarios) because of their representation of the full span of precipitation and temperature effects generated from the climate models. Over the period from 2000 to 2050, changes in precipitation are estimated to range from −100 millimeters (mm) to almost 300 mm annually; changes in temperature are estimated to range from 0.5 to more than 4 degrees Celsius over the entire period. We also considered two different assumptions about future allocations from the Yellow River (50 and 100 percent of the planned future allocation) and initial groundwater storage.

To explore the range of uncertainty as fully as possible, we defined one future for each combination of:

- 3 future demand projections
- 26 future climate projections + Historical Climate projection

**Table S.1**

**Summary of Key Factors in the Analysis**

<table>
<thead>
<tr>
<th>X: Uncertainties</th>
<th>L: Management Strategies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Future water demand</td>
<td>Completion of remaining IP projects</td>
</tr>
<tr>
<td>Residential, industrial, and agricultural growth</td>
<td>Increased efficiency</td>
</tr>
<tr>
<td>Water use rates</td>
<td>Residential and industrial</td>
</tr>
<tr>
<td>Climate change effects on water supply</td>
<td>Water reuse</td>
</tr>
<tr>
<td>Inflows</td>
<td>Adaptive groundwater management for springs</td>
</tr>
<tr>
<td>Groundwater recharge</td>
<td>Improve Xiaoqing River water quality to allow resource utilization</td>
</tr>
<tr>
<td>Agricultural demand</td>
<td>Reduced sensitivity of irrigated agriculture to climate changes</td>
</tr>
<tr>
<td>Water allocation from the Yellow River</td>
<td></td>
</tr>
<tr>
<td>Initial groundwater storage</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>R: Relationships</th>
<th>M: Performance Metrics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water management model (WEAP software)</td>
<td>Unmet water demand</td>
</tr>
<tr>
<td>Flood risk analysis (without modeling)</td>
<td>Residential, industrial, and agricultural</td>
</tr>
<tr>
<td></td>
<td>Flow rate at Baotu Springs</td>
</tr>
<tr>
<td></td>
<td>Groundwater levels</td>
</tr>
<tr>
<td></td>
<td>Achievement of water quality standards</td>
</tr>
<tr>
<td></td>
<td>Recurrence intervals of extreme flood events</td>
</tr>
</tbody>
</table>
• 2 Yellow River resource allotments
• 2 initial groundwater levels.

In total, we thus developed 324 futures. We ran these futures through the WEAP model to generate 324 cases that we then used to evaluate 16 different management strategies, including the system as currently configured.

Management Strategies
We considered how new projects and policies (collectively called strategies), extending beyond the current IP, could improve performance of the Jinan system over the long term. These included five projects at or near completion and two others for water supply expansion. Our analysis also considered broader management changes based on vulnerability to unmet demand identified in the system after completion of the IP. Options include:

• additional interconnections
• increases in water reuse across sectors
• increases in water use efficiency across sectors
• groundwater management that responds dynamically to changing spring levels
• increase industrial supply by drawing from the Xiaoqing River if water quality standards are met.

Table S.2
Strategies Evaluated as Part of the Experimental Design

<table>
<thead>
<tr>
<th>Strategy</th>
<th>Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Current Projects</td>
</tr>
<tr>
<td>2</td>
<td>Completion of IP</td>
</tr>
<tr>
<td>3</td>
<td>IP and Increased Water Reuse (IPR)</td>
</tr>
<tr>
<td>4</td>
<td>IPR + Springs Adaptive Groundwater Management (SAGM)</td>
</tr>
<tr>
<td>5</td>
<td>IPR + Water Quality (WQ)</td>
</tr>
<tr>
<td>6</td>
<td>IPR + WQ + SAGM</td>
</tr>
<tr>
<td>7</td>
<td>IPR + Residential Efficiency</td>
</tr>
<tr>
<td>8</td>
<td>IPR + Residential Efficiency + SAGM</td>
</tr>
<tr>
<td>9</td>
<td>IPR + Residential and Industrial (Res/Ind) Efficiency</td>
</tr>
<tr>
<td>10</td>
<td>IPR + Res/Ind Efficiency + Agricultural Climate–Induced Efficiency (IPR + EffAll)</td>
</tr>
<tr>
<td>11</td>
<td>IPR + EffAll + SAGM</td>
</tr>
<tr>
<td>12</td>
<td>IPR + EffAll + WQ</td>
</tr>
<tr>
<td>13</td>
<td>IPR + EffAll + WQ + SAGM</td>
</tr>
<tr>
<td>14</td>
<td>IPR + 50-Percent Efficiency (IPR + 50Eff)</td>
</tr>
<tr>
<td>15</td>
<td>IPR + 50Eff + WQ</td>
</tr>
<tr>
<td>16</td>
<td>IPR + 50Eff + WQ + SAGM</td>
</tr>
</tbody>
</table>
Because management actions do not work in isolation, we modeled strategies that incrementally increase the adaptations that JWRB could pursue. We developed a total of 16 possible strategies, including the current state of the Jinan system, summarized in Table S.2.

The Current Projects strategy refers to IP projects that have already been implemented, in addition to any scheduled changes in water supply due to policy. Two additional IP pipeline projects, as yet unconstructed, were identified as having the greatest potential effect on the system. These two projects are collectively denoted as “IP” in Table S.2. The WQ strategy represents a strategy of allowing industry to draw and treat water from the Xiaoqing River under the assumption that water quality standards for the river would be met by 2030. The SAGM policy represents an aggressive response to declining spring levels at the four largest springs in central Jinan.

Finally, we evaluated different efficiency standards to highlight the effect of water use rates on demand and unmet demand in Jinan. These standards were represented as percentage decreases in water use rates (residential and industrial sectors) or climate effects on demand (agricultural sector) by 2035. For each sector, efficiency standards were evaluated at a 100-percent implementation level (full implementation) and a 50-percent implementation level. For each sector and demand scenario, efficiency reduction targets were made on top of the previously projected water use rates. In the agricultural sector, increased efficiency was only applied to futures where demand increased as a consequence of climate change. In scenarios where demand increased under full implementation of an efficiency strategy, the increase in demand attributable to climate change was reduced by 50 percent. Under the 50-percent implementation, the increase in demand attributable to climate change was reduced by 25 percent.

Goals and Metrics
Jinan’s key management goals and metrics are summarized in Table S.3.

Relationships
The WEAP model described in this section generates performance metrics for the system as a whole and by sector and district. In a later section, we describe our approach to gaining some basic understanding of how flood frequency might shift as a consequence of a changing climate.

Development of a Jinan WEAP Model and Its Use With RDM
A WEAP model was developed to capture the long-term accounting of inflows, outflows, and changes in storage in the Jinan water management system as a key tool for understanding vulnerabilities of the system to future climate, demand, and other potentially important uncertainties that would affect supplies and demands over time. The WEAP simulation model

Table S.3
Summary of Key Performance Metrics

<table>
<thead>
<tr>
<th>Goal</th>
<th>Metric</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reliable and sustainable water supplies for all uses, including ecological flows</td>
<td>Unmet demand</td>
</tr>
<tr>
<td>Sustainable flows at Baotu Springs</td>
<td>Frequency of meeting or exceeding target water level</td>
</tr>
<tr>
<td>Sustainable groundwater use</td>
<td>Groundwater levels</td>
</tr>
<tr>
<td>Water quality</td>
<td>Frequency of not meeting the standard</td>
</tr>
<tr>
<td>Reduce flood damage</td>
<td>Change in recurrence intervals of extreme flood events</td>
</tr>
</tbody>
</table>
estimates demands and supplies over time on a monthly basis using historical data. The model represents Jinan’s actual physical system of reservoirs, interconnections, wells, rivers, streams, and water uses spread throughout the region through a set of supply nodes, demand nodes, storage nodes, and connections (arcs). Nodes represent locations of water inflows, storage (surface or groundwater), outflows, and demand centers. Arcs represent conveyance, either natural or constructed, between different nodes.

Figure S.3 outlines the process of analysis. RAND received data and other information from JWRB, enabling us to develop a schematic of the Jinan water system, using the WEAP software platform. The purpose of using WEAP was to analyze the effects of proposed projects and policy strategies across a wide range of possible future climate and demand projections that could reduce future vulnerabilities. Our focus was on longer-term trends, spanning the period between the present and 2050, and the implications of these trends for future investment decisions and water management in Jinan. RAND and JWRB also worked collaboratively to enhance JWRB’s ability to use modeling and decision support tools independent of RAND.

The Jinan WEAP model represents seven districts in Jinan: (1) Changqing District; (2) Licheng District; (3) Jiyang County; (4) the Jinan Urban Center, which is composed of Lixia, Shizhong, Tianqiao, Huaiyin, and (where applicable) Gaoxin districts; (5) Pingyin County; (6) Shanghe County; and (7) Zhangqiu District. These districts and counties are each associated with agricultural, industrial, residential (urban and rural), and other demands and their sources of supply, including groundwater and government-set allotments from the Yellow River. RAND used Tableau, a commercially available visualization software package, to assimilate output from the WEAP model, perform analyses and comparisons, and develop graphics for this report and more-detailed exploration of the results for JWRB.

**Figure S.3**  
Use of WEAP Within RDM Approach
Baseline Evaluation of Vulnerability of Current System Assuming Historical Climate Projection

Our focus in this analysis was to understand how different assumptions about the level of future demand growth across residential, industrial, and agricultural sectors could affect the supply system’s ability to meet those demands in each of the seven districts. For this baseline evaluation, we assumed the historical configuration of facilities and policies would remain in place until 2050 and that historical patterns of climate conditions would extend into the future. We also assumed that the volume of groundwater in storage was large enough to provide water as needed and therefore not be a binding constraint on available groundwater supply. Finally, we assumed that Current Yellow River Allocations would remain in place.

We expect that Jinan’s water system will evolve through 2050 in response to changing water demands, climatic changes, and adjustments to availability of groundwater and Yellow River Allocations. In this first stage of our analysis, we show where and when such adjustments might be necessary under historical patterns of climate conditions and assumptions of a continuation of current infrastructure and management. Note that demand and supply preferences were set within the Jinan WEAP model following multiple discussions with the JWRB technical team. Demand priorities have the general structure of residential, followed by spring flows in Jinan, industry, and lastly, agriculture. Supply preferences vary by sector and district.

Figure S.4 shows that significant levels of total unmet demand across sectors should be expected in the future under the assumed High Demand conditions. The Low and Medium Demand projections are derived from information provided by JWRB information. The High Demand case includes a residential High Demand projection consistent with per capita usage.

Figure S.4
Total Unmet Demand for Historical Climate Under Two Assumptions of Initial Groundwater Storage for the Three Demand Scenarios

NOTE: GW = groundwater.
rates in New York City. The High Demand projection also reflects high growth assumed in the industrial sector. To provide a sense of the scale of unmet demand, 400 million cubic meters (MCM) of unmet demand is about 20 percent of the total Low Demand projection of 1,800 MCM in 2030.

Results suggest that beyond 2025, the current Jinan water management system cannot accommodate all the demand growth under the Historical Climate projection, particularly in the Medium and High Demand projections. The vast majority of unmet demand would occur in the Jinan Urban Center and Zhangqiu District. Agricultural unmet demand is relatively low, as ample surface and groundwater supplies are available in the districts in which agriculture dominates.

**Evaluation of Vulnerabilities Across Future Climate Projections**

In the next stage of analysis, we analyzed future performance of the Jinan system under a range of future climate conditions, demand conditions, two different allocations of supply from the Yellow River, and two assumptions about initial groundwater storage. This helps to identify the most significant vulnerabilities in unmet demand that appear to be present in the system. It also provides insight into the ability of Jinan’s current water management infrastructure to meet potential future demands under a changing climate.

Figure S.5 shows a summary of results. Red symbols indicate futures in which the residential sector is vulnerable; green symbols are results for the residential sector that are not vulnerable. Here, we define futures to be vulnerable if average unmet residential demand from

![Figure S.5](image-url)

**Figure S.5**

*Summary of Unmet Residential Demand and Vulnerability Across All Futures and Groundwater Assumptions*

<table>
<thead>
<tr>
<th>Yellow River Allocation:</th>
<th>Low Demand</th>
<th>Medium Demand</th>
<th>High Demand</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Current 50%</td>
<td>Current 50%</td>
<td>Current 50%</td>
</tr>
<tr>
<td></td>
<td>Not Vulnerable, Large Initial GW storage</td>
<td>Not Vulnerable, Low Initial GW storage</td>
<td>Vulnerable, Large Initial GW storage</td>
</tr>
</tbody>
</table>

**NOTE:** The red X symbols indicate futures in which the system is vulnerable and the filled green circles indicate futures in which the system is not vulnerable, depending on the threshold for vulnerability chosen.
2031 to 2050 is more than 5 percent of demand.\footnote{For purposes of illustration, the threshold for unmet residential demand was chosen to be 30 MCM.} Lighter shades of red and green are results for the assumption of Low Initial Groundwater Storage. The symbols within each column are ordered by decreasing average precipitation (wetter to drier) within each column, showing that drier climates lead to higher unmet demand. This figure shows that the residential sector is highly vulnerable under the High Demand projection. The vulnerability is even greater when the Yellow River Allocation is decreased. Vulnerability is also greater under all futures with Low Initial Groundwater Storage (lighter symbols).

Results vary across sectors. The residential sector is only vulnerable to the High Demand projection and the Low Initial Groundwater Storage assumption. For the industrial sector (not shown in Figure S.5), when Yellow River allotments are reduced by 50 percent or there is High Demand, the industrial sector is always vulnerable. Under the Medium Demand scenario and Full Yellow River Allocation, the industrial sector is vulnerable only under the Low Initial Groundwater Storage assumption. Future climate exacerbates the industrial sector vulnerability but is not a driving factor. In contrast, the vulnerability of the agricultural sector (also not shown in Figure S.5) depends upon the future climate more than the residential and industrial sectors. Since agriculture uses groundwater as a key source, there is no vulnerability under the Large Initial Groundwater Storage assumption. With the Low Initial Groundwater Storage assumption, however, vulnerability is seen in most demand futures and those with a 50-Percent Yellow River Allocation. The climate effect is very strong as well, with no shortages in the wettest climates but very significant shortages in drier climates.

We also explored the vulnerability of the springs and groundwater. Jinan’s springs are an important source and symbol of the sustainability and quality of Jinan’s water supply. The springs are highly vulnerable to the climate projections and insensitive to the demand projections, Yellow River allotment, and initial groundwater storage. Groundwater basin storage is highly sensitive to the climate projections when the initial storage is assumed to be very large. In effect, the groundwater basins absorb most of the climate sensitivity, a reason why we do see climate effects (in the form of unmet demand) in the residential and industrial sectors. When initial groundwater storage is assumed to be limited, however, the basins are fully depleted and the climate variation is seen in unmet demand across sectors.

**Comparison of Strategies to Reduce Vulnerabilities**

In the final stage of analysis, we examined the effects that a wide array of management strategies could have on the key Jinan performance metrics—unmet demand in the residential, industrial, and agricultural sectors; number of months of low spring flow; and amount of decline in groundwater under the assumption of large initial groundwater storage. Figure S.6 shows that under historical patterns of climate conditions, the completion of the IP has no effect on unmet demand for the Medium Demand projection (when unmet demand appears after 2025), and only a very slight effect under the High Demand projection when unmet demand appears after 2020. (Note that the figure does not show results for the Low Demand projection, as there is no projected unmet demand under that assumption.) The IPR + Residential Efficiency strategy eliminates unmet demand under the Medium Demand projection and almost entirely eliminates unmet demand under the High Demand projection. Strategies with 50 percent of the efficiency improvements also eliminate unmet demand under
Figure 5.6
Residential Unmet Demand Under Select Strategies for Historical Climate

![Graph showing unmet demand over time for medium and high demand scenarios with different strategies.]

- **Medium Demand**
  - Strategy: Current Projects, Completion of IP, IPR, IPR + 50Eff, IPR + Residential Efficiency

- **High Demand**
  - Year: 2010 to 2050

Figure 5.7
Residential Unmet Demand Across All Futures for Select Strategies

<table>
<thead>
<tr>
<th>Yellow River Allocation</th>
<th>Current Projects</th>
<th>Completion of IP</th>
<th>IPR</th>
<th>IPR + Residential Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Current</td>
<td>50%</td>
<td>Current</td>
<td>50%</td>
</tr>
<tr>
<td>Current</td>
<td>![Symbol]</td>
<td></td>
<td>![Symbol]</td>
<td></td>
</tr>
<tr>
<td>50%</td>
<td>![Symbol]</td>
<td></td>
<td>![Symbol]</td>
<td></td>
</tr>
<tr>
<td>Low</td>
<td>![Symbol]</td>
<td></td>
<td>![Symbol]</td>
<td></td>
</tr>
<tr>
<td>Medium</td>
<td>![Symbol]</td>
<td></td>
<td>![Symbol]</td>
<td></td>
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<tr>
<td>High</td>
<td>![Symbol]</td>
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<td>![Symbol]</td>
<td></td>
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<tr>
<td>Low</td>
<td>![Symbol]</td>
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<td>![Symbol]</td>
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<tr>
<td>Medium</td>
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<tr>
<td>High</td>
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<tr>
<td>Low</td>
<td>![Symbol]</td>
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<td></td>
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<tr>
<td>Medium</td>
<td>![Symbol]</td>
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<tr>
<td>High</td>
<td>![Symbol]</td>
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<tr>
<td>Low</td>
<td>![Symbol]</td>
<td></td>
<td>![Symbol]</td>
<td></td>
</tr>
<tr>
<td>Medium</td>
<td>![Symbol]</td>
<td></td>
<td>![Symbol]</td>
<td></td>
</tr>
<tr>
<td>High</td>
<td>![Symbol]</td>
<td></td>
<td>![Symbol]</td>
<td></td>
</tr>
</tbody>
</table>

NOTE: The red X symbols indicate futures in which the system is vulnerable and the filled green circles indicate futures in which the system is not vulnerable, depending on the threshold for vulnerability chosen.
the Medium Demand projection and significantly reduce unmet demand under the High Demand projection.

Figure S.7 shows summaries of residential unmet demand for the same strategies as in Figure S.6 across all futures. Each symbol represents a particular combination of climate projection, demand projection, Yellow River allotment, and groundwater storage. Many symbols fall on top of one another, hence the appearance of only a few points. The red “X” symbols are those results corresponding to conditions of vulnerability that exceed a 5-percent average unmet demand threshold at some point in the future; any threshold could be chosen. The green circles represent futures in which the system is not considered vulnerable for the threshold chosen. As expected, strategies that include improvements in residential efficiency are effective in reducing unmet demand across all climates and allocations of the Yellow River.

Unmet demand is more significant in the industrial sector because its priority for supply is lower than the residential sector. As a consequence, more of the management strategies reduce unmet demand in the industrial sector. Reducing industrial vulnerability to unmet demand across all the futures requires a combination of the WQ strategy and efficiency. In contrast, unmet demand in the agricultural sector is modest, and none of the futures exhibit vulnerability. Including the WQ and groundwater management strategies reduces demand even further.

Table S.4 provides a comprehensive summary of key outcomes across all futures and modeling assumptions. Each modeled strategy is represented as a row in the table. The rows are grouped by residential, industrial, and agricultural sectors and by springs. The columns in the table are grouped by demand projection (Low, Medium, and High), Yellow River allotments, and initial groundwater storage assumption. The coloring and percentage value in each cell of the table summarizes the proportion of the 26 climate projections for which the sector or springs is vulnerable. Green shading in each cell indicates low or no future vulnerabilities. Results are summarized in the Findings section.

Findings

In this study, we set out to demonstrate the value of an innovative approach to incorporating climate, demand, and other uncertainties into the JWRB’s long-term water planning and management. Table S.4 summarizes the projected performance of Jinan’s surface and groundwater supply system under a wide range of possible future conditions. However, cautions about the limitations of data and models should be noted.

Limitations of Data

The results of any analysis are only as good as the data used. High-quality data collected in a consistent way over a long period of time are essential for hydrologic analysis and long-term water planning. As anticipated at the outset of the project, data availability was the single most challenging aspect of this project and the primary limiting factor in model development and analysis. Improvements in data collection will have a beneficial effect on analysis and the integrity of the Jinan WEAP model. As JWRB further refines the data behind the demand and supply nodes and other model components, results could shift.

At the same time, the Jinan WEAP model can guide future data collection. For example, sensitivity analyses can be performed that indicate how much results could change if
## Table S.4
### Evaluation of the Jinan City Water Ecological Development Implementation Plan

### Summary of Jinan Water Management Vulnerabilities for All Evaluated Strategies Across All Futures

<table>
<thead>
<tr>
<th>Strategy</th>
<th>Large Initial GW Storage</th>
<th>Low Initial GW Storage</th>
<th>Large Initial GW Storage</th>
<th>Low Initial GW Storage</th>
<th>Large Initial GW Storage</th>
<th>Low Initial GW Storage</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Current</td>
<td>50%</td>
<td>11%</td>
<td>YRA</td>
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<td>11%</td>
</tr>
<tr>
<td>Completion of IP</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>IPR</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>IPR + 50Eff</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>IPR + WQ</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>IPR + SAGM</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>IPR + Residential Efficiency</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>IPR + Residential Efficiency + SAGM</td>
<td>0%</td>
<td>0%</td>
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<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>IPR + Washed Efficiency</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>IPR + ETAI + SAGM</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>IPR + ETAI + WQ</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
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<td>0%</td>
</tr>
<tr>
<td>IPR + ETAI + WQ + SAGM</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>IPR + 50Eff</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>IPR + ETAI + QW + SAGM</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>IPR + 50Eff + QW</td>
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<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>IPR + ETAI + QW + SAGM</td>
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<td>0%</td>
</tr>
<tr>
<td>IPR + 50Eff + ETAI + QW + SAGM</td>
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<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
</tr>
</tbody>
</table>

**NOTE:** Numbers for the residential, industrial, and agricultural sectors indicate the percentage of climate projections in which the sector is vulnerable. Numbers for the springs at the bottom of the table reflect the average number of months of low flow across all climate projections. YRA = Yellow River Allocation.
selected model parameters were to be better estimated (on the basis of field studies) or if the model were calibrated against a longer and more complete time series of data. Finally, the Jinan WEAP model provides JWRB with an efficient means of exploring future strategies over a wide range of possible future conditions, rather than using only the Historical Climate projection and a few changes in demand projections. This provides JWRB with a powerful tool for future use.

Limitations of Models

The validity of the WEAP, or any water management model, depends on the quality and quantity of data, the model parameters that govern the mathematical relationships within the model, and the structure of the model itself. Under the best of circumstances, any simulation model of the Jinan water system is only an approximation of the real physical system. The degree to which the model is a “good” representation of reality depends on the quality and quantity of data available to calibrate it, and an understanding of the relationships among the model’s many supplies, demands, and interconnections. In addition, the relationships represented within the model as mathematical expressions are necessarily approximations of complex systems. All of these limitations apply to the Jinan WEAP model. Even with these limitations, the process of building the Jinan WEAP model and exercising it is a valuable means of gaining insights about future performance of the Jinan system under a wide range of possible future conditions.

Recommendations

Bearing in mind these caveats about data and models, we offer recommendations in response to the three questions posed at the beginning of our study, followed by recommendations regarding data, models, and processes.

How Will Future Demand and Climate Conditions Challenge Jinan’s System?

When uncertainties are considered about future climate conditions, demand, future Yellow River allocations, and initial storage levels in groundwater basins, model results indicated the following vulnerabilities for the Jinan system as it currently exists:

- Across all futures, the residential sector is most vulnerable to the High Demand projection. Under the Medium Demand projection, the residential sector is vulnerable under the Low Initial Groundwater Storage assumption, particularly under the 50-Percent Yellow River Allocation. In sum, unmet demand in the residential sector is driven more by the demand projection and allocation of Yellow River resources than by future climate.
- Under the 50-Percent Yellow River Allocation, the industrial sector is vulnerable under the three demand projections, regardless of initial groundwater assumptions. Under the Medium Demand projection and Full Yellow River Allocation, however, the industrial sector is vulnerable only under the Low Initial Groundwater Storage assumption. Future climate exacerbates the industrial sector vulnerability but is not a driving factor in the same way that allocation of Yellow River resources and, to a lesser extent, the assumption about initial groundwater storage are.
• The vulnerability of the agricultural sector depends on future climate more than the residential and industrial sectors. Since agriculture uses groundwater as a key source, there is no vulnerability under the assumption of Large Initial Groundwater Storage. For Low Initial Groundwater Storage, however, vulnerability is seen in most futures. The climate effect is very strong: We see no shortages in the wettest climates but very significant shortages in drier climates.

• Jinan’s springs are vulnerable across all futures. In wet climates, low spring flows each year occur around three months on average; in dry climates, low flows appear on average about eight months each year.

• The model was structured to require ecological flows to be met throughout the system, thereby forcing unmet demand to appear elsewhere, primarily in the industrial and residential sectors.

• All of the climate projections show warming. However, there is scientific disagreement about whether conditions will be getting wetter or drier. One of the benefits of the analysis in this study is that it helps JWRB understand how important this uncertainty is by looking at results across a wide range of wetter and drier conditions—although our study shows that it is not an important factor in most cases.

This vulnerability assessment helps to point the way toward more-robust planning. Planning based on one or only a few scenarios could lead to unfavorable outcomes if conditions in the future were to take a different course than the one on which project designs were based.

How Will JWRB’s Implementation Plan Address Future Climate and Other Uncertainties?

At the present time and for the next several years, Jinan’s current system appears to doing well in meeting current demands across districts and sectors. However, even with the completion of the IP, the springs remain highly vulnerable across all futures. Further in the future and without further investments beyond the IP or changes in policies, unmet demand is expected in the residential sector under the High and Medium Demand projections. Curtailment of Yellow River allotments will increase vulnerabilities. This same pattern is even more dominant for the industrial sector except that vulnerabilities appear earlier, even with the completion of the IP, under the Low Demand projection. The agricultural sector shows some vulnerability under the Medium Demand projection and the assumption of Low Initial Groundwater Storage. Vulnerability increases under the High Demand projection.

What Actions Could Be Taken to Reduce Vulnerabilities and Increase the Robustness of Jinan’s System?

Investments in additional projects beyond the IP and other strategies explored in this study could go a long way toward reducing the potential effects of uncertainties, reflecting adaptations to changing conditions. Depending on the mix of strategies chosen, these adaptations could benefit different sectors. Consistent with pursuit of a robust system for Jinan, decision makers will want to choose strategies that lead to good outcomes across sectors and districts for the Jinan system regardless of how these uncertain external factors evolve.

Overall, results confirm the value of pursuing full implementation of efficiency measures across the sectors and active management of groundwater withdrawals. Efficiency measures will counterbalance increases in population and industrial activities. Strategies to increase water reuse and improve the water quality in the Xiaoting River could help accommodate growth...
in the industrial sector. Strategies that improve groundwater management will be essential to ensuring adequate spring flows.

**Investments and Strategies for the Future**

- In the residential sector, strategies that include reuse and full implementation of residential water use efficiency reduce vulnerabilities significantly. Improving industrial efficiency also slightly benefits the residential sector when demand is high and Yellow River allotments are reduced.
- The industrial sector is more vulnerable than the residential sector, particularly under 50-Percent Yellow River Allocation and larger demand projections. While completion of the IP does improve performance in the Medium Demand projection, increasing reuse helps to eliminate unmet demand almost entirely. Vulnerabilities to the industrial sector can be completely eliminated if all efficiency improvements are implemented, water reuse is implemented, and the WQ strategy for the Xiaoqing River is available as a backstop.
- The agricultural sector is less vulnerable than the other sectors. Any measures that reduce irrigation demands in drier climates will be essential. Because agricultural unmet demand is relatively small and ample surface and groundwater supplies are available in the districts in which agriculture dominates, this suggests that excess supply could be transferred elsewhere in the system with new conveyance structures.
- While the Jinan WEAP model cannot resolve many of the complex interactions between surface and groundwater, the analysis suggests that all strategies that include the proposed SAGM policy reduce the number of months of low spring flow.
- Management of groundwater resources is a key to Jinan’s future. More extensive and efficient use of surface water resources to satisfy demands across the sectors will reduce pressure on groundwater.

**Data**

- Efforts should continue to improve the quality of input data to the Jinan WEAP model. Priority should be given to those parameters that relate to ground- and surface water interactions.
- Responsibility should be assigned to a single individual to properly manage all existing and future data required for the Jinan WEAP model. Data should reside in a central computerized database. All relevant paper data records should be converted into a common format to ease the updating and loading of data into the Jinan WEAP model.
- For water quality data to be usable within the WEAP model, the data need to be directly linked to concurrent stream flow data at the same location. This would enable the estimation of pollutant loadings to the system that then could serve as a measure of effectiveness of water pollution control strategies implemented in the future.

**Models**

- The Jinan WEAP model should be considered a work in progress and tool for improving understanding of Jinan’s complex water management system. We recommend that a single individual be responsible for overseeing model development, maintenance, and operations.
- Consideration should be given for linking the output of a well-calibrated, high-resolution groundwater model, such as MODFLOW, to the Jinan WEAP model. This would sub-
substantially improve the ability of the Jinan WEAP model to represent surface and ground-water interactions, particularly the behavior of the spring systems.

**Process**

- The XLRM method can be used in many other settings to guide clear thinking about the nature of the problem to be solved, the goals and performance metrics most relevant to potential solutions, and the key uncertainties that drive the analysis. Having the appropriate modeling tools for the decision at hand is essential.
- RDM provides a structured approach to analysis of future conditions and strategies for reducing future vulnerabilities and should become a routine feature of JWRB’s analysis potential new investments and the implementation of new policies.

**Approach to Understanding Changes in Flood Frequency Under a Changing Climate**

Jinan may face significantly greater flooding in the future than it has in the past. Historically, a 1-in-50-year precipitation event led to a 1-in-50-year river stage for the one location in which we had sufficient precipitation and river stage data (Huangtaiqiao).\(^2\) However, climate change in the East Asia region could make extreme precipitation events more frequent than they have been historically. Therefore, in the future, precipitation from a 1-in-15-year event could lead to the same river stage that is now observed for a 1-in-50-year precipitation event. Thus, flood risk management, which is already important for the region, will be critical in the coming decades.

We note that this analysis was conducted with limited data, no hydrologic models, and only low-resolution climate change information. Therefore, the results have corresponding limitations. Inferences cannot be made about longer return periods, and there is much uncertainty in the relationships between different factors (e.g., the precipitation that results in a particular river stage).

**Final Word**

The results presented in this report are suggestive at best of future conditions and their implications. The analysis highlights the challenges ahead and the importance for JWRB of pursuing a diversity of strategies to address them. However, given the provisional nature of the data and models, no decisions should be made on the basis of this analysis alone.

