Lake to Puddle: A System Dynamics Approach to Social, Economic, and Environmental Consequences of Water Use in Udaipur, India

Abstract

Water scarcity could define the modern era, as 67% of the world will experience water shortages by 2025. In Udaipur, India, shortages are already evident as lakes in the city dry to mere puddles every summer. The shortage in Udaipur results from the convergence of social, economic, and environmental factors and is especially detrimental due to the economic importance of lake tourism for city residents. Students from Washington University in St. Louis, in collaboration with the India Institute of Technology, Tata Institute of Social Sciences, and the Foundation for Ecological Security conducted a field study to investigate these shortages in greater depth. A system dynamics model was constructed in order to best examine: (1) interdependency of domestic, industrial, and tourist water use on the supply of Udaipur's water sources (2) areas for policy and conservation interventions to alleviate water shortages, and (3) areas of future research. While the availability of data limited the model that could be constructed, it allowed the authors to capture the interrelated factors influencing Udaipur's water supply. The collection of additional data will help test suggested interventions, which include reducing distribution losses, reducing water demand, and treating polluted water sources.

Keywords: water scarcity, system dynamics, lake tourism, Udaipur, India

Background

According to the World Watch Institute, "Water Scarcity may be the most underappreciated global environmental challenge of our time" (Barlow 2007, 3) which is making water "the oil of the 21st century" (Running Dry 2008). As early as 2025, it is estimated that 67% of the world's population will face water scarcity (Barlow 2007, 7) and the worldwide per capita water supply will decrease by one third before 2050 (World Water Assessment Programme 2009). This will cause 7 billion people in 60 countries to experience severe water shortages. These shortages will not only affect the ability of individuals and industries to meet their daily water needs, but are also projected to increase food shortages, the number of armed conflicts, and the occurrence of waterborne diseases (World Water Assessment Programme 2009).

The convergence of social, economic, and ecological factors is causing global water shortages. These factors include population growth, urbanization, changes in consumption patterns, industrialization and economic development, reduced rainfall, and increased water pollution. Developing countries such as India are disproportionately affected by these changes, due to their dry climates, and underdeveloped water infrastructure (World Water Assessment Programme 2009).

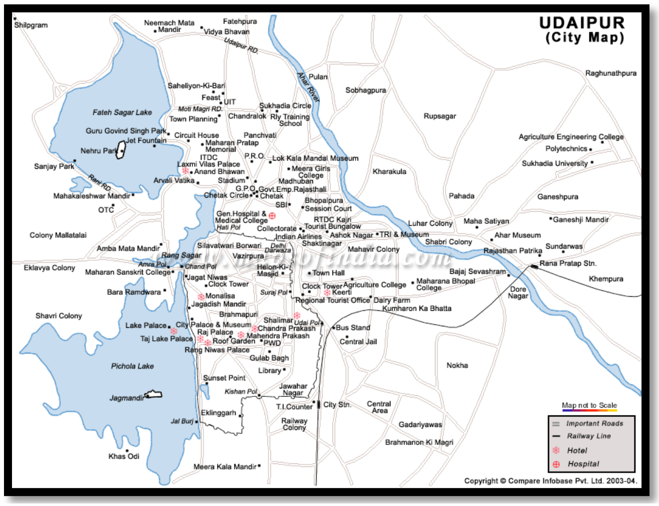
India currently suffers from an inadequate and polluted water supply. Some estimates claim that demand for groundwater in India will exceed supply by 2020 (Birkenholtz 2008, 266). India's urban water demand is expected to double by 2025, and the industrial water demand is expected to triple by this time (Barlow 2007, 3). Available water supplies are heavily polluted, causing 75% of India's rivers and lakes to be unsafe for bathing and drinking. More than 700 million Indians (67% of the population) lack sanitary water supplies, and 2.1 million Indian children under the age of five die each year from dirty water. The situation is only expected to intensify.

One city in India that is suffering from debilitating water shortages is Udaipur, located in the southern part of the state of Rajasthan (Figure 1).

Figure 1

Ranked as the Best City in the World by *Travel & Leisure* in 2009, this city of approximately 490,000 residents is one of the most popular tourist destinations in India. The city contains eight interconnected lakes (Dudh Talai, Pichola, Kumharia Talab, Fetah Sagar, Govardhan Sagar, Rang Sagar, Swaroop Sagar, and Amar kund) that were constructed between the 14th and 17th Centuries to meet the drinking and irrigation needs of the city residents (Rathore 2008). During the 17^{th} Century, a number of marble and sandstone imperial palaces were constructed along these lakes, which has made Udaipur a center of architecture, culture, natural beauty, and tourism (Paliwal 2005, 214) (Figure 2).

Figure 2



The lakes that define Udaipur are becoming increasingly threatened as rising water demands deplete the water supply. Similar to other cities worldwide that are subject to water shortages, Udaipur's water supply is being depleted as a result of social factors (population growth and increased tourism), economic factors (industrialization and development), and ecological factors (inadequate rainfall and pollution). As of 2006, only 69% of city residents had access to water, and this access was limited to 1.5 to 3 continuous hours of water service every 48 hours (Sancheti 2006, 38). Furthermore, the eight lakes found within the city are nearly dry every summer (Molpariya 2009). These shortages are particularly debilitating because lake tourism drives the economy of the city (Rajasthan Ministry of Tourism 2006).

This paper will explore the factors driving water shortages in Udaipur, India, which mirror the factors generating shortages on a global scale. It will then examine the interventions currently in place in Udaipur designed to safeguard the city's water supply. A system dynamics model will be used to begin to depict and quantify the problem, to illustrate gaps in existing data and research pertaining to the water supply in Udaipur, and to illustrate where current popular and discussed interventions can be implemented to reduce water shortages.

Methodology and Model Building

Data Collection

A study of the interconnected issues related to the water supply began during a field study that occurred in Udaipur in December of 2009. During this two-week study, students from Washington University in St. Louis collaborated with students from the India Institute of Technology in Mumbai and the Tata Institute of Social Sciences, as well as the Foundation for Ecology Security (FES) to examine the factors driving the supply and demand of Udiapur's water supply. The four stocks of water that feed Udaipur's city water supply were examined: rural water transfer mechanisms (dams), the lake system, ground water system, and city distribution system (see Figure 1). Teams met with local residents, government officials, experts in the field and business owners to gather information needed to form a complete image of the factors influencing the supply and demand on each of these four stocks of water. The research demonstrated that Udaipur is experiencing a water crisis driven by economic and environmental factors, which exhibit a tragic codependency. During the fieldwork, it became apparent that interventions to increase or conserve water supply in Udaipur led to externalities often affecting society's most vulnerable residents. A system dynamics model would provide a holistic view of the water supply, allowing interventions to minimize these externalities. Due to the interrelated nature of factors influencing the water supply as well as evidence of various feedback loops, it readily became apparent that a system dynamics model would best depict the factors influencing Udaipur's water supply.

Application of System Dynamics
The use of a system dynamics model in this study of Udaipur will seek to examine:

1. impacts of domestic, industrial, and tourist water use on the supply of Udaipur's water sources
2. potential areas for intervention with policy and conservation strategies
3. what additional information is necessary to complete a model and test policies and strategies both precisely and accurately

The construction of the model will allow experts to understand the repercussions of implementing water related policies, and to test the sustainability of water-related projects over time.

System Dynamics Modeling
Modeling was done in three main stages, each with a simplification and additive process to bring the model to its current state. An initial model was created based on what was experienced while in India. This initial model relies on an experiential understanding of the connections grounded by some of the key informant interviews. After a literature review, and research of similar modeling processes, the model was simplified to depict the core supply and demand issues. This step gave the structure for the demand piece of the model. A final iteration gave more depth to the supplies of water and incorporated seasonality and control mechanisms of flows. The model is now visually complete to illustrate the problems and areas to test future interventions, but is in desperate need of accurate yearly data.

The model stocks can be broken into three distinct groups: supplies of water, demands on water, and pollution. Supplies in the scope of this model are designated as stocks of water that feed into the municipal distribution system of Udaipur. Demands on the water are the populations of residents and tourists, as well as the growing industrial sector. Pollution is aggregated because it affects use of water and is a direct output of having population and industry.

Social and Economic Factors that Drive Water Demand

Social Factors Driving Water Shortages

Population Growth
Social factors relating to population expansion and development are significantly impacting the global water shortage. Consistent with other world cities, Udaipur City has experienced rapid

population growth. According to the Indian census, the population of Udaipur City increased from 34,800 in 1921 to 490,000 in 2001. Between 1991 and 2001 alone, the city experienced a 59% increase in its population, as the number of residents grew from 307,700 to 490,000 (Rathore 2008).

