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Title of Paper: Delivering sustainable wastewater infrastructure in an urbanizing world

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Abstract

For the first time in human history, urban population exceeds rural population. The rapidly urbanizing population is at a major health risk due to lack of adequate sanitation facilities, drainage systems, and piping for clean water. As urbanization and climatic change occurs, water scarcity may become a limiting factor in water and wastewater infrastructure design while at the same time, the world struggles to provide safe drinking water and sanitation to large populations without access. As urbanization and population growth continue, it is important to consider water and wastewater infrastructure designs that minimize water use while being cost-effective and health-beneficial. We examine the sanitation systems of 6 Bolivian communities which are quickly growing. Analysis of system type, management type, costs, and community perceptions are made in order to determine the appropriateness of the sanitation system to the capacity of the community. Our discussion of these issues concludes with new considerations in sanitation design, imperative for a sustainable future in a water-scarce and urbanizing world.

Introduction and Objective

For the first time in human history, urban population exceeds rural population (Figure 1a). In fact, by 2030, 61% of the global population is expected to reside in urban areas. It is also widely recognized that urbanization can be an important source of health problems. For example, 30-60% of the urban population in the developing world lacks adequate sanitary facilities and drainage systems, and piping for clean water. This is especially important because the risk factor *unsafe water, sanitation, and hygiene* makes up 46% of all environmental risks to global health (Figure 1b) and was responsible for about 5.5% of disease burden in high mortality developing countries in 2000 (WHO 2002). The Millennium Development Goals aim to reduce this risk by reducing by half the proportion of the population without access to safe drinking water and sanitation.

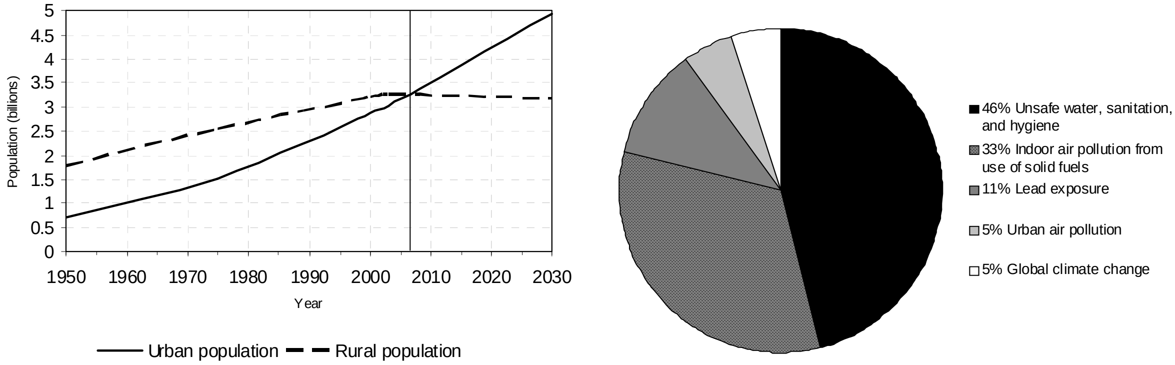

Figure 1. a) Urban and rural population growth of the world: 1950-2030 (adapted from UNESA, 2004). b) Attributable fraction of factors contributing to environmental risk, measured by Disability Adjusted Life Years (DALYs) (data from Ezzati *et al*, 2004).

The challenge of serving the world's 2.1 billion people who lack adequate sanitation results from many factors. Some factors related to inadequate sanitation are inadequate investment, poor/nonexistent policies and governance, too few resources, gender disparities, and water availability. Although at a global scale, water scarcity (the ratio of domestic, industrial, and agricultural water withdrawals to runoff, DIA/Q) does not appear to be a limiting factor for sanitation coverage, it is expected to be an important challenge for large numbers of populations living in already stressed regions (Figure 2).

Up to 8.7 million people could move into the severe water stress category (DIA/Q > 0.4) based only on increased water usage just to meet the MDG sanitation target by 2015. Looking further into the future, if the world achieves 100% sanitation coverage by 2025, this number could increase to up to 46 million people in the severe water stress category. The majority of the population expected to experience an increase in water stress due to sanitation are urban dwellers. Urbanization poses particular water-related challenges to achieving sanitation coverage, because sewers require water to transport waste, whereas in rural settings other less water-intensive sanitation technologies can be used such as latrines or composting toilets, (Fry *et al.* 2008).