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\(^2\) Daily precipitation and subdaily stage (river level) and flow data from 1950 to 2014, provided by JWRB.
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Abbreviations

50Eff  50-Percent Efficiency
CCAFS  Climate Change, Agriculture, and Food Security
DWR  Shandong Provincial Department of Water Resources
EffAll  efficiency for all (a strategy across residential, industrial, and agricultural sectors)
HTQ  Huangtaiqiao
IP  Implementation Plan (for the Jinan City Water System Ecological Development Plan)
IPCC  Intergovernmental Panel on Climate Change
IPR  Implementation Plan and increased water reuse (a strategy)
GCM  general circulation model
GDP  gross domestic product
GW  groundwater
IVA  industrial value added
JWRB  Jinan Water Resources Bureau
m  meter
m³  cubic meters
MCM  million cubic meters
mm  millimeters
PCA  Appendices of Jinan City Water Resources Public Communiqué
RCP  Representative Concentration Pathway
RCP 2.6  Emission pathway representative for scenarios leading to very low greenhouse gas concentration levels. It is a so-called peak scenario: It represents a strong mitigation scenario and is extended by assuming constant emissions after 2100 (including net negative CO₂ [carbon dioxide] emissions), leading to CO₂ concentrations returning to 360 parts per million by 2300.
RCP 4.5  A stabilization scenario where total radiative forcing is stabilized before 2100 by employment of a range of technologies and strategies for reducing greenhouse gas emissions.
RCP 6.0  A stabilization scenario where total radiative forcing is stabilized after 2100 without overshoot by employment of a range of technologies and strategies for reducing greenhouse gas emissions.
RCP 8.5  Characterized by increasing greenhouse gas emissions over time representative for scenarios in the literature leading to high greenhouse gas concentration levels.
RDM  Robust Decision Making
Res/Ind  residential/industrial
SAGM  Springs Adaptive Groundwater Management
SEI  Stockholm Environmental Institute
UNESA  United Nations Department of Economic and Social Affairs
WEAP  Water Evaluation and Planning
WTP  water treatment plant
WQ  Water Quality (strategy to enable industry to draw and treat Xiaoqing River water after 2030)
XLRM  decision-structuring matrix where X represents uncertainties,
      L represents levers (options and strategies),
      R represents relationships within a system, and
      M represents metrics
China’s Ministry of Water Resources has designated Jinan as the pilot city for National Water Ecological Civilization Development. In 2013, the Provincial Government of Shandong approved the Pilot Scheme for Water Ecological Civilization Construction in Jinan. Its purpose was to help Jinan achieve several goals cost-effectively, including increasing water reliability, improving water quality, improving aquatic ecosystem health, reducing damage from flooding, and increasing water use efficiency. As of this writing, most of the construction under the Pilot Scheme has been completed. Understanding how Jinan’s complex hydrologic system might perform in the coming decades with these new features and other planned projects and strategies is critical to ensuring that Jinan’s long-term goals are achieved.

The Jinan Municipal Water Resources Bureau (JWRB), with support from the Shandong Provincial Department of Water Resources (DWR), asked the RAND Corporation to assist in developing analytical tools to improve understanding and management of Jinan’s water system. The research plan included the following steps:

1. Articulate clear planning goals and metrics, using as appropriate some of the proposed indicators already developed for the Implementation Plan (IP) for the Pilot Scheme for Jinan from local, municipal, and provincial perspectives.
2. Understand how various socioeconomic, natural, and other future conditions could influence achievement of these goals and identify specific threats they may pose to achieving these goals.
3. Develop a simulation model of the Jinan water system and decision support tool for analysis of vulnerabilities and options.
4. Assess how management strategies and projects in the IP help mitigate these vulnerabilities.
5. Make recommendations on how JWRB could reduce the effect of these vulnerabilities in the future.

In executing these steps, RAND and JWRB worked collaboratively to strengthen JWRB’s ability to use modeling and decision support tools to establish priorities among specific water resource management strategies, projects, and actions.
A Brief Overview of Jinan’s Geography and Climate

Jinan is the capital city of Shandong Province, an eastern coastal province between Beijing and Shanghai (Figure 1.1). Jinan’s total population in 2014 was 7,067,900 (Shandong Provincial Bureau of Statistics, 2015, Table 3-4) and has a total administrative area of 8,177 square kilometers, of which 3,257 square kilometers are urbanized; agricultural and rural lands surround the urban center. Jinan is located in an alluvial valley in the center of Shandong, with the Yellow River to the north and the Tai Mountain (Taishan) to the south. Other major water features in Jinan include the Xiaoqing River, Daming Lake, and Baiyun Lake.

The Jinan groundwater system is characterized by a karst hydrology, composed largely of Ordovician limestone. Groundwater levels range from 10 to 100 meters (m) below the surface. Groundwater generally flows from the higher elevations of the south to the lower elevations of the north. Artesian springs exist at the north end of the groundwater system, where groundwater flows into confined subsurface chambers, eventually discharging to the surface in a system of 733 natural springs (Kang, Jin, and Qin, 2011; Zhao, 2015; Wu, Xing, and Zhou, 2009).

Recharge occurs primarily in the southern mountains and is largely attributed to direct recharge from precipitation, though significant recharge also occurs along the streambeds of the Beidasha and Yufu rivers (Wu, Xing, and Zhou, 2009). Recharge from precipitation has been estimated for four primary catchment areas: the Dong’er and Changxiao karst water catchments and the Jinan Spring and White Spring catchments (Kang, Jin, and Qin, 2011).

Jinan is known as the “City of Springs,” because of Baotu Springs and more than 70 other springs that discharge into Daming Lake and from many other springs in the northern region.

Figure 1.1
Location of Jinan in Shandong Province
The springs, the Yellow River, and the Yangtze South-North diversion are important sources of water for the city.

Jinan’s climate is hot and wet in the summer and dry and cool in the winter (Figure 1.2). In the recent past, Jinan’s average annual temperature has been 13.6 degrees Celsius with an annual average precipitation of 650 to 700 millimeters (mm). Interannual changes in precipitation can be large and summer heat and humidity can be particularly intense.

**Ecological Development and Implementation Plan**

In March 2012, the 18th Communist Party of China National Congress sought to accelerate what has become known as “water ecological civilization development.” The DWR submitted a proposal to the Ministry of Water Resources and, a month later, the Ministry confirmed its...

- Develop a safe and efficient water supply and disaster prevention system.
- Achieve basic development of a water conservation society.
- Ensure a well-connected water system and continuous flow of spring waters.
- Develop healthy and aesthetically appealing water ecology and environmental systems.
- Achieve high water quality, maintain ecological flow of rivers, and a “beautiful scenic view.”
- Develop a unique Spring City cultural system with high public awareness of water ecological civilization.

DWR describes the IP as: “one core, two belts, three areas, six corridors, and nine points.” Its elements include an ecological protection area in the South, a spring water scenic area in the Jinan Urban Center, a wetlands protection area along the Yellow River, and an ecological function area in the northern plain. The IP also sets forth water resources management policy, including three “red line” targets mandated by the provincial government related to an assured supply of water to residential areas, continuous flow of Jinan Urban Center’s springs, and improvements in water quality.

The IP is consistent with the “Four Systems”—that is, a scientific water management system, a healthy and beautiful water ecosystem, an intensive and safe water supply system, and an advanced water culture system. The IP also talks about strengthening the governance of the urban water system and the construction of the landscape, facilitating the protection of the main stream corridors of the Yellow River and the spring ecosystem, implementing restoration projects in the river flood plain and the wetlands, and promoting the comprehensive treatment and ecological restoration of the agricultural water network system in the northern plain (Jinan Water Resources Survey and Design Institute, 2013).

**Water Management Challenges Facing Jinan**

As true for any large and sprawling metropolis, Jinan faces a number of challenges in managing a complex water supply system drawing from surface and groundwater sources. The IP is intended to help Jinan achieve several goals cost-effectively, including increasing water reliability, improving water quality, improving aquatic ecosystem health, reducing damage from flooding, and increasing water use efficiency. Declines in aquatic ecosystem health are a particular concern as wetlands have been shrinking and many rivers run dry on a seasonal basis. These improvements are sought as the region is expected to continue to urbanize and support more people and industrial activity. Furthermore, climate trends and possible changes to access to important supplies from the Yellow River could affect Jinan’s ability to meet these goals.

Among the several goals noted, an immediate concern for JWRB is ensuring a reliable supply of clean water for urban and rural residents. Jinan faces a mismatch in the spatial distribution of water resources and its urban populations. Jinan has a policy in place that requires
that residential demand be met at all times; any unmet residential demand is unacceptable. Groundwater is the preferred source of water for residential use. Hence, continuous discharge of water from the city’s springs is one of the more visible signs of success in maintaining a sustainable yield of groundwater in the region, a condition not always met as industrial water demand has grown significantly since around 2000.

The Jinan water system, discussed in more detail in Chapter Three, expanded over time as population increased, industrial activity grew, and urbanization accelerated. Population increased from 5.7 million in 2001 to 7.1 million in 2015 and gross domestic product (GDP) attributed to Jinan grew by 600 percent over this same period (Jinan Economic and Social Development Statistics Public Communiqué, 2001; 2015). In response to the rapid growth, the city added new infrastructure where and when needed to stay apace of demand, making it difficult to optimize design and performance across the system as a whole. A question facing JWRB now is whether, by taking a systemwide perspective, demand could be more reliably met in the future if new management strategies and possibly new investments were made.

Water quality is another major concern in Jinan, with large segments of the Xiaoqing and other rivers exceeding China’s water quality standards and therefore unsuitable for use in any sector. A 2014 study found that water quality in Xiaoqing River downstream of central Jinan exceeded government-set Grade V water quality standards (Ren, Cui, and Sun, 2014). Levels of petroleum, ammonium nitrogen, chemical oxygen demand, and biochemical oxygen demand in the Xiaoqing River all exceed acceptable contaminant levels (Hong et al., 2010; Ren, Cui, and Sun, 2014).

Finally, flooding is a problem that has plagued Jinan for the better part of its thousands of years of history, situated as it is in the coastal plain with the Yellow and other rivers prone to overflowing their banks during periods of intense rainfall. As Jinan’s population has increased, so has its exposure to flood damage through extensive high-density development in flood-prone areas. Urban flood control and drainage systems are frequently overwhelmed during high-intensity rainfall events. Lack of proper drainage leads to a mixing of storm water and sewage flows. The most recent severe flooding occurred in 2007 and resulted in 1.32 billion renminbi (approximately $192 million) in damages. Jurisdiction over flood control is shared by JWRB and other agencies, such as the Jinan Hydrologic Bureau within the municipal and provincial governments.

For years to come, the IP’s effects will shape the municipal, industrial, and agricultural plans and policies for Jinan and the surrounding areas. Understanding how Jinan’s complex hydrologic system will be affected by the scale of recent economic development and the construction of these new projects is critical to ensuring that Jinan’s water management goals are achieved.

To focus our analysis, RAND sought guidance from JWRB’s experts and refined the initial set of research questions during a November 2015 workshop in Jinan and follow-up discussions among the RAND and JWRB teams. We agreed on the following questions:

- How will future conditions stress Jinan’s water management system? Changes to be considered include Jinan’s continued development, changes in water use efficiency, climate warming, changes in precipitation variability, and consequent changes in stream flow patterns.
- How do elements of JWRB’s IP address current and future challenges? Elements include increased connectivity within the water system; new storage, both surface and subsur-
face; increased water conservation and water efficiency; reduction in water pollution; and diversion of flood waters.

- What additional investments and management changes would increase the robustness of the Jinan water management system? Robustness is defined as the ability of the system to perform well over a wide range of possible future conditions and stands in contrast to a system designed to perform well under only a few possible futures.

Technical Road Map

To address these questions, we followed a phased approach, as shown in Figure 1.3. We began by developing the scope of analysis, defining key objectives and metrics, identifying preexisting infrastructure and newer IP elements, and specifying uncertainties to be addressed. The project team then developed a mathematical model of Jinan’s water management to simulate and evaluate current and future water management, following completion of the IP and under a range of future conditions. Our analysis of future conditions and future vulnerabilities extends from 2016 to 2050.

Using the results from the simulation model, the project team sought to understand how Jinan’s water system might perform as it currently exists, with the completion of all IP elements, and as it might be configured later if new projects and policies were implemented. We made this assessment under a range of possible future climate conditions and assumptions about future demand growth in the residential, industrial, and agricultural sectors. To facilitate the next step in the analysis, the project team developed a decision support tool to inform

Figure 1.3
Technical Road Map

- Define scope of analysis
  - Define key objectives and metrics
  - Identify key infrastructure and Implementation Plan elements
  - Specify uncertainty to address

- Develop water management systems model
  - Develop schematic of system
  - Populate with historical and current data
  - Develop future projections of factors driving change
  - Calibrate model

- Evaluate system and Implementation Plan
  - Evaluate current system for different baseline futures
  - Evaluate system with additional Implementation Plan projects
  - Consider flood issues

- Define options for increasing resiliency
  - Identify key vulnerabilities of the Implementation Plan
  - Evaluate additional adaptations options

- Support comparisons of options and trade-offs
  - Develop decision support tool
  - Use tool to compare and evaluate adaptation options and trade-offs
and guide deliberations about potential project and policies options to enhance system performance. The tool will help JWRB understand how well the current water system will perform over the next 35 years, and how various project and policy options might improve performance under a wide range of possible climate futures and demand scenarios. Further details are provided in subsequent chapters.

**How This Report Is Organized**

In Chapter Two, we describe the approach to structuring an analysis of future performance of Jinan’s water management system. This includes concise statements of goals and performance metrics; key uncertainties; planned and potential projects, policies, and strategies to reduce vulnerabilities to unmet demand; and mathematical relationships that relate inflows, storage, and outflows within this complex water system. This chapter also introduces the approach of Robust Decision Making (RDM) to characterize long-term performance of Jinan’s system and gain insights into adaptive strategies that could do well under a wide range of future conditions.

In Chapter Three, we describe the development and calibration of a mathematical simulation model of the Jinan system using the Water Evaluation and Planning (WEAP) software platform (Yates et al., 2005). In Chapter Four, we describe the approach to scenario development and the experimental design used to consider a wide range of possible futures reflecting uncertain future demand and climate conditions, as well as future allocations from the Yellow River. Chapter Five describes the baseline evaluation of the system with its current projects, assuming historical demands over the next 30 years. Chapter Six summarizes the WEAP model results over many possible future conditions, and describes where and when vulnerabilities may appear in the future under these different conditions. Chapter Seven summarizes our findings of performance of potential new projects and policies that could help to mitigate vulnerabilities to unmet demand. Chapter Eight describes an approach to considering how future changes in climate might affect flood frequency, an approach that requires more data to operationalize. Finally, Chapter Nine summarizes findings and presents RAND’s conclusions and recommendations to the JWRB.
RAND utilized an innovative and scientifically sound approach to analysis that is particularly well-suited for considering long-term challenges to the performance of a regional water management system with large uncertainties about future climate changes, changes in demand across sectors throughout the Jinan service area, and the effectiveness of proposed management strategies, particularly related to efficiency improvements and water quality. The approach is called RDM and can be described as a vulnerability-based framework in contrast to a more traditional “predict-then-act” approach to determining optimal improvements to a system under a very limited set of future conditions or scenarios. A system is vulnerable when it is unable to meet its stated goals under certain future conditions. For example, an urban drainage system can be vulnerable to extreme rainfall events above some threshold level.

We thus use climate science, for example, to inform Jinan’s future vulnerabilities to climate change, but we do not use climate model results to predict the future. In previous applications supported by the World Bank and other organizations, RDM has been used to help decision makers reach consensus even when they disagree on future expectations, reduce their overconfidence in results based on a limited number of scenarios, manage surprise, and use quantitative analysis in situations when key data are missing or imprecise (Cervigni et al., 2015; RAND Corporation, undated-a, undated-b).  

In this chapter, we lay the foundation for the decision analysis to follow. RAND has successfully used the RDM approach to analyze long-term water management issues in many other settings in the United States and other countries (Groves, Fischbach, Bloom, et al., 2013; Groves, Fischbach, Kalra, et al., 2014; Lempert and Groves, 2010; Lempert, Kalra, et al., 2013; Fischbach et al., 2015). As part of the RDM approach to help visualize the results of the analysis and enable decision makers to gain greater clarity about the implications of results, we also developed an interactive decision support tool, referred to as a Planning Tool.

**Technical Road Map**

RAND’s technical road map includes the following elements:

- Introduce RDM as an innovative approach to water resources planning under uncertainty.
- Demonstrate the use of a water-balance simulation model of the Jinan water management system with RDM to understand future vulnerabilities.

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1 The World Bank has also encouraged its water sector to use an RDM-related approach, called decision scaling (Ray and Brown, 2015).
• Demonstrate how results from an RDM analysis can help identify strategies that may lead to a more robust plan.
• Demonstrate how uncertainties about climate can be used in analysis of flood frequency.
• Build capacity within JWRB to apply these methods in future work.

With respect to capacity building, RAND built and ran a simulation model, then transferred it to JWRB for future use, built and demonstrated use of a decision support tool and then transferred it to JWRB for future use, trained JWRB staff to use the model and tool, and identified priorities for future data collection and analysis.

It should be noted that our focus was on introducing Jinan to a new and innovative approach to analysis of future water needs. Beyond the development of the Jinan WEAP model that could be refined and further improved in the future, JWRB and RAND agreed at the outset of the project that other hydrologic systems modeling was not feasible because of lack of sufficient data of good quality and lack of time.

**Overview of Robust Decision Making**

RDM is an iterative analytical process often used with stakeholders and designed to support decision making under deep uncertainty when the probabilities of future outcomes are not well understood or are unknown. Traditional engineering design methods are not appropriate in the presence of “deep” uncertainties, such as global climate change and future demand, across sectors and districts in Jinan. Under conditions of deep uncertainty, it is possible, however, to establish a basis for bounding the range of uncertainty for a given process, such as expected changes in annual precipitation or temperature, and then exploring the performance of a water system across that range to identify circumstances when the system may not be able to meet future demand. We call the process of exploring the performance of a system over a wide range of possible future conditions a vulnerability assessment.

An example helps to explain the difference between RDM and more-traditional engineering analysis. Suppose a new reservoir is to be built to increase storage in the Jinan system. How large should the reservoir be, how should it be operated, and what is the basis for these decisions? In a traditional analysis, planners and engineers might typically use one estimate of projected demand and the Historical Climate projection (based on an assumption that future climate conditions would be the same as the past) to make a determination about the optimal additional storage and operating rules required to meet the assumed level of future demand. They would then most likely conduct a sensitivity analysis by varying the level of assumed future demand and add a “margin of safety” factor to reduce the risk of failure.

In contrast, RDM takes advantage of inexpensive computing power to consider many different futures and a large number of potential strategies. Planners using RDM would simulate system operations to determine which climate and demand conditions cause shortages in the current system (the vulnerability analysis), then identify several different reservoir sizes and operational strategies, simulate operations, and determine the extent to which shortages would be reduced under the different potential sizes and strategies. Finally, decision makers would choose a design storage capacity that does best under a wider, but still plausible, range of future conditions.

Figure 2.1 shows the implications of these two different approaches. In this hypothetical example, the vertical axis represents unmet demand in the system as a whole. The horizontal axis
represents different assumptions about how aggregate demand may change in the future relative to current demand. (Another example could have shown the horizontal access as changes in precipitation relative to historical averages.) A value of zero means that demand in the future, say in 2030, is the same as demand in the present. The blue line represents the performance of the current system. The red line represents the performance of a proposed reservoir whose design storage capacity (\(X\)) was determined by a traditional method that sought to optimize reservoir capacity based on the Historical Climate projection. The traditional method does very well under the assumption that demand in the future will be less than demand in the present, for example, as a consequence of efficiency measures. However, its performance would not be satisfactory if demand did not decline as expected and instead turned out to increase in the future.

In contrast, the green line shows the performance of the system with a reservoir with the same capacity as before but in this case, additional investments in interconnections or changes in operations throughout the system are considered. The performance of this option is better under a wider range of demand conditions and may be more appealing to decision makers as a way to minimize future risk.

The first step of RDM, shown in Figure 2.2, is to organize key factors of the decision analysis, using a structured approach called the XLRM matrix (see next section), first described by Lempert, Popper, and Bankes (2003). In the second step of RDM, we use the results of the decision-structuring process to develop and calibrate a simulation model of the Jinan water management system. Having a model that captures the many relationships of supply and demand within the Jinan system enables us to understand how the system as it is currently configured might respond under conditions that differ from the present. We then run the model under many combinations of assumptions about possible future climate, demand, and
initial groundwater storage. This “case generation” step is guided by an experimental design discussed in more detail in Chapter Four. In the third step, we analyze the results generated in Step 2 and identify those sets of future conditions that show when and where the Jinan system as it is currently operating will experience unmet demand. We call this a vulnerability analysis. A water system is considered vulnerable when it is unlikely that it can meet its stated performance goals under certain future conditions. For example, if a water system cannot reliably meet user demands under persistent drought, then we say that the system is vulnerable. Or as another example, a city may be vulnerable to flooding if its drainage and flood control systems are overwhelmed by extreme, high-intensity rainfall events. Vulnerabilities will undermine system performance in the future and are a key component of risk.

At this point in the RDM process, we go back to Step 1 and consider how vulnerabilities could be reduced by introducing new projects or water management strategies. If vulnerabilities can be reduced by implementing various projects and strategies, then risk to Jinan’s economy and its residents can be reduced. JWRB provided RAND with guidance on which projects and strategies they wanted to examine. We then return to Steps 2 and 3 to examine how well the various proposed projects and strategies reduce unmet demand under a range of future climate, demand, and initial groundwater storage conditions. Finally, we move to the fourth step of the process: examining trade-offs across the various strategies. A robust strategy would be one that does well across a wide range of possible future conditions. Details of these steps follow.

**XLRM Matrix**

We use a 2-by-2 matrix to structure the decision process, as shown in Table 2.1. The XLRM matrix defines:
• key uncertainties (X) influencing future conditions
• water management options, sometimes called levers (L), including projects in the IP and other strategies to be developed
• mathematical relationships (R) used to estimate the performance of the system
• performance metrics (M) that summarize how the Jinan water system would perform under different futures and strategies.

Note that we use the term strategy to refer to potential future projects, policies, or combinations of projects and policies that could affect water management in the Jinan system.

Performance Metrics

Table 2.2 lists the key performance metrics that RAND identified in consultation with JWRB and the relationship of these metrics to JWRB’s long-term planning goals. Our analysis focuses primarily on evaluating how well the Jinan water management system meets residential (urban and rural), industrial, and agricultural demands, while also supporting flows to sustain aquatic ecosystems and the flows of the city’s famous springs. Residential, industrial, and agricultural needs are represented by projections of future water demands. Unmet demand is estimated when demand exceeds the availability of supplies to meet those demands.

To represent the status of Jinan’s springs, we estimate trends in monthly and annual spring flow of Baotu Springs and then relate these flows to water levels at Baotu. It should be noted that the modeling resolution of the groundwater and connected springs is low because of the high-level representation of groundwater flow and surface and groundwater interactions in the WEAP model and lack of data to develop a more-detailed representation of the surface and groundwater interactions. Groundwater sustainability is tracked in the WEAP model by changes in water levels at selected well locations.

Table 2.1
Summary of Key Factors in the Analysis

<table>
<thead>
<tr>
<th>X: Uncertainties</th>
<th>L: Management Options</th>
</tr>
</thead>
<tbody>
<tr>
<td>Future water demand</td>
<td>Current system including already-constructed IP projects</td>
</tr>
<tr>
<td>Residential, industrial, and agricultural growth</td>
<td>Completion of remaining IP projects</td>
</tr>
<tr>
<td>Water use rates</td>
<td>Increased efficiency</td>
</tr>
<tr>
<td>Climate change effects on water supply</td>
<td>Residential and industrial</td>
</tr>
<tr>
<td>Inflows</td>
<td>Water reuse</td>
</tr>
<tr>
<td>Groundwater recharge</td>
<td>Adaptive groundwater management for springs</td>
</tr>
<tr>
<td>Agricultural demand</td>
<td>Improve water quality of Xiaoqing River to allow</td>
</tr>
<tr>
<td>Water allocation from the Yellow River</td>
<td>utilization of resource</td>
</tr>
<tr>
<td>Initial groundwater storage</td>
<td>Reduced sensitivity of irrigated agriculture to climate changes</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>R: Relationships</th>
<th>M: Performance Metrics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water management model (WEAP)</td>
<td>Unmet water demand</td>
</tr>
<tr>
<td>Flood risk analysis (without modeling)</td>
<td>Residential, industrial, and agricultural</td>
</tr>
<tr>
<td>Flow rate at Baotu Springs</td>
<td>Groundwater levels</td>
</tr>
<tr>
<td>Groundwater levels</td>
<td>Achievement of water quality standards</td>
</tr>
<tr>
<td>Achievement of water quality standards</td>
<td>Recurrence intervals of extreme flood events</td>
</tr>
</tbody>
</table>

---

2 A detailed groundwater flow model in the MODFLOW software platform is available for Jinan (Kang, Jin, and Qin, 2011), but its coupling to the WEAP model was beyond the scope of this project.
Water quality data were provided to us in the form of the monthly water quality index values at nine locations along rivers in the Jinan system. We therefore used a metric that counts the number of months when the standard was not met.

We would have liked to analyze Jinan’s vulnerability to flooding under a wide range of climate scenarios (as represented by differences between precipitation and temperature historical averages generated by global climate models). However, we were limited by data available for streamflow, river stage, and precipitation at the same locations. Our key metric of interest is estimated changes in the recurrence interval of extreme flood events. Chapter Eight explains our approach to estimating this metric and provides a simple demonstration using available data.

**Uncertainties**

We analyzed the performance of the Jinan water management system from 2016 to 2050. We considered several types of uncertainties: changes in projected water use across residential (urban and rural), industrial, and agricultural sectors; changes in supply as a consequence of a changing climate, driven by changes in precipitation and temperature and their subsequent effects on streamflow, recharge, and evapotranspiration; adjustments to the allocation from the Yellow River; and initial groundwater storage. Details of the approach taken to develop demand and climate scenarios are provided in Chapter Four.

Projections of future water use are inherently tied to expected future demand, and we project future demand based on correlated factors. These correlated factors vary across different water use sectors. For example, residential water demand—which includes urban and rural residential, as well as commercial and public services water uses—generally varies with population growth but can be influenced by additional socioeconomic factors, such as income and population density, technology, and system maintenance (for example, leak detection and repair). Industrial water demand, including commercial services, might vary with Shandong’s GDP or industrial value added (IVA), and thus projected changes in industrial activity at the provincial level, as well as efficiency improvements, will be correlated with an overall change in water use. Finally, agricultural water demand varies with the area of irrigated land, though additional factors contribute to variation, including the types of crops grown and their related baseline evapotranspiration rates, seasonal variation, irrigation efficiency, management restrictions (including assurance rates), and the effects of temperature on evapotranspiration. These factors—population for residential demand, IVA for industrial, and irrigated acreage for agri-
cultural—are more generally referred to as *annual activity levels*, or those activities that drive demand in their respective sectors.

Future water supply uncertainties are tied to global climate conditions, particularly precipitation and temperature. Precipitation directly affects the volume of water captured by catchments, flows in rivers and streams, and inflows and storage in reservoirs and groundwater basins. Long-term changes in average temperature affects evaporation from soils and surface water bodies, such as lakes and reservoirs.

Jinan is only one of many other growing regions that share common water resources. As such, JWRB expressed interest in evaluating the effects that a 50-percent reduction in the allocation of the Yellow River would have on Jinan’s ability to meet future demands. The allocation of Yellow River resources is thus treated as an uncertain factor.

Finally, in the absence of more detailed information about initial conditions in the regional groundwater system, we chose to treat initial groundwater storage as an uncertainty and explore the sensitivity of the water balance in the system to upper and lower bounds on this factor. Thus, we chose one level in which initial groundwater storage was constrained (low) and another when it was essentially unlimited (high). Future analyses could include an average value as well.

**Management Options and Strategies**

JWRB is interested in understanding how well the IP elements will enable the achievement of key goals over the coming decades and how new strategies could improve performance of the system over the long term. The components of the IP are noted on Figure 2.3 and summarized in Tables B.1 and B.2 in Appendix B. These include:

1. Jiazhuang Gauge to Wohushan Reservoir Water Diversion Project (complete)
2. Beidianzi to Jinan City Center Water Diversion Project (complete)
3. five-reservoir transfer project (complete)
4. Duzhang to Jinan Steel Corporation (planning stage)
5. Duzhang to Langmaoshan (near completion).

Two additional non-IP projects included in the analysis are:

6. A hypothetical Xiaoqing water treatment plant, which would come online in 2030
7. Dazhan water treatment plant (WTP), which will be operational starting in 2017.

Our analysis also considered broader management changes based on vulnerability to unmet demand identified in the system after the completion of the IP. Options include:

- additional interconnections, as described in the IP
- increases in water reuse across sectors
- increases in water use efficiency across sectors
- groundwater management that responds dynamically to changing spring levels
- increased supply by drawing from the Xiaoqing River if water quality standards are met.
Relationships

The focus of this study was the development of a WEAP model to capture the long-term accounting of inflows, outflows, and changes in storage in the Jinan water management system as a key tool for understanding vulnerabilities of the system to future climate, demand, and other potentially important uncertainties that would affect supplies and demands over time. The model structure and relationships within it are described in Chapter Three and in accompanying appendixes.

Figure 2.4 outlines the relationship between WEAP and the RDM analysis. RAND received data and other information from JWRB, enabling us to develop a schematic within WEAP of the Jinan water system. The Jinan WEAP model could then be used to analyze the effects of proposed projects and policy strategies across a wide range of possible future climate and demand projections that could reduce future vulnerabilities. Our focus was on longer-term trends, spanning the period from 2016 to 2050, and their implications for future investment decisions and water management in Jinan. RAND and JWRB also worked collaboratively to enhance JWRB’s ability to use modeling and decision support tools independent of RAND.

The WEAP model represents seven districts in Jinan: (1) Changqing District; (2) Licheng District; (3) Jiyang County; (4) the Jinan Urban Center, which is composed of Lixia, Shizhong, Tianqiao, Huaiyin, and (where applicable) Gaoxin districts; (5) Pingyin County; (6) Shanghe County; and (7) Zhangqiu District. These districts and counties are each associated with agri-
cultural, industrial, residential (urban and rural), and other demands and their sources of supply, including groundwater and government-set allotments from the Yellow River.

As shown in Figure 2.4, RAND used Tableau, a commercially available visualization software package, to assimilate output from the WEAP model, perform statistical analyses and comparisons, and develop graphics both for this report and for more-detailed exploration of the results. The use of a Planning Tool is part of RAND’s approach of using analysis to support deliberation over choices, as recommended by the National Research Council (2009), and used to support high profile natural resources planning efforts (Groves and Bloom, 2013; Groves, Fischbach, Bloom, et al., 2013; Groves, Fischbach, Knopman, et al., 2013).

