The status of water and sanitation among Pacific Rim nations

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Abstract

Analysis of relationships among national wealth, access to improved water supply and sanitation facilities, and population health indices suggests that the adequacy of water resources at the national level is a poor predictor of economic development – namely, that low water stress is neither necessary nor sufficient for economic development at the present state of water stress among Pacific Rim nations. Although nations differ dramatically in terms of priority provided to improved water and sanitation, there is some level of wealth (per capita GNP) at which all nations promote the development of essential environmental services. Among the Pacific Rim countries for which there are data, no nation with a per capita GNP >US$18,000 per year has failed to provide near universal access to improved water supply and sanitation. Below US$18,000/person-year, however, there are decided differences in the provision of sanitary services (improved water supply and sanitation) among nations with similar economic success. There is a fairly strong relationship between child mortality/life expectancy and access to improved sanitation, as expected from the experiences of developed nations. Here no attempt is made to produce causal relationships among these data. Failure to meet Millennium Development Goals for the extension of improved sanitation is frequently evident in nations with large rural populations. Under those circumstances, capital intensive water and sanitation facilities are infeasible, and process selection for water/wastewater treatment requires an adaptation to local conditions, the use of appropriate materials, etc., constraints that are mostly absent in the developed world. Exceptions to these general ideas exist in water-stressed parts of developed countries, where water supplies are frequently augmented by water harvesting, water reclamation/reuse, and the desalination of brackish water resources. Each of these processes involves public acceptance of water resources that are at least initially of inferior quality. Despite predictions of looming increases in water stress throughout the world, adaptation and resourcefulness generally allow us to meet water demand while pursuing rational economic development, even in the most water-stressed areas of the Pacific Rim.

Keywords: Pacific Rim; sanitation; water supply.

Introduction

We will analyze (i) the status and trajectories of worldwide water supply and sanitation improvements, emphasizing progress among Pacific Rim nations; (ii) factors that contribute to or impede the extension of water supply and wastewater collection systems, including the relationship between economic status and environmental development; and (iii) the role of regional water stress as a determinant of economic growth and human health. In addition, we will illustrate the methods by which nations on the Pacific Rim have elected to reduce water stress. Some emphasis is placed on water availability in semi-arid regions of Australia and the United States, with which we have reasonable familiarity. Material presented by water professionals at the 13th International Meeting of the Pacific Basin Consortium for Environment and Health in Perth during November 2009 reinforces specific points. Because of their recent economic emergence and importance to regional environmental development, the nations of South Asia are included in the Pacific Rim analysis. Health, wealth, and access to improved water/sanitation are probably related. To clarify those relationships, we mined a number of United Nations' and World Health Organization databases. The results of those analyses are summarized.

Progress toward sanitary objectives

For decades, access to adequate water supply has been described as a human right (1). That right has proven elusive, particularly in the poorest nations of the world. Among their Millennium Development Goals (MDG) posited in 2001, the

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192 member states of the United Nations and 23 international organizations agreed to reduce by half the percentages of the world's population without access to improved water supply and sanitation by year 2015 (http://www.unmillenniumproject.org/goals/index.htm). The datum selected for statistical comparisons was 1990. Population growth and demographics make it difficult to satisfy these objectives. In fact, we will miss the MDG for worldwide sanitation, but meet or slightly exceed the goal for drinking water (Figure 1).

The fraction of the world's population without improved sanitation is projected to fall from 46% in 1990 to 36% in 2015. In 1990, 23% were without improved water service, but that figure is expected to reach just 9% in 2015. The world's population increased from 5.3 billion in 1990 to 6.75 billion in 2008, with the most rapid growth in nations within the lowest economic strata. Thus, an estimated 1.3 billion people gained access to improved sanitation during 1990–2008, but those without improved sanitation numbered 2.4 billion in 1990 and 2.6 billion in 2008. About 1.2 billion people were without access to improved drinking water in 1990. That number fell to 0.9 billion in 2008, as improved water supply was extended to almost 1.8 billion people. Figures 2A and B show the percentage of the population of Pacific Rim countries without improved sanitation and drinking water service.

The enormous influence of China and India on water and sanitation statistics is easy to illustrate. Together, China and India represented about 38% of the world population in 1990 and 37% in 2008 – essentially a constant fraction. From 1990 to 2008, the percentage of people in India without access to improved sanitation decreased from 82% to 69% (Table 1, Figure 2A) – hardly a 50% reduction. In China, the corresponding figures are 59% and 45%. In 1990, the two nations together accounted for 56% of those without access to improved sanitation. In 2008, that figure remained at 54%, and the number of those in India/China without such access increased slightly. Without greater progress toward improved sanitation in China and India, the remainder of the developing
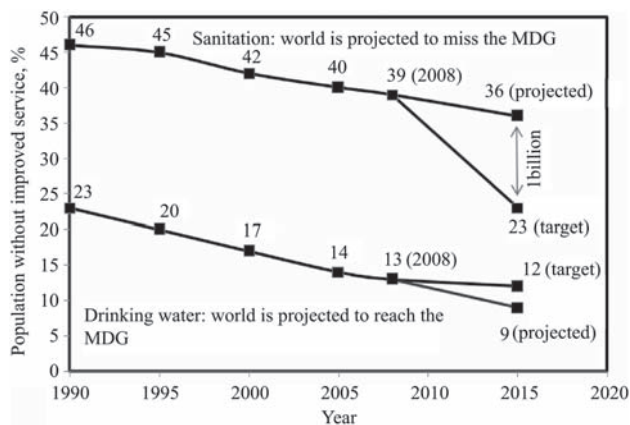

Figure 2 (A) Percent of population without improved sanitation by country in the Pacific Rim region (2008). Source: WHO/UNICEF. (B) Percent of population without improved drinking water by country in the Pacific Rim region (2008). Source: WHO/UNICEF.

Figure 1 Pursuit of MDG for access to improved water/sanitation. Primary MDGs are to halve the percentages of those without access to improved sanitation and water supply by 2015. The water access goal is likely to be satisfied, but the sanitation goal will not.
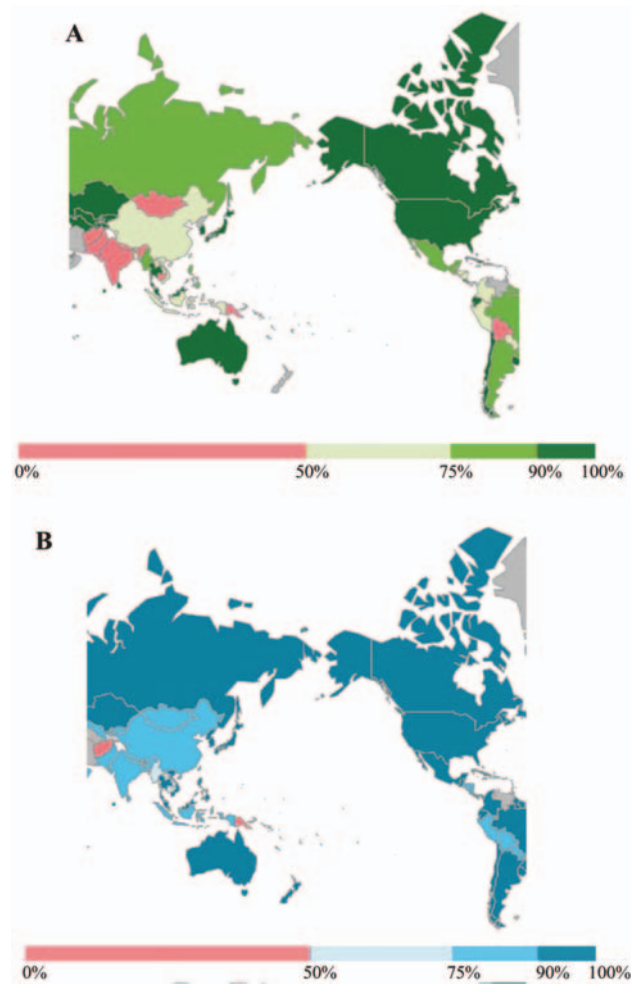
world must provide essentially universal access to improved sanitation by 2015 to satisfy the MDG. The pace of economic development in India and China is the fastest in the world, and the influence of these giants on the trajectory of global environmental health is likely to be overwhelming – for better or for worse.

