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Human Settlements, Energy, and Industry

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EXECUTIVE SUMMARY

Climate change will affect human settlements against a very dynamic background of other environmental and socioeconomic factors. Human settlements are expected to be among the sectors that could be most easily adapted to climate change, given appropriate planning and foresight and appropriate technical, institutional, and political capacity. This chapter covers the same general topic areas as Chapters 11 and 12 of the Second Assessment Report (SAR); however, this chapter analyzes a wider variety of settlement types, provides a specific assessment of uncertainty and confidence in findings and adaptive capacity in human settlements, and places much of the discussion in a context of development, sustainability, and equity (DSE) (see Munasinghe, 2000). Energy and industry are treated as part of settlements. Figure 7-1 characterizes the conclusions of this chapter on two dimensions: scientific support (evidence available in the literature to support the finding) and consensus in that literature. Both scales are described more fully in Box 1-1 of Chapter 1 and in Moss and Schneider (2000).

Major Effects on Human Settlements

Infrastructure would have increased vulnerability to urban flooding and landslides (established but incomplete). Detailed modeling of rainfall event frequency and intensity in the context of global warming has been linked to increased intensity and frequency of urban flooding, with considerable damage to infrastructure (see Chapters 4, 8, and 10–15). Although not definitive for any part of the world, the model-based analysis is plausible and demonstrates that flooding could be an increased threat for riverine settlements under climate change. More predictable is loss of snow pack in many regions, combined with more winter flooding. Landslides are a current threat in many hilly areas and could be more so with more intense rainfall events.

Tropical cyclones would be more destructive under climate change (established but incomplete). Close behind floods and landslides are tropical cyclones (hurricanes or typhoons), which could have higher peak intensity in a warmer world with warmer oceans (see Chapters 3 and 8, and TAR WGI Chapter 10). Tropical cyclones combine the effects of heavy rainfall, high winds, storm surge, and sea-level rise in coastal areas and can be disruptive far inland but are not as universally distributed as floods and landslides.

Water supplies for human settlements would be vulnerable to increased warming, dryness, and flooding (established but

Level of Agreement/Consensus	Low — Amount of Evidence (observations, model output, theory)	High
High	**Established but Incomplete** • Increased vulnerability of infrastructure to urban flooding and landslides • Tropical cyclones more destructive • Fire danger to urban/wildland fringe infrastructure increased • Sea-level rise increases cost/vulnerability of resource-based industry • Water supplies more vulnerable	**Well-Established** • Sea-level rise increases cost/vulnerability of coastal infrastructure • Energy demand sensitive; parts of energy supply vulnerable • Local capacity critical to successful adaptation • Infrastructure in permafrost regions vulnerable
Low	**Speculative** • Fire damage to key resources increased • More hail and windstorm damage	**Competing Explanations** • Agroindustry and artisanal fisheries vulnerable • Heat waves more serious for human health, resources • Nonclimate effects more important than climate • Heat island effects increase summer energy demand, reduce winter energy demand • Increased air and water quality problems

Figure 7-1: Human settlements impacts, categorized by state of scientific knowledge.

incomplete). There is reasonable consensus among experts that settlements in regions of the world that already are water-deficient (e.g., much of north Africa, the Middle East, southwest Asia, portions of western North America, and some Pacific islands) would face still higher demands for water with a warmer climate, with no obvious low-cost ways in which to obtain increased physical supplies. Observations on current water supply balances tend to back up this conclusion (see Chapters 4 and 10–13). However, theory and model output, though consistent with this view, are too weak quantitatively to offer much support, especially for urban areas. Repeated flooding also could create water quality problems in other areas.