In addition, the RAND team made some use of the published results of an analysis by Kang, Jin, and Qin (2011) in which Jinan’s groundwater system was modeled using a widely available code called MODFLOW (Harbaugh, 2005). At some future point, the MODFLOW model could be integrated with the WEAP model to significantly enhance the representation and understanding of surface and groundwater flow dynamics within the system.

Development and integration of a flood routing model within the overall analytical framework was outside the scope of this analysis, but such a model would enhance understanding of system dynamics during extreme precipitation events. Instead, RAND applied a straightforward statistical approach to get a sense of how changes in extreme precipitation events as a consequence of a changing climate might affect flood frequency. Because of the need to connect future projections of precipitation patterns to flood stage, this analysis required a distinctly different approach than engineering analysis of a design flood for reservoir sizing as prescribed in official facility design guidance documents (Hydrology Bureau of Changjiang Water Resources Commission, Ministry of Water Resources, 2006). Details of the recommended approach are provided in Chapter Eight.
Planning Tool

An important component of the RAND approach to analysis is a Planning Tool that provides an easy and interactive means of visualizing analysis results in ways that are meaningful to decision makers and other users. Figure 2.5 shows the iterative nature of the deliberations between analysts and stakeholders (decision makers) as results are examined and new strategies are considered.

The Planning Tool was made available to Jinan planners via a website to facilitate feedback on the analysis and results (Knopman, 2016). Figure 2.6 shows a screenshot of the welcome screen. Note that the user navigates through the visualizations via the tabs at the top of the screen or via a dropdown menu in the upper left.

Figure 2.5
Planning Tool and Approach to Deliberation over Trade-Offs

Figure 2.6
Screenshot of the Jinan Water Resources Bureau Planning Tool
In collaboration with JWRB, the RAND team developed a management model of the Jinan city water system using the WEAP modeling platform created by the Stockholm Environmental Institute (SEI) (Yates, 2005). The JWRB WEAP model provides two primary benefits for JWRB: (1) It calculates unmet demands, supply availability, and flows at streams and other locations of interest under a wide range of plausible projected futures for the purpose of gaining insights into vulnerabilities and potential strategies to reduce vulnerabilities to shortages; and (2) it serves as a data organization tool and centralizes the storage of relevant water management data. WEAP has the further virtue of having Chinese language tutorials and a user guide (SEI, undated-a, undated-b).

**WEAP Schematic**

The Jinan WEAP model represents Jinan’s actual physical system of reservoirs, interconnections, wells, rivers, streams, and water uses spread throughout the region through a set of supply nodes, demand nodes, storage nodes, and connections (arcs). Nodes represent locations of water inflows, storage (surface or groundwater), outflows, and demand centers. Arcs represent conveyance, either natural or constructed, between different nodes. The schematic in Figure 3.1 represents the spatial relationships among the arcs and nodes. WEAP uses a linear optimization approach to model volumes and flows of water moving through the system. WEAP allows for the integration of hydrological and climatic processes, including precipitation and evapotranspiration, into the modeling of demand. Through the incorporation of potential climatic, demand, and hydrologic conditions, extensive analyses can be conducted of system performance over intervals of time under a wide range of futures.

As shown in Figure 3.1, the WEAP model represents seven districts in Jinan: (1) Jinan Urban Center, which is composed of Lixia, Shizhong, Tianqiao, Huaiyin, and (where applicable) Gaoxin districts; (2) Zhangqiu District; (3) Pingyin County; (4) Jiyang County; (5) Shanghe County; (6) Licheng District; and (7) Changqing District. These districts and counties are each associated with agricultural, industrial, residential (urban and rural), and other demands and their sources of supply, including groundwater and government-set allotments from the Yellow River. Smaller, seasonal rivers and local reservoirs may serve multiple districts. The WEAP simulation model estimates demands and supplies over time on a monthly basis using historical data derived from reference documents provided to the study team by the JWRB (see Appendix A) and mathematical relationships described in this chapter and Appendixes C and D.
Water Demand

In the Jinan WEAP model, future water demand is estimated for three sectors—residential (urban and rural), industrial, and agricultural—for each of the seven Jinan districts, counties, and cities. All historical data for the demand nodes were taken from the Jinan Social Economic Indicator Summary for 2014 (Jinan Municipal Government, 2015).

The WEAP model includes seven residential demand nodes listed in Table 3.1. Residential demand consists of the sum of residential (urban and rural), public (e.g., public buildings, schools, and libraries), government, open and green space (e.g., parks), and municipal demand. The model includes seven industrial demand nodes listed in Table 3.2. Agricultural demand includes all water demands related to agriculture, including uses for livestock, irrigation, forestry, and fisheries. The model includes seven agricultural demand nodes, summarized in Table 3.3.
**Table 3.1**

**Residential Demand Nodes**

<table>
<thead>
<tr>
<th>Node</th>
<th>Area of Residential Demand</th>
<th>Primary Sources</th>
<th>2014 Population</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jinan Urban Center</td>
<td>Urban core of Jinan, including Huaiyin, Lixia, Shizhong, and Tianqiao districts</td>
<td>Groundwater and Yuqing, Queshan, Wohushan, and Jinxuichuan reservoirs (through various WTPs)</td>
<td>2,691,900</td>
</tr>
<tr>
<td>Zhangqiu</td>
<td>Zhangqiu District</td>
<td>Groundwater</td>
<td>1,020,000</td>
</tr>
<tr>
<td>Pingyin</td>
<td>Pingyin County</td>
<td>Groundwater</td>
<td>373,500</td>
</tr>
<tr>
<td>Jiyang</td>
<td>Jiyang County</td>
<td>Groundwater and the Yellow River</td>
<td>560,900</td>
</tr>
<tr>
<td>Shanghe</td>
<td>Shanghe County</td>
<td>Groundwater and the Yellow River (via the Xingjiadu Irrigation Channel and Fengyuan and Qinyuan lakes)</td>
<td>627,700</td>
</tr>
<tr>
<td>Licheng</td>
<td>Licheng District</td>
<td>Groundwater (from both Licheng groundwater and Dongjiao and Dongyuan WTPs and Langmaoshan)</td>
<td>1,160,000</td>
</tr>
<tr>
<td>Changqing</td>
<td>Changqing District</td>
<td>Groundwater and the Yellow River</td>
<td>600,000</td>
</tr>
</tbody>
</table>

**Table 3.2**

**Industrial Demand Nodes**

<table>
<thead>
<tr>
<th>Node</th>
<th>Area of Industrial Demand</th>
<th>Primary Sources</th>
<th>2014 IVA in billion renminbi</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jinan Urban Center</td>
<td>Urban core of Jinan, including Huaiyin, Lixia, Shizhong, and Tianqiao districts</td>
<td>Jinan groundwater, the Yellow River (via Queshan and Yuqing reservoirs), and Langmaoshan, Wohushan, and Jinxuichuan reservoirs</td>
<td>69.1</td>
</tr>
<tr>
<td>Zhangqiu</td>
<td>Zhangqiu District</td>
<td>Groundwater, Yangtze Transfer (via Longhu Reservoir), and Duozhang Reservoir</td>
<td>27.6</td>
</tr>
<tr>
<td>Pingyin</td>
<td>Pingyin County</td>
<td>Yellow River (via the Tianshan Irrigation Channel) and groundwater</td>
<td>8.1</td>
</tr>
<tr>
<td>Jiyang</td>
<td>Jiyang County</td>
<td>Groundwater</td>
<td>2.9</td>
</tr>
<tr>
<td>Shanghe</td>
<td>Shanghe County</td>
<td>Groundwater and the Yellow River (via the Xingjiadu Irrigation Channel and Fengyuan and Qinyuan lakes)</td>
<td>2.7</td>
</tr>
<tr>
<td>Licheng</td>
<td>Licheng District</td>
<td>Groundwater (from both Licheng groundwater and Dongjiao and Dongyuan WTPs, Yangtze Transfer, and the Yellow River</td>
<td>10.1</td>
</tr>
<tr>
<td>Changqing</td>
<td>Changqing District</td>
<td>Groundwater</td>
<td>3.7</td>
</tr>
</tbody>
</table>

**Table 3.3**

**Agricultural Demand Nodes**

<table>
<thead>
<tr>
<th>Node</th>
<th>Area of Agricultural Demand</th>
<th>Primary Sources</th>
<th>2014 Effective Irrigated Land Area (square kilometers)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jinan Urban Center</td>
<td>Urban core of Jinan, including Huaiyin, Lixia, Shizhong, and Tianqiao districts</td>
<td>Groundwater, Wohushan and Jinxuichuan reservoirs</td>
<td>151.87</td>
</tr>
<tr>
<td>Zhangqiu</td>
<td>Zhangqiu District</td>
<td>Groundwater, the Xiujiang River (via Dazhan and Duozhuang reservoirs), the Xinghua River (via Xinglin Reservoir), and Duozhuang Reservoir</td>
<td>540.13</td>
</tr>
<tr>
<td>Pingyin</td>
<td>Pingyin County</td>
<td>Groundwater and the Yellow River</td>
<td>187.13</td>
</tr>
<tr>
<td>Jiyang</td>
<td>Jiyang County</td>
<td>Groundwater and the Yellow River</td>
<td>698.73</td>
</tr>
<tr>
<td>Shanghe</td>
<td>Shanghe County</td>
<td>Groundwater and the Tuhai River</td>
<td>758.47</td>
</tr>
<tr>
<td>Licheng</td>
<td>Licheng District</td>
<td>Yellow River, Xiaoping River, and Jinxuichuan, Wohushan, and Langmaoshan reservoirs</td>
<td>281.00</td>
</tr>
<tr>
<td>Changqing</td>
<td>Changqing District</td>
<td>Groundwater and the Yellow River</td>
<td>223.33</td>
</tr>
</tbody>
</table>
Hydrology and Supplies

Rivers
The Jinan WEAP model represents 13 rivers and streams in Jinan. Historical flow data are available at several locations for model calibration, although data are not available for four rivers: Xijiang, Dongluo, Quanfu, and Daxin. However, these streams are generally seasonal, do not serve as a supply for any demand nodes, and are only included to evaluate the ability of smaller mountain reservoirs (Jiangshuiquan, Xinglong, and Longquan reservoirs) to maintain base flow. Table 3.4 lists each of the rivers contained in the WEAP model, the number and names of stations for which data are available, the types of data available, and the range of dates for which data are available.

Table 3.4
Rivers Included in the WEAP Model

<table>
<thead>
<tr>
<th>River</th>
<th>Gauging Stations Available</th>
<th>Station Names</th>
<th>Date Range</th>
<th>Reason for Inclusion in WEAP Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Xiaoqing</td>
<td>5</td>
<td>Mulizha, Huanggang, Huangtaiqiao, Chaizhuangzha, Wulongtang</td>
<td>2011–2014</td>
<td>Primary conveyance of wastewater in Jinan</td>
</tr>
<tr>
<td>Yufu</td>
<td>4</td>
<td>Mulliqiao, Zhaike, Wohushan, and Jinxiuchuan inflow</td>
<td>2011–2014</td>
<td>Significant source of water for Jinan; includes major reservoirs of Wohushan and Jinxiuchuan; significant source of indirect groundwater recharge</td>
</tr>
<tr>
<td>Xiujiang</td>
<td>3</td>
<td>Unknown, Dazhan and Duozhuang inflow</td>
<td>1977–2014 (total coverage)</td>
<td>Includes Dazhan and Duozhuang reservoirs; significant resource for Zhangqiu District</td>
</tr>
<tr>
<td>Beidasha</td>
<td>1</td>
<td>Nanzhangzhuang</td>
<td>2011–2014</td>
<td>Significant source of groundwater recharge and seasonal flow into the Yellow River</td>
</tr>
<tr>
<td>Yellow</td>
<td>1</td>
<td>Luokou Station</td>
<td>2004–2014</td>
<td>Significant source of surface water for Jinan Urban Center</td>
</tr>
<tr>
<td>Nandasha</td>
<td>1</td>
<td>Luzhuang Drainage Station</td>
<td>2011–2014</td>
<td>Significant source of groundwater recharge and seasonal flow into the Yellow River</td>
</tr>
<tr>
<td>Xinghua</td>
<td>1</td>
<td>Xinglin inflow</td>
<td>1972–2014</td>
<td>Significant source of surface water for Zhangqiu District</td>
</tr>
<tr>
<td>Daxin</td>
<td>0</td>
<td>—</td>
<td>—</td>
<td>Evaluation of baseline flow from Longquan Reservoir</td>
</tr>
<tr>
<td>Dongluo</td>
<td>0</td>
<td>—</td>
<td>—</td>
<td>Primary discharge from Bautou Springs</td>
</tr>
<tr>
<td>Quanfu</td>
<td>0</td>
<td>—</td>
<td>—</td>
<td>Evaluation of baseline flow from Jiangshuiquan Reservoir</td>
</tr>
<tr>
<td>Xingji</td>
<td>0</td>
<td>—</td>
<td>—</td>
<td>Evaluation of baseline flow as sourced from Xinglong Reservoir and the Beidianzi ecological transfer project</td>
</tr>
<tr>
<td>Yudai</td>
<td>0</td>
<td>—</td>
<td>—</td>
<td>Additional source of inflow to Yufu but less association with groundwater recharge</td>
</tr>
</tbody>
</table>

1 See Appendix A for more information on missing data.
Groundwater
Jinan’s groundwater is represented in the WEAP model by seven different aquifer nodes. Estimates of the volume of groundwater available to each district were provided to RAND by JWRB. These groundwater nodes correspond to the seven districts included in the WEAP model: Changqing District, Jinan Urban Center (composed of Lixia, Shizhong, Tianqiao, Huaiyin), Jiyang County, Licheng District, Pingyin County, Shanghe County, and Zhangqiu District. In addition, two nodes—Beidasha Recharge and Yufu Recharge—have been added to represent recharge to the Jinan groundwater system from the Beidasha and Yufu rivers. Total recharge from streambed percolation was estimated from literature sources (Baohua and Daqiu, 2006; Zhou et al., 2016).

Recharge has not been measured directly and can only be inferred through a reasonable representation of the surface and groundwater interaction in WEAP and a mass-balance calibration of the model. For this reason, we can only approximate the contribution of this important feature of the system. Improvements in spatial coverage of data and modeling of surface and groundwater interactions over the coming years will enable JWRB to refine its estimates of recharge.

Surface Reservoirs
The Jinan WEAP model represents 16 reservoirs. Information about these reservoirs is summarized in Table 3.5. These data were taken from various sources, including a table titled “Reservoir Information” from the second data tranche, received December 16, 2015; in-person discussions with the JWRB technical team during the second and third workshops; and email conversations between RAND and JWRB. See Appendix A for further details.

Conveyance
The Jinan WEAP model includes six primary conveyance facilities that route water from source to demand nodes through the Jinan system. These conveyances are summarized in Table 3.6.

Other Supplies
The Jiping Channel was included in the Jinan WEAP model to represent a diversion from the eastern portion of South-North Yangtze River transfer, a national project that transfers water from the Yangtze River to the northern part of China. Based on discussions with JWRB, this supply was included in the model as an annual allocation of 100 million cubic meters (MCM) per year, with 83 MCM per year for Jinan Urban Center and 17 MCM per year for Zhangqiu. An expected, doubling of this allocation to 200 MCM per year in 2030 was allotted according to projections provided by JWRB. With data unavailable on how future allotments would be diverted to each district, we made the following assumptions in the model:

• Jinan Urban Center and Zhangqiu District would continue to divert water from the South-North Transfer in the same way as under current conditions.

---

2 The allocation for Jinan Urban Center rose to 130 MCM per year; Zhangqiu to 40 MCM per year; Jiyang to 20 MCM per year; and Changqing to 10 MCM per year. According to JWRB, Pingyin County does not receive water from the South-North Transfer, and thus the projection for Pingyin was included in the Jinan Urban Center total, consistent with current conditions.

3 Note that allocations from the South-North transfer to Jiyang and Changqing agriculture were determined during the review process to be incorrectly allocated due to the high price of water from the South-North transfer; the final model as passed to JWRB includes corrected allocations, although model runs shown here do not. The change in allocation has a minor effect on results given the low unmet demands in these districts across future scenarios.
Jiyang would divert water from the South-North Transfer to agriculture because (1) agriculture is prominent among demands in Jiyang, and (2) groundwater is preferred for drinking water.

Chanqqing would receive water for its agricultural, industrial, and residential nodes.

### Springs

The Jinan WEAP model currently includes one node to represent the major Jinan springs in the city’s urban core including the spring groups of Baotu, Wulong (Five Dragons), Heihu (Black Tiger), and Zhenzhu (Pearl). The average total discharge of these four spring groups ranges from 300,000 m³ per day to 600,000 m³ per day, and the minimum groundwater

---

<table>
<thead>
<tr>
<th>Reservoirs</th>
<th>Maximum Storage Capacity (m³)</th>
<th>Normal Water Storage Level (m)</th>
<th>Construction Status</th>
<th>Inflows</th>
<th>Outflows</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baiyun</td>
<td>64,700,000 (9,000,000 normal storage)</td>
<td>—</td>
<td>Complete</td>
<td>Yellow River</td>
<td>Duzhuang Reservoir</td>
</tr>
<tr>
<td>Dazhan</td>
<td>9,610,000</td>
<td>78.0</td>
<td>Complete</td>
<td>Xiujiang River</td>
<td>Zhangqiu agricultural demand</td>
</tr>
<tr>
<td>Donghu</td>
<td>53,770,000</td>
<td>30.00</td>
<td>Complete</td>
<td>Yangtze Transfer</td>
<td>Zhangqiu industrial demand</td>
</tr>
<tr>
<td>Duozhuang</td>
<td>10,940,000</td>
<td>304.30</td>
<td>Complete</td>
<td>Xiujiang River</td>
<td>Zhangqiu agricultural demand</td>
</tr>
<tr>
<td>Duzhuang</td>
<td>6,830,000</td>
<td>46.60</td>
<td>Complete</td>
<td>Baiyun Reservoir (Yellow River)</td>
<td>Langmaoshan Reservoir, Jinan industrial and Zhangqiu agricultural and industrial demands</td>
</tr>
<tr>
<td>Fengyuan Lake</td>
<td>7,215,000</td>
<td>18.00</td>
<td>Complete</td>
<td>Xingjiadu Irrigation Channel</td>
<td>Shanghe industrial and residential demands</td>
</tr>
<tr>
<td>Jiangshuiquan</td>
<td>1,050,000</td>
<td>191.80</td>
<td>Near completion</td>
<td>Xinglong Reservoir</td>
<td>Quanfu River, Longquan Reservoir</td>
</tr>
<tr>
<td>Jinxiuchuan</td>
<td>35,920,000</td>
<td>251.00</td>
<td>Complete</td>
<td>Yufu River</td>
<td>Jinan and Licheng residential demand, Xinglong Reservoir</td>
</tr>
<tr>
<td>Langmaoshan</td>
<td>10,940,000</td>
<td>187.00</td>
<td>Complete</td>
<td>Duzhuang Reservoir</td>
<td>Licheng agricultural demand and Xueshan WTP</td>
</tr>
<tr>
<td>Longquan</td>
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<td>151.00</td>
<td>Near completion</td>
<td>Jiangshuiquan Reservoir</td>
<td>Daxin River</td>
</tr>
<tr>
<td>Qingyuan Lake</td>
<td>9,535,000</td>
<td>25.94</td>
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<td>Xingjiadu Irrigation Channel</td>
<td>Shanghe industrial and residential demands</td>
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<tr>
<td>Queshan</td>
<td>39,300,000</td>
<td>29.10</td>
<td>Complete</td>
<td>Yellow River</td>
<td>Queshan WTP and Jinan Steel Corp (IP)</td>
</tr>
<tr>
<td>Wohushan</td>
<td>61,500,000</td>
<td>130.50</td>
<td>Complete</td>
<td>Jiping Channel and Yufu River</td>
<td>Jinan and Licheng residential demand, Xinglong Reservoir</td>
</tr>
<tr>
<td>Xinglin</td>
<td>5,350,000</td>
<td>103.30</td>
<td>Complete</td>
<td>Xinghua</td>
<td>Zhangqiu agricultural demand</td>
</tr>
<tr>
<td>Xinglong</td>
<td>773,000</td>
<td>206.35</td>
<td>Near completion</td>
<td>Wohushan and Jinxiuchuan Reservoirs</td>
<td>Xingji River, Jiangshuiquan Reservoir</td>
</tr>
<tr>
<td>Yuqing</td>
<td>36,300,000</td>
<td>38.85</td>
<td>Complete</td>
<td>Jiping Channel and Yellow River</td>
<td>Yuqing WTP</td>
</tr>
</tbody>
</table>

* Elevation datum is average sea level.
pressure head required to sustain flow in Baotu Springs is 27m above sea level (Baohua and Daqiu, 2006).

Baotu Springs has been identified by JWRB as the spring group of greatest interest given its importance to the cultural heritage and economic vitality of Jinan. Baotu Springs discharges to the Jinan moat and Da Ming Lake, which flows into the Xiaoqing River. In the WEAP model, Baotu Springs water discharges into Dongluo channel (the eastern side of the moat), which then discharges into the Xiaoqing River. Additional springs in Licheng (Bai) and Zhangqiu (Baimai) have been included as well.4

Each spring node is connected to an adjacent groundwater node, which provides the spring’s source, and a surface river or stream, where the spring may discharge. Many of Jinan’s spring groups, while interconnected, rely on separate recharge zones and are largely divided by low or no impermeability faults (Kang, Jin, and Qin, 2011; Zhao, 2015). The dynamics of spring flow are among the more difficult features to capture in the Jinan WEAP model in the absence of more-detailed modeling and data analysis.

### Climate Interaction With Surface and Groundwater

For our analysis of future conditions and systems performance, we are particularly interested in modeling interactions between climate and surface water and climate and recharge. Precipitation is the primary source of recharge for Jinan’s groundwater system and is a direct driver of headflows to rivers included in the WEAP model. Temperature also has an effect on surface water runoff and recharge, as changes in temperature affect evapotranspiration and annual precipitation patterns.

To estimate the relationship between precipitation and stream flow on rivers in the WEAP model, monthly aggregate precipitation data from a station at Jinxiuchuan Reservoir

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4 Spring discharge at these nodes were calibrated assuming cyclical flow under cycled Historical Climate conditions with no trends in increasing discharge. Calibration of these springs is discussed later in this chapter.
have been compared with total monthly volumes of surface water runoff found at different reach points along each river. Figure 3.2 shows a linear regression between monthly precipitation (mm) at the Jinxiuchuan dam and total monthly inflow to the Jinxiuchuan Reservoir from 2010 to 2016, where inflow to Jinxiuchuan was used as the estimated headflow of the Yufu River. The curve shown in Figure 3.2 highlights the strong relationship between precipitation and monthly inflow.

In addition to precipitation, temperature is a climate factor that also drives surface water runoff and groundwater recharge. To estimate the added effect of temperature on surface water flows, daily temperature data from 2005 to 2016 were acquired from Raspisaniye Pogodi (undated) and used to develop multivariate regression models, using changes in precipitation and temperature to estimate changes in headflow in rivers. These models were developed for all rivers in the model except the Yellow and the Nandasha. Similar models were also developed for recharge; these relate changes in annual precipitation and temperature to changes in recharge by district. By allowing changes in climate to be reflected in changes in surface water runoff, head flows, and groundwater recharge, these relationships enable the key variables in the Jinan WEAP model to be consistent with the climate projections (see Chapter Six). Thus, the multivariate regression models translate climate change into changes in supply availability. A detailed explanation of the development of these regression models and how they relate precipitation and temperature to surface water flows can be found in Appendix D.

Figure 3.2
Relationship Between Observed Precipitation at Jinxiuchuan Dam and Jinxiuchuan River Inflow
Modeling of Infrastructure

Representation within the Jinan WEAP model of reservoirs and conveyance structures have already been discussed. In this section, we identify the representations of infrastructure associated with the Jinan system as it currently exists and of planned facilities, noted in the IP, 13th Five-Year Plan, and other sources.

Facilities in Operation as of 2016

Many IP projects included in the Jinan WEAP model have been completed recently (in 2015 or 2016; see Table B.1 in Appendix B). The Jiazhuang Gauge to Wohushan Reservoir Water Diversion Project (2016), Beidianzi to Jinan City Center Water Diversion Project (2015), and the five-reservoir transfer projects (2016) have all been completed, and are set to “turn on” in the appropriate year in the WEAP model. Additional IP infrastructure projects in the WEAP model that were completed earlier are included for all model years. These are the Yuqing River Water Diversion Project and the Jiping Conveyance to Yuqing Lake Water Diversion Project.

Planned Infrastructure

Infrastructure projects that were either nearing completion or planned were included in the WEAP model to provide insights into their potential effects on the Jinan water system. As part of the IP, a transfer from Duzhang to Langmaoshan, which is nearing completion, and a transfer from Duzhang to the Jinan Steel Corporation, which is still in its planning phase, were both included in the model. In addition to IP projects, two other infrastructure projects were added. First, the Dazhan WTP, which will be operational starting in 2017, will add surface water supply to Zhangiu. Second, an as-yet unplanned WTP sourcing water from the Xiaoqing River (starting in 2030) was added on the assumption that Jinan could increase water quality in the Xiaoqing to the higher Grade III standards by 2030.

Water Quality

We were provided with monthly water quality data for nine locations and three years (2013 to 2015) in the form of a water quality index value. In Figure 3.3, we display these data to provide a sense of the range in water quality present in the system: Red bars show when the target standard was not achieved and blue bars show when the target was met. These data confirm that the water quality of Xiaoqing River (fourth through seventh row in Figure 3.3) failed to meet water quality standards in virtually all months from 2013 to 2015 for all sampling locations, rendering the River an unusable supply. If the Xiaoqing could eventually meet Grade III water quality standards, it could become a new source of water to areas in need, as noted in the previous section. Without further information on source terms or flows associated with these monthly index values, we were not able to further evaluate water quality as a constraint or consider how quality levels would change in the future.
Figure 3.3

<table>
<thead>
<tr>
<th>River</th>
<th>Sampling Cross Section</th>
<th>2013</th>
<th>2014</th>
<th>2015</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beidasha River</td>
<td>Gushan</td>
<td>6</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td>Tuhai River</td>
<td>Liucheng Bridge</td>
<td>6</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td>Yingzi Gate</td>
<td></td>
<td>6</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td>Xiaoqing River</td>
<td>Chaizhuang Gate</td>
<td>6</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td>Huangtaiqiao (HQ)</td>
<td></td>
<td>6</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td>Wujiapu</td>
<td></td>
<td>6</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td>Wulongtang</td>
<td></td>
<td>6</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td>Xiujiang River</td>
<td>Dazhan Reservoir</td>
<td>6</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td>Yufu River</td>
<td>Above Wohushan Reservoir</td>
<td>6</td>
<td>4</td>
<td>6</td>
</tr>
</tbody>
</table>

NOTE: Red bars show when the target standard was not achieved; blue bars show when the target was met.

Calibration Process

The WEAP model, like any simulation model, needs to be capable of reproducing historical conditions and performance before it can be run “forward” to project future conditions and system performance. The process of matching historical observations to results from the simulation model is called calibration. Mathematical models can never fully represent the real physical system, and for this reason, calibration is never perfect. For the Jinan WEAP model, we ran the model to generate inflows, outflows, and storage in the surface and groundwater components of the Jinan system and match these model values as closely as possible to observed historical data. As with any calibration, model errors will always be present and model parameters will be, at best, approximations. The aim in any modeling analysis is to minimize such errors to the extent possible using the data (and time) available.

With these qualifications in mind, RAND first sought to demonstrate that the WEAP model, configured with Jinan’s existing supply and demand preferences, could replicate his-
Development and Calibration of the Jinan WEAP Model

Historical observations of flows and storage. Calibration points in the WEAP model included (1) groundwater flows, (2) groundwater storage, (3) surface and groundwater supply allocations by district, and (4) reservoir releases (where available).

Decade-long calibration periods are always more desirable for calibration of a regional water balance model than short periods. Long periods tend to capture a wider range of variability in the climate system. However, for a calibration to have validity, historical data used throughout the model need to have the same record lengths; otherwise, the WEAP calculations that match supply to demand in each month and year would not be using internally consistent data. For the Jinan WEAP model, consistent demand and supply data across the entire model domain were only available from 2010 to 2014 (see Appendix A). Even though historical data with record lengths as long as 30 years were available at some points in the model domain, many other nodes and arcs lacked such temporal coverage. For example, information on inflows, groundwater use, and even demand is quite sporadic outside the five-year period. Therefore, we used the five-year calibration period for the Jinan WEAP model from 2010 to 2014, but could not go one step further to test model performance with a sufficient and independent set of historical data.

In a second phase of calibration, we extended mean historical water use growth rates and changes in annual activity levels (those activities that drive demand in each sector, such as population in the residential sector and IVA in the industrial sector) from 2015 to 2050 to observe how the Jinan WEAP model would respond under the Historical Climate projection. We use the term Historical Climate projection to indicate a repetition of the historical record from 2010 to 2014 for each five-year period from 2015 to 2050. That is, every five-year period under assumed Historical Climate conditions has the same sequence of wet and dry years.

In the residential and agricultural demand sectors, mean historical water use growth rates and changes in annual activity levels were estimated using the entire five-year calibration period (2010 to 2014). In the industrial sector, steep increases in activity (industrial value added) and reductions in water use rates from 2010 to 2014 were found. Since these changes likely reflected overall growth in Jinan’s economy and concerted, lasting efforts to reduce industrial use, we used only 2013 and 2014 data to estimate mean annual activity levels and water use rates.

Supply and Demand Preferences

As part of the calibration process, we assumed the same supply and demand preferences and priorities provided to RAND by JWRB through data files and in-person meetings (see Appendix A). Supply preferences in the model were set to reflect selected observed conditions, including reservoir releases and water levels, releases from Wohushan reservoir to meet ecological needs, unmet demand, and observed surface and groundwater supplies delivered at the district level. Supply priorities specified by JWRB were used as guidance for setting supply priorities in WEAP. For example, JWRB explained that Jinan residential demand should be satisfied from groundwater; therefore, we reflected this preference in the Jinan residential demand node.

In some cases, we estimated certain quantities required in the model based on observational records, consumption statistics, and simulated reservoir operations in an effort to best reflect observed supply delivery records. For example, we applied this approach to the percentage of agricultural demand that could be fulfilled by releases from Wohushan reservoir.

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5 In some analyses, hydrologic data is “synthesized” through interpolation and statistical methods to fill in gaps in a time series. This practice is generally not advisable in the context of model calibration, and in fact, such an approach runs the risk of adding to model error.
Finally, the model calibration process required that there be no unmet demand during the period 2012 to 2050 under Historical Climate conditions and current water demands across all sectors. Calibration during these future time steps is intended to ensure that the model will be in equilibrium under the repeated five-year cycling of Historical Climate conditions. Next, we discuss points of calibration in the Jinan WEAP model.

