Title
Water Resource Dynamics in Asian Pacific Cities

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1 Introduction

Adequate water supplies are an obvious necessity for the health of cities and their residents. Water is used for drinking, hygiene, cleaning, waste disposal, irrigation, transportation, and a host of industrial processes. Yet, projections of the match between the demand for water and supply of water are grim (Lettenmaier et al. 1999; Gleick, 2000; HELP Task Force, 2000, Cosgrove and Rijsberman, 2000, Aldhous, 2003). For example, Jakarta and Bangkok may not be able to meet water demand within the next decade or so (Dupont 1998), and as many as 300 cities in China may already suffer already from water shortages (Postel 1996). In addition to issue of supply, many cities in the Asia Pacific suffer from substandard sewage connections, the commingling of drinking water and sewage, and inadequate waste removal, which all contribute to an increased incidence ground and surface water contamination and water borne diseases (Appan 1998; Elliott 1998). Indeed, the entire Bengal Delta in Bangladesh has been likened to “a giant toilet that is adequately flushed just once a year” (Clarke, 2003: 254)

The prospect of rapid climate change is not likely to help matters. Beyond possible reductions in precipitation in some locales, the timing and nature of precipitation events may no longer match local infrastructures. If with warming, for example, precipitation is more likely to fall as rain rather than snow, runoff patterns could differ dramatically. Water normally retained in snow pack for gradual release, would enter watersheds earlier and with greater flows than normal. Existing rivers, canals, aqueducts, and reservoirs could be overwhelmed, and the water lost.

Accurate documentation of existing water problems in cities, usefully precise forecasts of future trends, and the design effective responses depend in part on placing water issues in a proper conceptual framework and then, collecting enough data of sufficient quality to quantify matters. This paper provides a brief summary of a useful conceptual framework and some examples of the kinds of data and analyses necessary.

2 Conceptual Framework

The proper study of water resources in cities begins with a commitment to including both natural and human processes. A lack of adequate water supplies cannot be understood from either set of processes alone. Thus, a drought by itself does not lead to water shortages, nor does rapid population growth.

2.1 Water Shortages Defined

It is readily apparent that the supply of water on the planet is effectively limitless. The oceans of the world are essentially a bottomless well. The problem, of course, is that ocean water is not fit for the vast majority of human needs.

One solution is to treat ocean water, making sufficient quantities of the requisite quality. Of late, the necessary technology has become readily available so that many countries have built, or are building, desalination plants. Likewise, it is possible to treat wastewater from cities to any desired level of purity and here too, the necessary technology is readily available. Wastewater recycling is now common around the world, especially for irrigation and industrial applications. Finally, in many regions cities have too little water because farmers have too much. Traditional controls over water supplies do not lead to efficient allocations. For example, in California about 80% of the water used goes to irrigation. If the water districts in farming areas could be convinced to sell just 10% of their water to cities, there would be enough for urban areas throughout the State. Unfortunately, there is no direct way to make these water districts cooperate. Negotiations have dragged on for over a decade.

The real problems, therefore, are economic, environmental, and political. While the costs of water treatment are increasingly competitive with the costs of acquiring water in more conventional ways, they are often well beyond what developing countries and their cities can afford. In addition, water treatment can be energy intensive and lead to wastes that are difficult to dispose. Serious environmental consequences can follow. But whatever the costs and possible environmental consequences, there needs to be the political will for change, the capacity to make those changes stick, and the infrastructure (physical and institutional) to implement the changes intended.

These observations lead to a useful definition of a water shortage: *a water shortage is a mismatch between the demand for water of specified quality and the supply of water with that quality at a given price and under given institutional and legal constraints.* Thus, for all practical purposes, water shortages are a product of human activities, most of which can be altered. To paraphrase the famous words of the American cartoon character Pogo, "we have met the enemy and they are us."

2.2 Embedding Cities in the Hydrological Cycle

Although water shortages can be defined solely in human terms, it would be foolhardy to believe that natural processes can be ignored. Consider the water we drink every day in Los Angeles. Much of that water originates in the snow that falls in the Sierra Nevada Mountains in Northern California. As that snow gradually melts, it is carried in streams to rivers that have been altered to contribute to the distribution of water throughout all of California. Much of the Sacramento River, for instance, is lined with levies. From there the water is carried in canals or aqueducts, often being held in reservoirs along the way, to the pipes that make up the Los Angeles water supply system. Most of the water we use in Los Angeles is ultimately discarded and is then taken either to treatment plants or carried in storm drains directly to the ocean. The treated water may be reused to irrigate golf courses and the median strips along freeways. Some is also put to industrial uses. The untreated water flowing down storm drains help carry all manner of pollutants into the Santa Monica Bay.

How do natural processes figure in? Cities are in an important sense inserted into the natural hyrodological cycle altering the flow, location, and quality of water. In a very important way, cities become part of the hydrological cycle. Natural processes then affect human processes. But human processes can affect natural processes as well. For example, during the summer in Los Angeles outdoor water use applies the amount of water one would get from a major thundershower. As a result, microclimates are altered directly and through the mix of non-native plants that are supported, indirectly as well; water from the Northern California snow pack can reduce summer temperatures in Los Angeles by as much at 5 degrees F.

