



Introduction

Water resources modeling has become increasingly important to water managers and planners, due to the current ease of access to modeling software and the ability to realistically simulate water supply and demand across both space and time. Perhaps modeling is even more relevant in the developing world, where water resource data is often inconsistent, if it exists. In particular, modeling at the city scale is crucial, as many developing countries continue to face a rapidly growing, urbanizing population. Socioeconomic progress in these cities increases expectations, competition, and consequent strains on water resources.

This project presents one such set of models, based on the drinking water resources of Delhi, India. The Water Evaluation and Planning (WEAP) tool (www.weap21.org) was chosen for use as a modeling system due to its easy to use interface and functions as well as its ability to simultaneously simulate multiple scenarios surrounding hydrologic and other variables (such as population growth and socioeconomic status). The paper begins by giving an overview of water resources in Delhi, in terms of both supply and demand, and presents the main challenges presently facing the city. It then goes on to introduce a simple model developed in WEAP, representing current water resources and associated demands of the city, followed by three scenarios representing population growth, increasing supply capacity, and increasing water demands by allowing water for informal settlements within the city. Though each scenario is a simple approximation, there are still important lessons to be learned from these models, including where to focus efforts. The paper concludes by introducing a simple water allocation-optimization exercise, based on several demographic and socioeconomic variables across the city. Taken together, these simulations highlight the use and relative ease of modeling (even if simplified) in data-poor developing world contexts.

The Problem

Megacity, mega water problems

The National Capital Territory, Delhi is one of the fastest growing urban areas in the world (Rai, 2010). With a population of over 15 million people, Delhi is considered a “megacity”. Megacities are defined as metropolitan areas with populations exceeding 10 million. While the growth of megacities has occurred at a steady pace in developed nations, population growth in developing countries has occurred at an alarmingly rapid rate. Population expansion is often centered in areas of economic weakness, with limited water resources and incompetent water management. According to a World Bank report in 2001, of the 27 Asian cities with populations exceeding 1 million people, Delhi was tied with Chennai for worst water availability (Misra & Malhotra, 2012). Mumbai was ranked second and Calcutta was the fourth worst. Water scarcity issues throughout India are linked intrinsically with rapid population growth in urban areas (Misra & Malhotra, 2012).

Supply and Demand

The rapid rate of population growth and the unplanned growth of unauthorized colonies (jhuggis) have significantly increased municipal water demand and put tremendous stress on the water supply infrastructure in Delhi (Misra & Malhotra, 2012). Based on the Indian Government norm of 60 gallons per capita per day, water demand as of March 2011 was 1,020 MGD in Delhi (Economic Survey of Delhi, 2012-2013). Delhi’s municipal water supply comes from the Yamuna River (1,780 MLD), the Ganga Canal (947 MLD), and groundwater (379 MLD). The supply has a seasonal distribution, with most of the precipitation occurring during summer monsoon months and very little occurring during the dry season (Rai, 2010). The water supply is treated at eight water treatment plants of varying maximum capacities; the total current water treatment capacity is only 855 MGD. Furthermore, the deficit is even greater than the difference between supply and the demand, due to aging and poorly maintained infrastructure. Over 20 percent of the treated water is lost in transit (Misra & Malhotra, 2012).

Currently, the Delhi water system does not serve the entire population. Only 81.3 percent of residents receive water from the piped water supply system (Economic Survey of Delhi, 2012-2013), the remainder of the population supplies their own water from covered wells, hand pump wells, tube wells, tanks, ponds, lakes, and other sources. The failures in the water system force many people in the capital city to supply their own drinking water. Residents purchase water from private suppliers at five to ten times the municipal water price and extract groundwater through borehole wells (Misra & Malhotra, 2012). Areas that do not receive adequate water via the piped water supply system have seen drastic drops in aquifer levels due to the indiscriminate groundwater extraction to meet demand.

Distribution

Ironically, Delhi has the highest per capita water availability, but this water is so unevenly distributed that some areas receive an abundance of water while others do not receive nearly enough (Misra & Malhotra, 2012). Officially, Delhi is divided into 9 conveniently-named districts: North, Northeast, Northwest, Central, Delhi, East, West, Southwest, and South, though water supply and demand are certainly not distributed equally among districts. The water treatment plants are concentrated in the northern and central districts and water is distributed by these treatment plants throughout the city. Due to high losses from leaky pipes, the districts near to or containing water treatment plants receive more water than distant southern districts (Misra & Malhotra, 2012). Residents in these underserved areas must resort to other water sources to meet demand and often indiscriminately exploit groundwater resources. Over-drafting occurs in seven out of the nine districts, most notably in the Northwest, Southwest and South districts (Indian Ministry of Water Resources, n.d.).