**Equilibrium of Groundwater Storage**

For the five-year calibration period of 2010 to 2014, we assumed that groundwater storage was in equilibrium; that is, storage did not change over time. We made this assumption in the absence of evidence to the contrary and an understanding that pumping was consistent with a safe yield policy. This assumption allowed for the following groundwater properties to be estimated with consistency:

- changes in groundwater storage as a consequence of flow between groundwater nodes
- hydraulic conductivity and specific yield of the aquifers
- spring discharges when historical observed discharge values were available for comparison.

After all residential, industrial, and agricultural pumping and all other applicable withdrawals were accounted for, we sought to establish groundwater equilibrium in each five-year period from 2015 to 2050. A strong climate signal was found in historical groundwater data, allowing us to compare groundwater levels at different points in time in the model. Because the 2010–2014 climate is repeated in each five-year period from 2015 to 2050, groundwater levels in August 2013 (or any month) could be compared with levels in August 2048 (during the seventh repetition of Historical Climate conditions) to generate changes in groundwater storage over time. Changes in storage reflected groundwater flows into or out of the particular area.

The map in Figure 3.4 shows the interbasin groundwater flows used to guide calibration of the Jinan WEAP model. The map shows that water flows from the Dong’er karst water catchment, where Pingyin obtains much of its groundwater, to the northeast across the permeable Niujiadian fault to the Changxiao karst water catchment. Water in this catchment, which lies directly below part of Changqing, continues across the Mashan fault—which is a low permeability fault close to the Yellow River—to arrive in the Jinan Spring Water Catchment. The Jinan Spring Water Catchment includes part of Changqing and Licheng districts in addition to the Jinan district, and all flows eventually converge near central Jinan. Flows from Licheng and Changqing groundwater nodes to the Jinan groundwater node were included in the WEAP model to represent this connection. Additionally, flows from Shanghe and Jiyang counties were set to exit across the WEAP model boundary to the east in accordance with estimated groundwater flow there (Liu, Cheng and Yao, 2011).

As noted, changes in groundwater storage were estimated by comparing storage levels in August 2013 and August 2048 (two of the peak storage values in all districts). Flows across administrative boundaries (from one groundwater node to another) were estimated by setting the flow equal to the average annual increase in storage, and then allowing the storage to be in equilibrium within each five-year period from 2010 to 2049 (Figure 3.5).

**Spring Discharge**

Total spring discharges at the four primary spring groups of Baotuquan, Heihuquan, Zhen-zhuquan and Wulongquan were calibrated to observed discharge (measured in m$^3$) values from
Figure 3.4
Groundwater Flows Used to Guide Model Calibration

Legend*

SOURCE: Kang, Jin, and Qin, 2011. Used with permission.

* Hydrogeology of Jinan Karst Aquifer System, consisting of Jinan spring catchment, White spring catchment, Changxiao karstwater catchment and Dong’er karst water catchment.

1 karst groundwater abundant and discharge area.
2 karst groundwater recharge area.
3 karst groundwater buried below impermeable sandstone and shale.
4 impermeable igneous rock.
5 impermeable granitic gneiss.
6 permeable fault.
7 low permeability fault.
8 impermeable fault.
9 impermeable igneous dike.
10 surface and groundwater divide.
11 no-flow boundary.
12 lateral inflow boundary.
13 lateral outflow boundary.
14 karst spring.
15 general direction of karst groundwater flow.
16 karst groundwater wellfield and its number.
17 urban area of Jinan City.
18 towns.
19 Cambrian-Ordovician.
20 Carboniferous-Permian.
21 Archean.
22 magmatic rock.
2010 to 2013, as provided by JWRB. Additionally, spring levels (measured in m) provided by JWRB from 2003 to 2015 were used to provide estimates of aggregate discharge, using a model from Kang, Jin, and Qin (2011) to match spring levels to estimated discharge. In Figure 3.6, we compare trends in observed and simulated discharge, and also show estimated spring discharge (orange line) in the period for which we lacked historical data. For the period in which observational discharge records are available, Figure 3.6 shows that simulated aggregate discharge is similar in amplitude and phase to observed discharge. Additionally, outside of the period where observations are available, simulations tend to follow a similar pattern as the estimates.

The WEAP model uses the wedge method to model aggregate discharge from groundwater in the Jinan district to the four springs in central Jinan. The groundwater properties of hydraulic conductivity and specific yield in the Jinan district node were estimated as part of the calibration, although we used estimates from the literature to initialize these parameters (Qian et al., 2006).

Calibration of groundwater storage in Zhangqiu and Licheng districts included several steps to account for both discharge to Baimai Springs and Bai Springs, respectively, and any potential outflow from each district (Figure 3.7). In Zhangqiu, eastward flow was estimated to occur based on maps from Liu, Cheng, and Yao (2011). Discharge for Baimai Springs was esti-

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6 Detailed documentation of this method is available in the WEAP User Guide, which is available for download (SEI, undated-a).
mated to be proportional to Baotu Springs, with the ratio of mean peak monthly discharge at Baimai Springs Group to mean peak monthly discharge at Baotu Springs being approximately the ratio of historical average flow at Baimai (220,000 m³ per day) to historical average flow at Baotu (up to 400,000 m³ per day), or about 55 percent (Wu, Xing, and Zhao, 2009).

Because of the limited amount of information available to inform the representation of both Baimai and Bai springs—including observed discharge data and groundwater properties—the calibration focused on adjusting hydrologic properties from the Jinan aquifer to yield non-zero spring flow in 2010 and roughly stable discharge. Mean peak annual flows from Baimai were calibrated to around 43 percent of the mean peak annual discharge from Baotu Springs, about 12 percent lower than the 55-percent estimate. This is a point for future improvement in the WEAP model with the availability of more information. Bai Springs was included to represent spring discharge in Licheng. No records of discharge or data about flow were found or included for Bai Springs. Therefore, calibration of discharge at Bai Springs was set so that groundwater storage in Licheng would be in equilibrium after accounting for estimated flow from Licheng groundwater to Jinan groundwater. Figure 3.7 shows estimated discharges from Baotu Springs, Baimai Springs, and Bai Springs.

**District-Level Splits in Supply Between Surface and Groundwater**

Ensuring that quantities of surface and groundwater deliveries by district were representative of observed quantities was an important element of the calibration process for the Jinan WEAP model. In general, simulated withdrawals were in line with observations for the 2010–2014 period by setting demand priorities, source preferences, and transmission link capacities (pipe-
lines) in accordance with JWRB guidelines and information. In a few cases, some model parameters had to be adjusted or constrained to improve the fit. For example, for industrial nodes, preferences were set for use of surface water over groundwater. However, preferences among multiple surface water supply nodes for each industrial node had to be set in accordance with the model’s response as part of the calibration. If any preferences for a specific source (for example, a reservoir) were expressed by JWRB, then these preferences were taken into account. Figure 3.8 compares observed and simulated surface and groundwater supplies delivered during the calibration 2010–2014 period for Jinan Urban Center.

**Reservoir Operations**

Reservoir operations (releases) were an important component of calibration. Ensuring that reservoir supplies are being properly utilized in response to changing demand and supply conditions is important for interpretation of results later in the study. Among reservoirs included in the WEAP model, sufficient operations data were only available for Jinxiuchuan and Wohushan reservoirs, and thus these two reservoirs became important points of calibration in the model. Wohushan was used primarily for ecological withdrawals, including recharge of the Jinan groundwater basin through releases to the Yufu River. In addition, Wohushan provided water to satisfy both agricultural and municipal (residential and industrial) demands.

Reservoir operations are primarily a function of source preferences and demand priorities (including the priority of filling the reservoirs), and these preferences were adjusted iteratively to generate simulated storage volumes that generally reflected observed operations during the calibration period. Figures 3.9 and 3.10 show relatively good agreement for both Jinxiuchuan and Wohushan reservoirs, respectively.
Figure 3.8
Observed and Simulated Surface and Groundwater Supplied to Jinan Urban Center Node

![Bar chart showing supply delivered (10^8 m^3) for years 2010 to 2014. The chart includes bars for observed SW, simulated SW, observed GW, and simulated GW.]  

NOTE: GW = groundwater; SW = surface water.

Figure 3.9
Calibration for Jinxiuchuan Reservoir Operations

![Line chart showing storage volume, 10^8 m^3, from 2010 to 2016. The chart includes observed volume and simulated volume.]
Figure 3.10
Calibration of Wohushan Reservoir Operations

Observed volume
Simulated volume

Year
Storage volume ($10^8$ m$^3$)
In this chapter, we describe the development of scenarios used to address the first research question noted in Chapter One regarding how future conditions will stress Jinan’s water management system. Our focus is on two key uncertainties that will affect the system’s performance in the future: possible increases in demand and changes in precipitation and temperature patterns in the Jinan region as a consequence of a changing greenhouse gas–warmed climate. We also evaluate the effects of a 50-percent reduction in the allocation of Yellow River supplies.

**Demand Projections**

To support the vulnerability assessment of the Jinan water management system under future conditions, JWRB provided RAND with projections originally generated in 2009 for the following sectors: urban and rural residential, agricultural, forestry and fishery, industry, and urban ecological (parks and road water) (see Appendix A for details). Each projection provided by JWRB included annual activity levels and water use rates for the years 2009, 2015, 2020, and 2030. For each sector, JWRB’s information included projections for the districts of Jinan Urban Center (including an aggregate of estimates for Huaiyin, Lixia, Shizhong, Tianqiao, and Licheng districts), Zhangqiu District, Pingyin County, Jiyang County, Shanghe County, and Changqing District. We then grouped these projections provided by JWRB into the appropriate WEAP model classifications of residential, industrial and agricultural, and subsequently adjusted them to reflect historical trends during the model calibration period (2010–2014).

Demands for each sector depend on a number of factors that affect water use, including pricing, policies and incentives for water efficiency and conservation, and economic activity and growth. Residential demand projections build in variability in population growth and industrial demand projections build in variability in industrial activity.

Demand projections from JWRB were originally developed in 2009 and included projections for 2009, 2015, 2020, and 2030. Since these projections implicitly included historically observed years, they were adjusted to match the most recently available observed data year, which was 2014. To perform the adjustment, we first estimated the projected demand for the year 2014 by combining projected activity levels and water use rates to generate estimated total demand and then interpolating linearly between projected demands in 2009 and 2015. Then, based on observed data for each sector, we added an adjustment factor to aggregate water use rates for each sector included in the model to align estimated values with observed values in 2014. Details are provided in Appendix C. These adjustments were made to reflect gains made
in water efficiency in Jinan in the period since the projections were first generated in 2009 and to maintain these improvements in water use efficiency into the future.

Since JWRB's 2009 projections ended at 2030, we needed to estimate annual activity levels beyond 2030. The estimation techniques we used to generate post-2030 activity levels vary by sector, as will be discussed.

**Residential Demand Projections**

For each district included in the WEAP model, residential demand projections are the aggregate of urban and rural residential demand, green space ecological demand (including parks), and water required for road cleaning and maintenance. JWRB provided three separate water use projections for each demand component. Water use rates beyond 2030 were maintained at 2030 levels until 2050 in each scenario.

As shown in Table 4.1, Demand Scenario 0 (for all sectors) is a calibration demand scenario that assumes mean water use rates during the calibration period and mean activity levels during the calibration period will continue unchanged through 2050. These scenarios are used only for the calibration of the model and do not represent projections of demand. Scenario 1 represents the continuation of historical growth rates of both annual activity levels (in industrial and agriculture only) and annual water use rates (in all sectors).

In addition to projections of water use rates, JWRB provided population estimates by district. Population projections based on JWRB population data were developed by inferring growth rates between specified years and applying applicable growth rates to observed population data, beginning in 2012 (the most recent year where population data are available for all districts). Population data from 2012 were acquired from the 2012 Jinan Statistical Yearbook (Jinan, 2012). Growth rates beyond 2030—by district—were inferred by linearly interpolating between growth rates from previous years (2015, 2020, and 2020); a minimum growth of zero was set. While one of these population scenarios is included in Table 4.1 (and the WEAP model as delivered) as Population Scenario 2, we did not include it in subsequent analysis described in later chapters.

Instead, we developed population scenarios using population data from the United Nations Department of Economic and Social Affairs (UNESA, 2014). Population projections from UNESA ranged from 2005 to 2030 for Jinan and included the districts of Lixia, Shizhong, Tianqiao, Huaiyin, Changqing, Licheng, and Zhanqiu. We used these projections to generate growth rates for the Jinan, Changqing, Licheng, and Zhangqiu demand nodes in WEAP. We then applied these growth rates for both pre- and post-2012 to generate projections through 2030. UNESA projections also included growth rates for urban and rural population in China for five-year periods from 2015 to 2050. We followed a different procedure for the districts of Jiyang, Shanghe, and Pingyin, which are counties that were not included in UNESA population estimates. For these districts, we applied UNESA estimates for growth

<table>
<thead>
<tr>
<th>Table 4.1</th>
<th>Residential Demand Projections Included in the WEAP Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residential Demand Projection</td>
<td>Demand per Capita</td>
</tr>
<tr>
<td>0</td>
<td>Mean historical (calibration)</td>
</tr>
<tr>
<td>1</td>
<td>Historical (Low)</td>
</tr>
<tr>
<td>2</td>
<td>Medium B (JWRB Low)</td>
</tr>
<tr>
<td>3</td>
<td>Medium C (JWRB High)</td>
</tr>
<tr>
<td>4</td>
<td>Medium (JWRB Medium)</td>
</tr>
<tr>
<td>5</td>
<td>High (RAND NYC)</td>
</tr>
</tbody>
</table>
rates in rural populations for 2012 to generate estimates through 2030. After 2030, applicable
growth rates from UNESA data were applied to all districts.

Finally, an additional water use rate projection was developed by RAND at the request of
JWRB to reflect water use rates in the residential sector similar to cities in the United States.
Their reasoning was that a potential increase in water use rates could accompany continued
development in China. It should be noted, however, that residential per capita water use rates
have been trending downward in the United States since 2005, with a national average in 2010
of around 85 gallons per capita per day and a range among the states of 50 to 168 gallons per
capita per day (Donnelly and Cooley, 2015, p. 7). For this reason, this proposed High Demand
scenario should not be viewed as inevitable in the context of Jinan’s future development.

Current domestic public supply water use rates in New York City were selected for this
projection because, like Jinan, it has high urban density (and a low rate of single-family homes,
which tend to use more water) and it is located in a similar climate classification. New York
City residential water rates are well within the prevailing rates of other U.S. cities, and hence
do not represent an outlier. Data for New York City domestic water use rates were acquired
from the U.S. Geologic Survey (Maupin et al., 2014). All five of New York City’s boroughs
(comparable to counties) had domestic public supply water use rates of 75 gallons (283.9 liters)
per person per day.1 Note that the projection is driven primarily by water use rates rising to
parity with New York City, not due to an assumption of population growth. Note, however
that even if demand growth were attributable to population growth, efficiency improvements
could keep demand growth in check. This is in fact what happened in the United States over
the last three decades of the 20th century.

To develop this High Demand scenario, we assumed a water use rate of 284 liters per
person per day for Jinan Urban Center by 2030, representing an increase of 97.2 percent over
the highest water use of 144 liters per person per day in Jinan in any of the other scenarios.
We applied this proportional increase to the high rural and urban residential water use rates to
generate residential water use rates for Scenario 5.

In addition to increases in residential consumption, Scenario 5 included potential increases
in urban green space per capita that could accompany such development. Therefore, in this
scenario, urban green space per person in Jinan was increased 58.1 percent, from 17.9 square
meters per person to 28.3 square meters per person, using area per person from New York City
park data (Harnik, Martin, and Barnhart, 2015). New York City green space per capita repre-
sented a reasonable benchmark for the same reasons residential water use did, although it has
below-average park space per person for the United States. The 58.1-percent increase in green
space was applied to each of the seven districts in the Jinan WEAP model, while water require-
ments per square meter of green space did not change. Figure 4.1 shows each of the residential
demand scenarios from 2012 to 2050.

**Industrial Demand Projections**

Industrial demand projections were provided by JWRB. IVA is the annual activity level that
drives industrial demand and is defined as the proportion of GDP generated by primary and
secondary industries (Table 4.2). Three different water use rate projections were provided by
JWRB. Similarly to agricultural demand projections, industrial demand projections contained

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1 The U.S. Geologic Survey category of domestic public water supply is the same as urban residential water supply for
purposes of this study.
a single annual activity level projection applied to three different levels of water use rates. Historical IVA records were provided by JWRB (2009 to 2015) and used as the baseline for industrial growth projections.

Projections provided by JWRB included growth rates for industry over multiyear periods. These growth rates were applied to observed annual data, starting with the latest year (2015), to generate projections. For example, projections from JWRB for the Jinan Urban Center included a growth rate of 7 percent from 2015 to 2020 and 5 percent from 2020 to 2030. These growth rates were used to estimate demand through 2020. However, to eliminate extreme growth from industrial value projections going forward, projections after 2020 were reduced. Growth rates for each district from 2020 to 2025 were interpolated between JWRB’s specified growth rate in 2020 and a rate of 3.5 percent by 2025. Subsequent rates were interpolated linearly between the following benchmarks: 2.5 percent by 2030, 1.2 percent by 2040, and 0.1 percent by 2049. These growth rates were generated to “smooth out” demand curves by 2050, and show slower growth by 2030, with significant reductions in growth by 2040. Industrial demand scenarios used in the analysis are shown in Figure 4.2.

Table 4.2
Industrial Demand Projections Included in the WEAP Model

<table>
<thead>
<tr>
<th>Industrial Demand Projection</th>
<th>Demand per IVA (renminbi)</th>
<th>IVA Projection</th>
<th>Overall Demand Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Mean historical (calibration)</td>
<td>JWRB Adjusted</td>
<td>Calibration</td>
</tr>
<tr>
<td>1</td>
<td>High (historical)</td>
<td>JWRB Adjusted</td>
<td>Current, High</td>
</tr>
<tr>
<td>2</td>
<td>Medium (JWRB High)</td>
<td>JWRB Adjusted</td>
<td>Medium</td>
</tr>
<tr>
<td>3</td>
<td>Low (JWRB Low)</td>
<td>JWRB Adjusted</td>
<td>Low</td>
</tr>
<tr>
<td>4</td>
<td>JWRB Medium</td>
<td>JWRB Adjusted</td>
<td>—</td>
</tr>
</tbody>
</table>
Agricultural Demand Projections

Agricultural demand in irrigated areas was calculated using a formula provided by JWRB that relates irrigated area, irrigation water demand per unit area, and an irrigation water usage ratio. The irrigation water usage ratio relates to losses in the distribution of water between the withdrawal for agriculture use and the actual delivery to the irrigated lands (Food and Agricultural Organization, 2016) and is simply the volume of water delivered to the field divided by the total volume of water withdrawn at the source for agricultural use. The smaller the ratio, the greater are the losses between the point of withdrawal and field application, and hence, the larger the volume of water required for irrigation. We developed six demand projections in the agricultural sector by combining three irrigation water usage ratio projections with two irrigation assurance rates of 50 percent and 75 percent. An irrigation assurance rate is the expected percentage of irrigation water demand that can be met over a multiyear period. Table 4.3 summarizes the agricultural demand projections, including the assurance rates and irrigation usage ratios. These projections include separate water use rates and activity levels for the following categories of crops and other land uses: paddy, watering, vegetable fields, which

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2 The formula for the irrigated water demand under baseline climate conditions $D_\gamma$ was given as: $D_\gamma = AQ_\gamma / \gamma$, where $A$ is the effective irrigation area in 10,000 monetary units, $Q_\gamma$ is the water demand (m$^3$ per monetary unit), and $\gamma$ is the irrigation water usage ratio. A description of estimates of change in agricultural demand under different climate projections is provided in Appendix D.

3 This definition was provided to us by the Jinan team. Specifically, irrigation assurance rate is the probability calculated as the percentage of years that expected normal irrigation water demand has been met. The formula is $P = m / (n+1) \times 100\%$, where $P$ is the probability, $m$ is the number of years that designed irrigation water demand has been fully met, and $n$ is the total number of years considered and should be higher than 15.
used effective irrigation area as the activity level; forestry and fruits and grass fields, which used
(irrigation area); fish pond (total area); and small and large animal counts (population).

The Jinan WEAP model uses irrigated area as the single annual activity level driving agri-
cultural demand for water. Irrigated area included the total area of paddy, watering, vegetable,
and grass fields, forestry and fruits, and fish ponds. Aggregate demand was estimated using the
formula provided by JWRB for each projection in Table 4.3. A water use rate was then calculated
by dividing total demand by total irrigated area. In the Jinan WEAP model, a single agricultural
activity area was coupled with six different water use rate projections. Because little to no growth
in area is assumed across the projections, the 2030 value for irrigated area by district was main-
tained through 2050. Figure 4.3 shows the agricultural demand projections used in the analysis.

Reducing the Number of Demand Projections

JWRB provided multiple projections by sector: six projections in the agricultural sector and three
each in the residential and industrial sectors. With the addition of the historical baseline growth
projection estimated by RAND, this led to 112 possible combinations of demand projections by
sector: seven agricultural, four industrial, and four residential demand projections (7 × 4 × 4).

To reduce the number of combinations and to highlight projections that are most likely to affect
the Jinan water system in significantly different ways, we grouped these projections and reduced
the number to three plausible scenarios in addition to the baseline projection (historical growth)
for the purposes of this analysis. The three projections represent low, medium, and high aggregate
demand for the entire Jinan model domain. The combinations of agricultural, industrial, and
residential demand projections used to develop these three projections are shown in Table 4.4.

Climate Projections

This study uses a range of estimates of future climate based on simulations from a set of global
climate models (GCMs) developed for the Intergovernmental Panel on Climate Change’s
(IPCC’s) Fifth Assessment Report (2013). More than 20 models were used to develop cli-
mate simulations for the assessment, and each simulation was based on one of four standard-

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As the Jinan WEAP model is further developed, more agricultural nodes could be added to disaggregate irrigated lands
by cropping patterns.

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ized global emission pathways. According to Climate Change, Agriculture, and Food Security (CCAFS), the four pathways are:

- [Representative Concentration Pathway] RCP 2.6: The emission pathway is representative for scenarios in the literature leading to very low greenhouse gas concentration levels. It is a so-called peak scenario: It represents a strong mitigation scenario and is extended by assuming constant emissions after 2100 (including net negative CO₂ [carbon dioxide] emissions), leading to CO₂ concentrations returning to 360 parts per million by 2300.

- RCP 4.5: It is a stabilization scenario where total radiative forcing is stabilized before 2100 by employment of a range of technologies and strategies for reducing greenhouse gas emissions.

- RCP 6.0: It is a stabilization scenario where total radiative forcing is stabilized after 2100 without overshoot by employment of a range of technologies and strategies for reducing greenhouse gas emissions.

### Table 4.4

Demand Projections Included in Analysis of Jinan Water Management System

<table>
<thead>
<tr>
<th>Overall Demand Projection</th>
<th>Residential Demand Projection (from Table 4.1)</th>
<th>Industrial Demand Projection (from Table 4.2)</th>
<th>Agricultural Demand Projection (from Table 4.3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calibration</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Current</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Low</td>
<td>1</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Medium</td>
<td>4</td>
<td>2</td>
<td>6</td>
</tr>
<tr>
<td>High</td>
<td>5</td>
<td>1</td>
<td>2</td>
</tr>
</tbody>
</table>
- RCP 8.5: It is characterized by increasing greenhouse gas emissions over time representative for scenarios in the literature leading to high greenhouse gas concentration levels. (CCAFS, 2014b)

While these models are extremely sophisticated, they can only approximate the complex physical processes that affect future climate. As a result, even when they are evaluated using the same assumptions about greenhouse gas emissions, their estimates of basic atmospheric variables, such as daily temperature and precipitation, can vary significantly across the simulations.

The spatial scale of the GCMs is also coarse relative to processes that affect the hydrology of the world’s water basins. Downscaling procedures are used to (1) remove any biases that might exist between a given climate simulation and the actual climate in a localized region of the globe, and (2) spatially disaggregate to a higher resolution the climate projections to better reflect orography, for example. Downscaled projections of monthly temperature and precipitation from the Fifth Assessment Report are now available worldwide (Collins, et al., 2013). We used data that was statistically downscaled using the Delta Method and obtained from CCAFS (2014a), a global partnership that unites organizations engaged in research for a food-secure future (Ramirez and Jarvis, 2008). Using simulation results from these climate models (CCAFS, 2015), downscaled to the Jinan region, we developed projections of precipitation and temperature to 2050. These are shown in Figure 4.4.

These projections were then be used to estimate changes in river flows, groundwater recharge, and irrigation demand across a range of climate model simulations. The legend in Figure 4.4 uses international naming conventions to refer to four global emissions scenarios, each corresponding to different assumed rates of growth in greenhouse gas emissions. RCP 2.6 is the lowest assumed level of emissions growth; RCP 8.5 is the highest assumed growth rate. The colors correspond to the many different climate models used to generate these projections. (Figure 4.6 provides a legend for a selected set of these models.)

All of the projections show warming; scientists are quite confident that future conditions will be warmer. However, there is disagreement about whether conditions will be getting wetter or drier. All we can infer from the global climate modeling thus far is that it is possible that future conditions will be either wetter or drier. One of the benefits of the analysis in this study is that it helps JWRB understand how important this uncertainty is by looking at results across a wide range of wetter and drier conditions—although our study shows that it is not an important factor in most cases.

Methods

To represent the effects of climatic variation on water supply in the Jinan WEAP model, we estimated relationships between historical precipitation, temperature, and inflows. Using regression analysis, we estimated relationships between climatic variables and surface water flows and groundwater recharge. We then applied these statistically derived relationships to the downscaled climate projections and used them to generate projected estimates of future surface water flow and groundwater recharge in Jinan. These best-fit regression models were developed for each supply node included in the model. We used the best available climatic data (World Climate Research Programme, undated; Taylor, Stouffer, and Meehl, 2012), and the observed hydrologic data made available to us. For the Jinan WEAP model, the best available precipitation data were contained in records of observed monthly precipitation totals at Jinxiquchan Dam from 1992 to 2015. These data were provided to RAND by JWRB (see Appendix A).
To supplement the monthly precipitation records provided by JWRB, we acquired daily weather data from a weather station in central Jinan online at a website maintained by Raspisaniye Pogodi Ltd. (2016). These data included observed mean daily temperature and were used to calculate:

- estimated monthly mean temperature, which was then used in the development of stream headflow regression models
- estimated annual mean temperatures, which was then used in the development of groundwater recharge regression models.

Several precipitation data sets were received from JWRB, including monthly precipitation totals (mm) at or in Shanghe County, Jinxiuchuan Dam, and Tianshan Irrigation Area. A comparison of these records is shown in Figure 4.5. Because the Tianshan Irrigation Area data set contains many missing data points, we did not use it when generating potential regression models; the time series is also highly correlated with both the Shanghe and Jinxiuchuan data series. A detailed description of the process of developing regression models for head flows and groundwater recharge is provided in Appendix D.

Climate projections included in the Jinan WEAP model use cycled historical data (five years from 2010 to 2014) as described previously. The five-year length of the climate cycle is unfortunately short, given known historical variation in precipitation and temperature. However, this five-year period represents the longest period of overlap for the precipitation and temperature data and for the stream and inflow data for headflows being analyzed. To consider how large-scale changes in climate may affect the whole system, it is important that a historical cycle

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**Figure 4.4**

Downscaled Precipitation and Temperature Projections for the Jinan Region

- Change in annual precipitation (mm)
- Change in average annual temperature (degrees Celsius)
- Global emissions scenario: historical, RCP 2.6, RCP 4.5, RCP 6.0, RCP 8.5

 RAND R81602-4.4
For each climate scenario, the five-year cyclical climate was adjusted using a change in precipitation and temperature that was obtained from regionally downscaled GCMs for the year 2050. These changes are referred to as delta values, which are additive and represent the differences between historical average annual total precipitation and mean temperature and future projected values for annual total precipitation and mean temperature. For each climate scenario, temperature and precipitation delta values for years 2015 to 2049 were interpolated linearly from a value of 0 in 2014 (the first year assumed to be the baseline) to the year 2050 precipitation and temperature delta values. For headflows, estimates were made on a monthly basis (using the monthly deltas in 2050 available); for recharge, the estimation was done annually. Additional details on how the delta values were used in the regression models can be found in Appendix D.

**Approach to Selecting Climate Projections**

We chose 26 climate projections from those in Figure 4.4 because they represent the full span of precipitation and temperature effects generated from the climate models. Climate selection followed the methods of Carlsen et al. (2016). Briefly, an objective function accounting for variance in input models, climate model outcome space, and the range of model outcomes was maximized over 100,000 random samples. These selected futures are shown in Figure 4.6. A clearer explanation of the models can be found in Table F.2 in Appendix F.
We developed a large set of futures reflecting uncertainty in demand, climate conditions, Yellow River allotment, and initial groundwater levels. To explore the range of uncertainty as fully as possible, we defined one future for each combination of

- 3 future demand projections
- 26 future climate projections + Historical Climate projection
- 2 Yellow River resource allotments
- 2 initial groundwater levels.

In total, we thus developed 324 futures, which we then used to evaluate 16 different management strategies, including the system as currently configured. To facilitate the evaluation of the WEAP model almost 5,000 times, we distributed the runs over numerous virtual computers using the Amazon Web Service. Table F.1 in Appendix F shows each combination of climate and demand projections. Note that all combinations included in Table F.1 were run against the four possible combinations of groundwater uncertainty (high or low) and potential allocation of Yellow River resources (continued at 100 percent in 2030 or 50-percent reduction in 2030).

With this understanding of scenario development in hand, we turn in the next chapter to the results of our analysis, beginning with projections of system performance under the assumption that Historical Climate conditions remain the same in the future.
In this chapter, we summarize WEAP model results of our baseline evaluation of the system. In this baseline evaluation, we assume the historical configuration of facilities and policies in place and that past climate conditions extend into the future. This analysis indicates how future changes in demand across each of the sectors could affect the ability to meet those demands in the future in each of the districts. These results assume that stored groundwater is large enough to provide water as needed and therefore would not contribute to any unmet demand conditions.

**Projections of Demand**

Under the assumption of the Historical Climate projection, we first look at Low, Medium, and High Demand projections as described in Chapter Four. Under the Low Demand projection, total demand across all three sectors increases only slightly from 2015 to 2050 (Figure 5.1). Increases in the residential and industrial sectors are largely offset by declines in the agricultural sector. In this projection, total demand is just under 2,000 MCM by 2050.

Under the Medium Demand projection, we see a sustained and gradual increase in demand from about 1,800 MCM to 2,200 MCM (Figure 5.2). While demand in the agricultural sector is declining, increases in the residential and industrial sectors more than offset these declines.