Delivering sustainable waste infrastructure requires that technological solutions correspond to geographical and climatic restrictions, along with community characteristics. Sustainable sanitation technology thus implies that a community will be able to organize and afford the installation, management, operation and maintenance of a system that meets their population's health needs.

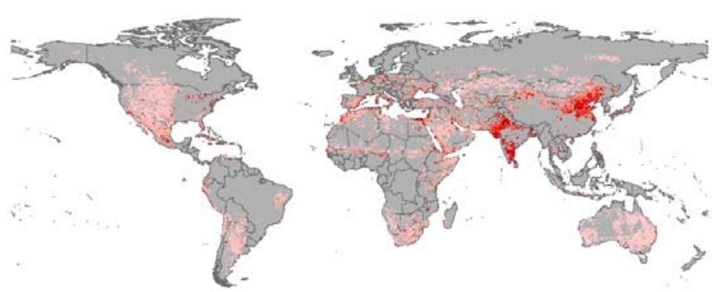

Figure 2. Distribution of the world's population currently living under water stress (adapted from Fry *et al.* 2008).

Here we review our research on the *sanitation development path* for rural communities in Bolivia that are advancing their choice of a particular sanitation technology. The study communities were chosen for their characteristic of urbanization: migration of people into the community at a rate greater than 3% per year (Inchausti, 2008) as well as some exhibiting the peri-urban stage on the development continuum from rural to urban (Ahrens and Mihelcic, 2006). We analyze whether or not the current sanitation solutions are appropriate for each particular community. The analysis is based on community population density, social capacity, and economic capacity. Infrastructure characteristics are also assessed qualitatively: technology complexity and design versus actual function and loading.

We then expand our discussion to the impact urbanization has on selection of sanitation technology. In urban settings, space often constrains construction of household latrines and public latrines are excluded by the global health community from the definition of adequate sanitation. Sewers have undeniably improved health in developed countries. In fact, in the 19th and early 20th century, before vast sewer coverage existed in industrialized countries, infant mortality rates ranged from 100-200 per 1,000 live births (UN-HABITAT 2003). However, sewers require up to 75 L/capita-day, whereas other sanitation technologies are available that require less or no water. This leads to the question of whether a sanitary sewer is an appropriate technology in a city that will become water scarce by 2025? Sewers can also distribute nutrients over a wide spatial scale while other sanitation technologies can consolidate nutrients at the community level. And if a sewer project is deemed appropriate today, what should the community do to prepare for future effects of climate change? These questions raise the issue of how to best meet basic human needs in terms of water and sanitation including technology selection and governance strategies, under increasingly variable, rapidly urbanizing, and water scarce circumstances.

Background

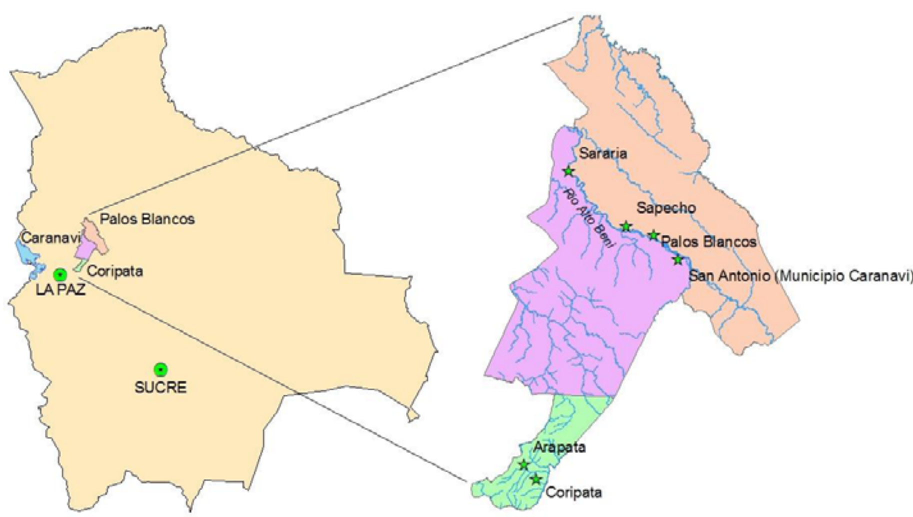

Figure 3. The South Yungas province and the six study communities located near La Paz, Bolivia.