Fire danger in settlements could increase with climate change (speculative for resource-dependent settlements; established but incomplete for infrastructure). Examples include forested and wildland/urban fringes in boreal regions (e.g., Canada, Alaska, Russia) and in Mediterranean climates in both hemispheres (e.g., California, southern Spain and France, and Australia) that could be affected (see Chapters 11, 12, 13, and 15). Although general circulation model (GCM)-projected summer climate in many regions looks similar to the hot, dry "fire weather" in many warm years of recent memory and economic activity in forests sometimes is restricted to reduce fire danger, impacts on the resource base have not been demonstrated, research has not shown what future fuel loadings would be, and it is unclear whether future economic activity and settlement infrastructure would be more vulnerable to fire.

Hail and windstorm could cause more damage to settlements (speculative). Although there is potential for more (and more severe) extreme weather episodes in a warmer atmosphere, modeling and data have not demonstrated a higher incidence of storms or of more severe storms (see Chapters 3, 8, 12, and 15).

Agroindustry and artisanal fisheries are sensitive to and in many cases vulnerable to climate change (well-established overall; competing explanations in specific regions). This conclusion dates back to the First Assessment Report (FAR). Additional studies and analysis conducted in the past 10 years have modified the details of the conclusion but have not overturned it. As described in Chapter 5, agriculture itself is sensitive to climate change. In some cases, yields may be reduced by as much as several tens of percent as a result of hotter weather, greater evaporation, and lower precipitation in mid-continental growing regions in particular. However, other regions may benefit, with higher yields possible. Impacts on agricultural processors and suppliers would tend to follow the impacts on agriculture itself. Changes in ocean conditions from El Niño episodes have demonstrated that changes such as ocean warming have substantial impacts on the locations and types of species available for fisheries, especially artisanal fisheries, but other regions could benefit (see Chapters 5, 6, and 10–17).

Heat waves would have more serious effects on human health and productivity (competing explanations). The impact of heat waves is most severe on the weakest parts of the populations (old, chronically ill, very young) that are not acclimated, but effects on future overall death rates are less clear (see Chapters 9, 11,13, 14, and 15). Because anthropogenic warming is projected to be greater at night than during the day, it would deprive sufferers of nighttime relief. Projections for several temperate climates show increased risk of severe heat waves (Chapter 3). As the weather becomes very warm, economic productivity of unprotected and outdoor populations declines.

Sea-level rise increases the cost/vulnerability of infrastructure and coastal resource-based industry (well-established for infrastructure; established but incomplete for resources). Although the amount of sea-level rise to be expected as a result of global warming by any given date and in any given location is uncertain, some studies are beginning to discuss likely ranges and probability distributions (e.g., Titus and Narayanan, 1995). The sensitivity of human infrastructure in coastal zones to given levels of sea-level rise is backed by theory, model results, and data on current rates of increase. In addition, several industries—such as tourism and recreation (the principal industry in many island economies)—are dependent on coastal resources (see Chapters 6, 8, and 10–17). Effective types of adaptive responses also are known in some circumstances, but vulnerability with adaptation is difficult to assess because the capacity and will to respond are uncertain or in doubt in many instances.

Energy demand in some locations is sensitive, and parts of the supply system are vulnerable (well-established). Modeling, theory, data, and expert opinion all say that warming of 1–5ºC would considerably reduce the amount of energy that would be needed to heat buildings at mid- and high latitudes and altitudes, whereas cooling energy use would increase (see Chapters 10–15 and 17). The net overall impact on energy use would depend on local circumstances. If temperature increases take place primarily at night and during winter months, heating demand would be smaller and the increase in demand for energy for cooling and irrigation would be somewhat smaller than otherwise. Future climate is expected to include more intense rainfall events (which would require more conservative water storage strategies to prevent flood damage), greater probability of water deficits (less hydroelectric production), and less precipitation falling as snow (less water available during warm months) (see Chapter 4). All three factors point to less (or, at least, less flexible) hydroelectric capacity at current powerhouses. Reduced flows in rivers and higher temperatures reduce the capabilities of thermal electric generation, and high temperatures may reduce transmission capabilities as well.