Cause and effect – national wealth and sanitation

We took a high-altitude look at the UN data for Pacific Rim nations to see if there are obvious nation-specific factors that limit or, conversely, facilitate achievement of water supply and sanitation objectives. Water-related, economic, and health-related statistics, including access to improved drinking water and sanitation by nation, are provided for most countries on the Pacific Rim (Table 1). To expose levels of

Table 1   Statistics related to geography, economy, water use, sanitation and health among Pacific Rim nations.

A. Geography/economy	Population 2008 (1000s)	Area, 10^3 km^2	Gross national product per capita (2009)	ΔGNP (2009)–Pop growth rate (2005–2010)
Developed countries (subtotal)	497,522	27,933	$41,850.00	
Australia	21,074	7692	$38,800.00	−0.2
Canada	33,259	9985	$38,400.00	−3.3
Japan	127,293	357	$32,600.00	−5.7
United States	311,666	9629	$46,400.00	−3.4
New Zealand	4230	270	$27,300.00	−2.2
Developing countries (by region)				
North/Central America (subtotal)	149,279	2396	$11,500.00	
Costa Rica	4519	51	$10,900.00	−4.0
El Salvador	6134	21	$7,100.00	−3.7
Guatemala	13,686	42	$5,200.00	−3.0
Honduras	7319	112	$4,200.00	−5.1
Mexico	108,555	1964	$13,500.00	−7.6
Panama	3399	76	$11,900.00	−4.1
Nicaragua	5667	130	$2,800.00	−4.2
South America (subtotal)	104,134	3439	$9,700.00	
Chile	16,804	756	$14,700.00	−2.5
Colombia	45,012	1142	$9,200.00	−1.4
Ecuador	13,481	256	$7,400.00	−2.1
Peru	28,837	1285	$8,600.00	−2.2
Eastern Asia (subtotal)	1,432,382	9854	$7,710.00	
China	1,337,411	9597	$6,600.00	+9.4
Korea DPR	23,819	121	ND	+3.4
Korea Rep	48,152	100	$28,000.00	−1.1
Taiwan	23,000 (2010)	36	$29,800.00	−2.9
Southern Asia (subtotal)	1,638,945	6488	$3,230.00	
Afghanistan	27,208	652	$935.00	−0.5
Bangladesh	160,000	144	$1,465.00	+4.0
India	1,181,412	3201	$3,100.00	+7.0
Iran	73,312	1629	$11,172.00	+1.2
Pakistan	176,952	796	$2,600.00	+0.9
Sri Lanka	20,061	66	$4,500.00	+3.0
Southeast Asia (subtotal)	574,526	4436.50	$4,725.00	
Brunei	392	5.8	ND	−4.0
Cambodia	14,562	181	$1,905.00 (2008)	−3.2
Indonesia	227,345	1860	$4,000.00	+3.2
Laos	6205	237	$2,266.00	+0.47
Malaysia	27,014	331	$14,800.00	−4.5
Myanmar	49,563	677	$1,200.00	+0.1
Philippines	90,348	300	$3,300.00	−0.8
Singapore	4615	0.7	$50,523.00	−4.3
Thailand	67,386	513	$8,100.00	−3.5
Vietnam	87,096	331	$2,900.00	+4.0
Total	4,396,788		$9,700.00	

B. Water use	Renewable freshwater, km^3/year	Annual freshwater withdrawal, km^3/year	Fraction of total resource withdrawn	Renewable freshwater per capita, m^3/person-day
Developed countries (subtotal)	7594.3	636.32	0.084	41.8
Australia	398.0 (1995)	24.06 (2000)	0.06	51.9
Canada	3300.0 (1985)	44.72 (1996)	0.014	271.8
Japan	430.5 (1999)	88.43 (2000)	0.206	9.3
United States	3069.0 (1985)	477.00 (2000)	0.155	27
New Zealand	397.0 (1995)	2.11 (2000)	0.005	257.1

(Table 1 continued)

B. Water use	Renewable freshwater, km³/year	Annual freshwater withdrawal, km³/year	Fraction of total resource withdrawn	Renewable freshwater per capita, m³/person-day
Developing countries (by region)				
North/Central America (subtotal)	1146.7	87.17	0.076	21
Costa Rica	112.4 (2000)	2.68 (2000)	0.024	68.1
El Salvador	25.2 (2001)	1.28 (2000)	0.051	11.3
Guatemala	111.3 (2000)	2.01 (2000)	0.018	22.3
Honduras	95.9 (2000)	0.86 (2000)	0.009	35.9
Mexico	457.2 (2000)	78.22 (2000)	0.171	11.5
Panama	148.0 (2000)	0.82 (2000)	0.006	119.3
Nicaragua	196.7 (2000)	1.30 (2000)	0.007	95.1
South America (subtotal)	5399	60.37	0.011	142
Chile	922.0 (2000)	12.55 (2000)	0.014	150.3
Columbia	2132.0 (2000)	10.71 (2000)	0.005	129.8
Ecuador	432.0 (2000)	16.98 (2000)	0.039	87.8
Peru	1913.0 (2000)	20.13 (2000)	0.011	181.7
Eastern Asia (subtotal)	3043.4	577.37	0.194	5.8
China	2829.6 (1999)	549.76 (2000)	0.194	5.8
Korea DPR	77.1 (1999)	9.02 (2000)	0.117	8.9
Korea Rep	69.7 (1999)	18.59 (2000)	0.267	3.9
Taiwan	67.0 (2000)	ND	ND	8
Southern Asia (subtotal)	3604.7	1003.38	0.278	6
Afghanistan	65.0 (1997)	23.26 (2000)	0.358	6.5
Bangladesh	1210.6 (1999)	79.40 (2000)	0.066	20.7
India	1907.8 (1999)	645.84 (2000)	0.339	4.4
Iran	137.5 (1997)	72.88 (2000)	0.53	5.1
Pakistan	233.8 (2003)	169.39 (2000)	0.725	3.6
Sri Lanka	50.0 (1999)	12.61 (2000)	0.252	6.6
Southeast Asia (subtotal)	7062.5	315.05	0.045	33.7
Brunei	8.5 (1999)	0.09 (1994)	0.011	59.4
Cambodia	476.1 (1999)	4.08 (2000)	0.009	89.6
Indonesia	2838.0 (1999)	82.78 (2000)	0.029	34.2
Laos	333.6 (2003)	3.00 (2000)	0.009	147.3
Malaysia	580.0 (1999)	9.02 (2000)	0.016	58.8
Myanmar	1045.6 (1999)	33.23 (2000)	0.032	57.8
Philippines	479.0 (1999)	28.52 (2000)	0.06	14
Singapore	0.6 (1975)	0.19 (1975)	0.317	0.36
Thailand	409.9 (1999)	82.75 (2000)	0.202	16.7
Vietnam	891.2 (1999)	71.39 (2000)	0.08	28
Total	27,850.30	2679.66	0.096	

C. Sanitation and health/welfare	% Pop w/ unimproved sanitation (1990/2008)	% Pop w/ unimproved drinking water (1990/2008)	Under 5 mortality (per 1000)	Life expectancy (WHO 2005–10)	HDI (2007)
Developed countries					
Australia	0/0	0/0	6	81.2	0.970
Canada	0/0	0/0	6	80.7	0.966
Japan	0/0	0/0	4	82.6	0.960
United States	0/0	1/1	8	78.2	0.956
New Zealand	ND	0/0	6	80.2	0.950
Developing countries (by region)					
North/Central America					
Costa Rica	7/5	7/3	10	78.8	0.854
El Salvador	25/13	26/13	36	71.9	0.747
Guatemala	35/19	18/6	47	70.3	0.704
Honduras	56/29	18/14	41	70.2	0.732
Mexico	34/15	15/6	28	76.2	0.854
Panama	42/31	16/7	24	75.5	0.840
Nicaragua	57/48	26/15	38	72.9	0.699
South America					
Chile	16/4	10/4	9	78.6	0.878