In the La Paz department of Bolivia, sanitation interventions are especially important. In a country where only 22% of the rural population has access to improved sanitation and diarrheoal diseases cause 6% of all deaths (WHOSIS, 2006), the La Paz department has the highest percentage of untreated diarrheoal cases (28.2% compared to 18.6% average of Bolivian departments) (STATcompiler, 2008). The non-governmental organization ACDI/VOCA has been implementing sanitation measures in rural communities in eastern La Paz department, in the province of South Yungas. We identified six communities in

South Yungas (Figure 3) with a variety of populations, sanitation technologies, social organization levels and economic capacities (Table 1).

The South Yungas region is characterized as the transition zone between the Andes Mountains and the Amazon river basin: smaller mountain ranges paralleling the Andes are divided by rivers which generally flow north to the Amazon. The economic activity of the area is based in agriculture; coffee, cacao, citrus and bananas are the most productive exports (Palos Blancos Municipal Report, 2007). The population is largely immigrants from the higher elevation Alti Plano region near La Paz. The population growth is greater than 3% per year as migrants move to this agriculturally productive area and the communities urbanize (Inchausti, 2008).

In these six communities, water and sanitation are managed together by local community organizations, "water committees", (some formalized into private incorporated cooperatives) except in the case of Palos Blancos, where potable water is managed by a cooperative while sanitation is under jurisdiction of the municipality.

Table 1. Data collected for this study on demographics, sanitation system, and system costs for six Bolivian communities located in the South Yungas area.

	Palos Blancos	Sapecho	San Antonio	Sararia	Arapata	Coripata
Wastewater System	Sewer to Septic Tank & Biofilter	Sewer to UASB	Sewer to Lagoon	Septic Absorption Pits	Sewer to Septic Tank & Biofilter	Sewer to Septic Tank & Biofilter
# Systems	1	1	1	91	6	7
Urban Population	2691	1039	420	546	1950	2680
# Connections	700	206	150	91	401	546
Mean Family Income	700 Bs	790 Bs	587 Bs	1159 Bs	--[a]	1125 Bs
Construction Cost	$33,616.66	$40,896.48	$21,168.44	$650.73	$29,428.30	$50,813.02
Consulting Cost	$0.00	$1,702.07	$789.32	$2,782.20	$1,097.80	$1,605.40
Training Cost	$0.00	$2,571.69	$1,731.59	$5,138.69	$3,387.40	$4,318.34
Supervision Cost	$0.00	$823.93	$2,149.97	$2,017.47	$1,205.05	$1,901.76
Counterpart Cost	$0.00	$19,196.08	$8,970.09	$3,900.00	$9,912.73	$13,376.76
Total Cost	$33,616.66	$46,896.14	$26,734.31	$10,621.90	$35,923.07	$59,591.87

[a] Data not available.

The World Health Organization classifies "improved sanitation" as either a pit latrine with slab, composting toilet, ventilated improved pit latrine (VIP), pour-flush or flush toilet to septic tank, and pour-flush or flush toilet to a sewer system. In these communities, improved sanitation systems range from latrines (pour flush to septic absorption well) to condominial sewers (small diameter sewers to cluster septic tanks, followed by gravel biofilter) to full sewers (to treatment lagoon or activated sludge reactor). The systems have all been implemented by ACDI/VOCA or other organizations within the last several years but it is unclear whether each technology was an appropriate choice for the community as they grow and urbanize from different stages of development.

Methods

Data were gathered from ACDI/VOCA engineers, economists and sociologists on the communities of Palos Blancos, Sapecho, San Antonio, Sararia, Arapata and Coripata. Engineering reports provided data on the sanitation design, total cost and cost breakdown of the project, and community population.