In order to study in depth how cities interact with the hydrological cycle, far more detail would need to be provided. For example, in developed countries water in cities used for irrigation will be driven in part by perceptions of the watering needs of various kinds of landscaping. What is it about local climate that shapes these perceptions? What is the response function, for instance, as the number of days since the last rainfall increase? In developing countries, water use in cities can be affected directly by temperature; there are seasonal patterns even for indoor water use. What is relationship between temperature and indoor water use? There is very little theoretical work on such matters.

Consequently, research on cities and the hydrological cycle tends to be primarily empirical and exploratory. Data are collected on a variety of variables and then with statistics, empirical relationships are constructed. But not just any data will do, and often the requisite data are not available.

3 Studying Cities and the Hydrological Cycle

Many different kinds of data are needed to consider empirically how cities and the hydrological cycle interact. Based on earlier pilot research funded by APN and START, examples include data on the following.

1. Climate (e.g., precipitation, temperature, wind speed, etc)
2. Water transport (e.g., pipes, aqueducts, etc)

3. Water use for different user types residential, commercial, industrial, and agricultural
4. Water losses (e.g., from leaks, evaporation, water theft)
5. Water quality (e.g., salinity, suspended solids, heavy metals, haloforms, natural organic matter bacteria)
6. Runoff volume and quality (e.g., measures of flow from storm drains)
7. Wastewater volume and quality (e.g., at sewage treatment plants)
8. Land use and land cover (e.g., digitized maps showing green space)
9. Water sources in addition to precipitation (e.g., use of ground water, water imported from rivers or reservoirs)
10. Institutional setting and regulations (e.g., who is responsible for providing water to city residents and how is it priced?)
11. Functioning of ecosystems
12. Public health
13. Population

Data such as these will typically not be available in developing countries and even for many developed countries.[1] But such data are generally available for many areas of Japan.

Over a period of several months, we were able to collect some of the kinds of data needed for the several Japanese cities: Kobe, Osaka, Fukuoka, Hiroshima, Yokohama, Sapporo, Kanazawa, and Tokyo Wards. The data cover the years 1971-1999 and include for each year the following variables:

1. Residential water use
2. Commercial water use

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[1] Sometimes useful information exists in administrative records of various sorts (e.g., land use information in tax records). Then, the resources are needed (along with access) to extract the data and transform it into a useful format. Sometimes, very little useful information exists at all. Then, a major investment in primary data collection is required.

3. Industrial water use
4. Population
5. Average income
6. Average price of water
7. Average temperature
8. Total Precipitation
9. Number of days with more than 30 mm of precipitation
10. Average humidity
11. Residential land use
12. Commercial Land use
13. Industrial land use

A key feature of these data is that they are longitudinal. In principle, therefore, one can study water use dynamics and even take a stab at forecasting water use. At the same time, we are keenly aware that any findings we report may have little relevance for other Asia Pacific cities, especially in developing countries. However, there may be more leverage in these data than first appear, as we explain later.

4 Making Use of Such Data

In the analyses to follow, we will focus on residential water use. These are the analyses that are most complete (but still in progress). We leave a discussion of commercial and industrial water use for another time.

There is surprisingly little formal theory on residential water use as we address it here. The existing theory comes from resource economics in which water demand is basically treated the same as demand for any other consumer good. As such, the theory speaks to short term adjustments made by residential users, primarily as a function of price, household income, water substitutes, and water complements.

For us, the relevant observational unit is not the individual consumer, but the city. And we are concerned with changes in water use over years, not days, weeks or even months. Thus, a theory of consumer decision-making does not necessarily apply very directly to the questions we are asking. For example, changes in the size of a city's population have no relevance for the water use of an individual consumer, and there is no compelling reason to assume that the relationship between population growth and aggregate residential water demand is even linear. Younger people probably use more water per day than older people, so the affect of population change on water use may be altered by how the age mix varies over time.

One way to begin empirical work is to determine at the city level which potential causal variables are the most promising. From the results of our earlier pilot study, we begin by tentatively assuming that for residential water use:

$$\text{Consumption} = f(\text{Population}, \text{Affluence}, \text{Price}). \tag{1}$$

We found in our earlier work that climate variables did not matter for Japanese cities. With respect to supply, the water infrastructure was sufficiently developed to compensate for historical variation in precipitation (e.g., with reservoirs). With respect to demand, the primary way in which climate affects residential water is through the need to water decorative landscaping. And in Japanese cities (in contrast to cities like Los Angeles), few homes have large landscaped areas that need to be irrigated.[2]

Population has long been a key signature of urbanization and clearly a critical factor in the urbanization we are likely to experience over the next generation. Population is just as obviously a driver of of residential water consumption. All humans require some minimum amount of water to survive and in developed countries, lifestyle considerations lead to consumption well beyond this minimum. In particular, with greater affluence is likely to come greater per capita residential water use. Histories of urbanization in the United States, for instance, show that with greater affluence has come larger investments in personal hygiene and public investments in urban infrastructures that can be water-use intensive (Melosi, 1999). It follows that population and affluence likely enter into Equation 1 multiplicatively.