(Table 1 continued)

C. Sanitation and health/welfare	% Pop w/ unimproved sanitation (1990/2008)	% Pop w/ unimproved drinking water (1990/2008)	Under 5 mortality (per 1000)	Life expectancy (WHO 2005–10)	HDI (2007)
Colombia	32/26	12/8	21	72.9	0.807
Ecuador	31/8	28/6	27	75	0.806
Peru	46/38	25/18	34	71.4	0.806
Eastern Asia					
China	59/45	33/11	37	73	0.772
Korea DPR	ND	0/0	55	67.3	ND
Korea Rep	0/0	ND/2	5	78.6	0.937
Taiwan	ND	ND	ND	78	0.943
Southern Asia					
Afghanistan	ND/63	ND/52	257	43.8	0.352
Bangladesh	61/47	22/20	69	64.1	0.543
India	82/69	28/12	87	64.7	0.612
Iran	17/ND	9/ND	39	71	ND
Pakistan	72/55	16/10	103	65.5	0.572
Sri Lanka	30/9	33/10	15	72.4	0.759
Southeast Asia					
Brunei	ND	ND	ND	77.1	0.920
Cambodia	91/71	65/39	140	59.7	0.593
Indonesia	67/48	29/20	41	70.7	0.734
Laos	ND/47	ND/43	91	64.4	0.619
Malaysia	16/4	12/0	7	74.2	0.829
Myanmar	ND/19	43/29	106	62.1	0.586
Philippines	42/24	16/9	36	71.7	0.751
Singapore	1/0	0/0	3	80	0.944
Thailand	20/4	9/2	26	70.6	0.783
Vietnam	65/25	42/6	23	74.2	0.725

Box 1 Measured progress in drinking water supply and sanitation rests upon the following definitions or characteristics of improved versus unimproved drinking water and sanitation facilities.

IMPROVED	UNIMPROVED
	SANITATION
Flush or pour-flush to piped sewer	Flush or pour-flush to anywhere else
Septic tank or pit latrine	Pit latrine without slab/open pit
Ventilated, improved pit latrine	Bucket
Pit latrine with slab	Hanging bucket or hanging latrine
Composting toilet	Shared facility of any type; no facility, open defecation
	DRINKING WATER
Piped water into dwelling or yard	Unprotected dug well
Public tap or standpipe	Unprotected spring
Tubewell or borehole	Cart with tank or drum
Protected dug well	Tanker truck
Protected spring	Surface water (direct)
Rainwater collection	Bottled water

From WHO/UNICEF [http://www.wssinfo.org/]: An improved sanitation facility is one that hygienically separates human excreta from human contact. An improved drinking-water source is one that by the nature of its construction adequately protects the source from outside contamination, in particular with fecal matter. Access to an improved supply does not ensure that the water provided is safe to drink.

water resources stress, the table includes estimates of the total renewable freshwater supply and annual water consumption. The renewable fresh water resource of a nation is the average quantity of fresh water available for use over a 1-year period from precipitation minus evapotranspiration, plus annual inflow by rivers and underground flow. A degree of double counting is reflected in the water resource numbers because surface flows sometimes cross international boundaries, leading to modest overestimation of water resource availability. The total freshwater consumption among the countries listed is about 10% of their combined renewable freshwater resource, a value close to the world average (2), but that ratio varies substantially from one region to another – from <1% in Honduras, Panama, Colombia, and Cambodia to >30%, as

in Afghanistan, India, Iran, Pakistan, and Singapore. India, Afghanistan, and Pakistan are approaching or beyond the UN-established level of high water-related stress (0.40 fractional use), at which water scarcity is alleged to limit economic growth. In Pakistan, an incredible 72.5% of the renewable water resource volume is used annually. The data suggest that South Asia (Sri Lanka, India, Afghanistan, Iran, and Pakistan) will not readily expand its agricultural economy due to water resource limitations.

Recent economic data suggest that water stress does not generally preclude economic growth. Here we took the percentage change in gross national product during 2009 minus the average annual population growth during 2005–2010 as a measure of relative economic growth (Table 1). Despite global recession, the relative economic growth in most of South Asia was positive. The values in India and Bangladesh were among the highest in the world. Japan, the United States, Mexico, China, Korea, and Sri Lanka each consume 16%–27% of their renewable water resource, placing their respective national levels of water stress at moderate to medium–high [Box 2; (3, 4)]. Nevertheless, the per capita GNP values in these countries span an order of magnitude. It seems that water stress and economic status/rate of development are not tightly coupled.

Conversely, it is certain that abundant water does not guarantee economic success or widespread access to an improved water supply. Many of the world's poorest nations in terms of per capita GNP use a minute fraction of their respective water resources (Figure 3) and are on a poor trajectory toward access to improved water supplies. Nations with a per capita GNP of less than US$5000 per year include Honduras, Nicaragua, Bangladesh, Sri Lanka, India, Afghanistan, and Pakistan. In this group, Honduras, Nicaragua and Bangladesh use <10% of their renewable water resources – Nicaragua and Honduras, <1%. South Asia and China, however, which are experiencing the highest rates of economic growth in the world, are water stressed, with ratios of consumptive use to renewable supply from 0.2–0.7.

Indochina provides another specific example. Vietnam, Laos, and Cambodia have reasonably similar per capita GNPs and water availabilities, yet 94% of Vietnamese have access to improved water, whereas almost 40% of Laotians and Cambodians lack improved water supplies. Although low
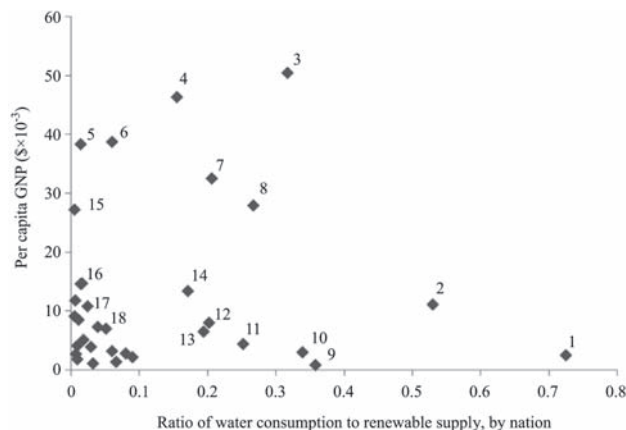

Figure 3 Per capita GNP versus fractional water use in Pacific Rim countries. Key: 1 – Pakistan, 2 – Iran, 3 – Singapore, 4 – USA, 5 – Canada, 6 – Australia, 7 – Japan, 8 – Korea, 9 – Afghanistan, 10 – India, 11 – Sri Lanka, 12 – Thailand, 13 – China, 14 – Mexico, 15 – New Zealand, 16 – Chile, 17 – Costa Rica, 18 – El Salvador, 19 – Vietnam, 20 – Bangladesh, 21 – Cambodia, 22 – Laos, 23 – Indonesia, 24 – Panama, 25 – Honduras, 26 – Malaysia, 27 – Colombia, 28 – Peru, 29 – Nicaragua, 30 – Philippines, 31 – Ecuador, 32 – Guatemala.

water stress is clearly a preferred condition, low water stress seems to be neither necessary nor sufficient for national economic prosperity, rapid economic growth, or universal access to improved water supply (Figures 3 and 4).