Under the High Demand projection, steep total increases in demand are seen from 2015 to 2030. The increases then lessen through 2050 (Figure 5.3). In this projection, total demand exceeds 2,800 MCM by 2050. Taken together, the three demand projections of Low, Medium, and High (Figures 5.1 to 5.3) span a range of demand from 1,950 MCM to 2,800 MCM—or an increase of 9 percent to 57 percent over 2015 demand.

**Residential Demand by District**

Figure 5.4 shows residential demand through 2050 by district for the Medium Demand projection. The largest demand increases over the 36 years occur in the Jinan Urban Center (orange) and Zhangqiu District (purple). Results are similar for the Low and High Demand projections (not shown).
Figure 5.1
Low Demand Projection by Sector Across All Districts

Figure 5.2
Medium Demand Projection by Sector Across All Districts
Figure 5.3
High Demand Projection by Sector Across All Districts

Figure 5.4
Residential Demand by District for the Medium Demand Projection
Industrial Demand by District
Growth in industrial demand under the Medium Demand projection is also concentrated in the Jinan Urban Center and Zhangqiu District (Figure 5.5), with projected growth in Licheng as well. Results are similar for the Low and High Demand projections (not shown).

Agricultural Demand by District
Changes in agricultural demand are uniform across the districts as they are driven by reductions in irrigation requirements that are applied equally to all irrigation areas. Figure 5.6 shows trends for the Medium Demand scenario under the Historical Climate projection. Figure 5.7 shows how the total irrigation demand varies across the range of climate projections for the Low and High Demand scenarios. The potential effect of climate change, which increases over time, leads to wide ranges of demand by 2050—a range between 20 percent higher and lower than Current Demand for the High Demand projection and a range between no change and 30 percent lower than Current Demand for the Low Demand projection.

Sources of Supply at Selected Demand Nodes
The WEAP model simulates how demand at each node is met by supply over time. To briefly summarize how the model represents water allocation, we show the supply mix for several key demand nodes.

As shown in Figure 5.8, Jinan’s residential demand currently is met by supplies from the Dongjiao and Dongyuan WTPs, which treat groundwater, and the Yuqing WTP, which treats...
Figure 5.6
Agricultural Demand by District for the Medium Demand and Historical Climate Projection

Figure 5.7
Agricultural Demand by District Across Climate Projections for the Low and High Demand Projections
water that originates primarily from the Yuqing reservoir, but also draws from groundwater. As demand grows, additional supply is met primarily by the Queshan WTP that draws water from Queshan reservoir. Both Yuqing and Queshan reservoirs store water from Jinan’s Yellow River allotment and both are able to provide water to satisfy Jinan residential and industrial demands. As shown in Figures 5.8 and 5.9, increasing supply from the Queshan WTP to fulfill residential demand comes at the expense of supply delivered to meet industrial demand under both Low and High Demand projections. Under the High Demand projection, the Queshan WTP provides water exclusively to satisfy Jinan residential demand, and additional supply is provided by Fenshuiling WTP. This supply is limited, however, and demand cannot be fully met.

**Jinan Industrial**

In the near term, Jinan industrial demand is met by the Queshan WTP, which treats water originally drawn from the Yellow River and stored in the Queshan Reservoir (Figure 5.9). Since fulfilling residential demand is a higher priority than meeting industrial demand in the WEAP model, industrial demand met by this source begins to decline as residential demand increasingly draws from it. Some additional water is supplied for Jinan industrial needs by the Fenshuiling WTP, which draws water from the Jinxiuchuan Reservoir. In 2030, additional supply is available from the Yuqing WTP, which increases because of greater available allocation from the South-North Yangtze River Transfer. The declining supply of industrial water, particularly in the High Demand projection, leads to significant unmet demand.
Jiyang Agriculture

Jiyang agriculture is an important demand node because of the relative weight of agricultural demand among all water demands there, and because of Jiyang’s status as the second largest agricultural demand node in Jinan. It receives a mix of supply from Jiyang groundwater, the Yellow River, the South-North Transfer Allocation (which draws water from the Yangtze River and is scheduled to come on line in 2030) and the Tuhai River (Figure 5.10). Agricultural users first look to surface water supplies, and there are abundant surface water sources available for agriculture in Jiyang, including the Tuhai, which is only used for agriculture because of its poor quality. The Tuhai River dries up periodically in the simulations. When it does, additional groundwater is used to meet demand.

Zhangqiu Agriculture

Zhangqiu agriculture, which represents the largest agricultural demand node in Jinan, derives almost all of its supply from groundwater in results from the WEAP model (Figure 5.11). A few other sources, including Duozhuang reservoir, provide some additional supply.

Unmet Demand by Sector

We recognize that government policy does not allow any unmet demand to occur in the residential sector. The intention of this analysis is to indicate the future supply and demand projections under which demand would be unmet across each of the sectors if policies to prevent shortages in the residential sector were not applied. The purpose is to show how much additional supply would need to come from other sectors to meet residential demand.
Figure 5.10
Sources of Supply for Jiyang Agricultural Demand Node for Historical Climate Projection

Figure 5.11
Sources of Supply for Zhangqiu Agricultural Demand Node for Historical Climate Projection
Residential Sector
In the residential sector, there is no projected unmet demand for the Low Demand projection through the analysis period (Figure 5.12). For the Medium Demand projection, a small amount of unmet demand—less than 3 percent—is projected after 2025 in the Zhangqiu District. For the High Demand projection, however, unmet demand is projected beginning after 2020 in the Zhangqiu, Jinan Urban Center, and Pingyin Districts (Figure 5.13). Unmet demand in Jinan Urban Center and Zhangqiu District is significant, reaching about 16 percent and 44 percent of demand by 2050, respectively.

Industrial Sector
In the industrial sector, unmet demand is expected for all three demand projections (Figure 5.14). For the Low Demand projection, unmet demand begins around 2023 and reaches 100 MCM by 2050, which is about 21 percent of the 2050 demand. For the Medium Demand projection, unmet demand begins in 2020 and reaches 200 MCM by 2050, which is about 33 percent of the 2050 demand. For the High Demand projection, unmet demand begins in 2019 and reaches about 350 MCM by 2049, which is about 49 percent of the demand. The dip in unmet demand beginning in 2030 is because of the increased supply from the Yangtze River that becomes available in 2030.

Figure 5.15 shows that the projected unmet industrial demand is mostly within the Jinan District—97 percent of the total by 2050. A smaller amount of unmet demand is projected after 2025 in Zhangqiu District.
Figure 5.13
Residential Unmet Demand by Sector for Historical Climate and High Demand Projections

<table>
<thead>
<tr>
<th>Year</th>
<th>2010</th>
<th>2015</th>
<th>2020</th>
<th>2025</th>
<th>2030</th>
<th>2035</th>
<th>2040</th>
<th>2045</th>
<th>2050</th>
</tr>
</thead>
<tbody>
<tr>
<td>Demand projection</td>
<td>Low</td>
<td>Medium</td>
<td>High</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 5.14
Industrial Unmet Demand for Historical Climate and Three Demand Projections
Agricultural Sector
Under the Historical Climate projection, there is a small amount of projected unmet demand in the agricultural sector for all three demand projections beginning in 2024 (Figure 5.16). The pattern of unmet demand mirrors the historical pattern. Under the wettest years, there is no unmet demand for all three demand projections. Under the driest years, however, unmet demand is not projected to exceed 2.2 percent under any demand projection. All the unmet demand in the agricultural sector is projected to occur in the Jinan District (not shown).

Springs
The WEAP model has been calibrated to represent the spring flow regime that would be expected under a continuation of the Historical Climate projection and current demands. Figure 5.17 shows the monthly aggregate spring flow for Baotu (Baotuquan), Black Tiger (Heihuquan), Pearl (Zhenzhuquan), and Five Dragon (Wulongquan) springs, referred to as Baotu Springs for the sake of simplicity. Monthly flows greater than 4.35 MCM (above the red line) are assumed to reflect noncritical flows, and flows greater than 5.64 MCM (above the dotted orange line) are considered adequate for robust spring flow. Values below the red line are critically low. As Figure 5.17 shows, flows remain above the 4.35-MCM threshold under Current Demand and Historical Climate (brown line). Under the Low Demand projection, however, flows would drop below the threshold more frequently—about half of each year, except for the wettest years. Results for the Medium and High Demand projections are identical to those shown for the Low Demand projection.
Figure 5.16
Agricultural Unmet Demand for Historical Climate and Three Demand Projections

Figure 5.17
Average Monthly Spring Flow for Baotu Springs Under Historical Climate and Current and Low Demand Projections (2041–2051)

NOTE: Monthly flows above the red line are assumed to reflect noncritical flows; flows above the dotted orange line are considered adequate.
Figure 5.18 summarizes the behavior of Baotu Springs for each year from 2012 to 2050 in terms of the minimum monthly flow (top) and number of months in which flow is below the threshold of 4.35 MCM per month. The figure shows that there is an immediate divergence in results among the three future demand projections and the Current Demand projections, with the future demand projections showing lower average flows (top) and more months with flows below the critical threshold (bottom). From 2024 on, the pattern of spring stabilizes and is similar among all three demand projections. For all three future demand scenarios, four out of five years have between three and seven low-flow months, and one out of five years has no low-flow months.

**Groundwater**

As described in Chapter Four, we did not have information pertaining to the amount of stored groundwater for each groundwater basin. Because many demands in Jinan are met through groundwater, the amount of stored groundwater has a significant effect on the estimated unmet demand results shown in the preceding section. Those results are based on an
assumption of unlimited groundwater, so the projected volumes of unmet demand represent lower-bound estimates.

In this section, we first show how groundwater storage would change under the bounding assumptions of unlimited groundwater storage. Any estimated depletion under this unlimited groundwater assumption may lead to unmet demand under more-realistic assumptions of limited groundwater storage. We next show how unmet demand projections change when we assume that groundwater storage is at the minimum amount needed to ensure that lack of groundwater availability does not contribute to unmet demand under the Current Demand and the Historical Climate projection. Last, we show how unmet demand changes under these two assumptions.

We summarize the evolution of groundwater basin storage by grouping the basins by urban districts—Jinan, Changqing, and Licheng—and by agricultural districts—Jinyang, Pingyin, and Shanghe. We summarize groundwater results on these two broad categories to concisely illustrate how groundwater assumptions lead to different outcomes for the basins used primarily for urban versus agricultural uses. Due to the coarse nature of the groundwater modeling, we do not disaggregate results further.

The top graph in Figure 5.19 shows the urban storage over time under the assumption of Large Initial Groundwater Storage for the three future demand scenarios and Current Demand. Under the Current Demand projection, groundwater is in steady state and only deviates small amounts each year until 2030, when additional Yangtze River supply comes online and leads to some increases in groundwater under the hypothetical Current Conditions simulation. Under the future demand scenarios, some groundwater depletion occurs, even after the additional Yangtze River supply becomes available in 2030. For the Low Demand scenario, slightly less than 1 billion m$^3$ are depleted by 2050, which is on average about 24 MCM per year of depletion. This average annual depletion rate is about 12.5 percent of the total residential and industrial unmet demand in 2050 for the corresponding urban districts. Depletion is about twice as high in the Medium Demand projection. For the High Demand projection, depletion is significantly higher, reaching a total depletion amount of nearly 5.5 billion m$^3$, or 156 MCM per year. This is about 37 percent of the 422 MCM of residential and industrial annual shortage for these districts in 2050. These results suggest that supply and demand for the urban basins is not in balance or equilibrium for the future demand projections—particularly under the High Demand scenario. According to the assumptions used in the model, the expected groundwater extractions exceed the average annual recharge.

The bottom graph in Figure 5.19 shows that under a Low Initial Groundwater Storage level (around 400 MCM) assumption, the assumed limited amount of storage is largely depleted by 2021 under the High Demand projection and by 2035 for the Low and Medium Demand projections, as seen by change in storage reaching –400 MCM. Note that this result is not intended to imply that Jinan’s groundwater will become depleted by 2021, only that if one were to assume only a very small amount of storage, then it would quickly be depleted and lead to high unmet demands because of less groundwater being available.

Constraining availability of groundwater leads to higher unmet demands and more interannual variability in unmet demand, particularly in the High Demand projection, as seen in Figure 5.20. The difference between the unmet demand in these two cases is equivalent to the amount of additional imbalance that exists under the three scenarios. For example, for the Medium Demand scenario, unmet demand reaches around 150 MCM by 2035 when assum-
Figure 5.19
Changes in Urban Groundwater Storage over Time with Large Initial Groundwater Storage and Low Initial Groundwater Storage

- Demand projection
  - Current
  - Low
  - Medium
  - High

Year
2010 2015 2020 2025 2030 2035 2040 2045 2050

Large Initial GW Storage: Groundwater storage change (billion m$^3$)

Low Initial GW Storage: Groundwater storage change (million m$^3$)
ing unlimited groundwater. However, as seen by the result when groundwater storage is minimal, the actual imbalance is greater by an additional 30 percent—more than 200 MCM.

Figure 5.21 shows the changes in groundwater storage in the agricultural districts for the two assumptions about initial groundwater storage levels. When initial storage is large, all future demand projections show increases in groundwater. Under this simulation, the agricultural sector in these three agricultural districts always receives sufficient supply to meet demand. Recall that calibration in these areas included the estimation of down-gradient flows out of the district during the 2010–2014 period to satisfy the assumption of groundwater storage remaining in equilibrium (see the discussion of groundwater calibration in Chapter Three for further discussion). Groundwater storage increases in the largely agricultural districts of Jiyang, Pingyin, and Shanghe under certain future conditions because of the combination of reduced agriculture demands in all future projections and high reliance on groundwater. Because groundwater is a large supply for agricultural demand in these districts, groundwater storage is sensitive to reductions in demand. Additionally, increased urbanization leads to further reduction in residential demands in rural areas. The change in the amount of water leaving these areas (groundwater flow) is less than the relative reduction in withdrawals (reductions in demand), and groundwater storage subsequently increases. The increase in groundwater suggests excess water availability in these districts that could be used for other sectors and/or districts.

Note, however, that the model’s representation of groundwater is simplistic and there are no constraints on the total amount of groundwater storage possible for these nodes. In reality, some portion of the additional water contributing to groundwater increases in the model simulations might actually lead to surface water flow instead.
Figure 5.21
Changes in Agricultural Groundwater Storage over Time with Large Initial Groundwater Storage and Low Initial Groundwater Storage

<table>
<thead>
<tr>
<th>Year</th>
<th>2010</th>
<th>2020</th>
<th>2030</th>
<th>2040</th>
<th>2050</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low Initial GW Storage: Groundwater storage change (million m³)</td>
<td>0</td>
<td>500</td>
<td>1,000</td>
<td>1,500</td>
<td>2,000</td>
</tr>
<tr>
<td>High</td>
<td>0</td>
<td>500</td>
<td>1,000</td>
<td>1,500</td>
<td>2,000</td>
</tr>
</tbody>
</table>

Demand projection:
- Current
- Low
- Medium
- High
Summary of Findings

This chapter provides a broad overview of how Jinan’s water system may evolve through 2050 in response to changing water demands and varying assumptions about groundwater storage. Results show that under assumptions of the Historical Climate projection and current management conditions, significant levels of unmet demand should be expected, although the timing varies depending on the demand projection. For the Low Demand projection, unmet demand is estimated to appear around 2023; for the Medium and High Demand projections, unmet demand would appear earlier. Chapter Six evaluates the conditions leading to this unmet demand in greater detail, and Chapter Seven shows how additional management approaches could alleviate most of this unmet demand.

As expected, these results mirror the projections of water use as inputs to the model. While the Low and Medium Demand projections are derived from JWRB information, the increased residential needs in the High Demand projection reflect per capita usage rates similar to those in large U.S. cities (New York City, in this case). These water use assumptions lead to much higher residential demand. In the industrial sector, projections of continued rapid growth in industrial activity drives increasing demands, particularly in the High Demand scenario.

The unmet demand results show clearly that, over time, the current Jinan water management system cannot accommodate all the demand growth under the assumption that climate conditions will continue in the future as they have in the past. The vast majority of unmet demand would occur in Jinan Urban Center and Zhangqiu District. Agricultural unmet demand is relatively small, as ample surface and groundwater supplies are available in the districts where agriculture dominates.
In Chapter Five, we looked at projections of future system performance under the assumption that previous climate conditions would prevail to at least 2050 and the current configuration of water management storage, conveyance, and other facilities would remain in place. In this chapter, we expand on consideration of future demand as we did in Chapter Five, but we evaluate future system performance under a range of future climate conditions generated from a suite of global climate models, and two different allocations of supply from the Yellow River. This provides insight into the ability of Jinan’s current water management infrastructure to meet potential future demands under a changing climate. We also defined those futures in which performance would not be acceptable with respect to key metrics, such as unmet demand, as vulnerable. This helps to identify the uncertain conditions most relevant to the management decisions that Jinan might take to improve the robustness of its system in relation to the uncertain future. Importantly, this approach enables us to compare different strategies without knowing precisely how likely different futures are. In Chapter Seven, we assess options and strategies for addressing the identified vulnerabilities, thus ensuring required performance across the range of plausible future conditions.

Unmet Demand Under a Wide Range of Futures

We now show results for unmet demand across the three future demand projections, 26 future climate projections in addition to a repeat of historical conditions, and two allocations of supply from the Yellow River. By comparing the projections of unmet demand across this large experimental design, we can identify the adaptation measures that would be required for Jinan’s water management system to perform well across these many scenarios (which we define as robustness), and which factors are most critical in influencing performance. The results presented below assume Large Initial Groundwater Storage and therefore should be considered a lower bound of unmet demand.

Residential Sector Vulnerability to a Changing Climate and Factors Affecting Results

Figure 6.1 shows the range of unmet demand over time for the three future demand projections, the two Yellow River allotments, and across all the climate projections (see the experimental design in Table F.1 in Appendix F). We use X symbols in this figure and subsequent figures in this chapter to highlight the simulation results based on the Historical Climate projection. The other filled circles correspond to simulations based on the climate change projections. The results are very similar to those for the Historical Climate case (Figure 5.12):
no unmet demand for the Low Demand projection, modest increases under the Medium Demand projection, and large unmet demands under the High Demand projection.

Note that there is relatively little variation in unmet demand across climate projections, reflecting the high priority for water supply for the residential sector. Under the 50-Percent Yellow River Allocation (right graph), however, unmet demand is both higher under the High Demand scenario and varies more across the range of climate projections. This suggests that reducing access to the Yellow River could make the residential sector much more vulnerable to future climate conditions if residential demands increase more than the Medium Demand projection.

Figure 6.2 again shows unmet residential demand for all three demand projections across climates for the Full Yellow River Allocation from 2015 to 2050, with the average unmet demand for the 2031–2050 period (in the shaded area) shown on the right. This 20-year statistic (unmet demand from 2031 to 2050) is used in the following figures to summarize results across the full set of futures.

Figure 6.3 summarizes residential unmet demand across all the futures, assuming Large Initial Groundwater Storage. In the figure, the height of the bar indicates the average annual unmet demand from 2031 to 2050 and the coloring indicates the district where the unmet demand is projected to occur. Figure 6.3 clearly shows the increasing unmet demand corresponding to increasing demand (e.g., Low, Medium, and High). It also shows that the Medium Demand projection leads to unmet demand in Zhangqiu District. In the High Demand projection, unmet demand appears in both Zhangqiu and the Jinan Urban Center under both Full and 50-Percent Yellow River Allocations. In this case, the climate conditions do not have a noticeable effect on the volume of unmet demand. For the High Demand projection, however, climate conditions do affect unmet demand: Drier climates (those on the right of each panel) lead to higher unmet demands. On balance, however, unmet demand for the residential sector is driven much more by the demand projection and Yellow River allotment than by future climate.
Figure 6.2
Unmet Residential Demand by Demand Projection Across Climates (left) and Summary of Unmet Demand from 2031 to 2050 (right)

NOTE: X symbols indicate results for the historical climate projection and the filled circles indicate results for the climate change projections.

Figure 6.3
Average Unmet Residential Demand (2031–2050) by District Across All Futures
We now classify outcomes based on unmet demand. For purposes of example, we define futures to be vulnerable if average unmet residential demand from 2031 to 2050 is higher than 5 percent of demand. Any other threshold value could be chosen. Figure 6.4 shows the results for all futures. Red symbols indicate futures in which the residential sector is vulnerable; green symbols are outcomes that are not vulnerable. Lighter shades are results for the assumption of Low Initial Groundwater Storage. The symbols are ordered by average precipitation within each column, showing that drier climates lead to more unmet demand. This visualization clearly shows that the residential sector is highly vulnerable under the High Demand projection and vulnerability to unmet demand is dependent upon allocation of Yellow River supply. Vulnerability is also greater under all futures with a Low Initial Groundwater Storage assumption (lighter symbols).

Industrial Sector Vulnerability to a Changing Climate and Factors Affecting Results

Figure 6.5 shows unmet industrial demand for all three demand projections across climates for the Full Yellow River Allocation scenario from 2015 to 2050, along with the average unmet demand for the 2031–2050 period (on right). Figure 6.6 displays this information disaggregated by district and shows most of the unmet demand is in Jinan Urban Center and, to a lesser extent, Zhangqiu District.

Figure 6.7 classifies outcomes based on unmet demand. As an example, these are futures in which average unmet industrial demand from 2031 to 2050 higher than 30 percent of demand is deemed vulnerable. As with the analysis for the residential sector, any threshold value could

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1. The threshold for unmet residential demand is preliminary and can be adjusted per JWRB comments.
2. Any value could be chosen for the threshold for unmet industrial demand and can be adjusted within the Planning Tool.
Figure 6.5
Unmet Industrial Demand by Demand Projection Across Climates (left) and Summary of Unmet Demand from 2031 to 2050 (right)

NOTE: X symbols indicate results for the historical climate projection and the filled circles indicate results for the climate change projections.

Figure 6.6
Average Unmet Industrial Demand (2031–2050) by District Across All Demand, Climate, and Yellow River Allocation Futures

NOTE: Within each column, futures are ordered from wetter to drier climates.
be selected. Red X symbols indicate futures in which the industrial sector is vulnerable to unmet demand. The symbols are ordered by average precipitation within each column. This visualization clearly shows that the industrial sector is highly vulnerable in all but the Low and Medium Demand projections with a Full Yellow River Allocation. The sensitivity of industrial unmet demand to climate is higher under the Low Initial Groundwater Storage assumption, but relatively minor compared with the demand projection and Yellow River allotments.

**Agricultural Sector Vulnerability to a Changing Climate and Factors Affecting Results**

Figure 6.8 shows unmet agricultural demand for all three demand projections across climates for the Full Yellow River Allocation scenario from 2015 to 2050, along with the average unmet demand for the 2031–2050 period (on right). Unlike the residential and industrial sectors, the agricultural sector's future unmet demand depends more on the climate than the demand projection, as seen by the vertical spread of results for a given year.

Figure 6.9 shows the average agricultural unmet demand from 2031 to 2050 across all the futures for both Low and Large Initial Groundwater Storage assumptions. With a large amount of initial storage, unmet demand varies from 0 in the wettest futures to between 18 million and 30 MCM per year, depending on the demand projection and allocation of Yellow River supply. All of the unmet demand for these futures is seen in the Jinan district. With Low Initial Groundwater Storage, however, unmet demand increases and is exhibited in four of the seven districts—Changqing, Jinan, Licheng, and Pingyin—for the Low and Medium Demand projections. Under the High Demand projection and 50-Percent Yellow River Allocation future, unmet demand is seen in Jiyang as well. Again, the effects of drier climates on agricultural unmet demand is clearly seen in this figure.
Figure 6.10 classifies outcomes based on unmet demand. As an example, futures in which average unmet agricultural demand from 2031 to 2050 is more than 5 percent of demand are deemed vulnerable.\(^3\) Other threshold values could be used. Red symbols indicate futures in which the agricultural sector is vulnerable to unmet demand. The symbols are ordered by average precipitation within each column. This visualization shows that the agricultural sector is largely invulnerable except when for Low Initial Groundwater Storage—and then only under the drier climates for the Medium and High Demand projections.

### Vulnerability of Springs to a Changing Climate and Factors Affecting Results

Figure 6.11 shows how the number of months per year in which the flow at Baotu Springs is below the flow threshold (described in Chapter Five and shown in Figure 5.20) varies over time and across the demand and climate projections. The left side shows results for three climates and the right side shows the results for all climates (highlighting the three shown on the left). These results assume Large Initial Groundwater Storage and Full Yellow River Allocation, although the results for the other storage and allocation assumptions are similar. The right side of the figure shows that for each demand projection, a wide range of results is seen across the individual climate projections (spread of dots). In wet climates, low flows each year occur around three months on average. In dry climates, the average number of months with low flows reaches about eight.

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\(^3\) The threshold for unmet agricultural demand is preliminary and can be adjusted by JWRB in future analyses.
Figure 6.9
Average Unmet Agricultural Demand (2031–2050) by District Across All Demand, Climate, and Yellow River Allocation Futures for Large Initial Groundwater Storage and Low Initial Groundwater Storage

NOTE: Within each column, futures are ordered from wetter to drier climates.
Figure 6.10
Summary of Unmet Agricultural Demand and Vulnerability Across All Futures and Initial Groundwater Assumptions

NOTE: The red X symbols indicate futures in which the system is vulnerable and the filled green circles indicate futures in which the system is not vulnerable, depending on the threshold for vulnerability chosen.

RAND RR1682-6.10

Figure 6.11
Average Number of Months per Year with Low Spring Flow by Demand Projection Across Climates (left) and Summary from 2031 to 2050 (right)

RAND RR1682-6.11
Vulnerability of Groundwater to a Changing Climate and Factors Affecting Results

Figures 6.12 and 6.13 show the sensitivity of groundwater storage to climate under the demand projections and initial storage level for the urban and agricultural groundwater basins, respectively. These figures show results for the Full Yellow River allotment, as there is very little sensitivity to the Yellow River allotment. Note that while groundwater provides supplies to the various demand nodes, it is not prescribed in the Jinan WEAP model. Recharge rates are dependent on assumptions about climate projection and initial storage, and thus the ability of groundwater to satisfy demands depends on the mass balance of each groundwater node. The sensitivity of groundwater is highly relevant to understanding the performance of the system and understanding vulnerabilities in all sectors.

Figure 6.12
Changes in Groundwater Storage for Urban Basins Across Demand and Climate Projections and Assumptions About Initial Groundwater Storage
For the predominantly urban basins in Figure 6.12, the range of climate projections has a significant effect on the ending groundwater level. The 2050 change in groundwater storage, for example, ranges from –1.4 billion to 0.3 billion m$^3$ for the Low Demand projection and Large Initial Groundwater Storage level. For the High Demand projection, the amount of groundwater storage depletion is highly dependent upon climate. Groundwater depletion is 64 percent more for the driest climate than for the wettest climate. When there is Low Initial Groundwater Storage, the climate effect is not seen in the groundwater level, but shows up in the unmet demand results as already shown.

Results in Figure 6.13 for the agricultural groundwater basins show a similar pattern of climate effects. The high sensitivity of groundwater to climate with Large Initial Groundwater Stor-
age is seen by the broad spread of results in the top of Figure 6.13. The lower sensitivity with Low Initial Groundwater Storage is shown by the small spread of results in the bottom of Figure 6.13.

Summary of Findings

Chapter Six expands upon Chapter Five by evaluating unmet demand in the residential, agricultural, and industrial sectors; Baotu Springs flow; and groundwater storage across the climate projections, Yellow River allotments, and assumptions about initial groundwater storage. Based on the thresholds used in this report, the residential sector is only vulnerable to the High Demand projection and the Low Initial Groundwater Storage assumption (Figure 6.4).

Industrial unmet demand depends on the demand scenario and the allocation of Yellow River supply. Under 50-Percent Yellow River Allocations or High Demand, the industrial sector is always vulnerable. Under the Medium Demand scenario and Full Yellow River Allocation, the industrial sector is vulnerable only under the Low Initial Groundwater Storage assumption. Future climate makes the industrial sector vulnerability worse but is not a driving factor (Figure 6.7).

The vulnerability of the agricultural sector, on the other hand, depends upon the future climate more than the residential and industrial sectors. Since agriculture uses groundwater as a key source, there is no vulnerability under the assumption of Large Initial Groundwater Storage. Under Low Initial Groundwater Storage, however, vulnerability is seen in all demand and Yellow River allotment futures except the Low Demand, Full Yellow River Allocation futures. The climate effect is very strong as well, with no shortages in the wettest climate but significant shortages in drier climates (see Figure 6.10).

Last, Chapter Six explored the vulnerability of the springs and groundwater. The springs are highly vulnerable to the climate projections and initial groundwater levels while insensitive to the demand projections and assumptions about Yellow River allotments and groundwater storage. Groundwater basin storage is highly sensitive to the climate projections when the initial storage is very large (shown in both Figures 6.12 and 6.13): In effect, groundwater basins absorb a lot of the climate sensitivity not seen in the residential and industrial sectors. When initial groundwater storage is limited, however, the basins are fully depleted and the climate variation is seen in the form of unmet demand and low spring flow.
In this chapter, we present the results of implementing new water management strategies and contrast them with the results in Chapter Six, in which the present Jinan water management system is assumed to remain as it is currently exists. We developed a total of 16 possible strategies. These strategies were constructed from combinations of projects and policies described in the next section.

Projects and Policies Used to Construct Potential Strategies

We distinguish among current projects that have already been implemented and new projects that are part of the IP. Policies refer to efficiency improvements and operational changes intended to improve water management in Jinan.

Current Projects
The Current Projects strategy refers to IP projects that have already been implemented in addition to any scheduled changes in water supply due to policy. These include:

1. The Five Reservoir Transfer Project, which connects Wohushan and Jinxiuchuan reservoirs to Xinglong, Longquan, and Jiangshuiquan reservoirs for the purpose of providing stable flow to seasonal streams in central Jinan
2. The pipeline from the South-North Transfer (Jiping Channel) to the Wohushan Reservoir, which is generally used to provide water for recharge to Jinan’s groundwater system
3. The scheduled doubling of Jinan’s Yangtze River allocation from the South-North Transfer.

These projects have been completed, are under contract, or are expected to be implemented, and therefore are included in all cases evaluated under the experimental design. They are denoted in our model as “current projects,” because they were not completed during the 2010–2014 calibration period.

New Implementation Plan Projects
After evaluating the scale and effects of other infrastructure projects included in the IP and discussion with JWRB, two projects were identified as having the greatest potential effect on the system: a pipeline connecting the Duzhang Reservoir to the Langmaoshan Reservoir,
and a pipeline connecting Duzhang reservoir to the Jinan Steel Corporation. In the WEAP model schematic, Jinan Steel Corporation is included in the Jinan Industry demand node, and we therefore refer to this project as Duzhang to Jinan Industry. For modeling purposes, we assumed that the Duzhang to Langmaoshan connection will be operational by January 1, 2018 (based on an expected completion by the end of 2017), and the Duzhang to Jinan Steel Corporation connection will be operational by January 1, 2023 (based on JWRB’s planning schedules). These two projects are collectively denoted as “IP” in the results later in this chapter.