The rapid population growth of Udaipur is due in part to the number of economic opportunities that exist in the city. Udaipur serves as the administrative capital of Udaipur district and contains a large number of educational institutions. The city also contains ten percent of the total large and medium sized industries (mineral and textile) that exist in the state of Rajasthan and is the merchant center for the surrounding region. The most lucrative industry in Udaipur is tourism (Rajasthan Ministry of Tourism 2006), which employs over 40% of city residents (Smith 2009) who serve as shopkeepers, transporters, hotel workers, tour guides, and who work in other industries indirectly related to tourism (Molpariya 2009).

Urbanization

Urbanization has caused Udaipur to experience rapid growth, and the dense concentration of individuals in one space puts extra stress on the natural resources of that area. According to some experts, the population growth of the city has resulted in large part from migration of individuals from rural areas (Singh 2009, 1). Urbanization is expanding the city limits; between 1948 and 2001, the city limits were expanded over seven times. From 1991 to 2001, the area included within the city limits grew by over 50%, increasing from 61.1 to 91.5 square kilometers (Rathore n.d.).

Change in Consumption Patterns

Increased economic development not only requires greater quantities of water to support the industries driving development, but is often accompanied by increased consumption patterns as individuals in developing countries adopt consumption patterns displayed by individuals in developed countries (World Water Assessment Programme 2009). This is problematic, because while estimates suggest that the average human needs 50 liters of water per day to fulfill his or her drinking, cooking, and sanitation needs, the average North American uses almost six hundred liters per day (United Nations Educational, Scientific, and Cultural Organization 2003) .

Economic Drivers of Water Shortages: Industrial Demand

Hard Industry: Mining

In addition to being a city rich in natural sources as a result of its lake system, Udaipur is also a city that is rich in its mineral resources such as lead, zinc, marble, granite, talc, limestone, sandstone, feldspar, copper, bauxite, and numerous other resources (Ranawat 2007). These resources fuel a number of large industries in the area (Udaipur has approximately ten percent of the all the total large and medium industries that exist in Rajasthan) that strain the local water supply. One of the largest industries is Hindustan Zinc, Inc., the largest producer of zinc and lead in India and the second largest producer in the world. This industry has four mines in Rajasthan, and two of its three smelters are located just outside of Udiapur (Hindustan Zinc Limited 2010). In order to help ensure its own water supply, Hindustan Zinc helped to finance 30% of the cost of the construction of the Mansi Wakal Dam, with the understanding that it would be entitled to 30% of the water redirected by this dam (Government of Rajasthan Planning Department n.d.). However, in doing this, the industry further usurped water from city residents.

In addition to metals, India is the 9th largest producer of marble worldwide, and as of 1995 over 25 million tons of marble were produced each year. Ninety percent of India's marble was produced in Rajasthan and was valued at US $450 million dollars (Udaipur Chamber of Commerce 2006). Over 100 marble industries exist in the greater Udaipur area. While economically lucrative, these companies dispose large quantities of marble slurry, a waste powder comprised of calcium carbonate and other mineral impurities found within the marble. This powder contaminates the air, ground, and water supplies (Garfinkel 2009), covers the ground with a fine powder that prevents rain from percolating into the nearby soil (Majumder 2004), and also generates large areas of white that reflect the sunlight in ways that can produce a micro-climate-warming effects (Garfinkel 2009). The industrial processes involved are also water intensive: one factory uses on average 10,000 liters of water each day to spray and cool the marble blocks while they are cut (Majumder 2004). The marble industries significantly stress local water supplies due to the contributions to water pollution and large consumption of water.

Soft Industry: Tourism

Tourism in India has contributed to an increasing portion of its economy. In 2009 alone, tourism brought five billion dollars to the Indian economy. This number was down nearly 22% from 2008, as a result of the economic downturn, but prior to that, India experienced tremendous growth in its tourism industry. From 2002 to 2008, the total foreign exchange earnings due to tourism increased from 3.1 to 11.7 billion. This corresponded to an increase in foreign tourists from 2.4 to 5.4 million tourists. Of those tourists, it is estimated that Rajasthan received nearly 1,478,000 tourists in 2008. In Udaipur, from April 2005-March 2006 the number of domestic tourists was 1,264,000 and foreign tourists numbered 184, 500 (Ministry of Tourism 2009). While the number of tourists in India has decreased recently due to the economic downturn (the estimated total number of tourists in the 2008-2009 season was 1.2 million) (Garfinkel 2009), it is believed that this number will rebound in 2010 due to attractions such as the Common Wealth Games that will be held in Delhi, and financial assistance given to rural tourists sites from the UN Development Council (RNCOS Industrial Research Solutions 2009).

Tourism not only provides immediate revenue, but also promotes additional economic and urban development. Tourism is a multi-sector activity, generating employment in multiple industries in a way that positively benefits the entire economy of a region. According to Anshuman Singh, the governor of the state of Rajasthan in 2002, tourism in Rajasthan produces jobs that are low in cost, concentrated in small businesses, employ a substantial amount of women and artisans, and revitalize the traditional arts, crafts, and culture of the state. The impacts of tourism on job creation in India are substantial: in 2002, tourism supported 9.3 million direct jobs (3.1% of employment) and 17.5 million indirect jobs (5.8% of employment). These numbers are expected to rise to 12.9 million jobs (3.5% of employment) and 25 million indirect jobs (6.8% of employment) by 2010 (Singh 2002, 96). Furthermore, tourism often strengthens the infrastructure of an area (airports, roads, communication technology, etc.) in ways that can benefit local residents.

Ecological Drivers of Water Shortages

Inadequate Rainfall

India has suffered from a series of recent droughts, which have caused the typical monsoon rains (India receives over 50% of its rainfall in a 15 day period) to become more contracted and unpredictable (Das 1996, 184). This inadequate rainfall has also affected water supplies in Udaipur. Udaipur basin is located in a semi-arid zone located 577 meters above sea level(Das 1999, 245), and receives an average rainfall of 65 cm, the majority of which (95%) is received during the Southwest Monsoons from June to September. However, the rainfall measured over the 85 year period from 1921 to 2005 was highly erratic in nature, such that 53 years received less rainfall than the 65cm average, and only 32 years received more rainfall than this average. During the 53 years of below average rainfall, eight droughts occurred that lasted for 3 years, and there were two droughts that lasted for 4 years. The period from 1999-2004 was a prolonged drought period (Rathore n.d,). In 2009 alone, Udaipur experienced a 43% decrease in the amount of rain that fell during the monsoon season compared to an average monsoon season (, 2009 #509). This has led to recent annual water shortages in Udaipur's lakes as well as the nearly complete dissolution of the lakes during the summers between 1998 and 2009 (Mehta n.d), since these lakes are fed predominately by rain

Pollution of Existing Water Sources

In addition to decreasing supplies, the supplies that do exist are becoming increasingly polluted. Lakes are especially prone to pollution, since they are closed ecosystems in which contaminates accumulate (Ranade 2008, 544). Globally, the most prevalent water quality problem is that of eutrophication, which occurs when the water contains excess organic matter (such as carbon, nitrogen, phosphorus) that makes water less viable for flora and fauna and less unsuitable for human use**.** Manufacturing waste, agricultural runoff, and sewage leaks serve as the greatest contributions to eutrophication (Nixon 2009, 7). Eutrophic water is especially prevalent in developing countries, where it is estimated that nearly 80% of sewage is discharged into water sources without being treated. This situation does not look to be improving soon, as more than 5 billion people, or 67% of the world population, may still lack public sewage systems by 2030. In addition to rendering water supplies unusable, according to World Health Organization estimates, contaminated water is implicated in 80% of all sicknesses and diseases worldwide (Barlow 2007, 3).

Inadequate sewage disposal has long been a problem in Udaipur. According to Tej Razdan, the head of Udaipur's Lake Conservation Society, up until 2003, 25 tons of solid waste and 6 million liters of sewage were dumped into Udaipur's lakes every day (while this has been reduced by 60%, the sewage is not treated but rather diverted downstream instead) (Garfinkel 2009). While a partial sewage system was constructed between 1978 and 1982 that would serve 30% of the population around the lakes, design limitations and improper maintenance makes this system obsolete, causing sewage to flow directly into Lake Pichola and Rangsagar (Center for Science and Environment 1997). As of 2006, only 42% of the city was covered by a sewage network, and there was no treatment and disposal service (Sancheti 2006, 39). As a result, large quantities of fecal coliforms (Center for Science and Environment 1997) as well as intestinal parasites can be found in the city water supply (Mehta n.d.). These organisms lead to high rates of typhoid, para-typhoid, amoebic dysentery, colitis, diarrhea, viral hepatitis, (Center for Science and Environment 1997) and gastroenteritis. Worse still, treatment of this water through chlorination or other available chemicals will not make this water potable (Mehta n.d.).