For example, the tenements that housed immigrants to the United States in the first half of the 20th century were often called "cold water flats" because

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[2] This is one of the reasons why per capita water use is about 50% higher in Los Angeles than in major Japanese cities

there was no hot water. Adults used public baths for bathing. Children were washed in small tubs with water heated on a coal burning stove. Clothes were washed about once a week and were worn several days in a row. The grandchildren of these immigrants, insofar as they live in cities, are likely to have plenty of hot water, showers as well as bathtubs, dishwashers and clothes washers. They bathe on a daily basis and fresh clothes are commonly put on at least once a day. If one goes back even farther in time, Melosi (1999) notes that in European cities before the industrial revolution, the common people used about 2 to 3 gallons of water per day per captia. That is equivalent to less than one flush in a modern, conventional 5 gallon toilet.[3] In short, population affects residential water use differently depending on the affluence of the local population.

The role of the price of water is less clear. In principle, with increases in the unit price of water, consumption per capita should fall. However, years of empirical research in the United States have found widely varying estimates of the price elasticity, with many estimates near zero. One explanation is that the price that residential consumers pay for water is very small relative their incomes. As such, the cost of water may too small to worry much about. In our data, average monthly income (adjusted for the value of the yen in 2000) is about 500,000 yen. That translates into a bit more than $4000 a month. The price for a month's water allocation of about $20.00.[4]

It is clear that we have no information on several potentially important variables. We have already mentioned the age mix of the population. We will later show, however, that the estimated functional form between population and aggregate water consumption may give us a bit of information on the impact of the age mix. More troubling is the absence of any information on water use technology: water efficient appliances, water substitutes, and water recycling. Affluence may capture part of technology's role, but we surely need to obtain more direct measures. For example, it would be important to know if city ordinances require the use of water efficient toilets and if so, when those ordinances were promulgated.

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[3] There are a number of brands of water efficient toilets that get the job done using about 1.5 gallons of water per flush.

[4] To help out this in context, the second author of this paper was on an NSF summer fellowship in Tokyo during the summer of 2002. She was given 10,000 yen per day, which is about 300,000 yen per month, This was barely enough to live on.

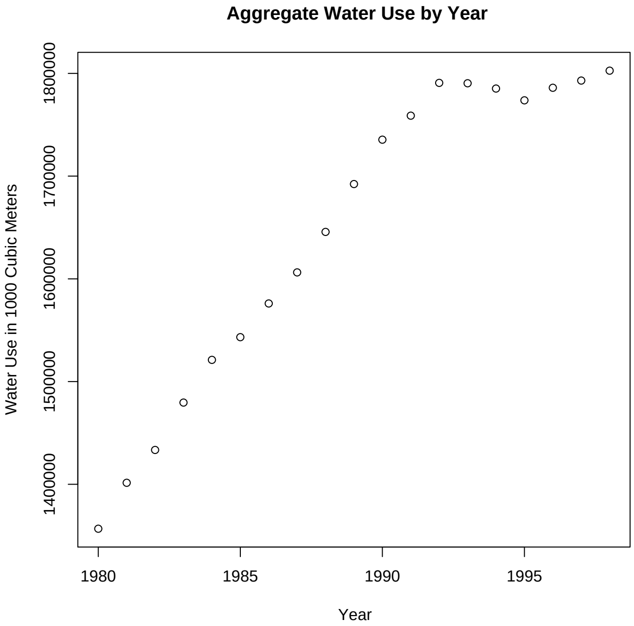

Figure 1: Water Use by Year Across All Cities with Complete Data

4.1 Some Preliminary Analyses

Figure 1 shows aggregate water use by year for the cities in which we have complete data; water use for 1971, 1972 and 1999 are missing for two cities. Other variable we use below are also missing some data before 1980.[5] Water consumption is measured in 1000's of cubic meters.

Aggregate water consumption ranges from a low of about of 1.3 million units to a high about 1.8 million units. The implications are straightforward, on the average residential water use has increased substantially and steadily until about 1999. Since then, water demand has been flat.

Figure 2 shows population growing from about 19 million to about 20 million with a very similar temporal pattern to residential water use. Per-

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[5] Analyses done city by city can use all of the data. But for any aggregate analyses across all cities, one can only work with the complete data. If, for example, a given city is missing an observation for water consumption in particular year, overall consumption will dip artifactually.