The WEAP Model

The Baseline Model

A simple model was constructed for the *current* water supply system in Delhi, using the best information available. Essentially, this model gives a detailed look at how Delhi's drinking water resources match its demand, varied by district (population center). Using this baseline model, we then (i) use it to compare likely scenarios including population growth, socioeconomic improvement (increasing demand), and additional supply projects; and (ii) make recommendations on possible improvements in the operation and efficiency of Delhi's water supply. Other scenarios were considered in this project, however only the three above are presented in this report.

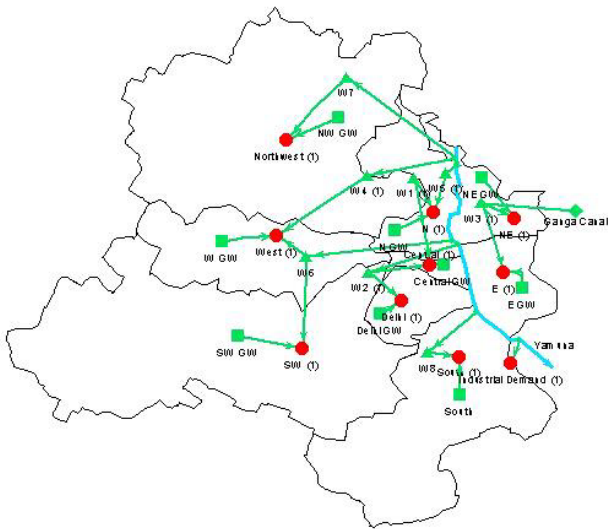


Figure 1: WEAP Model

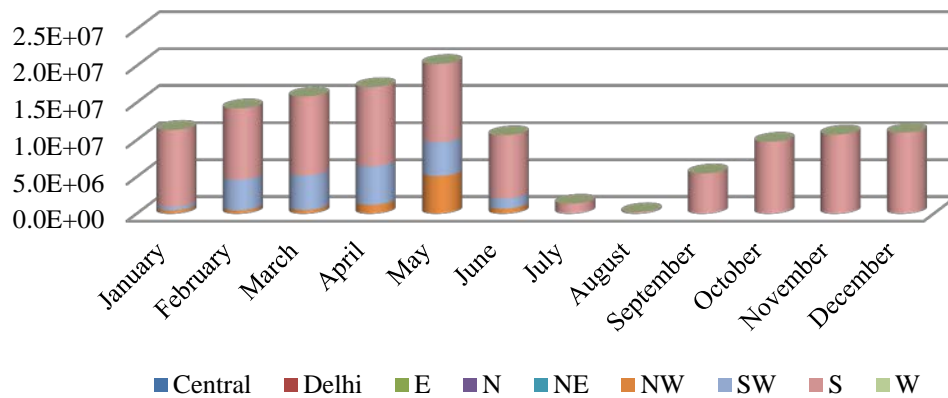
The following variables and assumptions were used in estimating a baseline model; this gives a look at the drinking water resources available to Delhi presently, as well as the *sustainable water supply* that Delhi has on hand. The sustainable supply was chosen as a baseline in order to compare models which might not be so sustainable, such as unregulated groundwater extraction, extreme population growth, or shrinking supply levels:

1. Population for each district gathered from 2011 Census Data.
2. Water use rate is 150L/capita/day.
3. Waste water treatment plants run at full capacity each day during the year.
4. All surface water comes from either the Yamuna River or the Ganga Canal.
5. Groundwater allotted to each district is the sustainable recharge per district. Districts could potentially draw more groundwater, yet this is not incorporated into the baseline model. Groundwater recharge is varied with average rainfall for Delhi.
6. Baseline year is 2011; projections are made from 2012-2021.
7. Losses are 20% through entire distribution system.
8. Commercial and Industrial interests draw water directly from the Yamuna River.