Degradation of catchment areas has also contributed to pollution of the lakes. The expansion of the city limits has caused encroachment upon the catchment areas of the River Ahar that feed the lakes, resulting in pollution of the catchment area and deforestation. It has been estimated that between 1960 and 2004, almost 60% of the forest cover from the Aravalli hill ranges surrounding the Udaipur Basin was removed, resulting in increased soil erosion (Rathore n.d.). This soil erosion leads to siltation of the lakes, which decreases lake capacity. Some estimate that siltation in Lake Pichola is causing it to reduce its capacity each year by one percent (Center for Science and Environment 1997). Siltation also increases the levels of organic matter found in lakes, which decreases stores of dissolved oxygen and diminishes the ability of the water to support fish and other aquatic life (Ranade 2008, 545).

In addition to sewage waste and siltation, Udaipur's lakes are also being polluted by domestic waste from the 6,000 residences and 100 hotels surrounding the lakes, by bathing and washing of clothes at the 73 ghats (Mehta n.d.), by industrial waste from the chemical and mining companies (Das 1999, 246), weathering of nearby land due to development, waste generated by tourist influx (Das 1996, 184), use of lakes for religious ceremonies and rituals, as well as recreational activities (Ranade 2008, 543). These activities are leading to excess nitrate and phosphate concentrations in the lakes, which support the growth of water hyacinth, algae, and submerged vegetation that host noxious pathogens that are detrimental to human and animal health. Chemical effluents from surrounding factories and mines have also been detected (Mehta n.d.). Furthermore, weathering and soil degradation has also led to excessive sodium and bicarbonate levels, resulting in alkaline conditions that are detrimental to aquatic life.

Conservation

While many have called for greater water conservation efforts to protect the city water supply, conservation efforts meet many challenges. Similar to other communal natural resources, lakes are subject to what is known as the tragedy of the commons. Garrett Hardin first conceptualized the tragedy of the commons in his 1968 article that appeared in *Science*. According to Hardin, this tragedy occurred when a natural resource, such as grazing land, was exploited by several individuals that shared this resource until it reached a degraded state (Hardin 1968, 1243). Common pool resources are subject to the tragedy of the commons due to the fact that they are both non-exclusive and rival. They are non-exclusive in the sense that they often lack clear boundaries and are indivisible (Healy 1994, 597), which makes it difficult if not impossible to exclude other individuals from accessing these resources. They are rival in that when one individual uses the common resource, it subtracts from the amount of that resource that is available to other users. As a result of their non-exclusive and rival nature, users lack the incentive to conserve or reinvest in the resource. Instead, each user often looks to maximize his or her gain, and therefore over consumes the resource until it is degraded beyond repair (Clapp and Meyer 2000, 6).

The tragedy of the commons that exists in tourist landscapes such as Udaipur is often intensified due to the presence of tourists. These tourists not only drive increased demand for these resources, but they do so in variable ways since there is both an inter-annual and intra-annual variability in tourist travel. This is significant because it makes it more difficult to organize management of these resources. In addition, tourist use of natural resources often differs from the patterns of use exhibited by local residents. Tourists tend to use natural resources more lavishly, since the depletion of these resources does not affect them as directly as it affects city residents. Furthermore, tensions between values and cultures that exist between tourists and locals can further exacerbate the tension that exists around the tragedy of tourist commons (Healy 1994, 597).

According to the five-year plan of the Rajasthan government for 2007-2012, state planning efforts are shifting in focus to emphasize conservation efforts. The government plans to motivate increased industrial recycling of wastewater, and seeks to promote increased public private partnerships to have industries become increasingly involved in water conservation efforts with governmental officials. This plan also looks to improve conservation in agricultural settings by implementing the use of more efficient sprinkler and irrigation systems. Finally, the five-year plan also called for the promotion of greater activity by NGOs and Water User Associations to help motivate private efforts. While current governmental standards require buildings with roofs that exceed $300m^2$ to have structures that harvest rainwater, the government hopes that NGOs will promote greater use of these structures in private residences. Furthermore, this plan calls for NGOs to motivate efforts and projects that will increase conservation behaviors, improve the efficiency of existing water systems by decreasing leakages, and improve the quality of drinking water supplies (Running dry 2008).

Despite the emphasis on conservation espoused by the Rajasthan Government Planning Department, the Udaipur governmental has struggled to effectively establish and enforce conservation measures according to some accounts. While the state high court directed the local government in 2007 to establish a city lake development authority, implement a no construction zone around the lake, and initiate desilting efforts, by 2009 none of these actions were implemented or enforced. According to one civilian conservation group, such governmental ineffectiveness results from the fact that there are multiple government departments responsible for lake conservation in Udaipur (Public Works Department, Water Supply Department, Irrigation Department, Medical and Health Department, Pollution Control Board, Fisheries Department, Revenue Department, Tourism Department, Urban Improvement Trust, Municipality, Forest Department, District Administration, etc.), which creates a situation of multiple responsibility and minimal accountability (Mehta n.d.). This has led to the establishment of 14 local environmental groups to attempt to preserve the waters(Garfinkel 2009).

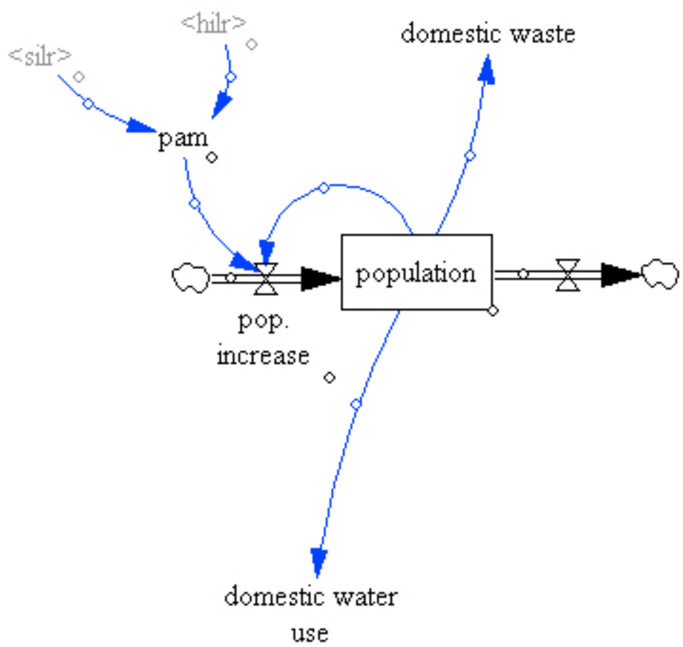
One of the most active conservation groups is the Jheel Sanrakshan Samiti or JJS (The Lake Conservation Society), founded in 1992 with the mission of arresting and reversing the rapid deterioration of the lakes of southern Rajasthan. Comprised of lake conservation professionals, local residents, and other professionals, this group regularly organizes rallies and seminars and has worked closely with the government to plan and implement various projects to improve the lakes of Udaipur. Since the 1990s, it has been involved in projects designed to preserve catchment areas, treat Pichola's watershed, fix leaky sewage manholes, educate villages about water preservation, oppose the destruction of small lakes, remove excess silt in the lakes, and worked closely with the government to get the government to implement various projects. For example, JJS drafted a plan for the conservation of catchment areas that would cover 16 villages and 12702 ha of land, which the Government of India sanctioned in 1995-1996. JJS also drafted a sewage project for Udaipur that the government enacted in 2000, which has already laid 23 sewage lines. JJS also petitioned the Rajasthan high court to restore small lakes and establish a conservation plan for these lakes, which the court approved and has implemented for 42 lakes.

Modeling Udaipur and its Water

System Dynamics Modeling: Demand Stocks
Major users of water fall into two categories: people and industry. Population increases and tourist increases are adding to the people use of water, and with those soft industry has increased to support the functions of the city, and hard industry has increased as it has a greater population to employ.