Reuse of Wastewater

Reuse of wastewater is an important component of JWRB’s management plan going forward. In results presented in Chapter Five, we used estimated reuse rates based on data contained in the Appendices of Jinan City Water Resources Public Communiqué (PCA) tables (Jinan Water Resources Bureau, 2008–2015a). However, JWRB’s future plans include a target to reuse 40 percent of wastewater treatment capacity by 2020, and 60 percent by 2030. In the model, only the Jinan Urban Center and three districts include WTPs—Licheng, Changqing, and Zhangqiu.

In discussions with JWRB, we understand that treated wastewater is primarily used as an industrial supply, although it could also be used in some circumstances to help meet urban ecological demand (including parks, greenery) and some irrigation. In the absence of data records available to base a proportional allocation of treated wastewater by sector, we make an assumption in the JWRB WEAP model to allocate 25 percent of treated wastewater to residential demand—including urban ecological demands—and 75 percent to satisfy industrial demands. This planned increase in wastewater reuse is incorporated into the model by adjusting reuse rates in residential and industrial demand nodes in each of the Jinan Urban Center and the three districts with existing wastewater treatment capacities to reflect achievement of these water reuse targets.

Water Quality Strategy

The Water Quality (WQ) strategy allows industry to draw and treat water under the assumption that WQ standards for the Xiaoqing River are met by 2030. In this strategy, if water quality in the Xiaoqing River improves, we assume that up to 250,000 m$^3$ day of cleaner Xiaoqing River could provide water to satisfy industrial demand in the Jinan Urban Center. The daily capacity was chosen after considering the availability of water in the Xiaoqing River.

Springs Adaptive Groundwater Management

The Springs Adaptive Groundwater Management (SAGM) policy represents an aggressive response to declining spring levels at the four largest springs in central Jinan: Baotu (Baotu Quan), Black Tiger (Heihuquan), Pearl (Zhenzhuquan), and Five Dragon (Wulongquan). The decision rule calls for dynamic adjustment of maximum groundwater withdrawals in the Jinan Urban Center. Currently, if the springs fall below certain thresholds, JWRB reduces groundwater withdrawals by a designated amount and releases additional water from Wohushan reservoir to increase recharge to the groundwater system (Kang, Jin, and Qin, 2011). Specifically,

- If the springs fall below 28m above sea level (orange warning level), then groundwater withdrawals in Jinan are reduced by 100,000 m$^3$ per day and 300,000 m$^3$ per day are released from Wohushan.
• If the springs continue to fall below 27.6m above sea level (red warning level), then groundwater withdrawals are reduced by 130,000 m$^3$ per day and 400,000 m$^3$ per day are released from Wohushan reservoir.
• If spring levels are above the orange level, groundwater withdrawal capacities are capped at the limit of the infrastructure (750,000 m$^3$ per day for Jinan Urban Center). (Kang, Jin, and Qin, 2011).

In the model, these levels have been estimated to correspond to monthly discharges of 5.64 million and 4.35 MCM per day, respectively. Reductions in groundwater withdrawals are applied directly to the Jinan Urban Center and are modeled as reductions to the maximum daily withdrawal from the Jinan Groundwater node. Reductions in other districts—such as Changqing and Licheng—were not modeled because of incomplete information on maximum withdrawal capacities in these districts.

The decision rule is represented in the model as follows: If the springs fall below the orange or red warning level, maximum groundwater withdrawals in the Jinan Urban Center are capped at the previous time step’s total groundwater supplied to the demand node, minus the warning level threshold and the previous time step’s groundwater discharge. This approach reduces withdrawals by the amount below the warning level threshold for spring discharge. Appendix E provides a mathematical expression for the decision rule.

**Efficiency Improvement Standards**
We evaluated different efficiency standards to highlight the effect of water use rates on demand and unmet demand in Jinan. It should be noted that these efficiency standards were not designed with any particular management actions in mind. Instead, they represent a means to evaluate how actions taken to improve efficiency might offset potential growth in water use across sectors and how sensitive unmet demand might be to these potential improvements in efficiency. These standards were represented as percentage decreases in water use rates (residential and industrial sectors) or climate effects on demand (agricultural sector) by 2035. For each sector, efficiency standards were evaluated at a 100-percent implementation level (full implementation) and a 50-percent implementation level. Implementation of efficiency improvements vary by sector:

• In the residential sector, we assumed that a fully implemented efficiency strategy would be successful if it could reduce the High Demand projection to the Low Demand projection. Using this assumption, a reduction by 44 percent was chosen because it represents the percentage reduction of the residential High Demand projection to the Low Demand projection for the year 2035. When the efficiency strategy is only implemented at a 50-percent level, water use rates would only decrease by 22 percent.
• In the industrial sector, full implementation of the efficiency strategy was represented as a 34-percent decrease in water use rates, where the change in water use rates was estimated in the same manner as residential efficiency rates were. Similarly, in the 50-percent implementation strategy, water use rates were decreased by 17 percent.
• In the agricultural sector, efficiency measures were only applied to futures where demand increased as a consequence of climate change. Therefore, improvements in efficiency were applied to increases in demand attributable to climate change, and thus these agricultural demands were still higher than they would be under the baseline climate. In scenarios
where demand increased, under full implementation of an efficiency strategy, the incremental increase in demand attributable to climate change was reduced by 50 percent. Under the 50-percent implementation, the incremental increase in demand attributable to climate change was reduced by 25 percent. The formula used to generate water use estimates under these efficiency regimes can be found in Appendix D.

For each sector and demand scenario, efficiency reduction targets were made on top of the previously projected water use rates.

**Strategies Considered for Analysis**

The projects and policies previously described were combined in different ways to generate 16 strategies that could be evaluated in model simulations. These combinations are summarized in Table 7.1.

**Effects of Management on Residential Sector**

Under the Historical Climate projection, Figure 7.1 shows unmet demand for the Current Project strategy, IP completion, IP and increased water reuse (IPR), and two strategies that include actions that significantly reduce residential unmet demand. The figure does not show

| Table 7.1 |
|---|---|---|
| **Strategies Evaluated as Part of the Experimental Design** |
| **Strategy** | **Name** | **Description** |
| 1 | Current Projects | Current state of Jinan system |
| 2 | Completion IP | Includes Current Projects and completion of IP projects |
| 3 | IPR | In addition to IP, includes increase of reuse rates in districts with WTPs specified to 40 percent of total district WTP capacity by 2020 and 60 percent of total district WTP capacity by 2030 |
| 4 | IPR + SAGM | In addition to IPR, includes SAGM strategy for reducing groundwater withdrawals in the Jinan Urban Center |
| 5 | IPR + WQ | In addition to IPR, includes WQ strategy of allowing industry to draw and treat Xiaoqing water after 2030 |
| 6 | IPR + WQ + SAGM | IPR + Xiaoqing WTP + SAGM |
| 7 | IPR + Residential Efficiency | In addition to IPR, includes 44-percent decrease in projected residential water use rates by 2035 |
| 8 | IPR + Residential Efficiency + SAGM | IPR + Residential Efficiency + SAGM |
| 9 | IPR + Residential and Industrial (Res/Ind) Efficiency | In addition to IPR + Residential Efficiency, includes 34-percent decrease in projected industrial water use rates by 2035 |
| 10 | IPR + Res/Ind Efficiency + Agricultural Climate-Induced Efficiency (EffAll) | In addition to IPR + Res/Ind Efficiency, strategy also includes 50-percent reduction of climate change–induced increases in agricultural demand by 2035, which we call Efficiency for All (EffAll) |
| 11 | IPR + EffAll + SAGM | IPR + EffAll + SAGM |
| 12 | IPR + EffAll + WQ | IPR + EffAll + WQ |
| 13 | IPR + EffAll + WQ + SAGM | IPR + EffAll + WQ + SAGM |
| 14 | IPR + 50 Percent Efficiency (50Eff) | 50-percent reduction in efficiency increases from IPR + EffAll |
| 15 | IPR + 50Eff + WQ | IPR + 50Eff + WQ |
| 16 | IPR + 50Eff + WQ + SAGM | IPR + 50Eff + WQ + SAGM |
results for the Low Demand projection because there is no projected unmet demand under that assumption. Figure 7.1 shows that completion of the IP has no effect on unmet demand for the Medium Demand projection (when unmet demand begins to appear after 2025), and only a very slight effect under the High Demand projection when unmet demand appears after 2020. The IPR strategy shows slight increases in unmet demand under the Historical Climate projection. This is because the increased reuse in this strategy goes primarily to the industrial sector (see next section). The IPR + Residential Efficiency eliminates unmet demand under the Medium Demand projection and almost eliminates unmet demand under the High Demand projection. Strategies with 50 percent of the residential efficiency improvements also eliminate unmet demand under the Medium Demand projection and significantly reduce unmet demand under the High Demand projection.

In contrast to the results in Figure 7.1 for the Historical Climate projection, Figure 7.2 shows summaries of residential unmet demand for the same five strategies across all futures. The red symbols are those results that exceed the 5-percent average unmet demand threshold at some point in the future. As expected, strategies that include improvements in residential efficiency are effective in reducing unmet demand across all climates and allocations of the Yellow River. In some future scenarios that include the wastewater reuse strategy, residential reuse rates (as a percentage of total residential demand) actually decline.

Effects of Management on Industrial Sector

Unmet demand is more significant in the industrial sector because its priority for supply is lower. As a consequence, more of the management strategies reduce unmet demand. Figure 7.3 shows the Current Project strategy and seven others, each of which affects unmet demand differently for the Historical Climate and Full Yellow River Allocation projections. As with the residential sector, completion of the IP has little effect on projected unmet demand after 2020.
IPR and WQ, however, lead to sharp reductions in unmet demand by about 100 MCM for each by 2030 when paired with just the IP. In some of these cases, wastewater reuse becomes the dominant supply source meeting industrial demand.

The IPR + Residential Efficiency strategy eliminates unmet demand under the Medium Demand projection. Under the High Demand projection, unmet demand is eliminated in
Reducing Vulnerability Through the Implementation Plan and Additional Management Strategies

2030 but then gradually increases. Adding efficiency in the industrial sector, the strategy of IPR + Res/Ind Efficiency eliminates unmet demand in the Medium and High Demand projections and reduces unmet demand by about 75 percent in the High Demand projection.

As with Figure 7.2, Figure 7.4 summarizes unmet demand in the industrial sector for select strategies across all futures. The red symbols are those results that exceed the 30-percent average unmet demand threshold. The figure shows that reducing industrial vulnerability to unmet demand across all the futures requires a combination of water reuse and efficiency improvements.

**Effects of Management on Agricultural Sector**

As shown in Chapter Six, unmet demand in the agricultural sector is modest, and none of the futures exhibit vulnerability as defined in that chapter. Figure 7.5 shows that inclusion of agricultural policy in the IPR + EFFall strategy reduces most of the unmet demand in the Medium Demand projection. Including the WQ and groundwater management elements reduce demand even further.

Figure 7.6 shows the agricultural unmet demand across all futures for key strategies that illustrate additional effects. Note that, based on the vulnerability threshold defined for its sector, agriculture is not projected to be vulnerable in any of the futures when Large Initial Groundwater Storage is assumed (see Figure 6.10). Increasing agricultural resilience to climate in the IPR + EFFall strategy, however, does eliminate unmet demand in the Medium Demand projection across all climate scenarios with Full Yellow River Allocation projections. In the High Demand projection, unmet demand is reduced but not eliminated with this strategy.

**Figure 7.4**

**Industrial Unmet Demand Across All Futures for Select Strategies**

<table>
<thead>
<tr>
<th>Completion of IP</th>
<th>IPR</th>
<th>IPR + WQ</th>
<th>IPR + Res/Ind Efficiency</th>
<th>IPR + 50Eff</th>
<th>IPR + 50Eff + WQ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current</td>
<td>50%</td>
<td>Current</td>
<td>Current</td>
<td>50%</td>
<td>Current</td>
</tr>
</tbody>
</table>

NOTE: The red X symbols indicate futures in which the system is vulnerable and the filled green circles indicate futures in which the system is not vulnerable, depending on the threshold for vulnerability chosen.

RAND RR1682-7.4
If only 50-percent efficiency is achieved, unmet demand is still eliminated in the Medium Demand scenario, but IPR + 50Eff + WQ improves outcomes under the High Demand projection. This shows the value of improving water quality in the Xiaoqing River so that additional surface supplies can be available to the agricultural sector. Figure 7.6 shows that these patterns hold across the climate scenarios and that inclusion of the agricultural efficiency and WQ project eliminates unmet demand in many climate futures.
Effects of Management on Springs

There are two management options that improve the performance of Baotu Springs—adding reuse and the SAGM project. Figure 7.7 compares the summary results for the average number of months (2031–2050) of projected low spring flow under the Current Project status (on left and in Figure 6.11) with those under IPR and IPR + SAGM, and shows significant improvement in spring flow because of reuse, which replaces groundwater withdrawals by the industrial sector. It also shows that if reuse is included, there is no additional improvement from the SAGM project. For all three strategies, the range of results are driven by the climate conditions—wetter futures lead to lower numbers of months with low flow. The level of the demand projection does not show an influence on future spring flows.

Effects of Management on Groundwater

Lastly, we show the effects of select management strategies on groundwater for the urban basins. Figure 7.8 shows that the strategies illustrating the largest improvements in groundwater declines are those that include reuse and residential and industrial efficiency improvements, coupled with smaller increases in agricultural irrigation under drier climate conditions. The strategies that include the highest levels of these actions (e.g., IPR + EffAll) lead to a stabilization of groundwater use for most climate projections under the Medium Demand projection. This strategy leads to a significant improvement in groundwater levels under the

Figure 7.7
Spring Flows Under IPR and IPR + SAGM, 2031–2050

Number of months/year of low spring flow across all climates and future demand projections for select strategies

![Graph showing the number of months/year of low spring flow across all climates and future demand projections for select strategies.](image)
High Demand projection as well. The strategies with only half of the efficiency improvements (for example, IPR + 50Eff) have a positive but smaller effect on groundwater levels over time (not shown). Groundwater levels are stabilized under the Medium Demand projection in only about one-third of the climate futures. Significant declines are seen for all climate projections under the High Demand projection.

Summary of Findings

This chapter has reviewed the effects that a wide array of management strategies could have on the key Jinan performance metrics—unmet demand in the residential, industrial, and agricultural sectors; number of months of low spring flow; and amount of decline in groundwater under the assumption of Large Initial Groundwater Storage. As management actions do not work in isolation, we modeled strategies of actions that incrementally increase the adaptations that JWRB could pursue.

Table 7.2 provides a comprehensive summary of key outcomes across all futures and modeling assumptions. Each modeled strategy is represented as a row in the table. The rows are grouped by residential, industrial, and agricultural sectors and by springs. The columns in the table are grouped by demand projection (Low, Medium, and High), Yellow River Allocation, and initial groundwater allocation. The coloring and percentage value in each cell of the table summarizes for the proportion of the 26 climate projections for which the sector or springs is vulnerable. Green shading in each cell indicates low or no future vulnerabilities.

In the following sections, we summarize the key finding by sector, using Table 7.2.
### Table 7.2
Summary of Jinan Water Management Vulnerabilities for All Evaluated Strategies Across All Futures

<table>
<thead>
<tr>
<th>Strategy</th>
<th>Low Demand</th>
<th></th>
<th>Medium Demand</th>
<th></th>
<th>High Demand</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Large Initial GW Storage</td>
<td>Low Initial GW Storage</td>
<td>Large Initial GW Storage</td>
<td>Low Initial GW Storage</td>
<td>Large Initial GW Storage</td>
</tr>
<tr>
<td></td>
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<td>Current 50% YRA</td>
<td>Current 50% YRA</td>
<td>Current 50% YRA</td>
<td>Current 50% YRA</td>
</tr>
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<td>0%</td>
<td>0%</td>
</tr>
<tr>
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<td>0%</td>
<td>0%</td>
</tr>
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<td>0%</td>
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<td>0%</td>
</tr>
<tr>
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<td>0%</td>
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<td>0%</td>
</tr>
<tr>
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<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
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</tr>
<tr>
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<tr>
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<tr>
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<tr>
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<tr>
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<tr>
<td>Completion of IP</td>
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<td>IPR + Residential Efficiency + SAGM</td>
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<tr>
<td>IPR + WQ</td>
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<td>0%</td>
<td>0%</td>
</tr>
</tbody>
</table>

**NOTE:** Numbers for the residential, industrial, and agricultural sectors indicate the percentage of climate low spring flow. YRA = Yellow River Allocation.
Residential Sector
Performance is good in the future for the residential sector except under High Demand or Low Initial Groundwater Storage conditions. In these cases, the strategies that include reuse and also the residential efficiency strategy reduce vulnerabilities significantly. Improving industrial efficiency also slightly benefits the residential sector under High Demand and 50-Percent Yellow River Allocation. While the strategies with half the efficiency reduce residential unmet demand, the reduction is not sufficient to reduce the percentages of climates in which the residential sector is vulnerable. Residential vulnerabilities can be completely eliminated under the Large Initial Groundwater Storage assumption with full implementation of the residential efficiency action.

Industrial Sector
The industrial sector is more vulnerable, particularly under the 50-Percent Yellow River Allocation and under the Medium and High Demand projections. The completion of the IP does improve performance in the Medium Demand projection—when unmet demand is more prevalent but not as severe under the High Demand projection. However, increasing reuse mostly eliminates unmet demand for the Medium Demand projection. The WQ project also provides significant benefits, particularly in the High Demand projection, as it adds a new supply that can serve industry. Much bigger improvements are seen under the High Demand projection with 50-Percent Yellow River Allocation when residential efficiency is improved. This strategy frees up water that can then serve industry—and thus industrial efficiency. Industrial vulnerabilities can be completely eliminated if all efficiency improvements are implemented plus the WQ project.

Agricultural Sector
The agricultural sector is much less vulnerable than the other sectors. Under the assumption of Large Initial Groundwater Storage, the sector is not vulnerable. Under the assumption of Low Initial Groundwater Storage, adaptation is needed to reduce irrigation needs under drier climates.

Springs
The springs are highly vulnerable across all futures under the Current Project status and completion of the IP. While the model used in this analysis does not resolve many of the complex interactions between surface and groundwater, the analysis suggests that strategies designed to more adaptively manage the groundwater will contribute to reducing vulnerability of the springs. Table 7.2 shows that all strategies that include the proposed SAGM policy reduce the number of months of low spring flow.
Understanding the effect of future climate change on flooding in Jinan is challenging, as is the case almost anywhere. Climate change affects precipitation, which is a major cause of flooding in the region. However, precipitation is not the only determinant of flooding: Other factors that are affected by climate change include ground saturation, vegetation and ground cover, upstream water withdrawals and diversions, and evaporation rates. In addition, future flooding will be shaped by other factors besides climate change, such as changes in population and land use, construction of infrastructure such as dams and diversions, and changes in the river itself—for example, deposition of silt and changes in river course (Szollosi-Nagy and Zevenbergen, 2004; UNESCO, 2010).

Assessment of future climate hazards requires substantial historical data as a starting point and mathematical models that can be used to generate future projections. In Jinan, however, concurrent historical time series of precipitation and flood risk exist for only one site, and the relatively short length of the series only allows for inferences over short time frames (50 to 100 years). We were also unable to identify the existence of appropriate flood risk models for the region. This makes it difficult to assess historical flooding. In addition, there are no existing downscaled projections of extreme precipitation, making it difficult to understand future climate hazards.

Approach

Our approach to analyzing changes in flood frequency under climate change is constrained by the available data. These data consist of daily precipitation and subdaily stage (river level) and flow data from 1950 to 2014 at HTQ, located on the Xiaoqing River. Relying on these data alone, our approach centers on answering three questions:

1. **How does intense precipitation contribute to flooding at HTQ?** Here, we develop a statistical model that predicts river stage from precipitation events, given historical stage and precipitation data at HTQ. There is uncertainty in the model because there are many factors that contribute to high water levels in addition to precipitation, and because the hydrology of the region will have changed over time.

2. **How frequently has intense precipitation occurred historically at HTQ and what is the effect on flooding?** We look at historical precipitation data to understand how frequently precipitation events of varying recurrence intervals occur. Then, using a statistical model, we can estimate how frequently corresponding river stages occur.
3. **How could a changing climate alter the frequency of intense precipitation and therefore flooding?** We use available climate data to approximate how precipitation events may increase in the region in the future. We use a statistical model to estimate how frequently corresponding river stages occur. The change in frequency of different river stages provides an indication of the effect of climate change on flooding in Jinan.

   In this analysis, we focus on tracking changes in the return period of a benchmark flood. The return period of an event (whether it is a flood, a rainstorm, or an earthquake) is an estimate of the likelihood of the event. A flood with a 50-year return period is one that has a 2-percent chance of occurring each year. We will use a 50-year river stage as a benchmark, tracking how climate change could change the return period of intense precipitation events and therefore change the return period of a 50-year stage.

   The next sections describe in further detail the available data and the benchmark flood and then answer these three questions.

### Historical Data and Benchmark River Stage

An analysis of precipitation and flooding requires historical daily data on precipitation and river stage. The only hydrologic station in Jinan with both of these data at this granularity is in HTQ, located on the Xiaoqing River. Figure 8.1 shows daily precipitation and subdaily stage (river level) data from 1950 to 2014 at HTQ station.¹

We determined the height of a 50-year river stage from this data. The technique uses the maximum river stage in each year, shown in Figure 8.2, to determine how frequently each stage is exceeded. We first fit the observed annual maximum water level series to a proper probability distribution. Three possible frequency distributions were tested: lognormal, exponential, and the Gumbel distribution.² After fitting the observed data using these three distributions, we conducted a goodness-of-fit test to identify the distribution with the best fit. The lognormal distribution was identified as the best model. The water level associated with different return periods can be estimated using the fitted model. We use this same technique to determine return periods for precipitation.

Figure 8.3 shows the river stage at different return periods. It shows, for example, that historically, a 50-year stage at HTQ has a height of 26.7m. This will serve as our benchmark throughout the remainder of the analysis.

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¹ HTQ station also has flow measurements. While flow and precipitation are clearly related, water level (m) is a better indicator of flooding than flow (m³ per second) because a high water level that exceeds the banks of the river will lead to flooding. Using water level alone leads to a simpler, cleaner model since the two are clearly correlated. Therefore, we omit the flow data in this discussion. Note that there are significant data gaps in the station, indicated by disconnected lines and points in the time series. There are generally no precipitation data from the months of November to April, which also corresponds to the dry season. There are also often no stage data unless preceded by a precipitation event.

² The Gumbel distribution is often used to fix extreme hydrological events (Oosterbaan, 1994).
Relationship Between Intense Precipitation and Flooding

We next develop a statistical model, \( s = f(p) \), that can be used to predict river stage \( s \) in meters given a particular precipitation intensity \( p \), where intensity is defined as the amount of precipitation that falls in a given time period (in this case, 24 hours). To do this, we construct from the historical record a data set of precipitation and stage pairs \((p_i, s_i)\) where \(i\) is simply a counter for each event.

Two time effects complicate this pairing. First, precipitation may last one day or stretch over several days. Second, precipitation’s effect on river stage might not be immediate; instead, it might be seen several days after the event dissipates because of storage and overland flow effects in the catchment upstream of the monitoring station. Thus, using daily pairings of precipitation and stage may result in a poor model.

To allow for these timed effects, we define a precipitation event as a sequence of days in which there are, at most, two days of zero precipitation. For example, the fictional 12-day record of 24-hour precipitation and stage shown in Table 8.1 has two events (indicated by the shading), the first event occurring from days 1 to 7 and the second event occurring from...
Figure 8.2
Maximum Annual River Stage

Figure 8.3
River Stage Return Periods
day 11 to day 12. We also define the corresponding stage as the highest stage observed from the start of the event to the six days that follow. Thus, even though the first event ends on day 7, the corresponding maximum stage occurs on day 8. We constructed a paired precipitation and stage data set based on these events. The precipitation $p_i$ is the maximum precipitation of any day in the event (i.e., 33mm, which occurs on day 6 in the first event) and $s_i$ is the maximum stage during or up to six days after the event (i.e., 26.5m, which occurs on day 8 of the series).3

The resulting data set is plotted in Figure 8.4. Each data point in gray represents a single event described by the maximum 24-hour precipitation on the horizontal axis and the maximum stage on the vertical axis. We then fit a polynomial to the data, shown as the dark blue line on the plot, resulting in the following relationship between precipitation and stage:

$$s_i = -3.6 \times 10^{-5} p_i^2 + 0.023 p_i + 23.3.$$  
Eq. 8.1

This precipitation-stage model predicts, for example, that a precipitation of 230 mm would lead to a 1-in-50-year water level of 26.7m. The model’s R-squared value is 0.43 and its P-value is less than 0.0001. This indicates that the model has predictive value—but, as expected, it does not fully explain the incidence of different river stages because it does not consider other contributing factors. Errors arise from both the model form and the data. Thus, there is uncertainty in the relationship between 24-hour maximum water level and precipitation estimated using the polynomial model. We use the 95-percent confidence interval, shown in light blue, to reflect a margin of error in the estimation of the maximum river stage from a given 24-hour precipitation intensity, with narrower intervals implying more-precise estimates. For an event with 24-hour maximum precipitation of 190mm, values from 26m to 26.8m are not statistically significant from the mean estimate of 26.4m at a 95-percent confidence level. This is shown in Figure 8.4.

3 Note that the decision to allow, at most, two days of zero precipitation in an event and to extend the window for maximum stage to six days are design choices selected through experimentation. Any size window could be chosen but these parameters showed good correlation. In addition, instead of the maximum precipitation in a single day of the event, one could use the total precipitation, average precipitation, or other measure. We explored models using all of these parameters and found that the model resulting from the 24-hour precipitation measure resulted in the simplest and best fit to the data.

4 One could also use a linear model, which fits the data well but does not adhere to the physical properties of the river channel. That is, there is a maximum water level beyond which the river will overtop its banks. A linear model overshoots this threshold at high precipitation levels, which is inconsistent with observations. A polynomial model also has its limitations: as $p_i$ increases beyond 320mm, the equation results in decreasing values of $s_i$. Thus, the polynomial model is only appropriate for precipitation values in the range shown.
Historical Frequency of Precipitation and Flooding

Our next step is to evaluate the historical frequency of precipitation events and, using the statistical model, estimate the resulting river stage. We use the same approach for calculating precipitation return periods as we did for calculating river stage return periods, but we use the annual maximum 24-hour precipitation data shown in Figure 8.5. Here, the lognormal model provides the best fit to the data.

Figure 8.6 shows the intensity of 24-hour precipitation return periods from 1-in-2-years to 1-in-100-years. It shows, for example, that the 1-in-50-year precipitation event has an intensity of 218mm. These intensities can be used as inputs into the precipitation-stage model shown in Equation 8.1 to predict the river stage for each precipitation intensity level. The predicted river stages are shown in Table 8.2. Because there is uncertainty in the model, the table also shows the 95-percent confidence interval or margin of error for the predicted river stage.

Figure 8.7 plots the predicted river stage (last two columns of Table 8.2) against the 24-hour precipitation event return period (first column of Table 8.2). From this figure we can see that our benchmark river stage of 26.7m, which occurs once every 50 years, is predicted by a 1-in-50-year precipitation return period, though given the uncertainty, it could occur with as little as a 1-in-25-year precipitation event.

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5 We ran a goodness-of-fit test comparing three different probability distribution models. The lognormal distribution returned the smallest test statistics for Kolmogorov-Smirnov, Cramer-von Mises, and Anderson-Darling statistics. Thus, we conclude that lognormal is the most appropriate distribution for our analysis.

6 Note that, unlike Figure 8.3, this figure shows the return period of precipitation, not river stage.
Figure 8.5
Annual Maximum 24-Hour Precipitation

Figure 8.6
Intensity of 24-hour Precipitation Events of Various Return Periods
Table 8.2
24-Hour Precipitation Return Period, Intensity, and Predicted River Stage

<table>
<thead>
<tr>
<th>Precipitation Return Period (years)</th>
<th>Precipitation (mm)</th>
<th>Mean Predicted River Stage (m)</th>
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<td>100</td>
<td>250</td>
<td>26.9</td>
<td>26.2–27.5</td>
</tr>
</tbody>
</table>

Figure 8.7
River Stage Predicted by Various Precipitation Return Periods

Future Climate-Driven Changes in Frequency of Precipitation and Flooding

The IPCC Special Report on Extreme Events assesses the change in extreme precipitation in different parts of the world (IPCC, 2012). The report divides the world into 22 different regions over which future return periods are predicted. For each region, the report summarizes the change in future frequency of a historical 1-in-20-year, 24-hour precipitation event.

Shandong Province lies in the East Asia region. The future return periods for the 1-in-20-year, 24-hour precipitation event in the East Asia region is shown on the left panel of Figure 8.8. Each box plot summarizes the return periods predicted by 14 global climate models, in two different time periods (2045–2065 and 2081–2100) and under three different emissions sce-

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7 To our knowledge, there are no analyses of future extreme precipitation events at greater granularity than the IPCC report. Although the report uses very coarse geography and uses scenarios and models from the Fourth Assessment Report, we believe it is the best available science for this study.
scenarios (B1 in blue, A1B in green, and A2 in red). The table in Figure 8.8 is a visual approximation of the minimum, mean, and maximum return periods predicted by the models under the three different emissions scenarios for the 2046–2065 time period. It suggests that in the most optimistic case, the 1-in-20-year event would occur every 17 years, an increase of 1.2 times. In the potentially worst case, the 1-in-20-year event would occur as frequently as once every six years, an increase of 3.3 times.

If we assume that this change in frequency applies to storms of other return periods, then we can estimate a shift in the entire precipitation event frequency curve. The second and third columns in Table 8.3 apply the 3.3 times and 1.2 times increase in frequency, respectively, to all return periods. Thus, what was a 1-in-100-year precipitation event could occur as frequently as once every 30 years.

Analogous to Figure 8.7, Figure 8.9 plots the predicted river stage (last two columns of Table 8.3) against the 24-hour precipitation event return period under historical conditions (first column of Table 8.3), worse-case future climate change (second column of Table 8.3) and better-case future climate change (third column of Table 8.3). In this figure, we can see that our benchmark river stage of 26.7m, which historically occurred once every 50 years, would occur at least as frequently as once every 43 years, but if climate change is severe, could occur as often as once every 15 years.
Summary of Findings

Jinan may face significantly greater flooding in the future than it has historically. Historically, a 1-in-50-year precipitation event led to a 1-in-50-year river stage (26.7m). However, climate change in the East Asia region could make extreme precipitation events more frequent than they have been historically. Therefore, in the future, a 1-in-15-year precipitation event could lead to this same river stage. Thus, flood risk management, which is already important for the region, will be critical in the coming decades.