Baseline Results

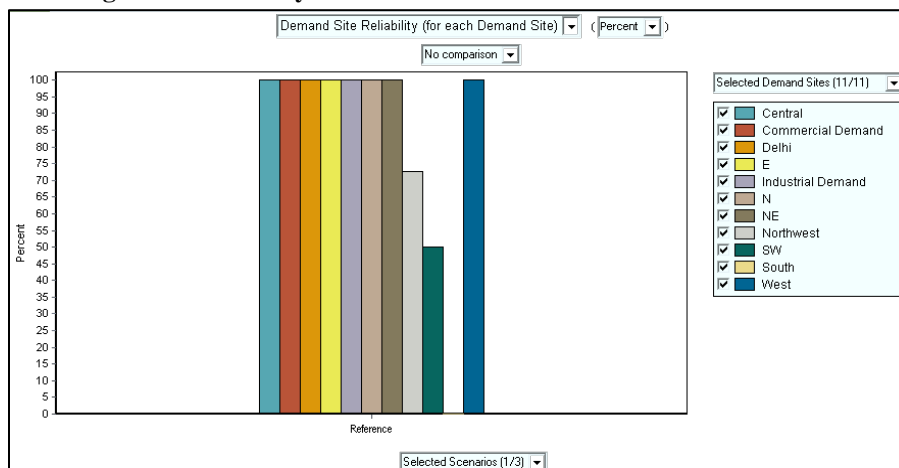
This simplified model corroborated media, academic, and even government information and publications on the crisis facing Delhi in terms of providing drinking water to its citizens. As expected, the baseline model shows a distinct gap between supply and demand in Delhi. The chart below shows the monthly unmet demand in the city, and we see that this is concentrated in the Northwest, Southwest, and South districts. This is particularly interesting, because these districts correspond directly to those withdrawing the most groundwater for consumption. WEAP also allows us to see that the monsoon season (July, August, and September) allows for more water to be supplied to these districts.

Figure 2: Monthly Average Unmet Demand (cubic meters)



Taking this information further, we can also model the demand site reliability, shown in the chart below. This confirms that the South district is the most unreliable, with zero percent reliability through the reference year.

Figure 3: Reliability for each district for the baseline WEAP model

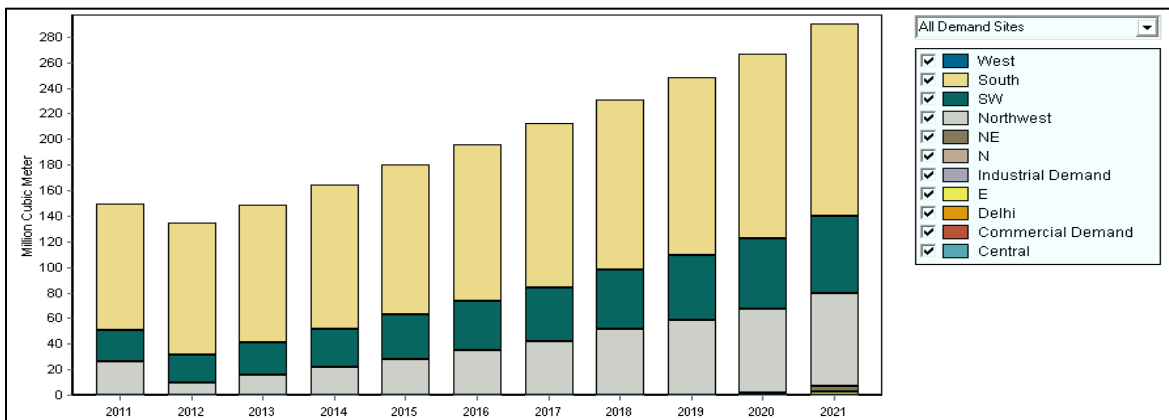


These results provide an interesting and in-depth look at the distribution of supply from both groundwater and surface water sources. The diversity of water resources is encouraging for the city, as both ground and surface water sources are viable; yet the difficulty comes in managing those resources responsibly and sustainably.

SCENARIO 1: Three Percent Population Growth

The chart below shows the unmet demand increase with a 3.0% increase in population growth per year over the decade (2012-2021). Again, we see a great shortfall occurring in the Southwest, South, and Northwest districts. Considering the population growth that has occurred in Delhi over the past five decades, this population growth estimate is not unreasonable, and shows the challenge that the water board in Delhi is facing in managing its demand.