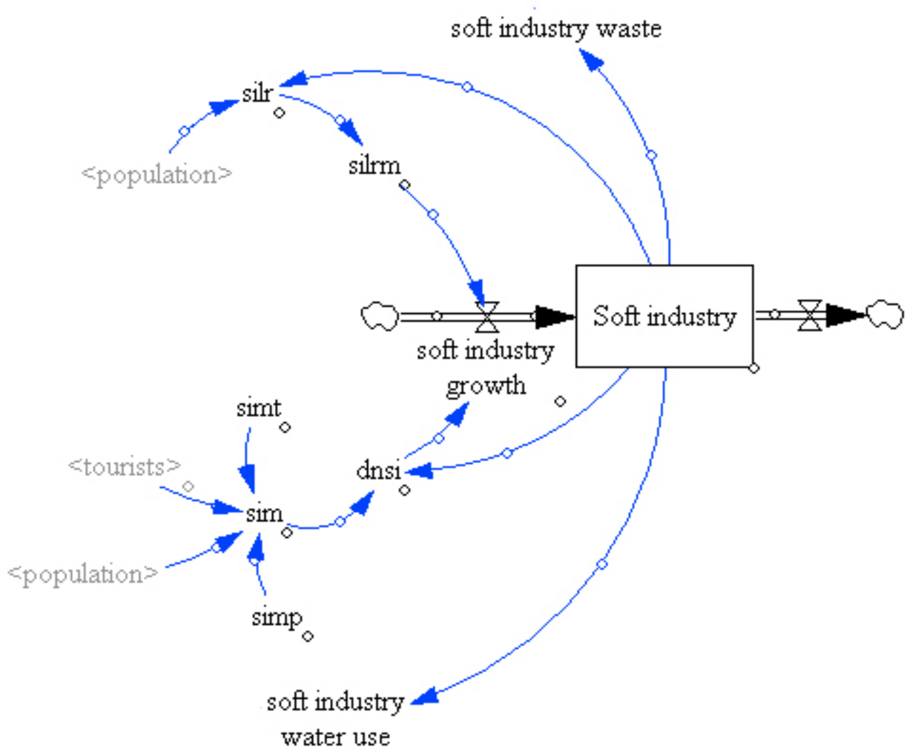
One element of demand on water is the population of the city. Population for the city of Udaipur has been increasing. The continued drive of this population growth would exist through a multiplier, represented in the model as pam: population attractiveness multiplier. This multiplier has proven effective in Forrester's Urban Dynamics model. Generally for Udaipur, the main attractor is the job economy. Both the soft industry and hard industry labor ratios (discussed below) are the main variables that alter the attractiveness of the city for migration. Currently growth in the city of Udaipur is at just over two percent. If either of these industries stagnates or begins to decline, there will be a corresponding drop in the population growth. Population also affects its own increase in two ways: one contributing to birth rate, though for the simplicity of the model, births are assumed to be part of the normal population growth rate, and the rate will not be allowed to drop to zero. The second is contributing to the social perception of the area: people draw people. The population in turn drives two main auxiliary variables, domestic water use and domestic waste. Domestic water use is a multiplication of water use per person and the total population in liters per year. Domestic waste is calculated in a similar way and focuses solely on sewage output (Figure 3).

Figure 3



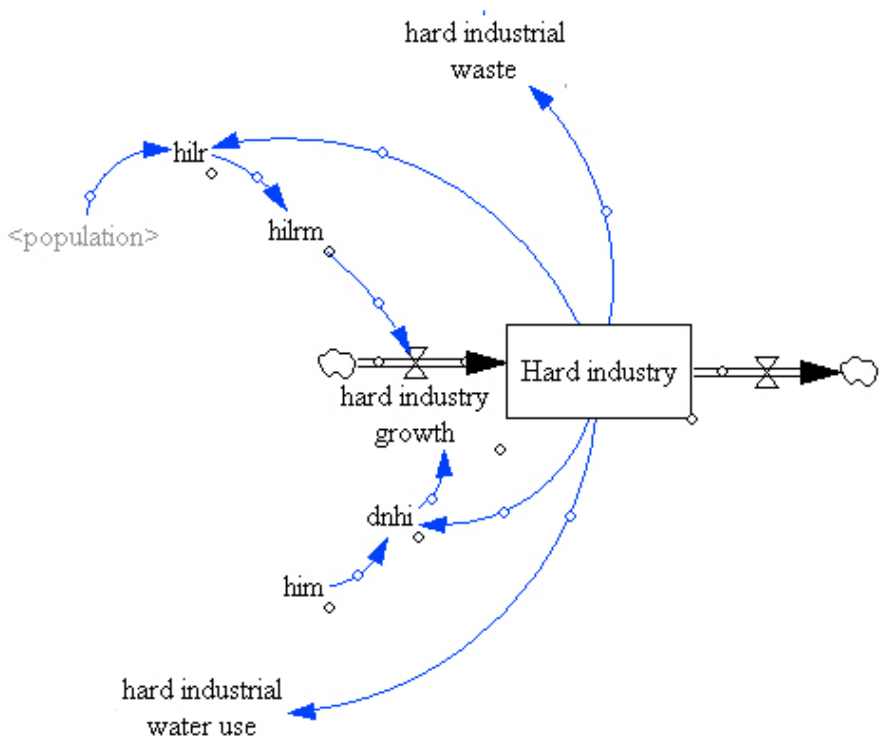
Soft industry is defined as the service industries in Udaipur, ranging from restaurants and shops to hotels and taxis. The growth of this sector is driven by both a desire for new soft industry and the ratio between soft industry and population. In general this means that the stock reacts to the populations of tourists primarily and to the general population in two capacities: as consumers of goods and as a labor force. Soft industry will increase to a point for the population alone, but will be driven to a significantly higher equilibrium with a tourist industry. Tourism relies solely on soft industries to function, while the general population uses it recreationally. Therefore tourism will drive the growth rate of this stock in a much more significant way. Desired new soft industry (dnsi) is defined in the model as a relationship between the current number of soft industry jobs and the total population and tourist populations through a multiplier adapted from Forrester's Urban Dynamics model (Figure 4). This use of population is representative of the consumer. Soft industry's other main increasing driver is through the soft industry labor ratio (silr), given as the total population divided by the number of soft industry jobs. This ratio will attract more migrants when it is low, indicating a low number of residents and a high number of jobs, and fewer migrants when it is high, indicating more competition for jobs. As with population, soft industry drives two main variables, waste and water use that will be aggregated with other similar variables to understand the total picture of Udaipur. Waste for both domestic and soft industry is calculated primarily as sewer drainage.

Figure 4



Hard industry in the majority refers to the marble industry that surrounds that city. Drivers for hard industry are similar to those of soft with the exception of tourists. If more industry is desired (e.g. one closes down, more marble is discovered, partners break up and begin their own business) it will more likely grow more quickly. Again with relation to population, hard industry provides an economy shown through the hard industry labor ratio. Hard industry's contributions to the model are the presence of waste and the use of water. Marble is cut with a wet blade, using large amounts of water consistently to manufacture the products. It also contributes substantially to pollution through the waste product, marble slurry, which is produced at 3.5 million liters/year (Figure 5).

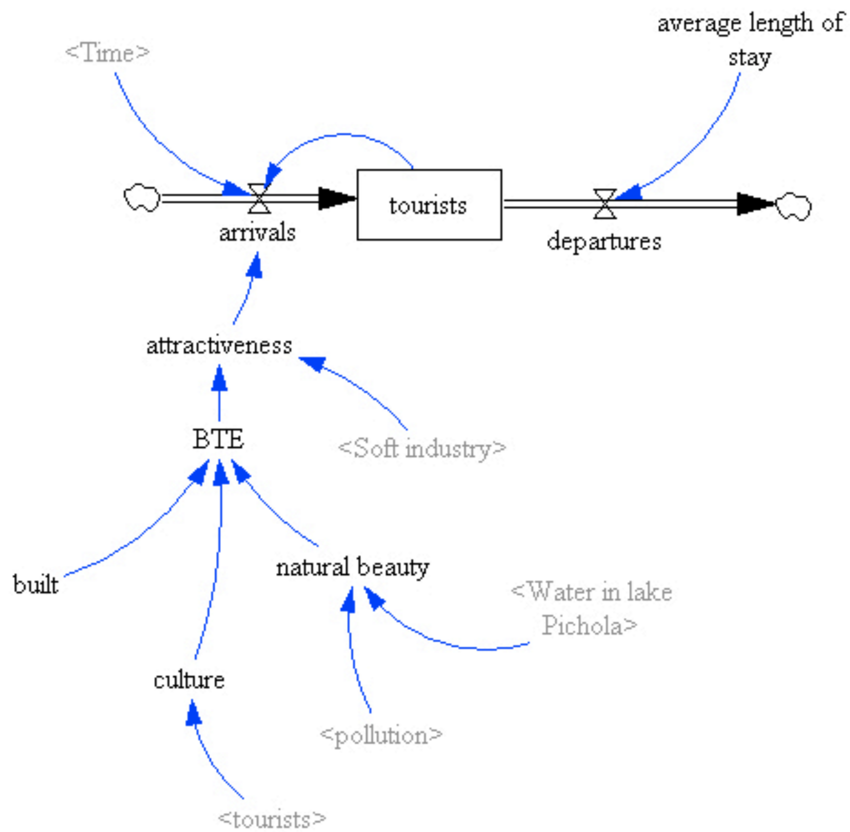
Figure 5



Tourism is the fourth main driver of demand in Udaipur. Tourism has been increasing in the city over the last ten years, and is highly driven by an attractiveness multiplier. Soft industry is an important driver of attractiveness because it is an essential background component, these facilities need to be in place to begin to draw tourists, and then will expand as the tourist numbers increase, creating a reinforcing feedback loop which makes the area even more attractive.