Importantly, this analysis was conducted with limited data, no hydrologic models, and only low-resolution climate change information. Therefore, the results have corresponding limitations. Inferences cannot be made about longer return periods, and there is much uncertainty in the relationships between different factors—for example, the precipitation that results in
a particular river stage. More and better quality data and better hydrologic models can help improve the accuracy and precision of analyses such as this. Downscaled climate data can help identify changes that are more specific to this region. These improvements can help reduce the uncertainty about how climate change will affect flooding in Jinan, which in turn can help policymakers better understand and manage flood risk.
This project was driven by several objectives. First, we sought to help JWRB better understand the potential consequences of a changing climate, changes in demand for water, and other longer-term uncertainties. Second, with the aid of the WEAP simulation model, we developed an approach to lend insight to JWRB regarding the potential value of new water projects and policies under a wide range of possible future conditions. Finally, we set out to demonstrate the value to JWRB of the Jinan WEAP model as a management and decision support tool and train JWRB’s technical staff on the refinement and use of the model for future work. In this chapter, we reflect on key observations and insights.

**Observations About Data**

The results of any analysis are only as good as the data used. High-quality data collected in a consistent way over a long period of time are essential for hydrologic analysis and long-term water planning. As anticipated at the outset of the project, data availability was the single most challenging aspect of this project and the primary limiting factor in model development and analysis. Improvements in data collection will have a beneficial effect on analysis and the integrity of the Jinan WEAP model. As JWRB further refines the data behind the demand and supply nodes and other model components, results could shift.

At the same time, the Jinan WEAP model can guide future data collection. For example, sensitivity analyses can be performed that indicate how much results could change if selected model parameters were better estimated (on the basis of field studies) or if the model were calibrated against a longer and more complete time series of data. Finally, the Jinan WEAP model provides JWRB with an efficient means of exploring future strategies over a wide range of possible future conditions, rather than only the Historical Climate projection and a few changes in demand projections. This provides JWRB with a powerful tool for future use.

**Observations About Models**

In this report, we present a first approximation of Jinan’s surface and groundwater supply system. We used this model to understand the performance of the system in its current configuration under the Historical Climate projection, a range of assumptions about future demand across the sectors, and a wide range of possible climate conditions generated from many global climate models. Results were sensitive to assumptions about initial groundwater storage; for
that reason, we compared results for Low and Large Initial Groundwater Storage projections. Finally, the model provided us with a means of examining the potential effects of implementing new projects and policies on top of the existing Jinan water system under a wide range of possible future conditions. This kind of analysis provided useful insights as to which uncertain future factors would have the most effect on unmet demand and other measures of performance.

The validity of the WEAP or any water management model depends on the quality and quantity of data, the model parameters that govern the mathematical relationships within the model, and the structure of the model itself. Under the best of circumstances, any simulation model of the Jinan water system is only an approximation of the real physical system. The degree to which the model is a “good” representation of reality depends on the quality and quantity of data available to calibrate it, and an understanding of the relationships among the model’s many supplies, demands, and interconnections. In addition, the relationships represented within the model as mathematical expressions are necessarily approximations of complex systems. All of these limitations apply to the Jinan WEAP model.

A famous statistician said: “All models are wrong, but some are useful” (Box, 1979). Even with these limitations, the process of building the Jinan WEAP model and exercising it is a valuable means of gaining insights about future performance of the Jinan system under a wide range of possible future conditions.

Recommendations

Bearing in mind the caveats previously noted about data and models, we offer recommendations in response to the three questions posed at the beginning of our study, followed by recommendations regarding data, models, and processes.

How Will Future Demand and Climate Conditions Challenge Jinan’s System?

When uncertainties are considered about future climate conditions, demand, future Yellow River allotments, and initial storage levels in groundwater basins, model results indicated the following vulnerabilities for the Jinan system as it currently exists:

- Across all futures, the residential sector is most vulnerable to the High Demand projection. Under the Medium Demand projection, the residential sector is vulnerable under the Low Initial Groundwater storage assumption, particularly with the 50-Percent Yellow River Allocation. In sum, unmet demand in the residential sector is driven more by the demand projection and Yellow River allotment than by future climate.
- Under the 50-Percent Yellow River Allocation, the industrial sector is vulnerable under all three demand projections, regardless of assumptions about groundwater storage. Under the Medium Demand projection and Full Yellow River Allocation, however, the industrial sector is vulnerable only under the Low Initial Groundwater Storage assumption. Future climate exacerbates the industrial sector vulnerability, but it is not a driving factor in the same way that Yellow River allotment and, to a lesser extent, the assumption about groundwater storage are.
- The vulnerability of the agricultural sector depends on future climate more than the residential and industrial sectors. Because agriculture uses groundwater as a key source, there
is no vulnerability under the assumption of Large Initial Groundwater Storage. Under Low Initial Groundwater Storage, however, vulnerability is seen in most futures. The climate effect is very strong: We see no shortages in the wettest climates but very significant shortages in drier climates.

• Jinan’s springs are vulnerable across all futures. In wet climates, low spring flows each year occur for around three months on average; in dry climates, low flows appear about eight months each year on average.

• The model was structured to require ecological flows to be met throughout the system, thereby forcing unmet demand to appear elsewhere, primarily in the industrial and residential sectors.

• All of the climate projections show warming. However, there is scientific disagreement about whether conditions will be getting wetter or drier. One of the benefits of the analysis in this study is that it helps JWRB understand how important this uncertainty is by looking at results across a wide range of wetter and drier conditions, although our study shows that it is not an important factor in most cases.

This vulnerability assessment helps to point the way toward more-robust planning. Planning based on one or only a few scenarios could lead to unfavorable outcomes if conditions in the future were to take a different course than the one on which project designs were based.

How Will JWRB’s Implementation Plan Address Future Climate and Other Uncertainties?
At the present time and for the next several years, Jinan’s current system appears to doing well in meeting demands across districts and sectors. However, even with the completion of the IP, the springs remain highly vulnerable across all futures. Further in the future and without further investments beyond the IP or changes in policies, unmet demand is expected in the residential sector under the High and Medium Demand projections. Curtailment of Yellow River allotments will increase vulnerabilities. This pattern is even more dominant for the industrial sector, except that vulnerabilities appear earlier, even with the completion of the IP, under the Low Demand projection. The agricultural sector shows some vulnerability under the Medium Demand projection and the assumption of Low Initial Groundwater Storage. Vulnerability increases under the High Demand projection.

What Actions Could Be Taken to Reduce Vulnerabilities and Increase the Robustness of Jinan’s System?
Investments in additional projects beyond the IP and other strategies explored in this study could go a long way to reducing the potential effects of uncertainties, reflecting as they do adaptations to changing conditions. Depending on the mix of strategies chosen, these adaptations could benefit different sectors. Consistent with pursuit of a robust system for Jinan, decision makers will want to choose strategies that lead to good outcomes across sectors and districts for the Jinan system regardless of how these uncertain external factors evolve.

Overall, results confirm the value of pursuing full implementation of efficiency measures across the sectors and active management of groundwater withdrawals. Efficiency measures will counterbalance increases in population and industrial activities. Strategies to increase water reuse and improve the water quality in the Xiaoqing River could help accommodate growth in the industrial sector. Strategies that improve management of the groundwater will be essential to ensuring adequate spring flows.
**Investments and Strategies for the Future**

- In the residential sector, strategies that include reuse and full implementation of residential water use efficiency reduce vulnerabilities significantly. Improving industrial efficiency also slightly benefits the residential sector under High Demand and 50-Percent Yellow River Allocation projections.
- The industrial sector is more vulnerable than the residential sector, particularly under higher demand and 50-Percent Yellow River Allocation projections. While completion of the IP does improve performance in the Medium Demand projection, increasing reuse helps eliminate unmet demand almost entirely. Vulnerabilities to the industrial sector can be completely eliminated if all efficiency improvements are implemented, water reuse is implemented, and the WQ strategy for the Xiaoqing River is available as a backstop.
- The agricultural sector is less vulnerable than the other sectors, but any measures that reduce irrigation demands in drier climates will be essential. Because agricultural unmet demand is relatively small, ample surface and groundwater supplies are available in the districts in which agriculture dominates, this suggests that with new conveyance structures, excess supply could be transferred elsewhere in the system.
- While the Jinan WEAP model cannot resolve many of the complex interactions between the surface and groundwater, the analysis suggests that all strategies that include the proposed SAGM policy reduce the number of months of low spring flow.
- Management of groundwater resources is a key to Jinan’s future. More extensive and efficient use of surface water resources to satisfy demands across the sectors will reduce pressure on groundwater.

**Data**

- Efforts should continue to improve the quality of input data to the Jinan WEAP model. Priority should be given to those parameters that relate to surface and groundwater interactions.
- Responsibility should be assigned to a single individual to properly manage all existing and future data required for the Jinan WEAP model. Data should reside in a central computerized database. All relevant paper data records should be converted into a common format to ease the updating and loading of data into the Jinan WEAP model.
- For water quality data to be usable within the WEAP model, the data need to be directly linked to concurrent stream flow data at the same location. This would enable the estimation of pollutant loadings to the system that then could serve as a measure of effectiveness of water pollution control strategies implemented in the future.

**Models**

- The Jinan WEAP model should be considered a work in progress and tool for improving understanding of Jinan’s complex water management system. We recommend that a single individual be responsible for overseeing model development, maintenance, and operations.
- Consideration should be given for linking the output of a well-calibrated, high-resolution groundwater model such as MODFLOW (Liu, Cheng, and Yao, 2011) to the Jinan WEAP model. This would substantially improve the ability of the Jinan WEAP model to represent ground- and surface water interactions, and particularly the behavior of the spring systems.
• If an overland flood routing model already exists within another agency of Jinan, consideration should be given to linking it with the approach to flood frequency analysis proposed in Chapter Eight as a means of exploring possible effects of a changing climate.

Process
• The XLRM method can be used in many other settings to guide clear thinking about the nature of the problem to be solved, the goals and performance metrics most relevant to potential solutions, and the key uncertainties that drive the analysis. Having the appropriate modeling tools for the decision at hand is essential.
• RDM provides a structured approach to analysis of future conditions and strategies for reducing future vulnerabilities and should become a routine feature of JWRB’s analysis potential new investments and the implementation of new policies.

Last Word
We close this report with this reminder: The results presented in this report are suggestive at best of future conditions and their implications. The analysis highlights the challenges ahead and the importance for JWRB of pursuing a diversity of strategies to address them. However, no decisions should be made on the basis of this analysis alone.
APPENDIX A

Data Collection

In the first task of this project, RAND provided the JWRB staff with a data request in the form of spreadsheets and accompanying emails that explained data needs in more detail. In response, JWRB staff provided RAND with many documents and data related to Jinan’s population, industry, water resources, and ecological heritage. Documents and data were provided electronically by JWRB on October 29, 2015 (first tranche); December 16, 2015 (second tranche); December 23, 2015 (third tranche); February 29, 2016 (fourth tranche); and March 27–April 1, 2016 (fifth tranche). Other documents were provided on November 13–14, 2015, January 20–22, 2016, and March 17–18, 2016 during the RAND team’s visits and workshops in Jinan. Furthermore, as part of the data-gathering process, RAND created a master data inventory table to track the availability of data relative to various components of the Jinan WEAP model. This spreadsheet has been shared with JWRB, and JWRB has contributed directly to the spreadsheet by identifying gaps and adding relevant information where needed. This spreadsheet was returned to RAND as part of the second tranche.

In this appendix, we focus particularly on those documents and data that relate to six goals for the Jinan system: improvement in reliability, water quality, water ecological system health, flood risk management, water usage efficiency, and cost-effectiveness. This data collection task has provided the foundation for understanding water resource needs and investment options, enabled the articulation of clearer planning goals for Jinan, and helped to define the scope of the project consistent with the project timeline and resources.

Data Needs for Simulation of Jinan’s System

RAND has worked collaboratively with JWRB to build graphical and mathematical representations of how the elements of Jinan’s water system relate to one another (Task 2 of Exhibit A of the Consultation Service Agreement between the Jinan Water Resources Bureau and the RAND Corporation). The subsequent analysis will compare the performance of potential future projects and strategies over a range of uncertain future conditions related to supply and demand.

In this project, we are using the WEAP modeling platform. The WEAP model represents storage and flows between the various surface and groundwater components of Jinan’s water system, as well as inputs and outputs in the form of interbasin transfers, evapotranspiration, withdrawals, and recharge through precipitation, drainage, and storm water flows.

1 WEAP is an open source software-modeling platform for water management and planning. Extensive information about WEAP is available at the website (SEI, undated-b).
WEAP has some capacity to model water quality, as well. This model will enable JWRB to estimate the flows through the entire system under a range of possible scenarios.

As a first step toward developing a WEAP model for Jinan, RAND conducted an inventory of data made available by JWRB to assess their value in supporting the development of a mathematical simulation model of the Jinan system. Several types of data are needed to complete a basic operational WEAP model:

1. historical demands and/or usage by relevant sectors, which include at least municipal, industrial, and agricultural sectors
2. precipitation records
3. relevant data pertaining to available water supplies, including observations from both surface sources (rivers, lakes, and reservoirs) and groundwater sources
4. information on the connectivity and capacity of physical infrastructure used to store and distribute water across the model area
5. observational data related to management of water releases from reservoirs, treatment plants, and other water-related infrastructure.

To assess the potential outcomes of future policy decisions, additional data will be needed to project the system’s performance under various plausible future conditions. These data include:

1. projections of demand growth by sector or projections of related indicators of demand, which might include estimates of future population, GDP growth by industrial sector, and changes in agricultural land use
2. projections of precipitation and temperature under various climate models as estimated for the model area
3. information on any proposed management and infrastructure projects that could affect connectivity in Jinan’s system, availability of supplies, or demand.

This appendix provides an assessment of our understanding of these data, explains how these data fit into the conceptual framework of the Jinan WEAP model, and identifies remaining key gaps in data and information. In the next section, we assess the documents and tranches of data made available to us by the JWRB. The assessment is organized by data related to demand, supply, conveyance, and other structural features. Flood data are discussed at the end of the section.

Overview of Information Provided

Multiple documents were included in each of the three primary electronic data packages sent to RAND, and additional documents were carried by hand to RAND following the initial meeting between JWRB and RAND in Jinan held November 13–15, 2015.

First Tranche: October 29, 2015

The first data package, received on October 29, 2015, contained several types of documents, including:
1. a comprehensive water resources plan
2. Ecological City development plans for Lixia, Shizhong, Tianqiao, Huaiyin, Changqing, Licheng, and Gaoxin districts
3. various flood and precipitation data
4. capacities and water levels for the Wohushan and Jinxiuchuan reservoirs
5. Jinan Statistical Yearbooks for 2009 (economic section only), 2013, and 2014 (economic section only), and an additional supporting table
7. various supply data, including Tianshan Irrigation Area infrastructure, precipitation, area of irrigated land data, and other supply data for Jinan Urban Center, Jiyang and Shanghe counties, and Zhangqiu District
8. additional infrastructure-related data.

Documents Received in Jinan Meeting: November 13–15, 2015
The RAND visit to JWRB concluded with the manual exchange of printed appendixes for Jinan City Water Resources Public Communiqués for years 2008–2013 and a book called Jinan Spring Water Geography (Zhao, 2015). The PCA, which RAND digitized, provide numerous tables and historical data that are directly applicable to the WEAP model. Additionally, Zhao (2015) provides tables and other data along with high-level information on Jinan’s groundwater hydrology that will be helpful in evaluating conditions under which Jinan’s major springs can maintain flow.

Second Tranche: December 16, 2015
The second electronic data set, received on December 16, 2015, included nine categories of data:

1. summaries of Jinan City Water Resources Public Communiqués for years 2006–2014
2. location of WTPs
3. groundwater withdrawals by district
4. information on water supply projects, WTPs, and the water infrastructure network in general
5. reservoir information for most of the midsize reservoirs included in the schematic diagram
6. information on major distribution links and respective capacities
7. information on wetland and ecological development requirements
8. information on currently irrigated areas
9. stream gauge observational data.

Third Tranche: December 23, 2015
The third data set, received December 23, 2015, included 13 files across several different categories:

1. summary and location of major public water plants, their water supply capacity, and water sources
2. reservoir information for most of the midsize reservoirs (appears to be the same as Item 5 of the second tranche of data)
3. forecasts of population, irrigated acreage, and industrial growth, as well as agricultural, residential, and industrial water use and demand for years 2009, 2015, 2020, and 2030 by district and scenario (assumptions used to generate these forecasts are also provided in a summary document)
4. summary of water supply layout and priorities
5. information on exploitable groundwater volume by district
6. characteristics of surface water resources by district
7. information on spring water catchments.

Fourth Tranche: February 29, 2016
The fourth tranche, received February 29, 2016, included flood statistics for the HTQ station:

1. daily precipitation statistics for HTQ from 1984 to 2014
2. key flood statistics at HTQ
3. additional precipitation data at HTQ since the 1950s.

Fifth Tranche: March 28–April 1, 2016
In the fifth tranche, which was received in multiple pieces in late March and early April, JWRB provided data to fill outstanding data gaps for both the WEAP model and flood analysis. These data include:

1. information about implementation plan projects
2. reservoir operational data for Dazhan, Duzhang, Duo Zhuong, and Xinglin reservoirs
3. additional stream flow information for the Xinghua and Xiujiang rivers
4. inventory of projects included under the IP, as well as their implementation statuses
5. a cross-section and vertical section map of the Xiaoqing River
6. Jinan river flood prevention monitoring station information
7. a summary description of the Xiaoqing River after the 2006 treatment project.

Water Demand

We obtained detailed data for historical water demand sectors for various geographical regions, including breakouts by each district of Jinan. These data include both monthly usage and monthly consumption. Additionally, projections of demand until 2030, associated indicators of demand, and a summary document describing the calculations of the demand projections were also received in the third data tranche. There are multiple demand estimate scenarios, which vary across agricultural, industrial, and residential demand types. Agricultural projections include three scenarios of water-use rates combined with two agricultural assurance rate scenarios, for a total of six agricultural demand scenarios. Projected growth in IVA is combined with three different water-use scenarios to generate three industrial water-use scenarios. Residential demand projections include a single estimate of population growth with three different water-use scenarios, for a total of three different projected demands. These demand projections are shown in Figures A.1–A.3, respectively.

Additionally, population projections, including population to 2030 and mean growth rates to 2050, were obtained from UNESA (2014) to give a baseline for population projections.
Figure A.1
Projections of Agricultural Demand Provided by Jinan Water Resources Bureau

Figure A.2
Projections of Industrial Demand Provided by Jinan Water Resources Bureau
Table A.1 provides a summary of water demand or usage data that are currently available and the file location of those data. The table includes breakouts by agricultural, industrial, municipal, and ecological demand categories.

**Demand by Sector**

Summary annual data on water demand for residential, industrial, agricultural irrigation, public utilities, farming, and ecological needs are available in Jinan City Water Resources Public Communiqués from 2006 to 2014 (Jinan Water Resources Bureau, 2007–2015a). More-detailed data are contained in tables in the associated appendixes and are available for the years ranging from 2008 to 2013. These demand data include annual total usage and consumption for each district broken out by sector and are shown in Tables 10 and 11 in the PCA (Jinan Water Resources Bureau, 2009–2014). Information regarding the volume and proportion of these demands that are met through groundwater withdrawals is also available in these appendix tables.

Some historical data for correlates of demand are available by each sector. With respect to correlates of agricultural demand, historical information regarding irrigation areas, irrigation coverage rates, and the proportion of irrigated land using more efficient irrigation systems are available in the PCA (Jinan Water Resources Bureau, 2007–2015a). Population data by district are also available for historical time periods (Jinan Statistics Bureau, 2014). These data, when used in conjunction with projected growth rates in each sector, could be useful for estimating future demand.
### Table A.1
Current Demand Data File Locations

<table>
<thead>
<tr>
<th>Sector</th>
<th>Historical Total Usage</th>
<th>Current Area</th>
<th>Projected Growth or Change in Demand Correlates or Usage</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Agricultural</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jinan Urban Center</td>
<td>2008–2013 PCA (Tables 10 [Demand] &amp; 11 [Consumption]), Monthly</td>
<td>Multiple files, irrigation area material (second tranche)</td>
<td>JWRB projections included in the third tranche</td>
</tr>
<tr>
<td>Zhangqiu</td>
<td>2008–2013 PCA (Tables 10 [Demand] &amp; 11 [Consumption]), Monthly</td>
<td>Multiple files, irrigation area material (second tranche)</td>
<td>8.2013–2014 Zhangqiu City Water Supply Data; JWRB projections included in the third tranche</td>
</tr>
<tr>
<td>Pingyin</td>
<td>2008–2013 PCA (Tables 10 [Demand] &amp; 11 [Consumption]), Monthly</td>
<td>Multiple files, irrigation area material (second tranche)</td>
<td>JWRB projections included in the third tranche (excluding Licheng)</td>
</tr>
<tr>
<td>Shanghe</td>
<td>2008–2013 PCA (Tables 10 [Demand] &amp; 11 [Consumption]), Monthly</td>
<td>Multiple files, irrigation area material (second tranche)</td>
<td></td>
</tr>
<tr>
<td>Licheng</td>
<td>2008–2013 PCA (Tables 10 [Demand] &amp; 11 [Consumption]), Monthly</td>
<td>Multiple files, irrigation area material (second tranche)</td>
<td>Projections estimated based on historical proportion of Jinan total</td>
</tr>
<tr>
<td>Changqing</td>
<td>2008–2013 PCA (Tables 10 [Demand] &amp; 11 [Consumption]), Monthly</td>
<td>Multiple files, irrigation area material (second tranche)</td>
<td>JWRB projections included in the third tranche (excluding Licheng)</td>
</tr>
<tr>
<td><strong>Industrial</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pingyin</td>
<td>2008–2013 PCA (Tables 10 [Demand] &amp; 11 [Consumption]), Monthly</td>
<td></td>
<td>—</td>
</tr>
<tr>
<td>Shanghe</td>
<td>2008–2013 PCA (Tables 10 [Demand] &amp; 11 [Consumption]), Monthly</td>
<td></td>
<td>—</td>
</tr>
<tr>
<td>Licheng</td>
<td>2008–2013 PCA (Tables 10 [Demand] &amp; 11 [Consumption]), Monthly</td>
<td></td>
<td>—</td>
</tr>
<tr>
<td>Changqing</td>
<td>2008–2013 PCA (Tables 10 [Demand] &amp; 11 [Consumption]), Monthly</td>
<td></td>
<td>JWRB projections included in the third tranche (excluding Licheng)</td>
</tr>
</tbody>
</table>
### Table A.1—Continued

<table>
<thead>
<tr>
<th>Residential Location</th>
<th>Historical Total Usage</th>
<th>Current Population</th>
<th>Projected Growth or Change in Demand Correlates or Usage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jinan Urban Center</td>
<td>2008–2013 PCA (Tables 10 [Demand] &amp; 11 [Consumption]), Monthly</td>
<td>2006–2013 Jinan Water Resources Public Communiqué</td>
<td>Economic indicators and statistics for 2009, 2013, and 2014 for Jinan are available in respective statistical yearbooks; JWRB projections included in the third tranche (excluding Licheng); this material only included population for the entire city; it was not not broken out by district.</td>
</tr>
<tr>
<td>Pingyin</td>
<td>2008–2013 PCA (Tables 10 [Demand] &amp; 11 [Consumption]), Monthly</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Licheng</td>
<td>2008–2013 PCA (Tables 10 [Demand] &amp; 11 [Consumption]), Monthly</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Changqing</td>
<td>2008–2013 PCA (Tables 10 [Demand] &amp; 11 [Consumption]), Monthly</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Ecological Project</th>
<th>Historical Total Usage</th>
<th>Minimum Requirements (annual or monthly)</th>
<th>Projected Growth or Change in Demand Correlates or Usage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yuqing Hu Reservoir Restoration Project</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Yufu Wetlands Restoration</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Additional Environmental Projects (to be determined)</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Springs/Spring Zones</th>
<th>Minimum Groundwater Level/Pressure Head Requirements</th>
<th>Notes</th>
<th>Projected Growth or Change in Demand Correlates or Usage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Springs/Spring Zones</td>
<td>1998–2004: Jinan Spring Water Geography, Annual; Additional journal articles</td>
<td>Some spring flow and level data received in third data tranche</td>
<td>—</td>
</tr>
</tbody>
</table>

**NOTE:** — indicates missing data.

### Demand by Geographic Unit

The Jinan City Water Resources Public Communiqué also provides monthly usage and consumption data broken down by city districts and major river basins. As already discussed, information in Tables 10 and 11 of the PCA includes these breakouts by district.

### Wetlands and Ecological Demands

Various data about wetlands and ecological projects were included in the first and second tranches. These include projects that are elements of the IP for Jinan Water Ecological City Development Plan (Jinan Water Resources Survey and Design Institute et al., 2014), both from the first tranche of electronic data and a wetland information file from the second tranche. Further clarification of the nature of these demand sites would be needed before additional information could be incorporated into the WEAP model as demand nodes. After the third
Jinan workshop with JWRB, which took place March 16–18, 2016, JWRB offered to provide additional information to improve the project team’s understanding of ecological projects and their requirements.

**Demand for Spring Water**
JWRB emphasized that flowing springs in Jinan are a high priority now and in the future. To aid in RAND’s effort to evaluate this key goal, JWRB provided several data tables relating spring flow and water levels to groundwater withdrawals. These data include (1) information provided in *Jinan Spring Water Geography* (Zhao, 2015), which includes annual mean levels and groundwater withdrawals, and (2) an additional data table provided in the third tranche that includes monthly flow data for the four primary springs in Jinan.

**Water Supplies**
Summary annual water supply data are available in each of the Jinan City Water Resources Public Communiqués, with more-detailed monthly data available in tables in associated appendixes. Water supply data appear to be based largely on actual usage rather than estimated maximum exploitable resources for both surface and groundwater supplies. Groundwater supply estimates appear to be incomplete in this source, although annual total recharge quantities by district are available in tables in each of the included JWRB PCA. Additional water supply data, including information about additional reservoirs, stream flows, and groundwater monitoring locations, were requested during the third Jinan workshop in March 2016.

**Precipitation Records**
Annual average precipitation data are available in each annual Jinan City Water Resources Public Communiqué (2008–2013). These records are available categorized by both city districts and river basins. More-detailed precipitation data are available for the following areas: Shizhong district (total annual precipitation in mm, 2008–2014), Jinxiuchuan Dam (monthly total precipitation, mm, 1992–2015), Shanghe county (monthly precipitation, mm, 2000–2014), and Tianshan Irrigation Area (monthly total precipitation in mm, 1971–2014). Additionally, flood event–based precipitation data are available for multiple flood events from 1998 to 2015 for the Xiaoqing River (see the section on flood data for more information on flood records for the Xiaoqing).

**Stream Gauge Records for Rivers and Streams**
An Excel file received in the second tranche contains monthly records of river flows in and out of Jinan districts. This data set contains records for 25 stations covering rivers in Jinan between 2011 and 2014. Stream gauge monthly total flow observations for the Anluan, Beidasha, Hui, Linshang, Luo, Jinshui, Nandasha, Qiji, Sha, Shangdong, Shangzhong, Tuhai, Tuma, Xiaoqing, Yudai, and Yufu rivers are contained in this file. All stations include an inflow and outflow district to aid in their placement in the schematic. The locations of these stations were confirmed with JWRB during the second workshop in Jinan in January 2016.

Additional records for the Xinghua and Xiujiang rivers were requested during the third RAND visit to JWRB in March 2016. Annual and seasonal inflow data for the Xinglin reservoir (located on Xinghua) and Xinghua river capacity information were received on March 27,
2016. Additional data for the Xiujiang, including annual mean flow for years 1977–2010 and some reservoir inflow data for Dazhan and Duozhuang reservoirs, were also received as part of the fifth tranche. Table A.2 provides a summary of the number and name of stream gauges available for each river with available data.

Only one stream gauge, the Luokou Station, along the Yellow River is contained in the data. Data are available at the Luokou Station between 2004 and 2014 and include mean, minimum, and maximum values for both observed flow and water level. The station is roughly located in the center of the Jinan Urban Center; stream gauges measuring flow in and out of the model boundary area are unavailable. This station will suffice as an indicator of head flow across the WEAP model boundary for the Yellow River. With the addition of head flow data for the Xinghua and the Xiujiang rivers in the fifth tranche, all major rivers in the WEAP model that provide water to demand sites have usable head flow time series information included. Additionally, detailed historical monthly Yellow River diversion records, representing several gauges between 2008 and 2014, were received in the second data tranche. Information regarding usage of these diversions by sector is also available.

Additional descriptive river information, including river basin area, average annual flow, and average annual precipitation within the basin, was provided by JWRB for five rivers in Jinan: the Nandasha, Beidasha, Yufu, Xiaomoqing, and Xiujiang. These data have been incorporated, where applicable, into the Jinan WEAP model.

**Groundwater Levels and Yields**

Average annual groundwater volume available for pumping is available from the PCA for years 2008 through 2013. These data are available by district and are located in Table 6 in

<table>
<thead>
<tr>
<th>Table A.2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Summary of Available Stream Gauge Data</strong></td>
</tr>
<tr>
<td>River</td>
</tr>
<tr>
<td>------------------------</td>
</tr>
<tr>
<td>Tuhai</td>
</tr>
<tr>
<td>Yufu</td>
</tr>
<tr>
<td>Xiujiang</td>
</tr>
<tr>
<td>Anluan</td>
</tr>
<tr>
<td>Beidasha</td>
</tr>
<tr>
<td>Jinshui</td>
</tr>
<tr>
<td>Linshang</td>
</tr>
<tr>
<td>Luo</td>
</tr>
<tr>
<td>Nandasha</td>
</tr>
<tr>
<td>Qiji</td>
</tr>
<tr>
<td>Sha</td>
</tr>
<tr>
<td>Shangdong</td>
</tr>
<tr>
<td>Shangzhong</td>
</tr>
<tr>
<td>Tuma</td>
</tr>
<tr>
<td>Xinghua</td>
</tr>
</tbody>
</table>
each of these appendixes. Average recharge by district is located in Table 5, while both usage and consumption have been found in Tables 10 and 11 for all years. Additionally, estimated withdrawals by private wells in agricultural regions are included for the year 2011 in the first tranche.

Based on information communicated to RAND through a call with the JWRB technical team, Jinan has set up maximum allowable groundwater withdrawal thresholds by district, but these thresholds are included. Information about groundwater levels and piezometric surfaces (for confined aquifers) also was received following the third Jinan workshop in March 2016. A map showing primary recharge zones within Jinan was provided during the March workshop. Table A.3 lists file locations of applicable groundwater demand data for each district.