Figure 4: Unmet demand for 3% population scenario



SCENARIO 2: Addition of a new water treatment plant

The obvious remedy for Delhi’s water worries is the installation of more capacity. In fact, the city has been concentrating on this possibility, with help from the World Bank and the Japanese International Cooperation

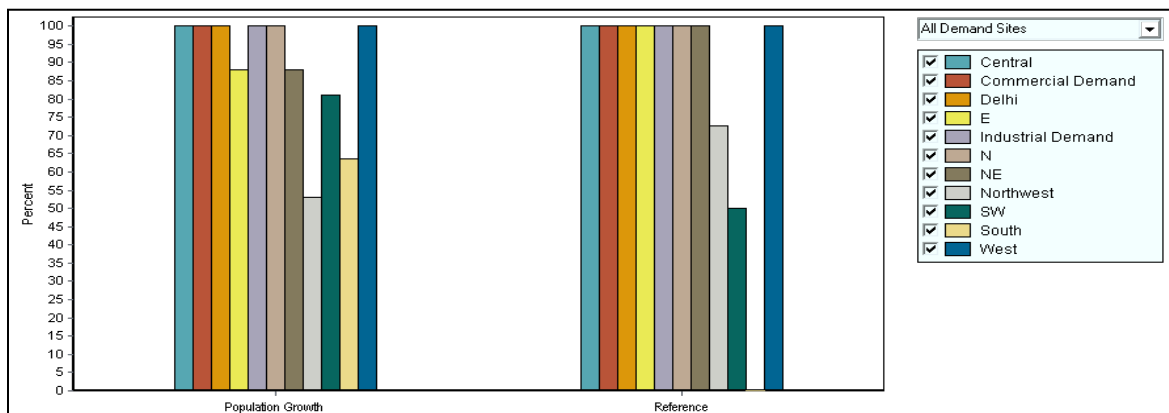


Figure 5: Reliability for New Treatment Plant and Reference Scenarios

Agency (JICA). WEAP allows simulation of new capacity within the system; in this case a 200 million gallon per day water treatment plant is added to supply water to both the South and Southwest districts.

The results of this scenario suggest that the South and Southwest districts will be greatly helped by this addition of capacity, yet will continue face shortfalls (shown in the plots of reliability for the baseline and additional capacity model which also includes population growth). Furthermore, the Northwest district (which is the most populous) will not be helped at all by this increase in supply. We can conclude from this model that Delhi faces not simply a water supply problem, but also a distribution problem, because of the lack of connectivity between water supply facilities. This is also exacerbated by the large losses faced by the system, due to illegal connections and aging infrastructure.

SCENARIO 3: Increasing demand for informal settlements

In order to attempt to address the inequity in supply in Delhi (between rich and poor areas), increasing demand from new connections to informal settlements (Jhuggis) was modeled by adding a new demand site to each district as shown below. The priority of each demand site was maintained across districts and types of demand. The results of the model confirm the problems faced by South, Southwest, and Northwest districts, shown in the reliability plot below; other districts are able to meet this additional demand. Therefore, special focus must be given to these three districts in order to address the water supply and distribution issues faced by Delhi. In particular, according to these models, an organization such as the World Bank - wishing to mitigate as much water deprivation as possible per dollar spent - might choose to focus on these areas of the city.