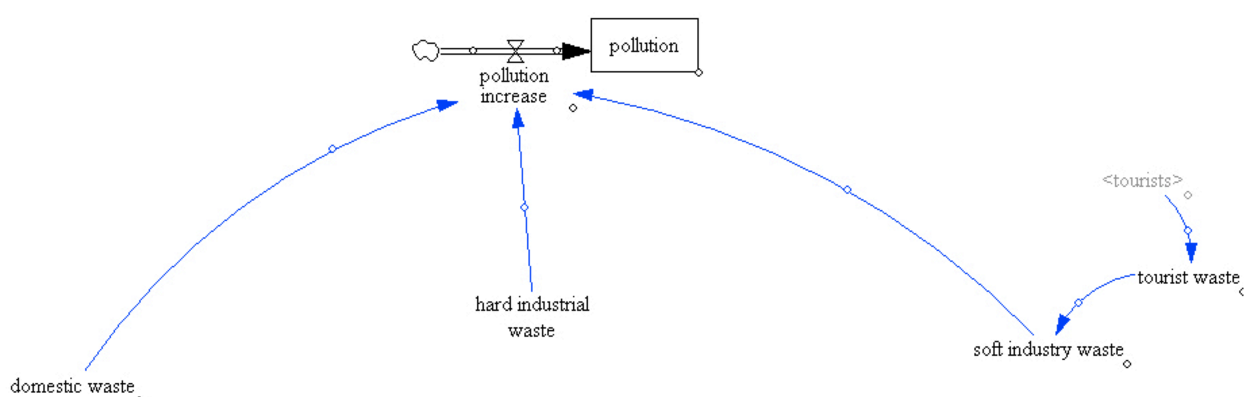
Arrivals are also driven by a seasonal affect, drawing more tourists in the winter months and less in the summer due to the average temperatures of the region. Tourists also draw more tourists, either by a return visit, or in the same way that people draw people, the more tourists that go add to the attractiveness because it is known as a place for tourism (Figure 6). Tourists then drain by an average length of stay, which is estimated at one week.

Figure 6



System Dynamics Modeling: Pollution
Pollution is a combination of each waste product produced by the demand stocks. Domestic, soft industry and tourist waste is primarily sewer output in liters, and hard industry as industrial waste, primarily marble slurry as mentioned previously. Pollution is allowed to accumulate as a single stock without an outflow as currently there are no hard methods of pollution remediation taking place in Udaipur (Figure 7).

Figure 7

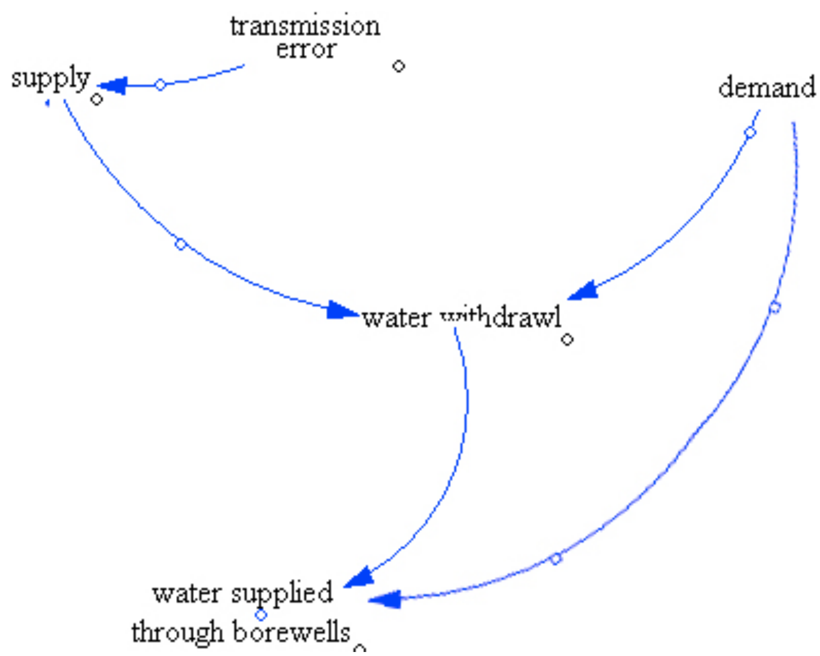


Water Shortages in Udaipur

As a result of the aforementioned factors, the government of Udaipur is not able to meet the daily water needs of its residents. As of 2006, only 69% of city residents had access to water, and this access was limited to 1.5 hours to 3 hours of water service every 48 hours. According to the Udaipur City Development Plan established by the Urban Infrastructure Development for Scheme for Small and Medium Towns, the city plans to increase coverage to supply 90% of the city with water for 4 hours every 48 hours by 2011, and will continue to improve coverage such that 100% of the city will receive water for 6 hours every day by 2021. This improvement is estimated to cost 345 crores (US $75.9 million) (Sancheti 2006, 41), which demonstrates that even with careful planning and significant investment, the water supply of city residents will still be limited.

Water Withdrawal
The total demand is a combination of the users of water based on their average use to date. One limitation of the model is that it does not allow for a changing use rate per person or per industry. Water withdrawal is the main variable that ultimately is the water used by the city. Demand and Supply are combined, with supply limiting the withdrawal no matter what the demand. One concern for the issue of water use is the construction of bore wells. The function of water withdrawal is limited by supply, and in the event that demand surpasses the supply of the dams and lake, people will begin to draw on borewells for their water needs. Currently, neither borewell regulation nor data on existing borewells in Udaipur exists (Figure 8).

Figure 8



Current Interventions

In India, management of water supplies falls to the state government. While the central government funds large scale projects, local governmental officials and departments (such as the

Public Health and Engineering Department) manage the operation of water supply systems and are responsible for upkeep of existing infrastructure as well as future project planning (Mehta 2005).

Dam Construction

Since the 1950s, planners and politicians in India have considered dam construction to be one of the most efficient ways to address water shortages (Mehta 2005). This has proven to be true in Udaipur, where dam projects were first proposed to solve the city water shortage in the 1970s. The first large dam project proposed by the Udaipur government was that of the Devas dam scheme, proposed in the early 1970s. This scheme planned for the construction of four dams in the Sabarmati River Basin that would supply water to Udaipur through a tunnel system that linked the dams with Lake Pichola. The first of the four Devas Dams (Devas I) was completed in 1973. Following its completion, the construction of the following three Devas dams was postponed until recently when construction on Devas II was initiated. This dam is currently still under construction near the Akodra village in Jhadol taluka.

During the severe drought of 1986-1987, the Devas I dam did not supply adequate water to fulfill the needs of the city residents, which prompted planning of the Jaisamand lift scheme. This project diverts water from Jaisamand lake directly to pipe water distribution system of Udaipur (Ranawat and Sharma 2010). While originally intended to be a temporary solution and source of water, this diversion system has remained in operation since its completion in 1995 (Government of Rajasthan Planning Department, n.d.).