Access to improved sanitation generally lags behind the provision of water from improved supplies (Figure 5) and provides a slightly different perspective. The summary of UN data (Figure 6) suggests that access to sanitation is inevitably extended as nations acquire sufficient wealth. That is, essentially, no Pacific Rim countries lie below the dotted line shown. The dashed line represents the likely trajectory of sanitation improvements in nations that are slowest to extend such access – that is, in those nations where improved sanitation is a low-priority endeavor. The performances of most developing nations place them far above the dotted-line relationship, and the solid line in the figure represents the central tendency among Pacific Rim countries. It is relevant to ask why some nations accelerate the extension of sanitation and some do not. Improvement in public sanitation between 1990 and 2008 was

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Box 2 The World Water Council has formally established four degrees of water stress based on the ratio of annual demand to renewable water resources as follows: [http://www.worldwatercouncil.org/index.php?id=25]

- Low: use of <10% of available fresh water – no major stress on available resources.
- Moderate: use of 10%–20% of available water – availability is becoming a limiting factor, and significant effort/investments are needed to increase supply/reduce demand.
- Medium–high: water withdrawals of 20%–40% of renewable volume – management of both supply and demand is required to ensure that use is sustainable. The need to resolve competing human uses is typically increasing, and human needs compete with aquatic ecosystems for water.
- High: use of >40% of available water. Serious scarcity is indicated, usually accompanied by an increasing dependence on desalination and groundwater mining. There is an urgent need for intensive management of supply and demand. Water scarcity becomes a limiting factor to economic growth.
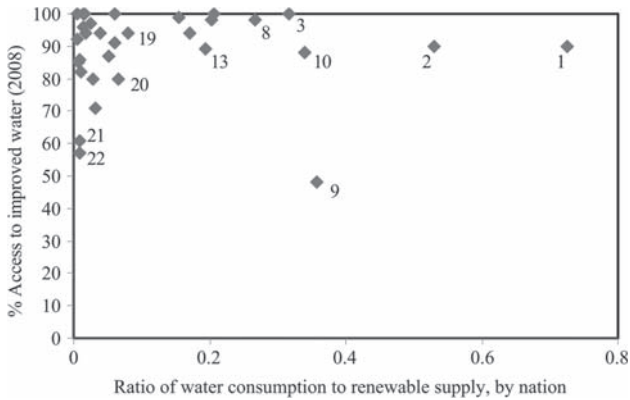
Figure 4   Percent of population with access to improved water supply in 2008 (UN estimate) as a function of water stress. Countries by number are listed in Figure 3.
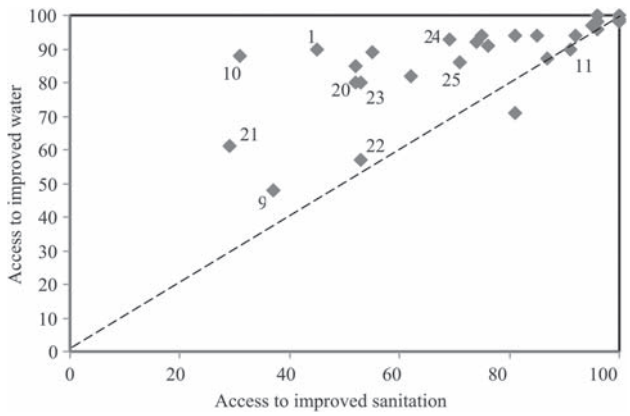

Figure 5   Correlation between percent of population with access to improved water supply and access to improved sanitation, by nation. The position of nations relative to the 1:1 line shows that water supply improvements generally precede access to improved sanitation. Countries by number are listed in Figure 3.

Figure 6   Percent of people with access to improved sanitation as a function of wealth (by nation). Year 2008–09 UN data. The dashed line represents a lower-bound to the data envelope, while the solid line is a least-squared error fit to all the data, represented by $y=100[1-\exp(-0.216x)]$, where x is per capita GNP and y is percent with access to improved sanitation. Countries by number are listed in Figure 3.

Figure 7   Fractional reduction in percentage of those without improved sanitation, by country (1990–2008), as a function of per capita GNP in 2009. Fractional improvement in access to sanitation is defined as the fraction of population without such access in 1990 minus the fraction without sanitation in 2008, divided by the fraction without access to sanitation in 1990. Solid lines represent linear fits to specific groups of data: the low GNP group fit is $y=0.090x+0.050$, the high GNP group fit is $y=0.087x-0.595$. Countries by number are listed in Figure 3.

not obviously related to national wealth (Figure 7). Perhaps using more imagination than is warranted, it is possible to separate nations represented in the figure into groups with per capita GNPs (i) above, and (ii) below US$8000 per year, leading to fairly strong correlations for nations in each group (Figure 7). That is, a positive correlation is seen between national performance in providing access to improved sanitation from 1990 to 2008 and average per capita GNP among those nations with GNP/population <US$8000 per year. A second positive correlation is apparent for nations with a 2008 per capita GNP >US$8000 per year, although the higher and lower GNP groups of nations are clearly separate.

Significant among the weaknesses of the analysis is the lack of convincing causative explanations for the disparity in national performances among those nations that lie near the US$8000 per person-year line of demarcation. The great differences between Ecuador and Thailand, where considerable progress was made in extending sanitation to the public between 1990 and 2008, and Peru and Colombia, where
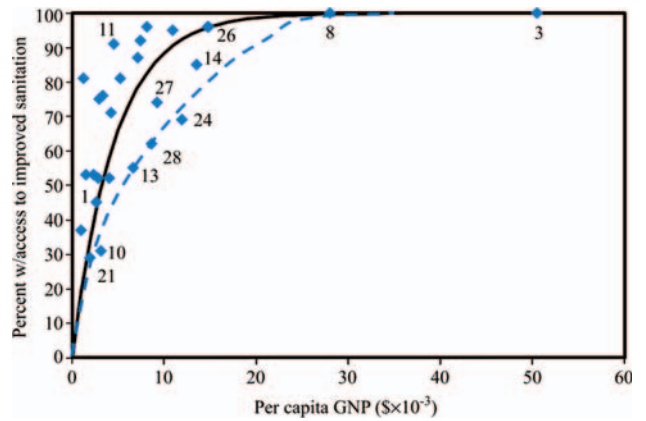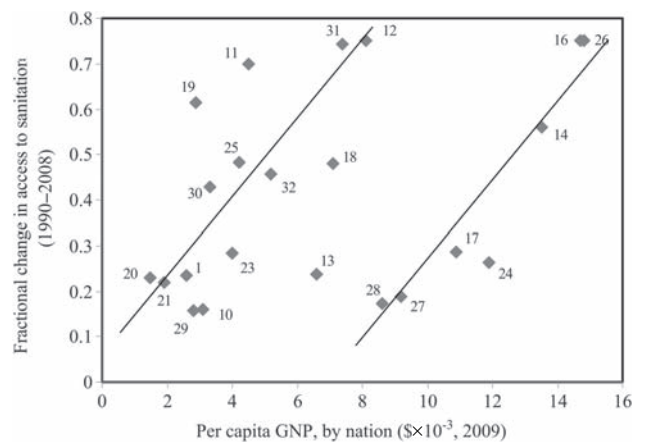
relatively little progress was made, remain unexplained. Costa Rica was removed from the comparison because access to sanitation in that country is approaching universal (95% in 2008). There is also no clear reason for the relatively poor performance of China, although it may be difficult to provide access to improved sanitation in countries with large rural populations. Economic and non-economic factors apparently affect the rate of implementation of sanitation improvements in developing countries. Non-economic explanations lie in government stability or environmental and public health priorities. Related hypotheses are beyond the present scope.

Adequate wealth undoubtedly offers nations an opportunity to expand public access to improved water supply and sanitation services. When countries have sufficient wealth, governments that possess the necessary organization, determination, and energy succeed (Figure 6). Overachievers in terms of providing access to sanitation appear to include Vietnam, Sri Lanka, Ecuador, and Thailand, where progress toward adequate sanitation has occurred in advance of economic progress, at least relative to other countries. Nations with relatively poor performance in this area include Peru, Colombia, and to some extent China. It follows that the level of wealth at which access to improved water supply/sanitation is provided is a matter of government priority. It would be interesting and perhaps instructive to determine the cultural, demographic, and institutional factors that contribute to relative success in this area.