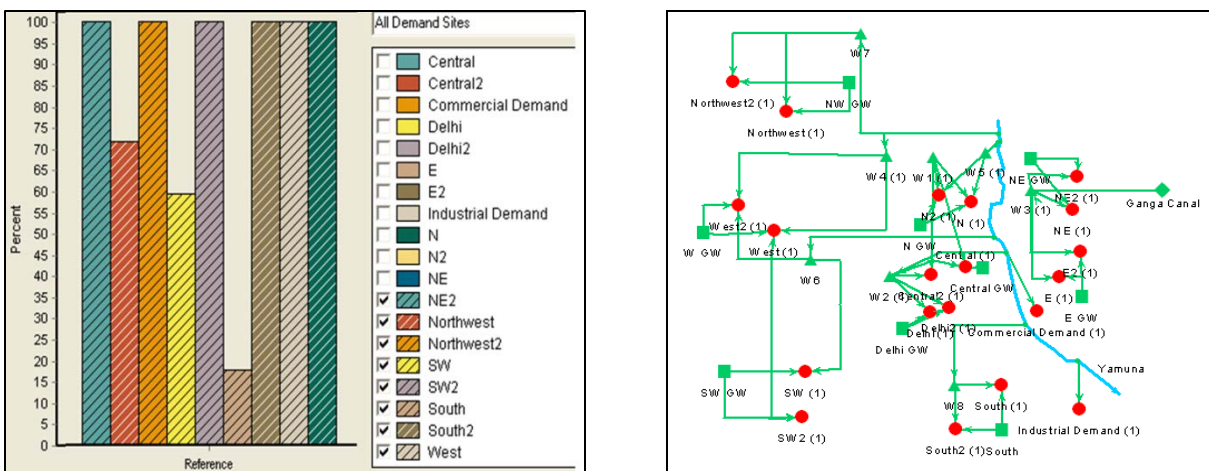


Figure 6: WEAP Model and Reliability for Increasing Demand Scenario

Optimization of Water Distribution

The WEAP analysis above describes how various scenarios supply the water demands of Delhi. Another scenario evaluated concerns the changes in availability of water occurring when losses in the distribution system are reduced. Various sources have listed these current losses as between 20 and 59 percent of all water entering the distribution system. In this section, a quasi-optimization scheme will show how that additional water (surplus) could be distributed between the various districts.

The available literature presents various studies which have determined Willingness to Pay (WTP) functions for Delhi based on information gained through household surveys and other means not available in the present study (Nallathiga, 2009). For a public entity, the objective is to maximize WTP minus cost. In the absence of this data, a simplified demand function is created below:

$$\text{Optimized Share} = (\text{Surplus} - \text{Slum Demand}) \times \left(\frac{\text{Pop}}{\sum \text{Pop}} \right)^1 \left(\frac{\text{Pop Den}}{\text{Avg}} \right)^1 \left(\frac{\% \text{Phone}}{\text{Avg}} \right)^{2.1} + \text{Slum Demand}$$

This optimization model includes the constraint that all of the slums currently unserved by a water source within 100 meters from the census data will receive the survival requirement of 50 lpcd. The population density factor implies that with a greater population density, more water will optimally be delivered, as the costs associated with distributing a quantity in a population dense area should be lower. The percentage of households with both a landline and cell phone is used to model wealth, and is associated with WTP for the water. The exponents are scaling factors that would need to be calibrated to reflect actual WTP.

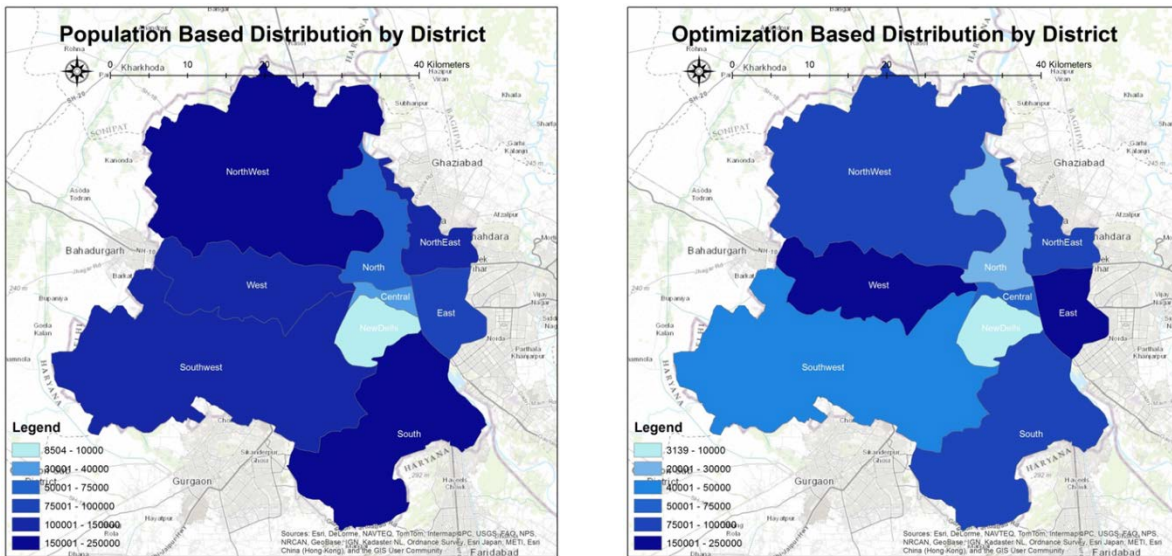
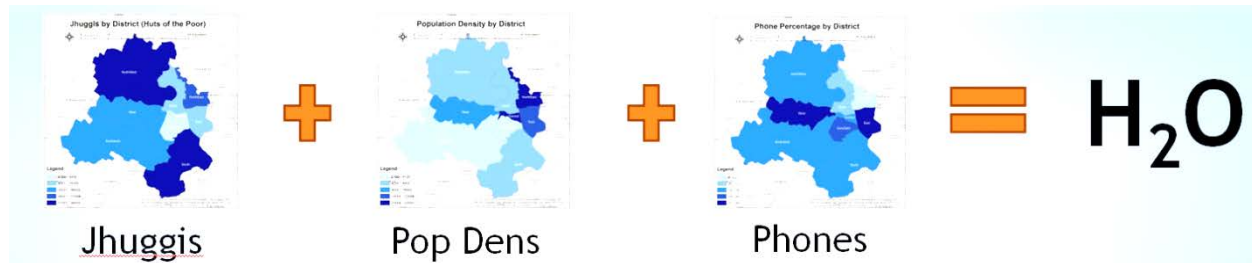