There will be increased air and water pollution impacts (competing explanations). Climate change could contribute to water pollution problems in human settlements through drought or flooding, although not by simple increases in flow (which offers more dilution for pollutants). If droughts and floods become more frequent (see Chapter 3), so would instances of poor water quality (see Chapters 4, 10–15, and 17). Air pollution could be exacerbated if climate change alters the stability of air sheds and permits greater buildup of atmospheric pollutants (see Chapters 10–15). However, the outcomes remain largely theoretical, unsupported by data or modeling.

Infrastructure in permafrost regions is vulnerable to warming (well-established). Data from circumpolar regions and model results suggest that permafrost areas would see some melting of permafrost. Permafrost melting is a threat to infrastructure in these regions because of increased landslides and loss of foundation stability for structures, as well as increased damage from freeze-thaw cycles, among other impacts. In addition, melting permafrost is thought to be a source of methane (CH_4) and carbon dioxide (CO_2) gases (see Chapters 15 and 16).

Heat island effects could increase heat stress, increase summer energy demand, and reduce winter energy demand (competing explanations). As discussed in Chapters 3 and 9, heat waves may increase in frequency and severity in a warmer world, leading directly to increases in mortality among sensitive populations that are not acclimated. Heat island effects exacerbate the oppressive effects of heat waves by increasing temperatures experienced in the summer by up to several °C; at the same time, increased demand for air conditioning increases the demand for electricity and the severity of the heat island itself through thermal electric production. Winter energy use for heating would be reduced by the same phenomenon (see Chapters 11, 13, 14, and 15). Effects in specific regions are far less clear.

Other Observations

Local capacity is critical to successful adaptation (well-established). Adaptation means local tuning of settlements to a changing environment, not just warmer temperatures. Urban experts are unanimous that successful environmental adaptation cannot occur without locally based, technically and institutionally competent, and politically supported leadership. Local adaptive capacity generally is strongly correlated with the wealth, human capital, and institutional strength of the settlement. In addition, capacity depends in part on the settlement's access to national resources. Attempts to impose environmental solutions on settlements from the international or national level frequently have been maladapted to local circumstances. The most effective sustainable solutions are strongly supported and often developed locally, with technical assistance and institutional support from higher level bodies (see Chapters 10, 11, 14, 17, and 18).

Nonclimate effects are likely to be more important than climate change (competing explanations). The effects of climate change would occur against a background of other socioeconomic and environmental change that is itself very uncertain and complex (see Chapter 3). Model results, the current rate of environmental change, and economic theory all suggest that climate would be a relatively small additional uncertainty for most human settlements. Climate change in isolation also is unlikely to be as important a factor for DSE effects as other aspects of development, such as economic and technological change. In combination with other stresses from other processes such as population growth, however, climate change is likely to exacerbate total stresses in a multi-stress context. Particularly important could be effects of climate change on equity because relatively advantaged parts of global and local societies are likely to have better coping capacities than less advantaged parts.

Managing growth to ensure that it is sustainable and equitably distributed currently is a greater problem for most countries than the impacts of climate change. However, some experts are not in agreement on this point for the future, pointing out that the economic models do not show climate feedback to the economy and that climate effects are so uncertain that they could well dominate in some regions, especially by the end of the 21st century.

7.1. Introduction and Purpose

Humans live in a wide variety of settlements, ranging from hunter-gatherer camps and villages of a handful of families to modern megacities and metropolitan regions of tens of millions of inhabitants. Settlement economic and social structure—and the components of infrastructure that support settlements: energy, water supply, transportation, drains, waste disposal, and so forth—have varying degrees of vulnerability to climate change and generally are evolving far more quickly than the natural environment. Settlements can be affected directly through changes in human health and infrastructure and indirectly through impacts on the environment, natural resources, and local industries such as tourism or agriculture. Furthermore, these effects on human settlements theoretically could lead to tertiary impacts such as altered land use, redistribution of population and activities to other regions, and altered trade patterns among regions, resulting in still further changes in natural resources and other activities. Tertiary effects, however, are largely speculative at the current state of knowledge. Some of these tertiary effects could be either positive or negative at the regional level.