China's growing influence in the Far East and beyond makes it impossible not to dwell on that country's water and sanitation situations. Particularly, China's approach to recognizing and solving rural water supply problems is of interest in this context. It is estimated that 320 million rural inhabitants of China drink water from unsafe supplies. Although the most common type of water issues are related to biological contaminants, 63 million drink water with fluoride content >2 mg/L – more than double the national standard. This number dwarfs the numbers of those exposed to high arsenic levels (2.3 million) and schistosomiasis (11 million) through their water supply. At levels >1.5 mg/L, chronic exposure to fluoride in water leads to fluorosis of teeth and bones. In some areas of China, exposure routes include both water supply and indoor air – when coal that is burned for heat contains high fluorine levels. Fluoride removal technologies that have been investigated for widespread deployment in rural China include alum coagulation/sedimentation, adsorption on powdered activated carbon, electrolytic decomposition of an aluminum anode (coagulation), adsorption on activated alumina or bone charcoal, electrodialysis, reverse osmosis, and electro-sorption. Each carries specific advantages and disadvantages. The disadvantages of alum coagulation, for example, include the need for skilled operation, chemical demand, and sludge disposal requirements. Ion exchange on activated alumina is handicapped in the presence of competing anions, including hydroxide and bicarbonate ions, and to be effective must be carried out at relatively low pH. Electrolytic and membrane treatment technologies tend to be energy intensive. The conclusion was that while several of the candidate processes were well suited for deployment in situations in which Chinese villages were relatively advanced technologically, adsorption to bone charcoal or well relocation were the best solutions to fluoride problems when such sophistication was absent. Alternative water sources such as harvested rainfall are also a possible remedy.

Box 3   In water-short developing countries – making do.

From a water supply perspective, the worst-case situation clearly arises in nations or regions where water stress is severe and public funds cannot support traditional water resources development – generally where the indicators of water stress are high and per capita GNP is low. Where there is water stress, expansion of the regional water supply inevitably requires development of water resources of impaired initial quality. These could include, for example, municipal or industrial wastewaters, ground waters with relatively high metal/metalloid content, and so forth. Absent the capital required for widely deployed water treatment processes, it may be necessary to think beyond conventional water purification strategies that are appropriate for developed nations. Examples of such approaches follow.

Wastewater from Mexico City is extensively used for crop irrigation in nearby agricultural areas. Following infiltration, the quality of recovered irrigation water is much improved and may be suitable for local potable use or replenishing over-subscribed aquifers in Mexico City that serve as municipal water sources (5). Management solutions of this kind would probably be rejected where good quality water is more readily available or where adequate public funds exist for traditional engineered wastewater purification systems.

In Pakistan, a variety of natural materials have been tested as sorbents for removal of metals from contaminated groundwater resources. Metals of interest in this context include copper, lead, cadmium, and nickel, sometimes presented in concert. A promising sorbent is okra leaves, which near neutral pH show exceptional affinity for copper, lead, and cadmium. Leaf affinity for nickel increases dramatically above pH 9, probably as a consequence of pH-dependent changes in Ni(II) speciation. A summary of metal-specific adsorption capacities for okra leaves follows:

- Copper (II)   453 mg/g
- Lead (II)   81 mg/g
- Cd (II)   13.8 mg/g
- Ni (II)   1.0 mg/g

Nickel adsorption characteristics are greatly improved in alkaline solutions. (From material presented at the 13th International Conference of the Pacific Basin Consortium in Perth, 2009.)

In addition to favorable sorption characteristics, materials useful for water purification must be readily available at low cost and in great quantity. Waste products are preferred for obvious reasons. Okra leaves and perhaps other materials that have not yet been identified can satisfy those criteria, and it is possible that similar approaches can be taken to remove oxyanions such as arsenate ion from ground water inexpensively. Such approaches could provide at least a bridge to more established water purification strategies after better economic conditions evolve. Low cost technological approaches for arsenic and fluoride removal from water are of exceptional importance because of the numbers affected in India, Bangladesh, Taiwan, and so forth.

Sanitation and human health

At least as important is the potential relationship between access to adequate sanitation and improved human health. Widely available statistical indications of population health include (i) life expectancy at birth and (ii) child mortality rates – i.e., the fraction of newborns that die in their first five years of life. In fact, these national health statistics are themselves highly correlated in data derived from the Pacific Rim nations (Figure 8), as might be expected, so that a strong relationship between any of a variety of independent variables (per capita GNP, access to sanitation, literacy rate, among others), and either dependent variable (life expectancy or child mortality) necessarily implies a relationship with the other. The apparent influence of access to sanitation on child mortality is plain (Figure 9). The line indicating central tendency in the figure suggests that halving the fraction of people without access to improved sanitation from 46% to 23% would decrease

the child mortality rate from about 50 per thousand to perhaps 20 per thousand and increase expected life from 66 to 73 years of age. Of course, it is naive to apply the supposed relationships between health indicators and sanitation in this way. Although there is a functional dependence of population health on access to sanitation, no cause-effect relationship has been shown, and improved health could more accurately be a function of superior pre-natal care or other health-related services in nations with healthier populations. Furthermore, the non-linear relation between child mortality and sanitation suggests that public health could depend on the distribution of sanitary improvements within countries as opposed to national average values. Finally, a relatively high degree of scatter in health data is unexplained by access to sanitation, indicating that other factors contribute significantly to population health. An examination of improved water supply as a determinant of population health was not undertaken because clean water alone, without accompanying sanitation improvements, is unlikely to achieve health related aims, and because improved water supply generally precedes sanitation improvements among the nations examined (Figure 5).

Literacy, life expectancy, and per capita GNP determine the UN's human development index (HDI), a composite statistical representation of population well-being. The relation between HDI and access to improved sanitation (Figure 10) represents an attempt to include other population characteristics that are potentially related to national access to sanitation. Not surprisingly, HDI and development of sanitary services are related among nations on the Pacific Rim. The figure suggests that the greatest overachievers in terms of sanitation are Myanmar and Afghanistan. In the latter case, however, the distinction is of dubious value owing to the nation's low HDI. Even at <40% access to improved sanitation, Afghanistan performs well above expectations based on HDI. The accuracy of sanitation data from Myanmar may be the origin of above average performance in that nation. Among the nations
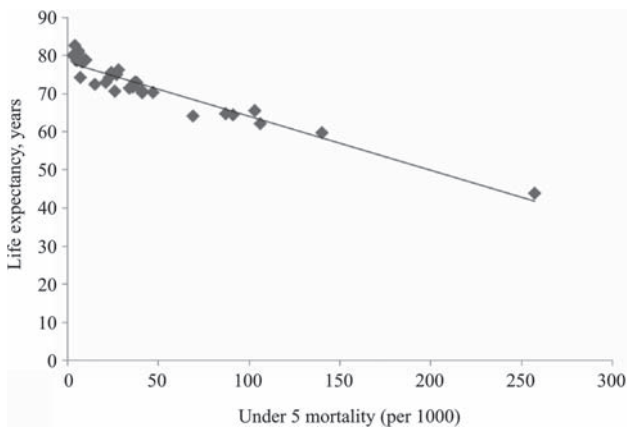

Figure 8 Life expectancy versus child mortality for Pacific Rim countries. The solid line represents the fit: y=–0.142x+78.2.
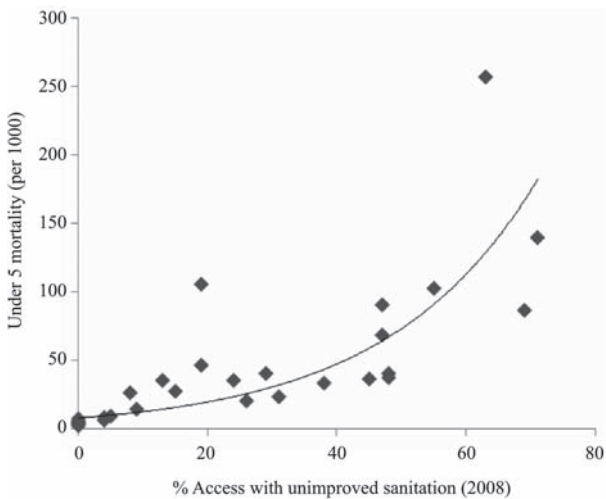

Figure 9 Correlation between access to sanitation and child mortality rates for Pacific Rim countries. The solid line corresponds to the fit: y=8.54exp(0.043x).
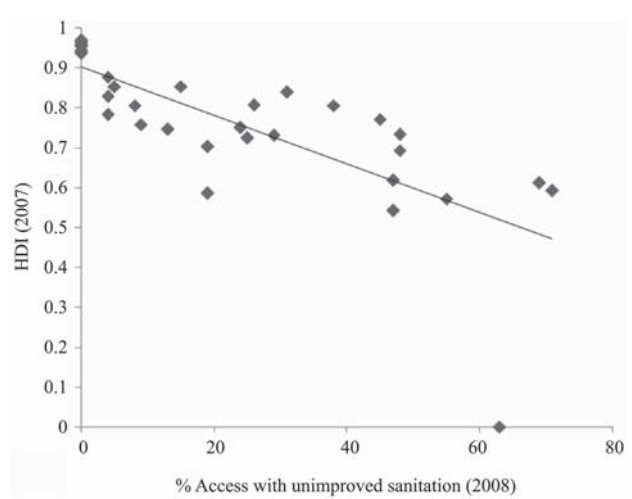

Figure 10 Correlation between HDI and access to sanitation for Pacific Rim countries. The solid line corresponds to the fit: y=–0.0061x+0.9026.

with below-expected access to sanitation based on the HGI are Peru, Panama, and China.