Figure 7: Spatial distribution of water by Population and by Optimization model results

In Figure 7, as darker colors represent a higher distribution share, it is clear that when cost and demand factors beyond simple population based estimates are considered in combination with the survival delivery constraint, the optimized distribution is shifted away from the Northwest and Southwest priority sections discussed above in the WEAP analysis, to the wealthier areas, where there is assumed to be a greater demand and associated WTP.



While this is a very simplified model that has not been properly calibrated, the intent here is to illustrate some of the factors regarding the complicated nature of the water resources management situation in Delhi.

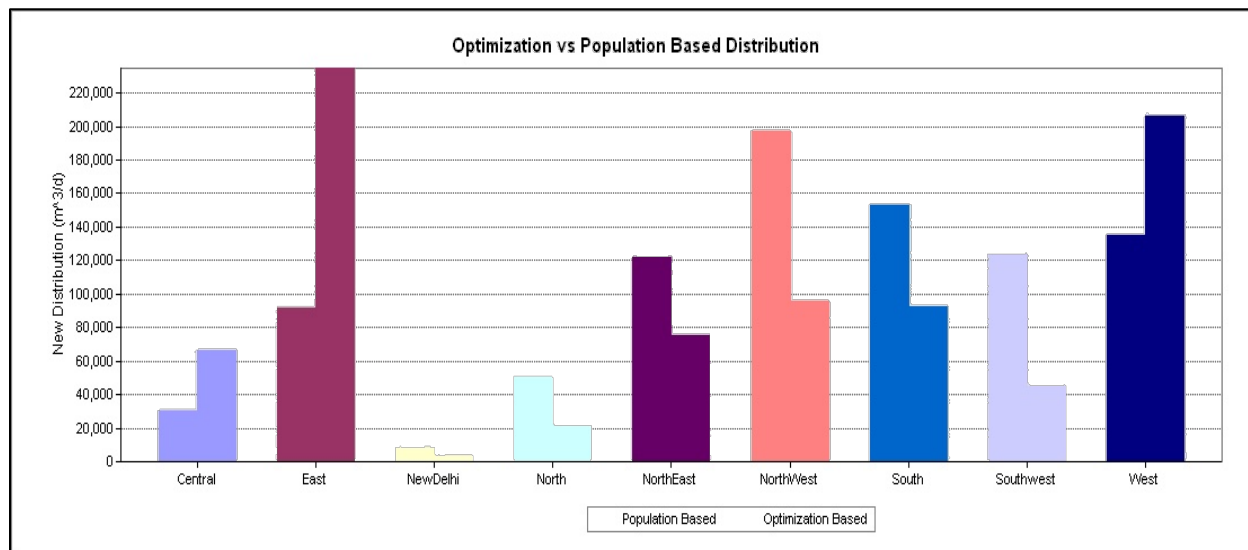


Figure 8: Spatial distribution of Optimization model results

Conclusion

The WEAP simulations showed that of the nine districts, three are particularly water-stressed. The South district has unmet demand throughout most of the year, which will only be exacerbated by population growth in the decade to come, whereas the Northwest and South districts have unmet demand during the dry season and receive some reprieve during the monsoon season. Throughout the various WEAP scenarios, the Northwest, Southwest and South districts are consistently in deficit. The other scenarios had little effect on the remaining six districts, reiterating the idea that the water scarcity problem in Delhi has a clear spatial element. The districts that WEAP diagnosed as water stressed are also the three districts that are most over-drafting their available groundwater resources. This is a serious side effect of the system failure that will have impacts on future water supplies in Delhi. As the surface water becomes more scarce and polluted, groundwater will be the preferred supply source; better planning and management is certainly needed to protect this critical supply.

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