In 2007, a willingness-to-pay survey was completed in Palos Blancos, Sapecho and San Antonio to identify whether the communities would pay more for better services; the survey was offered in Sararia in 2008. The survey aimed to include 10-15% of the connections to water/wastewater systems, with a minimum of 20 surveys in each community. Each community was divided into 3-5 areas with surveys distributed among the areas to ensure a geographic distribution of responses. Along with the willingness-to-pay question, residents were also surveyed on their level of understanding of the treatment system, fees paid for water and wastewater services, and agreement with utility fees.

The water committees were also surveyed to characterize the social organization capacity of the community. Through informal interviews and surveys, water committee members (except in Palos Blancos) were asked about the size, structure and responsibilities of the committee, operations of the wastewater services, how many people benefit from the wastewater services, and advantages/disadvantages of current and previous systems.

Results and Discussion

Socio-economic Indicators

Capital Costs: Table 1 provided great detail on the sanitation project costs. Construction costs include materials, transportation and construction. Consulting costs are related to the professional design, engineering time, and technical evaluation. Training costs are for educating the community and water committee about the wastewater system. Supervision covers oversight and planning hours. Counterpart cost is the amount (monetary or non-monetary) that the community pays for the project. The total cost is the sum of all project costs (in Table 1, the Total Cost is greater than the sum of the other costs because smaller budgetary items, such as direct purchases and general expenses, have been excluded from this report). Figure 4 shows the breakdown of specific capital costs for the six communities. The wastewater systems were also compared by total and counterpart costs per beneficiary and per connection. Figure 5 shows that the condominial sewer systems (clustered shallow sewers to septic tank and biofilter) appear to be least costly. They do not require expensive excavation and construction of deep sewers or reactors, and also do not require construction of individual household systems.

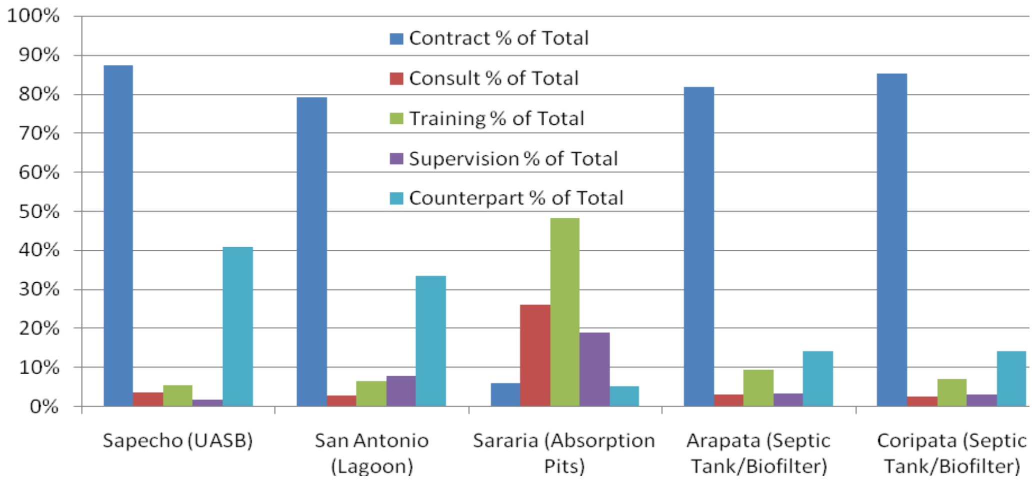

Figure 4. Capital cost breakdown for wastewater systems (data for Palos Blancos not available).