Australian experiences

In large, geographically diverse nations (e.g., China, the United States, and Australia), nationwide averages offer limited insight regarding water stress due to inter-regional differences in water availability. Spatial/temporal variation in rainfall/water availability in Australia, for example, exceeds that of other continental regions and illustrates the utility of regional statistics for assessment of water resource sufficiency. The Australian record since 1985 (Figure 11) indicates that the national average annual rainfall is ≈450 mm per year. Were all this water somehow available for human use, the renewable freshwater resource in Australia would amount to 465 m³ per person per day, a volume greater than that enjoyed by any other Pacific Rim nation (Table 1). Because only about 10% of rainfall is available as runoff or replenishes the useable groundwater resource, however, the 2004–2005 volume of renewable water was just 32.7 m³ per person (Australian Bureau of Statistics, http://www.abs.gov.au/AUSSTATS/abs@.nsf/mf/4610.0/). Water consumed in Australia during the same relatively dry year was 7.7% of that value, supporting the Table 1 data that Australian freshwater withdrawals, on average, amount to only about 6% of the available renewable resource (low water stress, Box 2).

In 2004–2005, the population of Australia was just over 20 million, or about equal to that of Sri Lanka, distributed over an area more than 100 times Sri Lanka's. It is hardly surprising that an enormous variation is seen in the spatial and temporal patterns of Australian rainfall/runoff (Figure 12) or that the regional water shortages can be acute despite the overall abundance of water. Ample recent evidence indicates that Australian geographic diversity is also evident in demand patterns. Whereas the nationwide ratio of agricultural to municipal water use is nearly 7:1, Australia's population is highly concentrated in relatively few urban areas, so that the regional distortions in this ratio are considerable. In Sydney
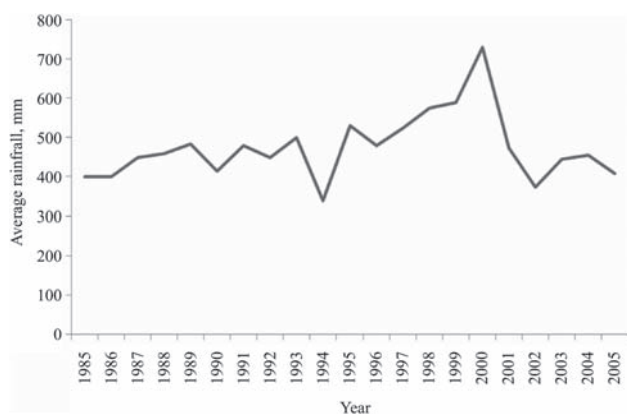

Figure 11 National average annual rainfall in Australia (1985–2005).

and surroundings, for example, 70% of water consumption is domestic (http://www.cityofsydney.nsw.gov.au/). The data regarding water availability/use in five Australian states [New South Wales, South Australia (SA), Queensland, Tasmania, and Western Australia (WA)] in 2004–2005 are provided for illustration (Table 2).

The water resources of South Australia in 2004–2005 clearly fit anyone's definition of highly stressed. The volume of water consumed for domestic and industrial purposes was at least as great as the estimated runoff, and water in storage could satisfy normal demand for only a month. Stress arose from a combination of factors. First, the average rainfall in South Australia was just 150 mm (roughly one-third of the long-term national average). This amount was 30% of the rainfall in New South Wales, which itself experienced water shortage in 2000–2005, and 60% of the average rainfall in Western Australia. The runoff in South Australia was <1% of rainfall, unlike NSW and WA, where the runoff was almost 9% and 4% of rainfall, respectively. Water demand in SA is entirely consumptive, a consequence of agricultural development and domestic use. Agriculture accounted for 75% of the total demand in 2004–2005. The domestic water supply was 11% of demand. In NSW, 69% of water consumption was for agriculture, and in WA that figure was 36%. Finally, SA has very little water storage capacity. In 2004–2005, the acknowledged capacity of its large dams was just 258×10⁶ m³, including dead storage, or <20% of annual consumptive demand. Actual water in storage was 8.5% of annual consumption – or enough water for about a month. In NSW, the storage capacity was four times annual consumption during the same period, and actual water in storage was 140% of annual consumption. In WA, where water supply was far less stressed, the storage capacity was >8 times the 2004–2005 consumption, and the volume of water stored was 6.8 times the volume of water consumed annually. The ratio of water consumption to runoff in 2004–2005, a dry year, in the five Australian states ranged from 106% (SA) to 1.4% (Tasmania), a difference of almost two orders of magnitude. Regional differences in levels of water stress in Australia span a range as broad as those reported for the Pacific Rim nations as a whole (Table 1). Thus, although national statistics suggest that stress on Australian water resources is minimal, an inspection of the country's regional water resources in relation to demand leads to a very different conclusion.