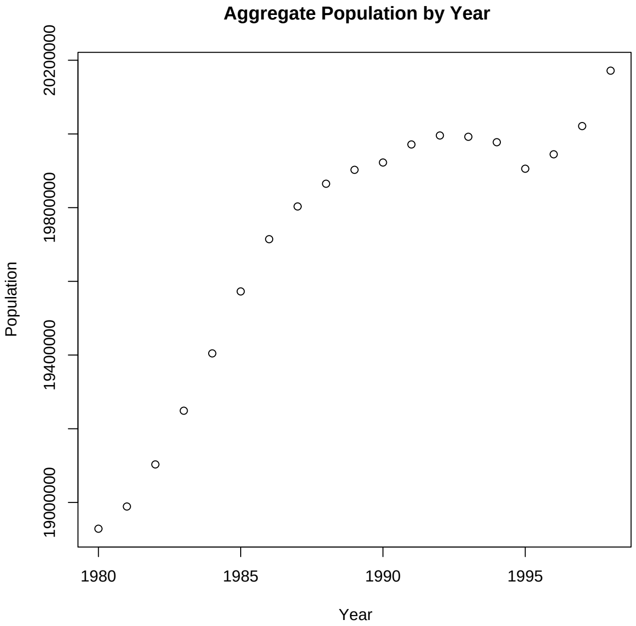

Figure 2: Population by Year Across All Cities with Complete Data

haps the major exception is that while population growth in these cities accelerates in the middle 1990's, residential water use does not. Nevertheless, a reasonable inference, consistent common sense, is that population is an important driver of residential water use. But there is much more to the story.

We will use average household monthly income as our measure of affluence[6] At this point, the monthly averages are simply summed across the city

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[6] Data for average income are from the Annual Report on the Family Income and Expenditure Survey, published by the Ministry of Public Management, which samples over 8000 households out of 31 million qualified households throughout Japan each year. Households are defined as two or more people, but no more than three wage earners. In the ward area of Tokyo, about 400 households are sampled, while a total of 1100 households are sampled from cities with populations greater than 50,000. Because income distributions tend to be skewed, data for median income are preferable, but are not available. A more thorough income survey occurs every five years, in which average income is reported for five to seven income groups. While the sample size is small, this survey has the advantage of occurring every year. Information on this survey can be found at

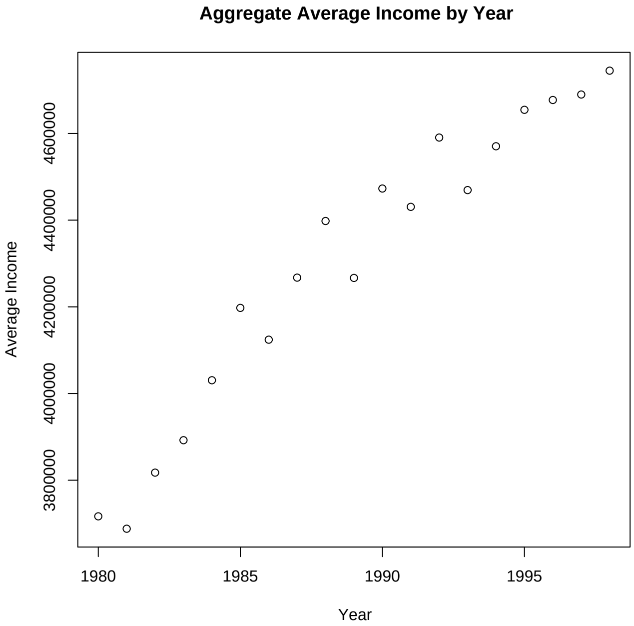

Figure 3: Average Income by Year Across All Cities with Complete Data

consistent with the way aggregate water consumption is computed. It ranges from around 3.5 million yen to a little over 4.6 million yet. Figure 3 shows that average income has also been increasing over time although with more year to year variability. So it too becomes an obvious candidate to explain longitudinal patterns of water use in these Japanese cities.

In the cities for which we have data, water is priced in units of 20 cubic meters. There is a fixed base amount with price beyond that determined by increasing blocks. We have data on the average monthly price for residential users, which ranges from about 8000 yen to about 20,000 yen.

From Figure 4, we see that the price of water has generally been increasing too. But one would expect that other things equal, price increases would lead to *less* residential water consumption. Perhaps the most important message is that all three of our favored predictors generally increase over time. It will be hard, therefore, to estimate their separate effects on water use.

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www.stat.go.jp/english/data/kakei/1560.htm.

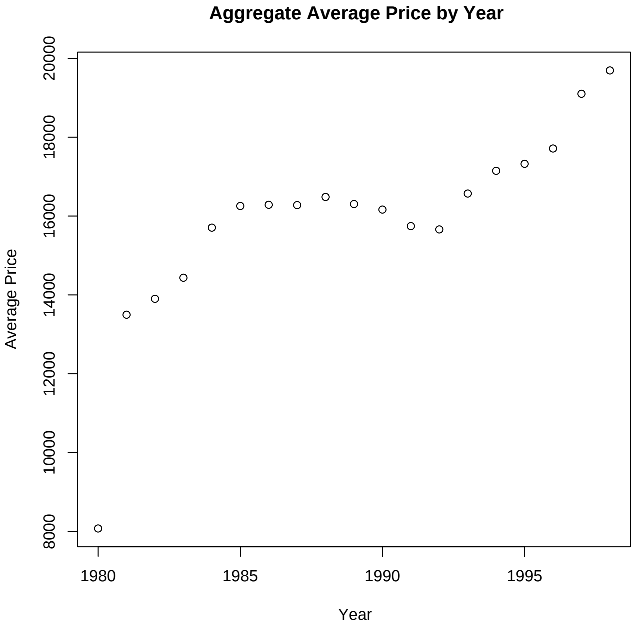

Figure 4: Average Price by Year Across All Cities with Complete Data

Further complicating matters is that underneath these plots that aggregate over cities, some cities show temporal patterns that differ from other cities. In particular, for Osaka, Kobe, Yokohama, and Tokyo wards, population has actually be declining over the past decade or so.