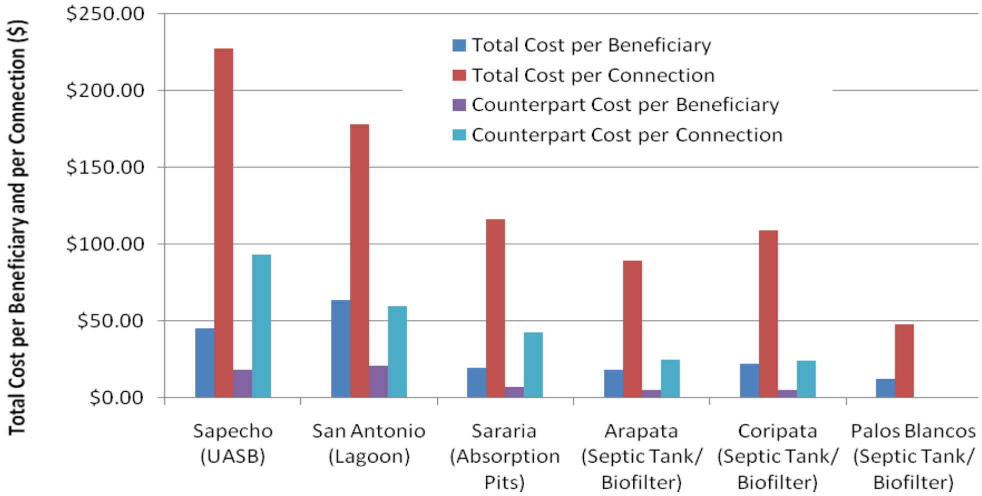

Figure 5. Total and counterpart costs per beneficiary and connection.

Economic Capacity/Willingness to Pay: Residents in Palos Blancos, Sapecho, San Antonio and Sararia were surveyed regarding their willingness to pay for water and wastewater services. The survey question did not differentiate between potable water and wastewater rates; residents typically pay both fees as one sum to the water committee. In Sararia there is no sanitation fee imposed by the water committee because residents manage their own latrines. In Palos Blancos, the municipality does not collect a sanitation fee. Residents were not surveyed about the feasibility of paying a higher fee; willingness to pay a higher fee may not reflect their actual economic capacity to pay. In Palos Blancos and Sararia, 40% and 65% of residents respectively were willing to pay the highest fee (20 Bs/month) for nearly perfect service. However, the communities with larger sewer systems were only willing by plurality to pay 10 Bs/month for present level of service (San Antonio, 41%) or 15 Bs per month for improved service (Sapecho, 53%). These results have not been reflected in recent votes to set or change rates. San Antonio residents recently voted for a rate of 11.5 Bs/month for both water and wastewater services, while Sararia residents set their rate at 15 Bs/month for water only and no fee for sanitation.

Water committee organization: The ability of the community to organize a management system for sanitation services should be considered in the design of sanitation systems. A community that can formalize a water governance system is most likely to maintain and operate the sanitation service at the highest level. For example, San Antonio formed and incorporated a water cooperative with regular meetings, collected fees, hired operators, and building space in order to represent the full community population and manage the water and wastewater utilities. The utilities are well-maintained, and San Antonio has shown the capacity to manage a large sewered wastewater system. On the other hand, a community that cannot organize to govern its own utilities or can more easily govern in sub-groups may more appropriately manage individual or cluster systems (latrines and septic systems). Initiating a sanitation design calls for evaluating (with the community) their organizational capacity.

Urbanization and Migration: Population movement, seasonally and otherwise, is a difficult social problem for sanitation implementation. Seasonality of work can account for use and disuse of any type of wastewater treatment system. In agricultural societies, workers often live in their fields during growing and harvest season, leaving latrines or sewer systems unused at home. Habitations in the field are typically without sanitation. Seasonal habitants may not be interested in paying a fee for basic services at a part-time habitation. In communities which have begun to urbanize, rapid population growth and renters make it difficult for the community to organize for basic service provision. New and seasonal habitants have not had time to build an interest in communal services and often do not want to pay as much for services as permanent, long-standing community members are willing to pay. Likewise, new or non-permanent residents are less likely to be involved in a water committee or cooperative, and may be excluded by service provisions.

Perception/Knowledge: Residents were also surveyed on how well they understand the function and use/maintenance of their sanitation systems. Responses showed that better understanding is correlated to higher training costs (data not shown). In Palos Blancos, where the fewest responders claimed to understand the wastewater system well or very well, no funds had been allocated to training and education. In Sapecho, San Antonio and Sararia, increasing knowledge of the wastewater systems reflects inputs of funds toward training. This indicates that a community may be able to increase its social capacity for accepting a wastewater project through further support of training.