Rainwater harvesting has grown into a well-accepted practice in rural Australia as a means for augmenting water supply. In SA, households using tank rainwater as their primary source of drinking water are as numerous as those that rely on centrally distributed water. Rainfall is collected primarily from rooftops and stored in tanks without treatment pending unrestricted potable use. Evidence of fecal contamination from birds, etc., in stored water is readily available, suggesting that water harvesting has the potential to influence waterborne disease incidence – particularly gastroenteritis. Comparison of gastroenteritis data, however, representing populations of children aged 4–6 years who drank (i) tank rainwater or (ii) water from public supplies produced no statistically significant differences. The study involved a thousand subjects
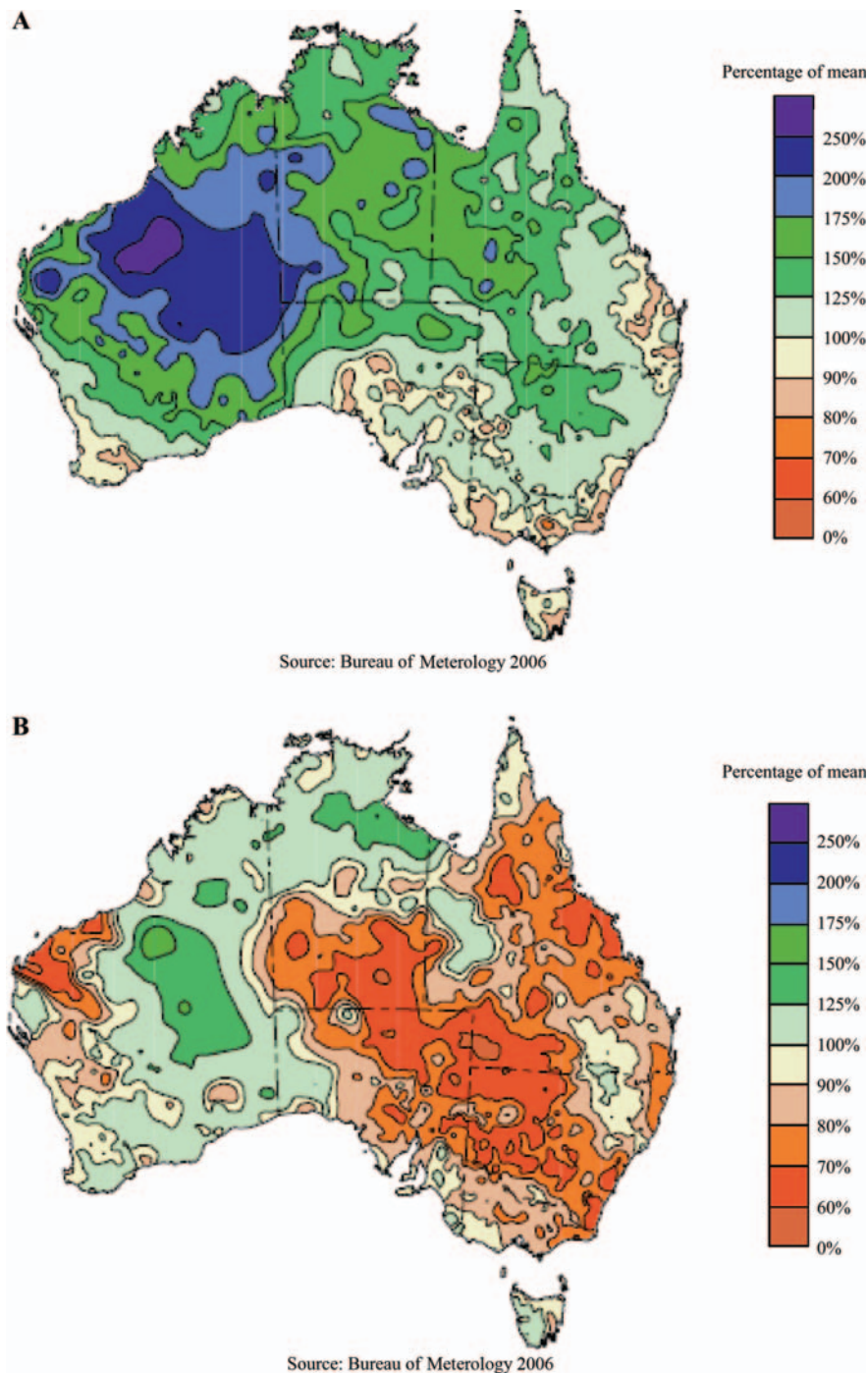
Figure 12   Spatial distribution of rainfall throughout Australia during (A) 1998–2001, a relatively wet period, and (B) 2002–05, among the drier periods in the 21-year record of Figure 11. Values represent the ratio of rainfall during the periods shown to the mean annual rainfall. The average rainfall during 1985–2005 was 455 mm.

in a rural area of SA, where the background incidence of gastroenteritis was fairly high – 3.5 to 5.3 episodes per child-year. The normalized risk to children drinking rainwater (95% confidence interval) in the cohort study (compared with those relying on distributed water supply) was 0.84 (0.63–1.13). The difference, which favors those drinking rainwater, was not statistically significant (6). In a follow-on study involving

300 households in Adelaide using primarily tank rainwater, participants were divided into groups that drank filtered or unfiltered water. No statistically significant difference was found in gastroenteritis incidence between the groups (7).

Figure 13, which illustrates both Australian water harvesting practice and its potential pitfalls, shows that good housekeeping methods can reduce the risk from potable use

Table 2   Water resource summary table – Australia, 2004–05.

	NSW	SA	WA	TAS	QLD
Rainfall (m^3×10^{-6})	406,562	147,773	639,609	75,189	865,993
Runoff (m^3×10^{-6})	30,266	1285	24,560	32,084	95,018
Water extracted (m^3×10^{-6})	16,528	1352	3417	39,081	7964
Water consumed (m^3×10^{-6})	5922	1365	1495	434	4361
Water stored (m^3×10^{-6})	8200	116	10,135	11,191	5309
Population (1000s)	6774	1542	2010	485	3964
Area (km^2×10^{-3})	800	982	2522	67	1726
Per capita runoff (m^3/yr)	4470	830	12,220	66,153	23,466

NSW, New South Wales; SA, South Australia; WA, Western Australia; TAS, Tasmania; QLD, Queensland.

of tank rainwater. The elimination of branches above collection surfaces, periodic tank cleaning, water storage in the dark, and separation of water from mosquitoes and wildlife during storage are recommended. Potable use of tank rainfall by the immune-compromised, the very old, and the very young should be avoided. Furthermore, water harvesting for potable use should be carefully evaluated in areas of poor air quality, where the accumulation of contaminants like lead on rooftop surfaces is likely. With those caveats, however, water harvesting can play an important role in water-stressed areas and other areas that lack universal access to improved water service. In the SA study already described, households that relied on tank rainwater felt that theirs was a healthier source of potable water than the local distributed water supply. Those on the central water system felt just the opposite. The local distribution of gastroenteritis was silent on the subject.

A second Australian epidemiologic water study that was described at the Perth conference was carried out in greater Perth to examine cause and effect between exposure to tri-halomethanes (THM) in drinking water and the incidence of birth defects. Pregnant women exposed to >130 µg/L total THM concentrations experienced an increased risk of producing a fetus with a birth defect (odds ratio 1.22). Methods

Figure 13   Illustration of rainfall harvesting practices in rural Western Australia. Good housekeeping measures such as tree trimming and gutter cleaning are clearly warranted in order to reduce risk.

suggested to avoid incremental risk included use of bottled water; boiling delivered water to drive off THMs before ingestion; and such structural changes in water supply infrastructure as water treatment process improvements, managed aquifer recharge before recovery and water delivery, and improved water catchment management. The options ranged from low-cost alternatives that depend primarily on individual initiative, to more organized solutions involving either improved treatment systems design or better use of the natural environment to protect the quality of delivered water – that is, to remove organics ahead of water disinfection. If solutions are to be affordable in the developing world, they are likely to be decentralized and technologically straightforward. Watershed or catchment protection fits the latter description, as does rainfall harvesting.

Like other major Australian cities, the demand for water in Perth is projected to exceed the renewable supply – under some scenarios by as much as 120B liters in 2030 and 365B liters in 2060. Among the city's options to restore the balance between water use and supply is the use of treated wastewater for groundwater replenishment. The 50-year plan for Perth water supply includes increasing the fraction of treated wastewater that is reused from 6% (current level of reuse, entirely for industrial needs) to 60% in 2060 (8). This goal would be accomplished through a combination of improvements to aboveground wastewater treatment, recharge, and water polishing during underground transport and storage. Use of the recovered water would be unrestricted. Advanced aboveground treatments ahead of recharge might include micro-filtration, reverse osmosis (RO), and advanced oxidation (ultraviolet/hydrogen peroxide). The travel time between the points of injection and recovery could be as long as 50 years. The combination of aboveground treatments and polishing during underground storage/transport provides multiple barriers to human exposure to chemical toxicants in municipal wastewater. A 3-year study has been completed to establish the attenuations of select metals, pesticides, disinfection by-products, n-nitrosamines, volatile organics (for example, 1,2-dichlorobenzene and tetrachloroethene), PAHs, dioxins/furans, radionuclides, pharmaceuticals, and hormones (396 chemicals in all) during conventional wastewater treatment and reverse osmosis. The chemicals were selected based on commercial volume in WA, toxicological concern, presence in wastewater in previous studies, and likelihood of transport
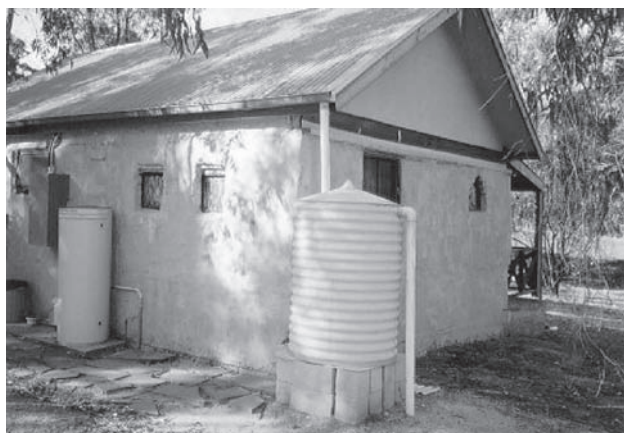
through RO membranes. Pre- and post-treatment concentrations were compared with guideline values in the Australian Drinking Water Guidelines (9) and other sources to calculate risk quotients (RQ). The majority of chemicals tested were effectively attenuated to low-risk levels by the treatments investigated. A few, including *N*-nitrosodimethylamine, survived RO treatment at levels that produced RQ values >1.