4.2 Some Multivariate Analyses

Given how little is actually known about how population, income and the price of water are related to aggregate residential water use, we applied a form a non-parametric regression based on the generalized additive model (Hastie and Tibshirani, 1990). Each of the three predictors was entered log-transformed, consistent with a multiplicative impact on residential water use. Then each logged variable was iteratively fit to water use using a cubic spline smoother. The results can be seen in Figure 5.

The "rug plots" along the bottom of each of the three graphs show where the observations are. Each graph is labeled so that the predictor as employed

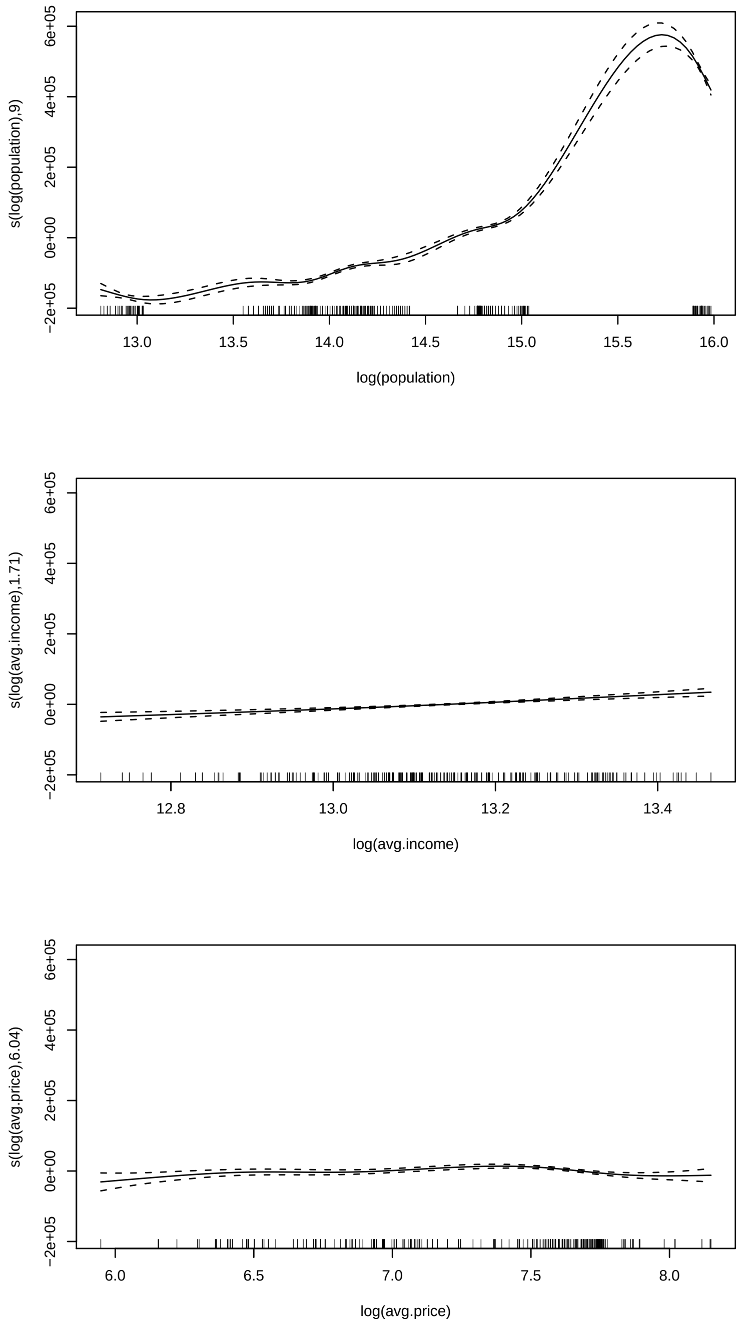

Figure 5: Estimated Drivers of Residential Water Use

in the analysis is on the horizontal axis and the same predictor as fitted (as a cubic spline function) is on the vertical axis. Note that year is necessarily scrambled; the data are ordered not by year but by the values of the predictor in question. Nevertheless, because the values for all three predictors tend to increase over time, one can get a rough sense of the temporal patterns.

The label on each vertical axis also shows the estimated degrees of freedom of the spline function, which need not concern us here.[7] All of the effects shown are, in effect, covariance adjusted, and represent the effect of each variable with the others "held constant." Each curve has the 95% confidence interval overlaid.