Infrastructure Indicators

Complexity and User Interface: In Sapecho, the total cost for one connection to the sewer network is 800 USD (Martinez, 2008); the cost does not include construction of a home bathroom which would discharge to the sewer. Families constructed bathrooms with other funding in a different project. While the Sapecho residents voted for a single sewer network rather than latrines or condominial systems, stating “we want to live in the city,” misuse and disuse as well as water shortages have caused problems with the sewer system, and have made the Sapecho residents less agreeable to using their bathrooms (Inchausti, 2008). In Sararia, 800 USD is also the cost for one Family Hygiene Unit (FHU: latrine building with toilet, shower, handwashing station and laundry station, piped to a septic absorption well). An FHU is a very high quality building by Bolivian standards; "when a family with an FHU is ready to improve their house they say 'we want our house to be at least as nice as our bathroom,' and they take a step to raise their quality of life" (Martinez, 2008). Families pride themselves on ownership, use and maintenance of the FHU. Despite comparable costs between the sewer connection and the bathroom installation, the use appeared to be very different. Clearly there is a connection between the quality of the user interface of the technology and the use and maintenance.

Design versus Operating Size: We observed that the larger wastewater systems are currently underutilized. They had been designed for much larger hydraulic loadings than they currently receive; the current influent also has a much higher organic (Biochemical Oxygen Demand) concentration than the design organic loading. As the communities develop and urbanize, they will tend to consume more water, increasing the hydraulic load and thus decreasing the organic load, moving toward the design loads. These loads also fluctuate seasonally: during growing seasons, many people in these developing communities live in the fields. During this time, wastewater input into the systems should decrease, but as communities develop, people will tend to stay year-round, increasing the wastewater flows during the entire year. The current fluctuating loads are more difficult to manage and treat than the design loads, and the systems need to be designed to treat current (as well as future) wastewater loads properly.

Technology Water Use and Resources: In the communities where sewers were implemented, we observed challenges related to water needs of wastewater technology. Lack of sufficient water in Sapecho from the existing potable water source limited the sewer's ability to transport waste. The community was constructing a springbox to augment the gravity-fed potable water system in order to improve operation of the sewer. Although this region is not normally considered water-scarce, potable water is typically drawn from distant springs and requires considerable financial, human, and material resources to transport the water to the users. This water need was not considered during the design of the sewer system and reactor; it has placed an additional burden on the water committee and on the community.

Conclusions

The numerous effects of urbanization heavily impact wastewater infrastructure design: systems need to be modular, quickly implemented, cost-effective, health-beneficial, and less dependent on water. Selection of sanitation technologies that are appropriate for specific populations will demand creative solutions in regions where water is scarce and where population density limits the use of traditional dry sanitation technologies such as VIP latrines.

Appropriate and sustainable sanitation must be designed to operate through a range of hydraulic and organic loads as the community develops. Systems such as condominial sewers which are more modular and less water-dependent than large centralized designs may be most effective for meeting this requirement. Along with a range of operation, phased training will be necessary to ensure that operators and managing organizations develop their capacity as the sanitation systems and communities grow and urbanize.

As communities in Bolivia and around the world continue to urbanize, it is important to view wastewater treatment from a systems perspective, included in the larger picture of water resources management. With guidance, communities can plan water resource use into the future, designing wastewater treatment to fit within it. Water use and wastewater treatment should consider societal needs, industrial needs and ecosystem needs, and sanitation systems can be designed to fit into this sustainable framework. Principles of commons governance, green engineering and low impact development can be followed to design wastewater treatment systems within water resource management plans for a sustainable future (Table 2). In a world with a rapidly growing urban population and ever more unpredictable climate, infrastructure which sustainably meets both human (social and economic) and ecological resource needs will allow for the stability necessary to continue to thrive.

Table 2. Principles for sustainable water resource management (adapted from Ballard *et al.*, 2008).