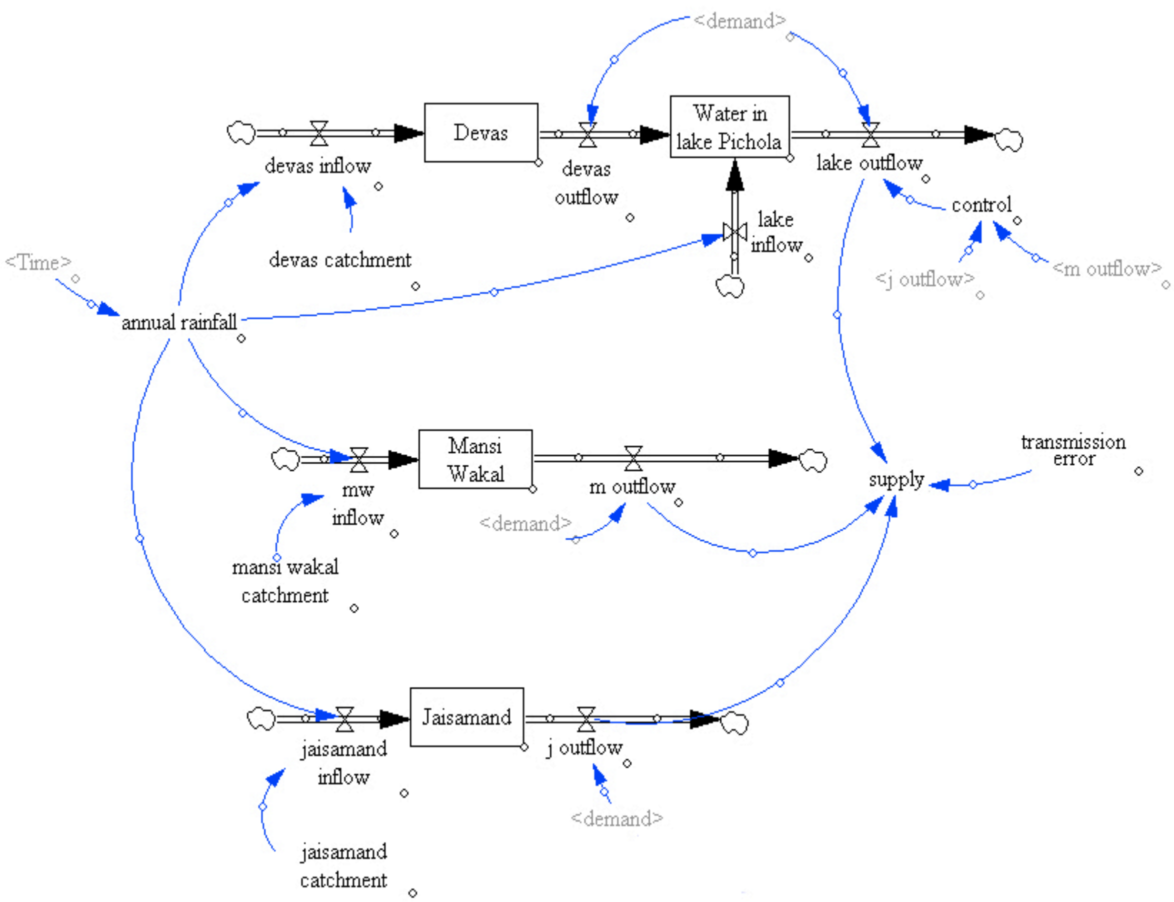
Due to the inability of the Devas and Jaisamand dams to meet increasing water demands, the next large dam project proposed by the Udaipur government was the Mansi-Wakal project, a 2-phase dam project that would build dams on the Mansi and Wakal rivers. The first phase of this project, initiated in 1998(Ranawat and Sharma 2007) and completed in 2007, consists of a dam constructed at Gorana village that transfers water to the city. Hindustan Zinc signed a memorandum of understanding with the Government of Rajasthan in which they agreed to fund 30% of the cost of this dam in return for rights to 30% of the water supplied by this dam (Government of Rajasthan Planning Department, n.d.). The second phase of this project is anticipated to be completed in 2021 (Ranawat and Sharma 2010).

Supply Stocks

The main suppliers of water into Udaipur are the lake system and the series of projects and dams that have taken shape over the last thirty years. The three main projects are Devas, Jaisamand, and Mansi Wakal. Each of these projects is predominantly rain fed. This variable drives the inflows to each of the projects as well as Lake Pichola when combined with the catchment areas. Rainfall is driven by a seasonal affect, raining more in monsoon months (September through November) and being fairly dry for the larger part of the year.

Outflows from the dams are controlled by two factors, combined demand and the maximum amount of water that can be reasonably extracted. All three dams are constructed to only be able to withdraw a fixed amount of water in a day that provides the maximum outflow. Water withdrawal from the Lake, which is fed by both rainfall and the extraction of water from Devas is controlled by another factor, the water being withdrawn from the other two projects. There is a clear order of ideal withdrawal from the system: Mansi Wakal, Jaisamand and the Devas, and finally the Lake. The model was constructed to draw water from the two larger and newer sources fist, leaving the lake to be enjoyed by keeping it full of water until needed. All outflows of the system combine to make a total supply. This total supply is less than the combination of the flows as there is a 21% transmission loss. The total supply is also less than the aggregate of the stocks because of the technological limitations of the dams and the water extraction process only allow for 36 mLD and 20 mLD from Mansi Wakal and Jaisamand respectively (Figure 9).

Figure 9



Additional Considerations

It is clear that water policy interventions are necessary for the city of Udaipur. Projections suggest that given the current rates of change of rainfall, population, industry and tourism, the water situation will reach yet another crisis point.

Bore Wells

Due to the inability of the government to meet urban water needs even with the construction of large dams, individuals have taken matters into their own hands through the construction of private bore wells. These wells directly extract groundwater, and are cited to be one of the primary drivers of decreasing ground water and water table supplies (Paliwal 2005, 217).

Extensive tube well drilling began in the 1990s, and it is estimated that there are at least 1500 hand pumps and 700 private tube wells currently in Udaipur and that this number is steadily increasing. However, since there is no official regulation of these wells (Ranawat and Sharma 2007), it is difficult to accurately assess their prevalence as well as their affect on the water supply.

Bore wells are not fully explored by this model. The technological innovations have helped explore deeper into the earth, as the water table decreased and volume needs increased. It is estimated that every household outside the walled city has a bore well. Although the adoption of bore wells is a technology used in many parts of the world, the adequacy of the aquifers under Udaipur city pose a unique dilemma. The aquifers in this area are characterized as hard-rock type structures, indicating that digging deeper into the ground does not guarantee the presence of more water, thereby limiting the potential water the aquifers can hold. Aquifers are recharged through the percolation of surface water to the aquifer. The primary porosity of the aquifer determines the degree to which the aquifer can absorb the percolated water. Hard-rocks, like the ones under Udaipur are characterized as having very little primary porosity, meaning that once water is extracted from the aquifer, the possibility of recharge is limited. With an incredibly high extraction rate, it is undeniable that without regulation the Udaipur aquifers will run dry and the possibility of recharging the aquifers to a usable level is nearly impossible. Secondly, the aquifers are characterized as having low specific yield meaning that the amount of water that can be extracted by a unit volume of the aquifer is low. Compounding this problem is the fact that the ease, with which the aquifer will transfer water from one place to another, or transmissivity, is low. Although bore wells can access water, the amount of water residents can extract is limited, the energy required to extract water is high, and the possibility of permanently depleting the supply is imminent. The characteristics of Udaipur's aquifers put the city at great risk for ground water depletion even before other social, political, and economic factors are considered.

This variable is shown in the model, but contains no data and does not participate in any equation. It is currently calculated as the difference between the demand and water withdrawal, if demand outpaces supply, bore wells will make up for some of this difference.

Rural Impacts

While a common governmental solution to address water shortages in urban areas, the construction of dams in rural areas inflicts heavy social, environmental, and economic costs. During the construction of the first phase of the Mansi-Wakal dam, 6,500 people from six rural villages (Chandwas, Gayariyawas, Talai, Mundawali, Dewas and Gorana) were displaced during dam construction. The second phase of the Mansi-Wakal project is projected to affect an additional 11,000 people in 17 additional villages(Ravages Through India 2005). The building of the dam led to a significant destruction of the catchment area causing irreversible damage to the environment. Furthermore, the aforementioned dams all experienced cost overages and longer construction periods than was anticipated. Due to the social and environmental costs, as well as the intensive economic and time investment required to construct dams, alternative management interventions must be considered—especially since dams are failing to fully alleviate water shortages.

Future Work

This model provides a clear outline as to which data needs to be collected by Udaipur government officials and NGO's such as FES. Through the research conducted during the field study, it became evident that the quality and *quantity of available data served as an impediment to thoroughly researching the water crisis in Udaipur.* While in India, students relied on interviewing local stakeholders and accessing available governmental and academic documents relating to Udaipur's water supply. However, the use of interviews presented challenges in ensuring accuracy and consistency of information. The few available documents also limited research due to the fact that they were outdated (the majority were from the 1970s and 1980s). Even after conducting an extensive literature review upon their return to the United States, it was discovered that few governmental and academic studies exist pertaining to the Udaipur water shortage. Additional fieldwork is planned to collect this data and gain further understanding of the trends behind the many complex relationships regarding water in Udaipur. Once the appropriate data is collected and put into the model, the model can be used to test other water-related interventions and policy implementations. In the meantime, the building of the model has provided insight as to areas where interventions can occur.

Due to the preliminary and working condition of the model, the authors make no assumptions that any work or interventions can be done in the system without a full understanding of Udaipur's water. While interconnections are shown and understood, there is a large gap of data that is desperately needed by all groups involved with the growth of this city to continue research and make positive impacts on the water supplies and residents.