Storage Reservoirs
Jinan has one large-scale reservoir, 12 midscale reservoirs, and 173 small reservoirs. Robust observational data—including water levels (m), maximum storage capacity (m³), current storage (m³), and water storage inflow and outflow (m³)—are available for both Jinxiuchuan (a midscale reservoir) and Wohushan (the largest reservoir) reservoirs, both of which are used for flood control and storage. Daily records for the Jinxiuchuan Reservoir are available for the period from 2010 to 2015 at the Jinxiuchuan Reservoir and from 2004 to 2013 at the Wohushan Reservoir. Additionally, storage capacities and average water levels are available for all large and midscale reservoirs. These data, taken from the second tranche, are shown in Table 2.4, along with the file locations of time series data for Jinxiuchuan and Wohushan reservoirs. In the March workshop, RAND requested additional volume/elevation and inflow/outflow time series data for four additional reservoirs—Dazhan, Duozhuang, Queshan, and Xinglin. Additional reservoir statistics were received on March 28, 2016, for Dazhan, Duozhuang, Duzhang, Jianshuiquan, Xinglin, and Xinglong reservoirs. To complete the catalog of available information for the five reservoir transfer projects, reservoir operational data for Longquan reservoir, including volume elevation and inflow/outflow time series records, were requested on April 11, 2016.

### Table A.3
**Groundwater Data File Locations**

<table>
<thead>
<tr>
<th>District</th>
<th>Recharge</th>
<th>Total Volume Available</th>
<th>Withdrawals (Volume per Year or Month)</th>
<th>Destination (Demand Fulfilled)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Changqing</td>
<td>2008–2013 PCA (Table 5), annual</td>
<td>2008–2013 PCA (Table 6), annual</td>
<td>2008–2013 PCA</td>
<td>(Tables 10 [usage] &amp; 11 [Consumption]), Monthly</td>
</tr>
<tr>
<td>Jinan Urban Center</td>
<td>2008–2013 PCA (Table 5), annual</td>
<td>2008–2013 PCA (Table 6), annual</td>
<td>2008–2013 PCA</td>
<td>(Tables 10 [usage] &amp; 11 [Consumption]), Monthly</td>
</tr>
<tr>
<td>Jiyang</td>
<td>2008–2013 PCA (Table 5), annual</td>
<td>2008–2013 PCA (Table 6), annual</td>
<td>2008–2013 PCA</td>
<td>Jinan Self-Provided Well Ground Level Water Withdrawal Categorized Data</td>
</tr>
<tr>
<td>Licheng</td>
<td>2008–2013 PCA (Table 5), annual</td>
<td>2008–2013 PCA (Table 6), annual</td>
<td>2008–2013 PCA</td>
<td>(Tables 10 [usage] &amp; 11 [Consumption]), Monthly</td>
</tr>
<tr>
<td>Pingyin</td>
<td>2008–2013 PCA (Table 5), annual</td>
<td>2008–2013 PCA (Table 6), annual</td>
<td>2008–2013 PCA</td>
<td>(Tables 10 [usage] &amp; 11 [Consumption]), Monthly</td>
</tr>
<tr>
<td>Shanghe</td>
<td>2008–2013 PCA (Table 5), annual</td>
<td>2008–2013 PCA (Table 6), annual</td>
<td>2008–2013 PCA</td>
<td>(Tables 10 [usage] &amp; 11 [Consumption]), Monthly</td>
</tr>
<tr>
<td>Zhangqiu</td>
<td>2008–2013 PCA (Table 5), annual</td>
<td>2008–2013 PCA (Table 6), annual</td>
<td>2008–2013 PCA</td>
<td>(Tables 10 [usage] &amp; 11 [Consumption]), Monthly</td>
</tr>
</tbody>
</table>
Total volumetric storage capacities of reservoirs by district are also available (Table A.4). These storage capacities are categorized by usage type, such as flood prevention, electricity generation, water supply, and irrigation. Planned total reservoir capacity expansion information is also available by district. These planned capacity expansions may be considered as uncertainties in the analysis of potential future conditions and water management strategies.

### Conveyances, Water Treatment Plants, and Other Structural Features

Information about water diversion capacity (given in increments of 10,000 metric tons per day\(^2\)) is available for five completed water diversion projects, one under construction, and three planned projects. Descriptions of these water diversion projects are also available from the Jinan Water Ecological City Development Master Plan (Jinan Water Resources Survey and Design Institute et al., 2014) and Jinan Water System Connecting Project Plan Summary (Jinan Water Resources Bureau, 2015b). These data were sent as part of the first and second tranches and are located in multiple files. Additionally, conveyances have been added to the master data inventory table created by RAND to help track available data and correlate these data with their respective WEAP schematic counterparts. The table containing data on these links has not been fully reviewed to identify gaps, but most data needed appear to be available.

Capacities and locations of water treatment and purification plants are only available for plants located within the Jinan Urban Center. There are four water purification plants, which are used to provide drinking water for the city, and 15 WTPs, which are used to reduce pollution from “used water” re-entering surface and ground water systems.

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\(^2\) One metric ton of water is equivalent to one cubic meter in volume.
Flood Data

Flood event records, rainfall data for storm events, and historical peak flood records are available for the Xiaoqing from 1998 to 2015. These data were included in the first tranche. A summary table of flood depth and damage was provided during our second trip to Jinan on January 20, 2016.

There were also four types of flood-related data in the fourth tranche. First, it included precipitation and flood statistics for one station, HTQ, located on the Xiaoqing. Second, it included a table of the locations and characteristics of existing and planned river monitoring stations. Different data are available for different monitoring stations but each generally includes river geometry (elevation of the river bed, river banks, and surrounding land, as well as slope), catchment areas, design flows, and thresholds for different flood levels. Third, geometry data for the Xiaoqing is available, including elevation of the river bottom, riverbanks, and area around the banks, as well as cross-sections.
APPENDIX B

Status of Implementation Plan

Based on our in-person discussions with JWRB staff during the November 2015 and January 2016 workshops, we understand that construction of most of the major elements of the IP are either complete or under way. However, our understanding of the construction time line and plan elements remains incomplete. In Tables B.1 and B.2, we list projects that we believe are completed and those that we believe are under construction or soon to be under way. JWRB staff is working to complete these two tables, as well as add a third table of projects in the IP for which construction has not yet been started.

Table B.1
Completed Implementation Plan Projects

<table>
<thead>
<tr>
<th>Project Name</th>
<th>Water Diversion Capacity (10,000 metric tons per day)</th>
<th>Construction Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yuqing River Water Diversion Project</td>
<td>77</td>
<td>Complete</td>
</tr>
<tr>
<td>Jiping Conveyance to Yuqing Lake Water Diversion Project</td>
<td>104</td>
<td>Complete</td>
</tr>
<tr>
<td>Jiazhuaung Gauge to Wohushan Reservoir Water Diversion Project</td>
<td>30</td>
<td>Complete</td>
</tr>
<tr>
<td>Beidianzi to Jinan City Center Water Diversion Project</td>
<td>20</td>
<td>Complete</td>
</tr>
</tbody>
</table>

Table B.2
Implementation Plan Projects Currently Under Construction

<table>
<thead>
<tr>
<th>Project Name</th>
<th>Water Diversion Capacity (10,000 metric tons per day)</th>
<th>Construction Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modification of Wohushan Reservoir Water Supply Conveyance Project</td>
<td>15</td>
<td>Implementing</td>
</tr>
<tr>
<td>Langmaoshan Reservoir Water Diversion Project</td>
<td>2</td>
<td>Planned completion by 2020</td>
</tr>
<tr>
<td>Duzhang Reservoir to Langmaoshan Reservoir Water Diversion Project</td>
<td>5</td>
<td>Planned completion by 2020</td>
</tr>
<tr>
<td>Donghu Reservoir Water Supply Project</td>
<td>30</td>
<td>Planned completion by 2020</td>
</tr>
<tr>
<td>Dongsian Water Supply Project Phase II: Jinan Steel to Duzhang Reservoir</td>
<td>10</td>
<td>Planned completion by 2020</td>
</tr>
</tbody>
</table>
APPENDIX C
Adjustment of Demand Projections

Demand projections from JWRB were originally developed in 2009 and included projections for 2009, 2015, 2020, and 2030. Since these projections implicitly included historically observed years, they were adjusted to match the most recently available observed data year, which was 2014. To perform the adjustment, we first estimated the projected demand for the year 2014 by (1) combining projected activity levels and water use rates to generate estimated total demand and (2) interpolating linearly between projected demands in 2009 and 2015. Then, based on observed data for each sector, we added an adjustment factor to aggregate water use rates for each sector included in the model to align estimated values with observed values in 2014. Details of these calculations are provided in this appendix.

For a given demand projection provided to us by JWRB, we define the following parameters for sector $i$ and year $y$:

- $r_{iy}$ projected annual water use rates
- $a_{iy}$ activity levels
- $d_{iy}$ total water demands.

Thus, $d_{iy} = r_{iy}a_{iy}$ for each sector $i$ and year $y$. However, each sector included in the JWRB WEAP model—agricultural, industrial, and residential—is the aggregation of subsectors provided by JWRB. For this reason, we need to call the sectors within WEAP sector $s$ rather than sector $i$. Therefore, within the WEAP model, we define the corresponding values of these parameters as:

- $r_{sy}$ projected annual water use rates
- $a_{sy}$ activity levels
- $d_{sy}$ total water demands

where $d_{sy} = r_{sy}a_{sy}$ for each sector $s$ and year $y$.

To generate the adjustment factor for demand $d$ in each sector $s$, we first developed an interpolation relationship for demand as follows:

$$d_{sy} = \frac{y - 2009}{2015 - 2009} * d_{s(2015)} + \frac{y - 2014}{2015 - 2009} * d_{s(2009)}$$

for each year from 2009 to 2015. Therefore, projected demand $d_{s(2014)}$ for 2014 in sector $s$ is given by:

$$d_{s(2014)} = (5/6)d_{s(2015)} + (1/6)d_{s(2009)}.$$
We also needed to estimate a projected activity level in 2014. This relationship \( r \) is given by:

\[
    r_{i(2014)} = \frac{d_{i(2014)}}{A_{i(2014)}},
\]

where \( A_{i(2014)} \) is the observed activity level in 2014.

For each sector \( s \), we estimated an additive factor \( \gamma_s \):

\[
    \gamma_s = \frac{(D_{s(2014)} - d_{s(2014)})}{a_y},
\]

and an adjustment ratio:

\[
    \varphi_s = \frac{d_{s(2014)}}{D_{s(2014)}},
\]

where \( D_{s} \) is the observed water demand in sector \( s \) for year \( y \), which in this example is 2014, and \( \varphi_{s} \) is the water use rate. Since the projections provided by JWRB included only changes to water use rates, factors were applied to \( a_y \). The use of the ratio \( \gamma_s \) enabled us to develop a lower bound for water use rates in sector \( s \) that would ensure that adjusted projected water use rates, which we revised downward to reflect historical trends, never fell below zero. Therefore, the adjusted water use rate \( a^*_{sy} \) is given as:

\[
a_{s y}^* = \begin{cases} 
    a_s \varphi_s & m_s - \gamma_s < m_s \varphi_s \\
    a_s - \gamma_s & \text{else}
\end{cases}
\]

where \( m_s \) is the minimum projected water use rate associated with demand \( d_s \) across all years (2009 to 2030) provided by JWRB.
In this appendix, we present our method of developing regression models that can yield values for future headflow of rivers and groundwater recharge based on values of precipitation and temperature generated from downscaling results from global climate models. We rely on basic methods of regression described in Helsel and Hirsch (2002). Note that “headflow” is the name given for streamflow associated with the furthest upstream node of a river represented in WEAP.

**Regression Models of Headflows**

Regression models relating precipitation, temperature, and river headflow were estimated for each stream that serves as a water source in the Jinan WEAP model. For each river included in the model that varied with climate change, headflow estimates took the general form of:

\[
\text{HEADFLOW in River } x = a_x + b_x \times \text{Precipitation}_x + c_x \times \text{Temperature}_x,
\]

where \(a_x\), \(b_x\), and \(c_x\) represent the estimated regression parameters.

Multivariate linear regressions were fit using all available months of data for all three data elements (precipitation, temperature, and headflow). Potential models to estimate observed headflow were first generated by considering both the Shanghe and Jinxiuchuan precipitation data sets, and were then paired with the temperature data as estimators of observed headflow.

Figure D.1 shows a comparison of model fit as measured by the adjusted R-squared for each of the models generated by the river and precipitation data set. The model fit for each river using the Jinxiuchuan precipitation data set (green bars in Figure D.1) was either similar or much better than the model fit using the Shanghe precipitation data set (blue bars). Therefore, the Jinxiuchuan data were used to generate regression fits for all river headflows to maintain simplicity.

While most of the individual river regression models perform relatively well, the Beidasha model (far left) is a poor predictor; this is likely a consequence of the stream gauge location relative to headflow. The Beidasha River is dammed at several points, and it is also a significant source of recharge to the karst groundwater system; thus, downstream flow is significantly altered from its headflow. The Nanzhangzhuang stream gauge provided by JWRB appears to be located near the confluence of the Beidasha River with the Yellow River. Its location far downstream

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1 While not initially included in our analysis, following discussions with JWRB, we also evaluated relationships between headflow and climate for the Xiaoqing River. However, additional data may be necessary to fully represent the Xiaoqing/South-North Yangtze River transfer interaction properly.
indicates that it is not a good representation of historical headflow. In fact, only four months of the year appear to have any flow, and these months are associated with large precipitation and/or flood events when compared with other records in the Jinan area. However, this model still stands as the best available approximation of headflow, given the availability of stream flow data, and based on a comparison between estimated headflow patterns for the Beidasha River and headflows from other streams originating in the south mountains (e.g., the Yufu River).

Table D.1 shows the multivariate linear regressions used to estimate head flows in m$^3$ per month, where $p$ is monthly precipitation at Jinxiuchuan Dam in millimeters (mm) and $t$ is the monthly average temperature (calculated at Jinan Urban Center) in degrees Celsius.

Finally, as an example, we show in Figure D.2 a comparison of observed Yufu headflow (taken from the Jinxiuchuan inflow data set) with estimated Yufu headflow generated from the
regression model in Table D.1. The regression model does a good job of capturing both the timing and amplitude of peak flows.

Regression Models to Estimate Groundwater Recharge

We use nonlinear regression models to estimate groundwater recharge. Recharge values were fit by comparing annual precipitation data and annual mean temperature with annual total recharge values taken from the PCA, with annual recharge statistics available from 2008 to 2014. Note that, for every district, a recharge model was estimated using precipitation data from Jinxiuchuan dam and temperature data from Raspisaniye Pogodi Ltd. (undated); i.e., estimates were of the form:

\[
RECHARGE \text{ at District } x = a_x + b_x \left(1 + e^t\right)^{-1} + c_x \cdot p,
\]

where \(p\) is precipitation, \(t\) is temperature and \(a_x, b_x,\) and \(c_x\) are regression parameters unique to district \(x\).

To evaluate the travel time of precipitation in the south mountains to spring discharge and/or movement out of the groundwater basin, shifts of zero to three months were evaluated; the literature has noted that groundwater residence times might range from zero to two months (Liu, Cheng, and Yao, 2011). Regressions developed using linear models were initially considered, but in all cases, these models showed high sensitivity to changes in temperature.
Because most climate projections show annual temperatures rising by more than 1°C by 2050, this high sensitivity to temperature led to extreme changes in recharge. To curb this behavior, nonlinear models were fit using a linear component for precipitation, and a logistic component for temperature. The logistic component prevents high temperature increases from leading to projections of little to no recharge, while the linear component represents high responsiveness to precipitation, a desirable property.

Results are summarized in Table D.2. Given the small number of points used to fit the curves, both R-squared and adjusted R-squared fit statistics were greater than 0.9 in all cases, and thus are not reported in Table D.2. Figure D.3 shows comparisons between observed recharge values for each district and recharge values estimated using historical precipitation and temperature data.

### Use of Delta Values in Regressions

Because GCMs produce results at a coarse spatial resolution relative to the hydrologic processes relevant to Jinan’s hydrology, we used data that was statistically downscaled using the “Delta Method” and obtained from the CCAFS GCM Downscaled Data Portal (CCAFS, 2014a; Ramirez, 2008). As described by the data providers, the Delta Method follows the following steps:

1. Gathering of baseline data (current climates corresponding to WorldClim).
2. Gathering of full GCM timeseries.
3. Calculation of 30 year running averages for present day simulations (1961–1990) and 7 future periods.
4. Calculation of anomalies as the absolute difference between future values in each of the 3 variables to be interpolated (minimum and maximum temperature and total precipitation).
5. Interpolation of these anomalies using centroids of GCM cells as points for interpolation.
6. Addition of the interpolated surfaces to the current climates from WorldClim, using absolute sum for temperatures, and addition of relative changes for precipitation.
7. Calculation of mean temperature as the average of maximum and minimum temperatures. (CCAFS, 2014b)

Interpolated delta values were used as inputs to the appropriate regression model, which were then used to adjust the historically cycled data (recharge or headflow) in accordance with the trend indicated by the GCM delta. To represent a more realistic change in recharge due to

<table>
<thead>
<tr>
<th>District</th>
<th>Recharge Model ( (m^3 \text{ per year}) )</th>
<th>Fit Residual</th>
</tr>
</thead>
<tbody>
<tr>
<td>Changqing</td>
<td>( 16.41 + 3.40 \times 10^7 (1 + e^t)^{-1} + 0.17p )</td>
<td>89.22</td>
</tr>
<tr>
<td>Jinan Urban Center</td>
<td>( 50.17 + 2.63 \times 10^7 (1 + e^t)^{-1} + 0.07p )</td>
<td>28.17</td>
</tr>
<tr>
<td>Jiyang</td>
<td>( 112.47 + 7.22 \times 10^7 (1 + e^t)^{-1} + 0.05p )</td>
<td>127.56</td>
</tr>
<tr>
<td>Licheng</td>
<td>( 84.92 + 4.90 \times 10^7 (1 + e^t)^{-1} + 0.12p )</td>
<td>88.14</td>
</tr>
<tr>
<td>Pingyin</td>
<td>( 41.66 + 3.17 \times 10^7 (1 + e^t)^{-1} + 0.09p )</td>
<td>71.42</td>
</tr>
<tr>
<td>Shanghe</td>
<td>( -19.93 + 5.01 \times 10^7 (1 + e^t)^{-1} + 0.31p )</td>
<td>149.67</td>
</tr>
<tr>
<td>Zhangqiu</td>
<td>( 86.03 + 2.34 \times 10^8 (1 + e^t)^{-1} + 0.25p )</td>
<td>82.41</td>
</tr>
</tbody>
</table>
climate change, deltas for recharge were developed by setting \( \Delta r_i = g_d(0, 0) - g_d(\Delta p_i, \Delta t_i) \), where \( \Delta r_i \), \( \Delta p_i \), and \( \Delta t_i \) are the changes in recharge, precipitation, and temperature at year \( i \), and \( g_d \) is the estimated recharge function for district \( d \). This was performed for recharge and not reach headflows primarily because of the different sizes of data sets available to perform regressions; recharge regressions were performed with seven data points. To represent the temporal distribution of annual recharge was additionally mapped proportionally to historically cycled precipitation patterns.

### Estimating Effects of Climate Change on Agricultural Demand

Future changes in precipitation and temperature patterns will affect irrigation and agricultural demands. Increased rainfall might lead to reduced demand for irrigation, while decreased rainfall might lead to increased demand for irrigation. To represent this effect within the WEAP model, we developed a simple regression model using relationships drawn from the technical literature. In particular, Wang, Huang, and Yan (2013) estimated potential effects of climate change on water and agricultural production in the Yellow River basin. Changes in agricultural demand were assessed in the Yellow River basin for three climate change scenarios drawn from the IPCC Fourth Assessment report (IPCC, 2007)—A1B, A2, and B2. Changes were estimated for the year 2030, assuming a 2010 baseline. Each climate change scenario was represented as average changes in temperature and precipitation. These parameters are shown in Table D.3.
The values shown in Table D.3 were used to develop two separate regression models: (1) the relationship between the change in agricultural water demand (dependent variable) and the average change in annual mean temperature (independent variable); and (2) the relationship between the change in agricultural water demand (dependent variable) and the average change in annual precipitation (independent variable). The mean of each of these models was used to develop an estimated multivariate model relating changes in agricultural demand to changes in precipitation and temperature. We took this approach because of the small number of data points and after comparing model estimates across climate scenarios. The final regression model was estimated to be:

\[ d_0(p, t) = -1.474p + 0.0594t, \]

where \( d_0(p, t) \) is the change in annual agricultural water demand by 2030, \( p \) is the change in average annual precipitation by 2030 (percent), and \( t \) is the change in average annual temperature (degrees Celsius) by 2030. With so few data points used to estimate the regression, model estimates were bounded by –20 percent and +20 percent growth. Thus, the percentage change in agricultural demand by 2030 \( (d(p, t)) \) was estimated as follows:

\[
d(p, t) = \begin{cases} 
0.2 & d_0(p, t) \geq 0.2 \\
0.2 < d_0(p, t) < 0.2 \\
-0.2 & d_0(p, t) \leq -0.2 
\end{cases}
\]

Changes in demand were applied to water use rates for each agricultural demand node included in the Jinan WEAP model and varied for each climate projection. Changes in agricultural efficiency, as described in Chapter Seven, were also applied to agricultural water use rates for those scenarios where climate change increased agricultural demand. For a given district, time, and demand scenario, let \( \gamma \) represent a proportional increase in efficiency, where \( \gamma = 0 \) under futures with no change in efficiency. Water use rates \( w \) under each climate scenario are given by:

\[ w = w_o[1 + (1 - \gamma) d(p, t)], \]

where \( w_o \) is the baseline agricultural water use rate for the given district, time, and demand scenario.
APPENDIX E

Decision Rule for Springs Adaptive Groundwater Management

The decision rule for SAGM can be expressed in notation that provides clarity to the strategy. We define the following terms:

\( T_{\text{red}} \) and \( T_{\text{orange}} \) are the red and orange spring discharge thresholds for reducing withdrawals, estimated as 4.35 million and 5.64 MCM per month, respectively;
\( C \) is the real maximum monthly withdrawal from the Jinan Urban Center (daily capacity across all sectors, given as 750,000 m\(^3\) per day);
\( M_i \) is the maximum monthly withdrawal as specified by JWRB at time \( i \);
\( B_i \) is the aggregate monthly discharge from Baotu Springs at time step \( i \);
\( O_i \) is the total monthly quantity of water pumped from the Jinan urban groundwater node to satisfy demand at time \( i \).

The maximum monthly withdrawal \( M_{i+1} \) at time \( i + 1 \) is therefore:

\[
M_{i+1} = \begin{cases} 
O_i + B_i - T_{\text{red}} & B_i < T_{\text{red}} \\
O_i + B_i - T_{\text{orange}} & B_i < T_{\text{orange}} \\
C & \text{else}
\end{cases}
\]

For example, if the springs discharged 3.35 MCM per month at time \( i \) and the total groundwater supplied to demand in the Jinan Urban Center at time \( i \) was 18 MCM, then groundwater withdrawals at time \( i + 1 \) would be capped at \( M_i = O_i + B_i - T_{\text{red}} = 18 + 3.35 - 4.35 = 17 \) MCM per month. If spring discharge rises to the orange level, then the orange level is used as the upper limit. Finally, when spring levels are above the orange level, groundwater withdrawal capacities are capped at infrastructure limits (750,000 m\(^3\) per day for Jinan Urban Center).
### Experimental Design for WEAP Model Runs

<table>
<thead>
<tr>
<th>Climate Projection</th>
<th>Demand Projection</th>
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<tr>
<td>RAND-Designated Climate Projection Number</td>
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<td>giss_e2_r</td>
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<td>64</td>
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<td>miroc_esm</td>
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<td>79</td>
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<td>81</td>
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<tr>
<td>84</td>
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<td>88</td>
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<tr>
<td>89</td>
<td>mpi_esm_lr</td>
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</table>

SOURCE: Flato et al., 2013.

*For the Low Demand projection, simulations were only run for management strategies 1 to 6 in Table 7.1.*
Table F.2
Identification and Ownership of Global Climate Models

<table>
<thead>
<tr>
<th>Global Climate Model Name</th>
<th>Institution</th>
<th>Year of First Publication</th>
</tr>
</thead>
<tbody>
<tr>
<td>bcc_csm1_1</td>
<td>Beijing Climate Center, China Meteorological Administration</td>
<td>2011</td>
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<tr>
<td>cccma_canesm2</td>
<td>Canadian Center for Climate Modeling and Analysis</td>
<td>2010</td>
</tr>
<tr>
<td>csiro_access1_0</td>
<td>Commonwealth Scientific and Industrial Research Organisation and Bureau of Meteorology, Australia</td>
<td>2011</td>
</tr>
<tr>
<td>csiro_access1_3</td>
<td>Commonwealth Scientific and Industrial Research Organisation and Bureau of Meteorology, Australia</td>
<td>2011</td>
</tr>
<tr>
<td>csiro_mk3_6_0</td>
<td>Queensland Climate Change Centre of Excellence and Commonwealth Scientific and Industrial Research Organisation</td>
<td>2009</td>
</tr>
<tr>
<td>fio_esm</td>
<td>First Institute of Oceanography, State Oceanic Administration, China</td>
<td>2011</td>
</tr>
<tr>
<td>gfdl_cm3</td>
<td>U.S. National Oceanic and Atmospheric Administration Geophysical Fluid Dynamics Laboratory</td>
<td>2011</td>
</tr>
<tr>
<td>gfdl_esm2g</td>
<td>U.S. National Oceanic and Atmospheric Administration Geophysical Fluid Dynamics Laboratory</td>
<td>2012</td>
</tr>
<tr>
<td>gfdl_esm2m</td>
<td>U.S. National Oceanic and Atmospheric Administration Geophysical Fluid Dynamics Laboratory</td>
<td>2011</td>
</tr>
<tr>
<td>giss_e2_h</td>
<td>U.S. National Aeronautics and Space Administration’s Goddard Institute for Space Studies</td>
<td>2011</td>
</tr>
<tr>
<td>giss_e2_r</td>
<td>U.S. National Aeronautics and Space Administration’s Goddard Institute for Space Studies</td>
<td>2011</td>
</tr>
<tr>
<td>ipsl_cm5a_mr</td>
<td>Institute Pierre Simon Laplace</td>
<td>2010</td>
</tr>
<tr>
<td>miroc_esm</td>
<td>University of Tokyo, National institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology</td>
<td>2010</td>
</tr>
<tr>
<td>miroc_miroc5</td>
<td>University of Tokyo, National institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology</td>
<td>2010</td>
</tr>
<tr>
<td>mohc_hadgem2_cc</td>
<td>UK Met Office Hadley Centre</td>
<td>2010</td>
</tr>
<tr>
<td>mohc_hadgem2_es</td>
<td>UK Met Office Hadley Centre</td>
<td>2009</td>
</tr>
<tr>
<td>mpi_esm_lr</td>
<td>Max Planck Institute for Meteorology</td>
<td>2009</td>
</tr>
</tbody>
</table>

Water balance tables can be created from the Jinan WEAP model’s output that include the following parameters: demand, supply delivered, amount of reuse, and unmet demand. To help focus on the range of plausible outcomes, we present an example of results for the baseline historical case and five future climate scenarios. These representative climate scenarios, shown in blue in Figure G.1, were selected to span the range of temperature and precipitation changes.

In our example, Table G.1 shows the water balance values for the Changqing district for the following conditions:

- Climate Projection = Historical
- Demand Projection = Medium Demand
- Strategy = Current Project

Figure G.1
Climate Projections Presented in the Data Tables

NOTE: Blue shading indicates representative climate scenarios.
• Groundwater Initial Storage = Large Initial Groundwater Storage
• Yellow River Allocation = Full Yellow River Allocation.

Table G.1  
Example Water Balance for a Single Future (in MCM)  

<table>
<thead>
<tr>
<th>Water Balance Component</th>
<th>2012</th>
<th>2030</th>
<th>2050</th>
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</thead>
<tbody>
<tr>
<td>Demand (Changqing Residential)</td>
<td>20.0</td>
<td>37.1</td>
<td>41.2</td>
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<tr>
<td>Supply (Changqing Residential)</td>
<td>17.6</td>
<td>32.6</td>
<td>36.3</td>
</tr>
<tr>
<td>Reuse (Changqing Residential)</td>
<td>2.4</td>
<td>4.5</td>
<td>5.0</td>
</tr>
<tr>
<td>Unmet (Changqing Residential)</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Demand (Changqing Industry)</td>
<td>1.9</td>
<td>8.3</td>
<td>10.7</td>
</tr>
<tr>
<td>Supply (Changqing Industrial)</td>
<td>1.7</td>
<td>7.3</td>
<td>9.4</td>
</tr>
<tr>
<td>Reuse (Changqing Industrial)</td>
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<td>1.0</td>
<td>1.3</td>
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<tr>
<td>Unmet (Changqing Industrial)</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Demand (Changqing Agriculture)</td>
<td>103.2</td>
<td>100.7</td>
<td>100.7</td>
</tr>
<tr>
<td>Supply (Changqing Agricultural)</td>
<td>103.2</td>
<td>100.7</td>
<td>100.7</td>
</tr>
<tr>
<td>Reuse (Changqing Agricultural)</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
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<tr>
<td>Unmet (Changqing Agricultural)</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
</tbody>
</table>
References


CCAFS—See Climate Change, Agriculture and Food Security.


IPCC—See Intergovernmental Panel on Climate Change.

———, “Statistical Communiqué on Jinan’s National Economic and Social Development in 2015,” 2015. As of December 14, 2016: http://www.jntj.gov.cn/content.jsp?id=46267b45614c4d929c638ab5d94d1f31&classid=4028813e4dad18a2014db398e02d02c4


Jinan Water Resources Survey and Design Institute, Jinan Planning and Design Institute, Jinan Municipal Project Design Institute, Jinan Landscape Design Institute, and Jinan Environmental Protection Planning Institute, Jinan Water Ecological Pilot City Development Implementation Plan, Jinan, 2013.


SEI—See Stockholm Environmental Institute.


UNESA—See United Nations, Department of Economic and Social Affairs.


The Jinan Municipal Water Resources Bureau, with support from the Shandong Provincial Department of Water Resources, asked RAND to evaluate potential effects of demand and climate uncertainties on investments recently undertaken according to the Jinan City Water Ecological Development Implementation Plan. RAND was also asked to assess the potential of new investments and management strategies to help Jinan meet its long-term water resources goals. RAND’s approach uses well-tested methods of decision support, starting with building a shared understanding of the nature of the decision, metrics to evaluate progress toward goals, key uncertainties that drive outcomes, and relevant physical and other relationships within Jinan’s complex water system. The approach also uses visualizations to help policymakers understand the implications of the results, build consensus, and facilitate decision making. This document describes RAND’s approach and results, including the development of a mathematical simulation model of the Jinan water system, using the Water Evaluation and Planning software developed by the Stockholm Environmental Institute, and analysis of the system’s performance under a range of uncertainties about future climate and demand across sectors.