It is clear that population and residential water use of strongly related, but in a non-linear fashion. The overall relationship is generally positive, and the rate of increase generally increases. But at the highest population figures, the marginal impact of an addition person actually turns negative. negative. Note, however, that the negative relationship is being driven by a relatively few observations some distance away from the mass of the data, which represent the highest population figures in the largest cities. Why these cities should be different is not clear, but perhaps the population declines reflect at least in part the relative out-migration of younger families. If so, that might help to explain the flat water consumption figures in the 1990's. Note also that some of the fitted values are negative, which is potentially troubling. We will return this issue shortly.

The relationship between average income and residential water use is generally, linear, positive, and modest. At this point, there is little more to be said, except that once again, there are some negative fitted values. The relationship between average price and residual water use is also generally positive, except for the large price figures, and even more modest. If one takes the positive relationship seriously, it is perplexing.[8]

Figures 6 and 7 replay the same analyses separately for cities in which

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[7] The fitted values are constructed by multiplying the response variable by a finite linear operator constructed from the spline basis functions, known as the smoother matrix. The trace of this matrix is the effective degrees of freedom. This is a generalization of degrees of freedom that can be computed in the usual linear models from the "hat" matrix.

[8] The adjusted R^2 is .99; the fit is nearly perfect. As a result, there is considerable statistical power and one can reject the null hypothesis of no effect for all three predictors. In this case, such tests are probably not very instructive. Very large values for R^2 are common for relatively smooth time series data. And in this case, the flexibility of the nonparametric regression virtually guarantees a near-perfect fit.

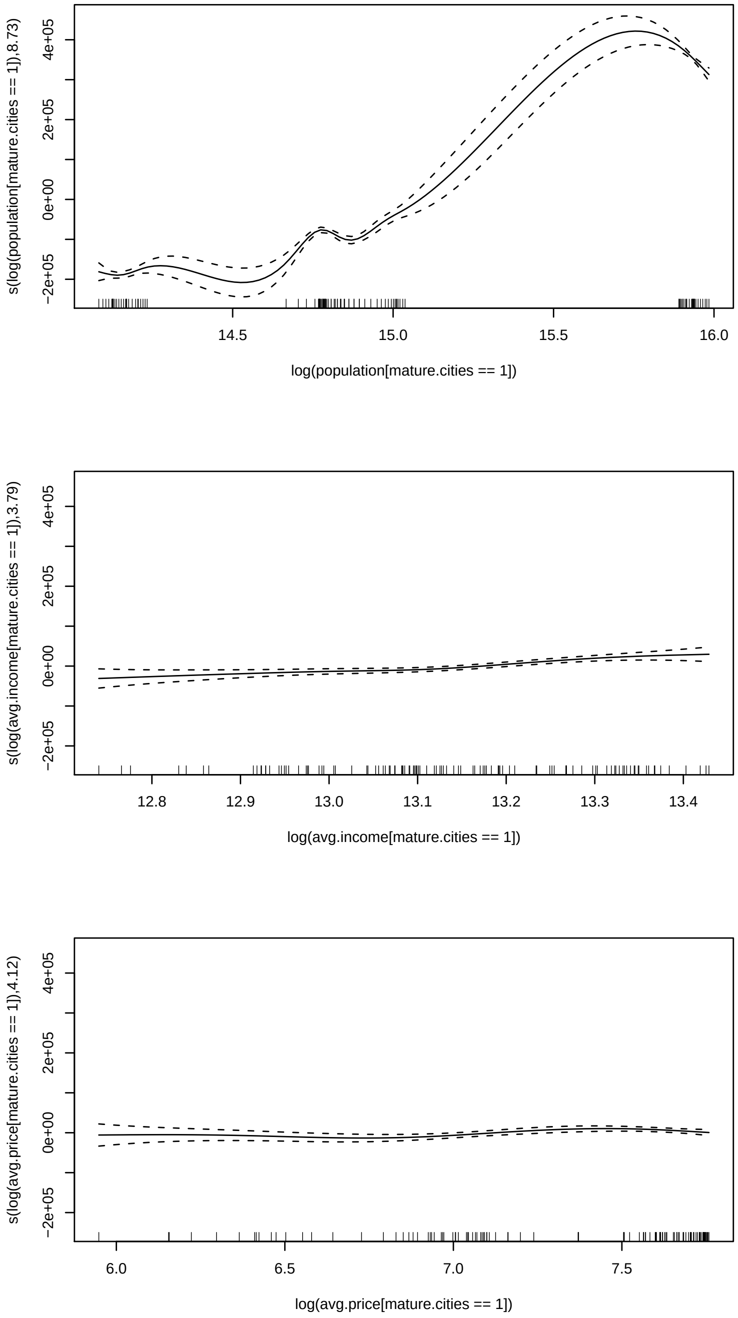

Figure 6: Estimated Drivers of Residential Water Use for "Developed Cities"