The following section outlines interventions that have been mentioned in various levels of seriousness and capacity by residents, local leaders and the group gathered in Udaipur for the Institute and how they may impact the system. They represent a researched qualitative understanding of the system along with potential reactions and considerations that may influence choosing an intervention.

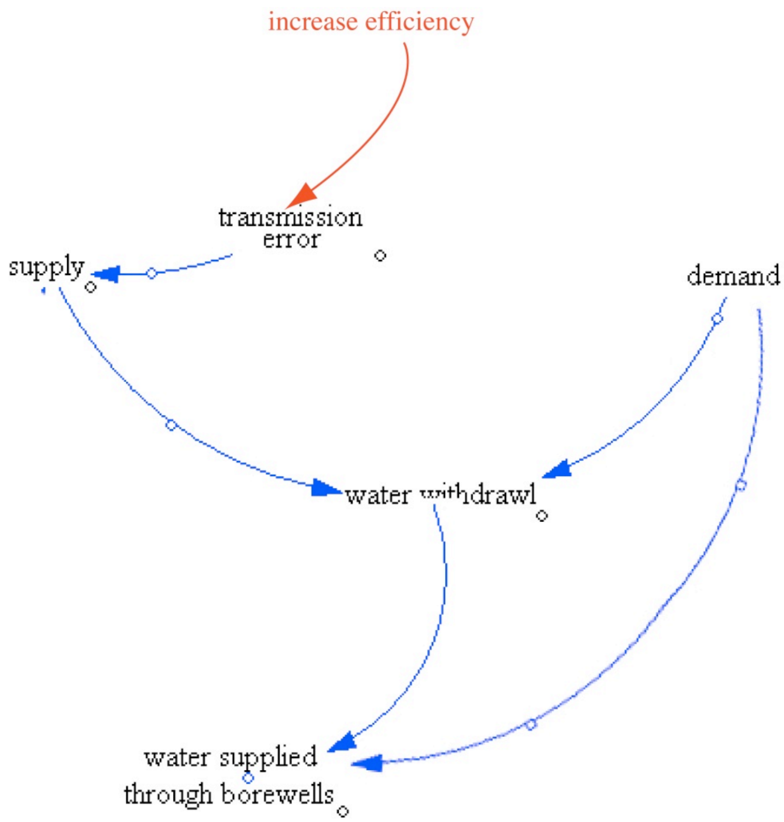
Discussion: Places for Policy and Intervention

One of the major goals of this project is to evaluate the impact and interconnectivity of the supply of water and the continued growth of the tourist industry. If future policy interventions and recommendations are to be developed, the dynamics of this careful balance between the ecological and economic requirements of water needs to first be thoroughly understood. Below are areas for potential intervention and where they would directly fit into the model. With a complete data set, variables for these suggestions can be input at varying levels and the impact on both the ecology and the economy can be seen.

Reduce Distribution Losses

The most important way to increase water supply to the city is to increase the efficiency of the pipe systems already in place by reduced the transmission losses. Currently approximately 21% of water drawn through pipes is lost in transmission. While transmission losses may not ever reach zero to have a completely efficient system, this effort would be able to increase the supply of water without new large construction projects (Figure 10). The intermediate implications of having to temporarily close off supply from one source or another to make repairs or change pipelines would have a temporary impact likely no greater than that of a drought, but could also be studied before a project were to begin.

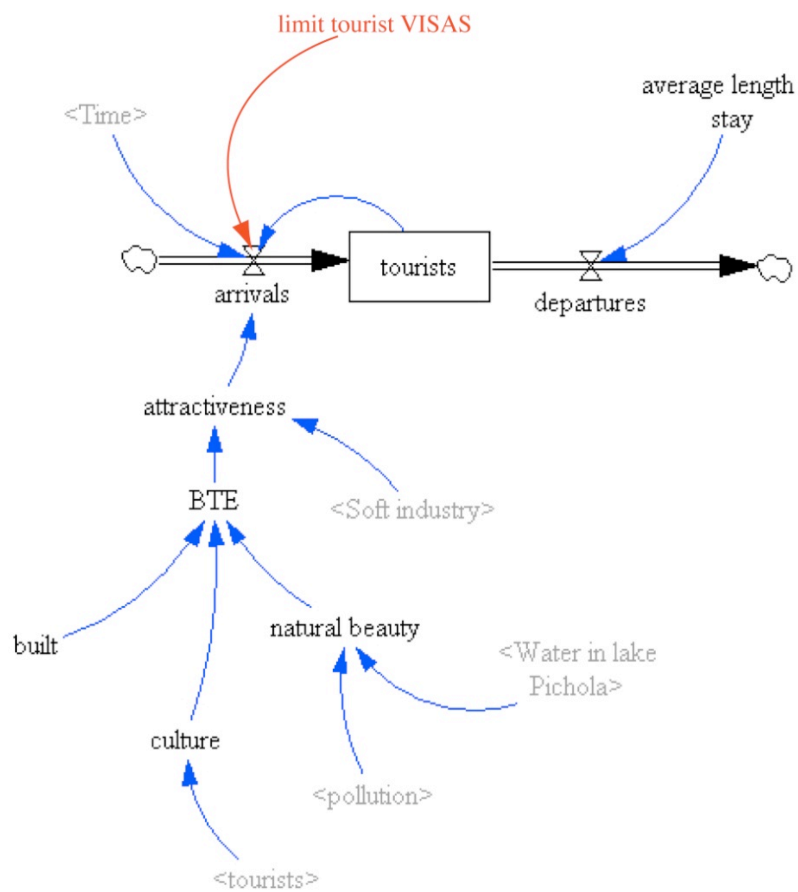
Figure 10



Reduce Tourism

The city of Udaipur relies on tourism as its main driver of economy. This intervention is worth mentioning not because of its ultimate plausibility, but because it is an obvious one. One tourist in a day uses far more water than one resident. Reducing the number of tourists (most recently at 1.2 million in a year) would reduce a lavish use of water. The impact of a cap or limit on tourists issued VISAs to visit Udaipur would potentially have grave effects (Figure 11). The questions to be explored are: What would the cap be? Can a cap be created that stabilizes the economy at a high equilibrium? Can a cap be created that stabilizes both the economy and the water demand within the limits of the supply without changing the use of domestic or industrial water? Is there a natural goal-seeking limit to the number of tourists that would come anyway? Does that number allow for both economic and ecological stability?

Figure 11



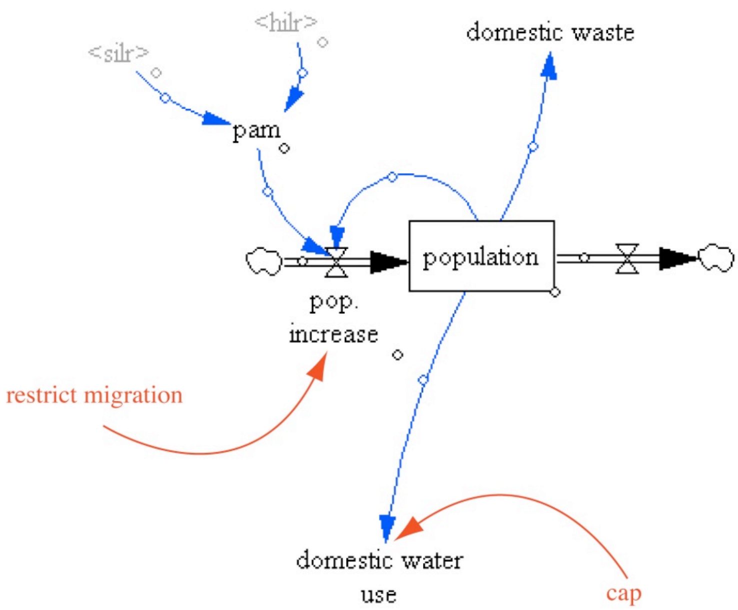
Promote Ecologically Conscious Tourism
A cap could also be placed on the amount of water one tourist uses. Ecotourism as a new phenomenon is highly popular in developing countries for Western visitors. Udaipur could rebrand its own image in support of the ecology of the lake and limit the water used by tourists through soft industry. A change like this would likely create a small shock to the system, where during the change tourism would drop. The correct timing of an intervention could push a change through to hit during off-peak season that would lessen the impact of a change in tourist arrivals.

Reduce Population Growth
Although tourist draw is the greatest per day per person, the total domestic water uses far outpaces all other water use in total for the year. Udaipur has established a level primacy in the region and has a large draw on rural populations of Rajasthan and adjacent states for migration.

A restriction on this migration will not reduce the overall current domestic water use, but may promote a static equilibrium that will allow temporarily for alternate solutions to be found.