Societal Water: **Commons Governance** (adapted from Ostrom, 1990 in Ramaswami et al., 2007).	**Industrial Water:** **Principles of Green Engineering** (adapted from Anastas and Zimmerman, 2003).	**Ecosystem Water:** **Low Impact Development** (adapted from Davis, 2005).
Define the physical boundaries of water resources and resource users.	Principle 1: Material and energy (*water*) inputs and outputs should be as inherently nonhazardous as possible.	Replicate pre-development hydrologic conditions as closely as possible.
Co-develop water use rules with the community that meets ecological conditions.	Principle 4: Products, processes and systems should maximize mass, energy, space, time (*and water*) efficiency.	Design facilities to minimize environmental disruption, capture rainwater, create pervious surfaces, and minimize soil compaction.
Involve all water resource users in developing rules for resource use through collective choice arrangements and analytic deliberation.	Principle 6: Embodied energy and complexity of natural waters, wastewaters and materials must be viewed as an investment when locating treatment facilities and making design choices for recycle, reuse, or beneficial disposition.	Manage facilities and local ecosystems to collect, store, infiltrate and treat runoff and wastewater; vegetate roofs and lots, and manage water onsite.
Devise mechanisms for monitoring and accountability in water (quantity and quality) and wastewater treatment.	Principle 10: Design of products, processes, and systems must include integration and interconnectivity with available energy and materials (*water*) flows.	Design manufacturing facilities to reduce, reuse, and treat water resources, in conjunction with the local community and ecosystem.

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References

Ahrens, B.T. and J.R. Mihelcic, "Making Wastewater Construction Projects Sustainable in Urban, Rural, and Peri-Urban Areas," *Journal of Engineering for Sustainable Development: Energy, Environment, Health*, Vol. 1, No. 1, pp. 13-32, 2006.

Anastas, P.T. and J.B. Zimmerman, "Design through the 12 Principles of Green Engineering," *Environmental Science and Technology*, pp. 94A-101A, 2003.

Ballard, M.M., A.R. Clarke, A.E. Sather-Knutsen, et al. Final Report: International Sustainable Development Engineering Research Experiences Program, 2007.

Ballard, M.M., V.J. Fuchs, L.M. Fry, H.E. Wright, J.R. Mihelcic and D.W. Watkins, Jr. "Systems Thinking Applied to Industrial Management of Water Resources," *Proceedings of the Global Conference on Sustainable Product Development and Life Cycle Engineering (Sustainability and Remanufacturing VI, SMR VI)*, Busan, Korea, 29 September to October 1, 2008.

Davis, A., "Green Engineering Principles Promote Low Impact Development," *Environmental Science and Technology*, pp. 339A, 2005.

Ezzati, M., A. Rodgers, A.D. Lopez et al. "Mortality and Burden of Disease Attributable to Individual Risk Factors," In Ezzati, M., A.D. Lopez et al. (Eds). *Comparative Quantification of Health Risks: Global and Regional Burden of Disease Attributable to Selected Major Risk Factors*, Volume 2. Geneva, World Health Organization, 2004.

Fry, L.M., J.R. Mihelcic, and D.W. Watkins, Jr. "Water and Nonwater-related Challenges of Achieving Global Sanitation Coverage," *Environmental Science and Technology*, Vol. 42, No. 12, pp. 4298-4304, 2008.

Inchausti, J.C., personal communication with authors, 23 June, 2008.

Martinez, P., personal communication with V.J. Fuchs, 28 June, 2008.

Palos Blancos Municipal Report, (Plan de Desarrollo Municipal Palos Blancos, 2008-2012), Municipality of Palos Blancos, La Paz Department, Bolivia, 2007.

Ramaswami, A., Zimmerman, J.B., and J.R. Mihelcic, "Integrating Developed and Developing World Knowledge Into Global Discussions and strategies for Sustainability. 2. Economics and Governance," *Environmental Science and Technology*, 41: pp. 3422-3430, 2007.

STATcompiler Custom Table, http://www.statcompiler.com/tablebuilderController.cfm?userid=243115&usertabid=264167. Measure Demographic and Health Surveys, table built and accessed March, 2008.

UNESA. *World Urbanization Prospects: The 2003 Revision*. UN Sale No. E.04.XIII.6. UNESA Population Division, New York, 2004.

UN-HABITAT. *Water and Sanitation in the World's Cities: Local Action for Global Goals.* Earthscan Publications, Ltd: London, 2003.

World Health Organization. *World Health Report 2002: Reducing Risks, Promoting Healthy Life*. Geneva: WHO Press, 2002.

World Health Organization Statistical Information System (WHOSIS). *Mortality Country Fact Sheet 2006*, http://www.who.int/whosis/mort/profiles/mort_amro_bol_bolivia.pdf, 2006.