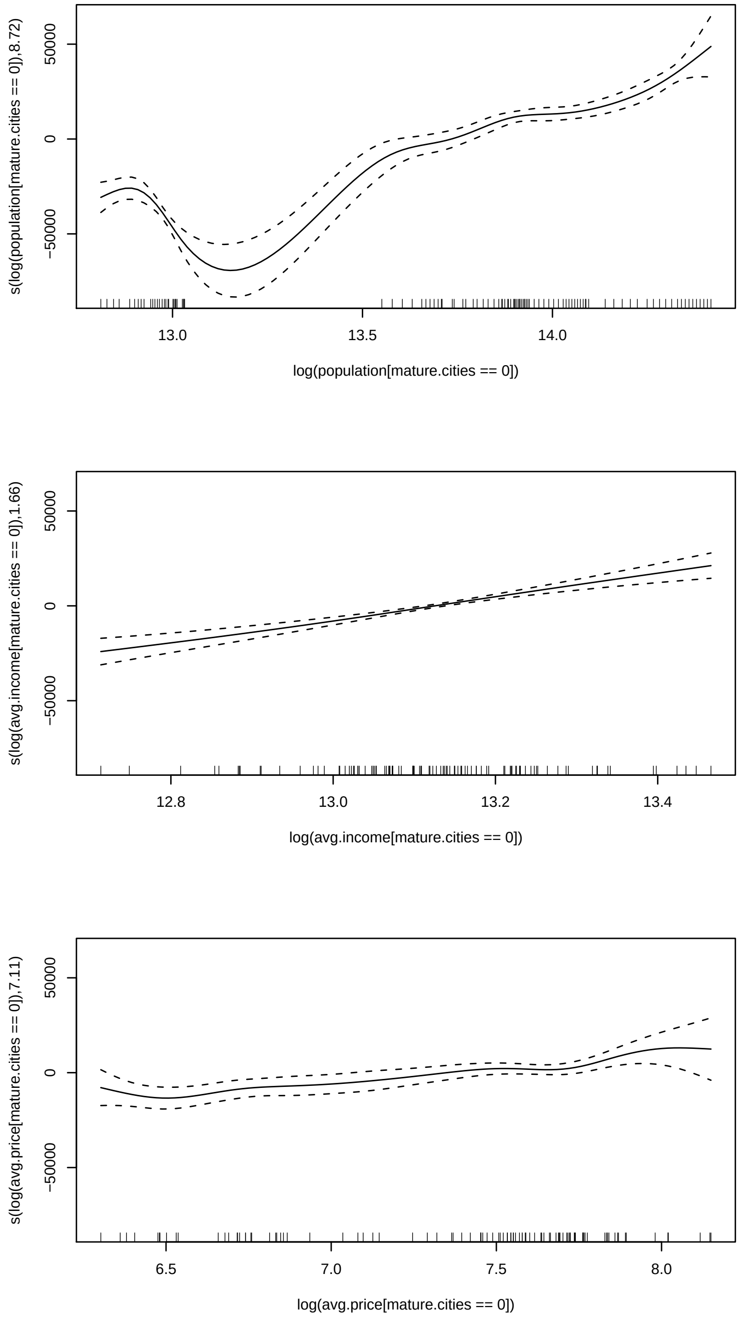

Figure 7: Estimated Drivers of Residential Water Use for "Developing Cities"

the for recent years the population has been flat or declining and for cities in which for recent years the population has continued grow. We call these cities "developed" and "developing" respectively, although the "developed" cities continue to evolve and "developing" are in many ways highly developed. This is Japan, after all. The initial goal is to remove some heterogeneity from the fully pooled analysis by treating "developed" and "developing" cities separately.[9]

The relationships for the "developed cities" look much the same as the overall relationships in figure 5.[10] The relationships for the "developing cities" look a bit different. In particular, the relationship between residential water consumption and population remains positive throughout. And the impact of average income looks to be a bit stronger, but it is very hard to tell because the units on the vertical axes vary between Figures 6 and 7. In fact, the relationship between population and water consumption is a bit smaller.

In summary, population matters a lot, but for "developed" cities not in a simple way. The reasons why the relationship with residential water use changes are unclear. We speculate that in addition to possible changes in the population mix, that the negative relationship may reflects a significant infusion of water efficient technology for which we have no measures. For both "developed" and "developing" cities, wealth also matters, but with the ranges of historical variation, not nearly as much as population. Cities with more affluent residents use more water per capita and within a city, increases in affluence are linked to increases in per capita residential water use. For example, average per capita water use increases from about 70 cubic meters a year to about 90 cubic meters a year over the period for which we have.[11] Finally, there is not much of a story to tell about price, at least within the range of historical variation we have. But this was anticipated. This is not to say that price would necessarily be an ineffective policy instrument if large price increases were politically palatable.[12]

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[9] This could be undertaken formally within a framework for pooled cross-section and time series data. At this point we see gains for going this route, in part because those formulations are fully parametric.

[10] The small bumps in the early years in part a result of incomplete data for aggregate water use.

[11] Average per capita residential water use in Los Angeles is about 140 cubic meters per year.

[12] In Los Angeles, for example, they are not.