And from the United States

The situation in the United States is not altogether different from the Australian experiences, particularly if the focus is on the lower Colorado River basin. Southern California, Arizona, and Nevada in the semi-arid Southwest are subject to extreme water stress (consumptive demand>renewable supply; Figure 14), leading to water reuse and groundwater mining as strategies for satisfying demand. Under the terms of an international treaty and the Colorado River Compact (http://www.usbr. gov/lc/region/g1000/lawofvr.html), seven western states and Mexico hold rights to 16,400 GL per year of water from the Colorado River, which is so heavily subscribed and regulated that in most years flow does not reach the river mouth in the Gulf of California. The safe yield of the Colorado River itself was based on hydrological observations during an unusually wet period and has been questioned. The average flow in the Colorado may be considerably less than the combined volumes of established water rights. Finally, it has been widely asserted that the regional consequences of climate change are

likely to include reduced rainfall in the Colorado River basin, again bringing into question the sustainability of water withdrawals from the Colorado, especially in the three lower basin states (10, 11). Again, the importance of regional water stress as opposed to national figures is apparent.

Despite ample evidence of water stress, before 2008 the Lower Colorado region was among the fastest growing areas in the United States. For contrast, we should note that ratio of consumption to renewable supply on the east coast of the United States is in the range 1%–3% – hardly a stressed condition. Yet water scarcity was experienced among the South Atlantic Gulf states in 2009, particularly in Georgia. Ironically, the same area suffered severe flood damage in 2010. The basis of such nearly contemporary extremes could be chronically inadequate water storage and other flood control measures, changing rainfall patterns, poor operation of engineered water control systems, or bad luck. For these purposes, it is sufficient to note that the UN water stress indicators seem to have limited relevance in the developed world, or at least that water stress is poorly related to regional economic development. We have already shown that water stress is an imperfect correlate to national wealth, economic growth rate and human health in developing countries.

In the American Southwest, the demand for water has simply outgrown the traditional renewable supplies, and waters of initially impaired quality – brackish ground water, seawater and reclaimed wastewater – are now widely included in regional water resource portfolios. The situation is well illustrated in Arizona, where the total water budget has grown
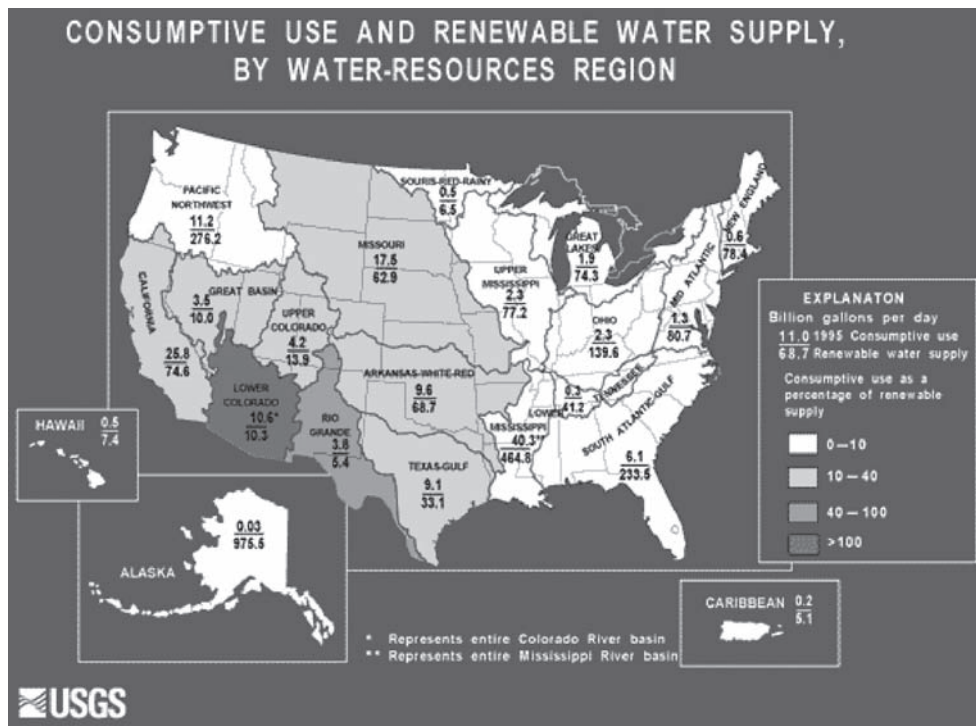

Figure 14   The pattern of water stress in major river basins of the United States. Data reflect renewable supply and consumptive water use in 1995.

to 7750 GL per year. Renewable sources include the flows of "in-state" rivers that begin (and now generally end) in Arizona (about 1380 GL), water imported from the Colorado River (2850 GL, or 37% of demand), reclaimed wastewater (about 760 GL, or 10% of demand) and a relatively small amount of runoff that recharges the state's regional aquifers. The remaining 30% to 35% of demand is satisfied by mining the state's groundwater resources.

Taking a more focused look, the southern Arizona region centered in Tucson has a consumptive water demand of 500 GL per year that is satisfied using renewable groundwater (75 GL), water imported from the Colorado River (300 GL), and a combination of planned and inadvertent water reuse [125 GL (12)]. Near-term growth will be accommodated via greater reliance on water reclamation/reuse, water conservation, and retirement of agricultural land. The provision of water will grow more complex if future water shortages occur on the Colorado River due to oversubscription or climate change that affect Arizona's water rights. As things stand, the regional groundwater resource is an effective buffer during relatively brief periods of water shortage.

Regional/national objectives in water supply and sanitation are necessarily complex because (i) regional water withdrawals can approach supply in magnitude, (ii) surface water is both a carrier for human and chemical waste and a source of potable water, and (iii) intimacies between human/environmental health and water quality are not completely understood. To justify the use of natural waters as a potable water source and also a conduit for waste, it is commonly held that surface waters have a significant, although finite, assimilative capacity. The same practice encourages us to pursue a single regional strategy for joint water supply and sanitation, an idea that has begun to flourish, but is not yet generally accepted, even within the sanitary engineering profession.

Stress on regional water resources motivates us to include waters of ever decreasing initial quality in our respective water resource portfolios. Municipal wastewater is frequently seen as a resource, with nutrient value for agriculture or, after restorative measures, as a candidate for unrestricted use. It is acknowledged with irony that wastewater is the only renewable water resource that expands as a consequence of increased human activity. The impact of wastewater discharge on surface water quality and the likelihood of inadvertent or planned water reuse, are incentives for improved sanitation practices in developed nations. In the developing world, the benefits of improved sanitation are likely to be more dramatic – through reduced incidence of waterborne disease and water-related mortality, particularly among children.

Concluding remarks

At best, a weak relationship has been found between access to improved water supply/sanitation and the per capita GNP in developing countries on the Pacific Rim, suggesting that non-economic factors are important to the extension of improved water supply and sanitation practices. Such factors might include the priority given to water and sanitation

improvements, the degree of organization, effectiveness of government, or the fraction of population living in rural settings.

On the Pacific Rim, water stress is not a major impediment to the improvement of water supply and sanitation or a primary determinant of economic growth. In South Asia, stress on renewable water resources suggests that there is limited capacity for agricultural development, but those nations seem able to find other pathways to economic growth. In countries with great hydrologic diversity, such as Australia and the United States, there is likely to be regional water stress despite statistical indications of overall water sufficiency. Nevertheless, water stress has not, in general, limited economic expansion, and other factors tend to outweigh the availability of water as determinants of growth. From the UN data derived from developing nations on the Pacific Rim, water stress is not an important determinant of either the availability of improved water supply/sanitation or per capita GNP. The cost of providing water may some day limit economic expansion and population growth, but that point is not yet here.

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