Cap Domestic Water Use
A second intervention on the general population of the city would be to cap water use. In some ways this policy is already being used, as water is only supplied during specified hours as noted above. A variable to control this restriction will be used to estimate the impact on total draw of water. The questions to this cap would be how to restrict water. Currently water comes per household for two hours in a 48-hour period (Figure 12). This does not account for people per household and therefore creates greater impact on larger families.

Figure 12

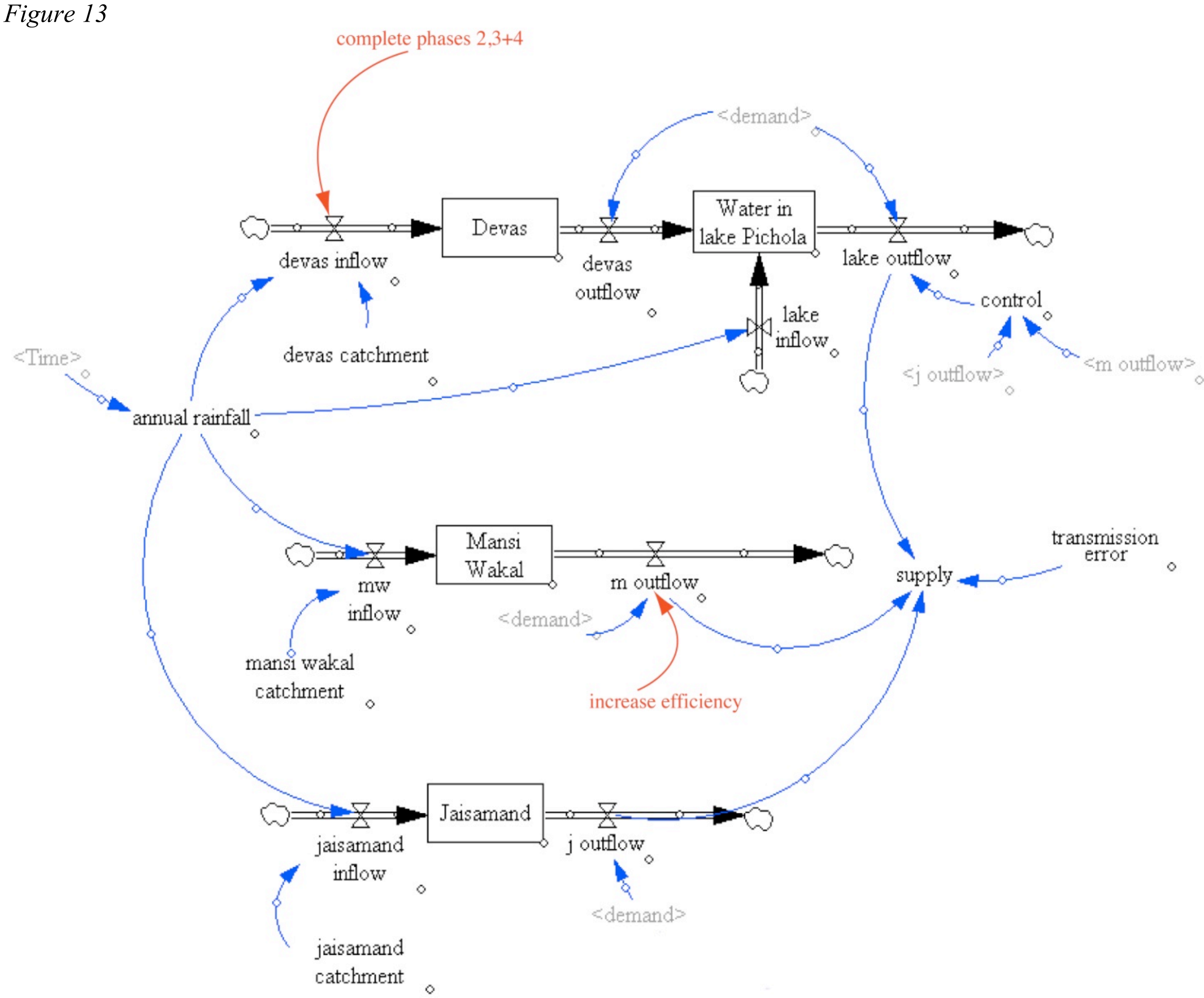


Increase Draw on Mansi Wakal
In terms of efficiency, there is the potential for another solution. Currently the dams can only supply a certain amount of water no matter the total stock of water in the dams. It would be beneficial to explore if more water could sustainably be withdrawn from the dam. This analysis would also determine if the process is not sustainable in its current condition. The question is, what is the number at which the system maintains the highest equilibrium while continuing to supply the demands of the city?

Devas II, III and IV.
The Devas scheme has to date only complete phase one of the four-phase proposal. Currently phase II construction is underway. These phases have projected values that would add to the current supply of water and should be evaluated and the full impact of growing the water supply understood. Increased water supply will obviously alleviate the gap between supply and demand, and would decrease the draw on bore wells (see discussion under Implications section), but may also lead to a changing use level of water, a continually growing population and other factors

that ultimately outpace the new supply lines (Figure 13). The further construction of dams also has impacts on rural areas (see discussion under Implications section).

Figure 13



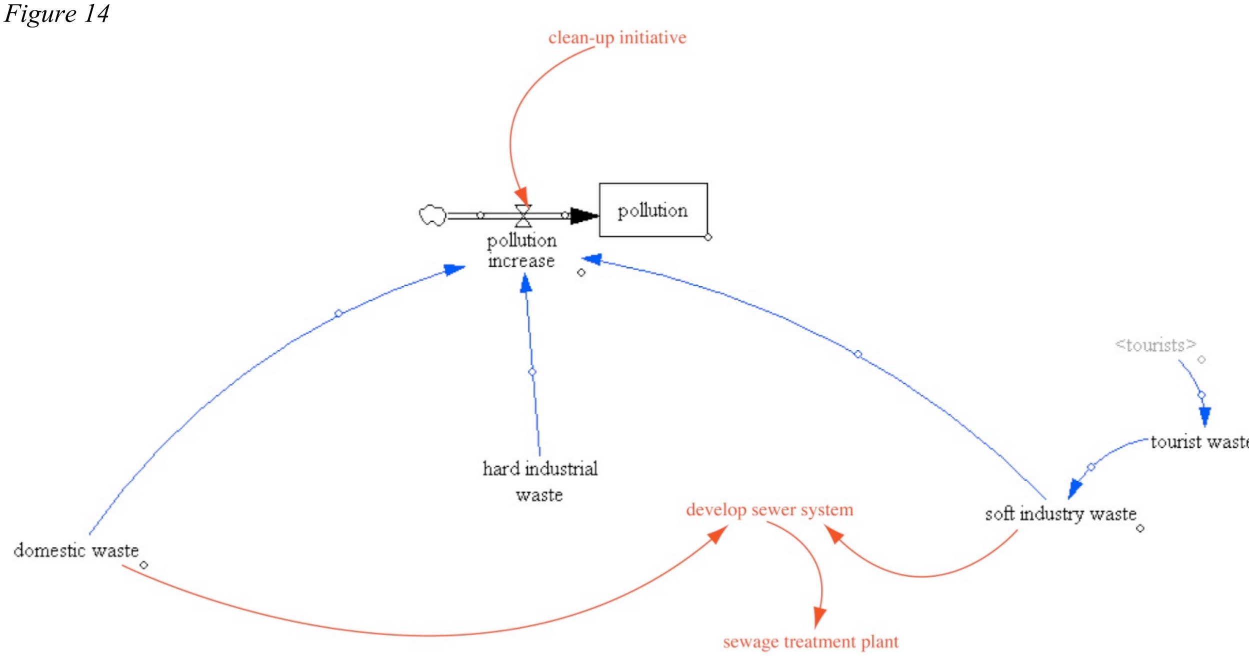
Waste Water Treatment

The construction of a proper water treatment facility would provide a decrease the accumulation of waste toward the pollution stock. Wastewater treatment would also potentially be able to create a flow of water back into the main system after the treatment process, thereby eliminating some of the increasing demands on water as recycled water is reused by industries. The elimination of pollution will change the attractiveness of the area to tourists through the natural beauty multiplier and may impact a tourist flow. Depending on the capacity of such a system, the pollution treatment may or may not be sustainable as other populations grow beyond its capacity.

Clean Up Initiatives

Clean up of lakes and surrounding areas will add a negative factor into pollution increase. Depending on the initiative, this driver could be as minimal as solid waste and trash pick up to decrease the flow into the lake, or dredging and removing pollutants, actually creating a negative pollution increase and reducing the total amount of pollution that is present (Figure 14).

Figure 14



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