Finally, there are some grounds for being uneasy with the results. The negative fitted value imply the need for more constraints on the model than we have allowed for. While such constraints would probably not change the overall conclusions, they need to considered. For example, one might use the log of residential water consumption as the response variable.

4.3 Forecasting

It is difficult to construct quantitative forecasts from the nonparametric regression results. But one can build conventional parametric regression models using what was learned that perform nearly as well. If linear regression is used, but with all of the variables log transformed (including the response variable water consumption), the adjusted R^2's are nearly as good as those obtained from the nonparametric regressions. With one exception, we lose very little that matters. The results are shown in Table 1.

Variable	Developing	Developed
log(population)	.94	.94
log(income)	.88	.33
log(price)	.08	.11
Adjusted R^2	.95	.98

Table 1: Parametric Regression Results Using the Log of Aggregate Residential Water Consumption

The regression coefficients are now estimated elasticities. They indicate the percentage by which water consumption changes on the average for a 1% change in the given predictor, everything else in the equation held constant.

The results for population are about the same for developing and developed cities. Adding a quadratic term for population to the equation for developed cities not change things much, although the sign is negative as expected[13] For income, the effects are rather different for "developing" and "developed" cities. For the former, a 1% increase in income implies on the

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[13] In this case, one can see from the non-parametric results that a quadratic is not likely to be helpful. The population effect does not bend smoothly, but abruptly. So, the spline fit is likely to be superior.

average an increase of about .9% water consumed. For the latter, a 1% increase in income implies on the average an increase of about .3% in water. The income effect is more than twice as large in "developing cities." We suspect that the difference reflects the the lack of water use increases in "developed" cities during the late 1990's. And perhaps this results from the introduction more efficient water use technology that more affluence households could afford. Change in the population mix may also be a factor. In any case, we need to fit a somewhat more flexible function to the data to better capture the water use trends in recent years.

The role of price remains unclear. Both regression coefficients are positive, and the regression coefficient for developing cities is relatively large. We suspect that these effects reflect some instability in the results because all three predictors are highly correlated. We are not inclined to take the regression coefficients seriously. Indeed, dropping price from the equations reduces the goodness-of-fit in the third decimal place. It really does not matter.

With the regression coefficients in hand, it is possible to provide some first approximation forecasts. When one does not extrapolate too far beyond the range of the data we have, one can simply apply the elasticities. For example, if population is 20 million, a 1% increase is 200,000 people. For 20 million people, aggregate residential water use is about 2 million water use units (equal to 1000 cubic meters each). Then, a 1% increase is about 20,000 water units, or an increase about 20 million cubic meters.

But to what cities would such forecasts apply? The results for the "developed" Japanese cities may apply to highly developed cities elsewhere in the Asia Pacific region such as Singapore or Hong Kong. The results for "developing" Japanese cities may apply to developing cities in the Asia Pacific region such as Tianjin and any number of similar cities in China. The most serious generalization problems surface for cities just beginning to develop, such as Phnom Pen and Ho Chi Min City, or for cities whose water infrastructure is being overwhelmed by rapid population growth. There are many possible examples of the latter; Bangkok, Kuala Lumpur, and Karachi come to mind. Some insight might be gained from data on Japanese cities selected to more closely mirror Asia Pacific cities for whom generalizations from the data we have are probably not useful. For example, there are perhaps smaller cities in Japan that have some of the same look and feel as Tianjin, Shanghai, Nanjing, and Shi Jia Zhuang.[14]

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[14] According to three of my Chinese students.

5 Conclusions

Understanding the urban water cycle must come initially from rich data on human and natural processes that are then properly analyzed. The data requirements are likely to mean that much of the initial work will be done in developed countries where the existing data are often readily available and of good quality. Collecting comparable data in developing countries would be very costly, even when it is political feasible. Moreover, the kinds of questions asked about water resources are likely to be quite different. It is one thing to examine the residential demand for water in affluent countries where water quality can be taken for granted, and quite another to examine residential water demand in countries where large fractions of the population use water that is not fit to drink. However, there may be an interim strategy. It may be possible to work outward from knowledge based on cities with high quality data to to cities that are perhaps comparable, but lacking in good data.

Perhaps the major substantive message is that affluence cuts two ways. On the hand, with affluence comes the resources to solve water quality and shortage problems. On the other hand, with affluence comes increased demand for water from residential users. And if these are allowed to play out in a reasonably free market or at least in a setting in which price is a dominant factor, it is likely that serious water resource problems can be averted. And with sufficient foresight to build the requisite infrastructure, adjustments to changing natural forces, such as climate change, can be managed.

The real problem is with cities that lack economic resources or that even with those resources, have inadequate institutional mechanisms to invest effectively in water infrastructure. There, water supplies are already marginal (or worse), and there will be major difficulties meeting the demands of a growing population and responding to historical variation in precipitation. And it is also in these cities where climate change will can have major impacts. A water supply system that is already struggling will surely be overmatched if precipitation or snow runoff decline, or if the timing of either changes substantially. In short, the crisis in water is ultimately about money and politics. Natural variation in water availability need only be a serious issue if the water supply system is already fragile.

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