7.1.1. Overview of the SAR

This chapter builds on Chapters 11 and 12 of the IPCC Second Assessment Report (IPCC, 1996), and on the findings in the *Special Report on Regional Impacts of Climate Change* (RICC) (IPCC, 1998). The SAR identifies the most vulnerable types of communities, many examples of which are documented in RICC. The SAR states that the most vulnerable communities are not only poorer coastal and agrarian communities in arid areas identified in the First Assessment Report in 1990; they also include a great variety of settlements, most of them informal or illegal and with a predominance of low-income residents, built on hazardous sites such as wetlands or steep hillsides in or around many urban areas in the developing world.

The SAR and RICC also identify two categories of climate-sensitive industries. Sectors with activities that are sensitive to climate include construction, transportation operations and infrastructure, energy transportation and transmission, offshore oil and gas, thermal power generation, water availability for industry, pollution control, coastal-sited industry, and tourism and recreation. Sectors in which economic activity is dependent on climate-sensitive resources are agroindustry, biomass, and other renewable energy.

The SAR notes that infrastructure typically is designed to tolerate a reasonable level of variability within the climate regime that existed when it was designed and built. However, climate change could affect both average conditions and the probability of extreme events.

This Third Assessment Report (TAR) confirms most of these conclusions. However, the analyses in the SAR and RICC are concerned mostly with identifying and documenting potential effects. The TAR assesses their relative importance and the certainty/confidence of the conclusions reached.

Although literature published since the SAR was issued has not changed the catalog of potential impacts, much more has been learned about the quantitative details of many of the effects, which are being studied more systematically than was true 5–10 years ago. The results are becoming somewhat more quantitative, and it is becoming possible to assign confidence ratings to many of the effects for the first time. More also is known concerning adaptation options. It is now possible to describe many of the options more quantitatively and in the context of development, sustainability, and equity (see Munasinghe, 2000). Energy, industry, and infrastructure are treated as part of settlements in the TAR.

7.1.2. Overview of Types of Effects

Human settlements integrate many climate impacts initially felt in other sectors and differ from each other in geographic location, size, economic circumstances, and technical, political, institutional, and social capacities. Climate affects human settlements by one of three major pathways, which provides an organizational structure for the settlements effects discussion in this chapter:

1) Changes in productive capacity (e.g., in agriculture or fisheries) or changes in market demand for goods and services produced in settlements (including demand from those living nearby and from tourism). The importance of this impact depends on the range of economic alternatives. Rural settlements generally depend on one or two resources, whereas urban settlements usually (but not always) have a broader array of alternative resources. Impacts also depend on the adaptive capacity of the settlement, which in turn depends on socioeconomic factors such as the wealth, human capital, and institutional capability of the settlement.
2) Physical infrastructure or services may be directly affected (e.g., by flooding). Concentration of population and infrastructure in urban areas can mean higher numbers of persons and value of physical capital at risk, although there also are many economies of scale and proximity that help to assure well-managed infrastructure and provision of services such as fire protection and may help reduce risk. Smaller settlements (including villages and small urban centers) and many larger urban centers in Africa and much of Asia, Latin America, and the Caribbean often have less wealth, political power, and institutional capacity to reduce risks in this way.
3) Populations may be directly affected through extreme weather, changes in health status, or migration. Extreme weather episodes may lead to changes in deaths, injuries, or illness. Health status may improve as a result of less cold stress, for example, or deteriorate as a result of more heat stress and disease.

The discussion of impacts on human settlements, energy, and industry that follows begins with a discussion of nonclimate trends that affect settlements. The discussion then assesses potential impacts of climate change on three general types of settlements: resource-dependent settlements; riverine, coastal, and steeplands settlements; and urban settlements. This discussion is followed by a discussion of impacts on the energy sector and industries that may be particularly affected by climate change and an assessment of potential impacts on infrastructure. The chapter next discusses management and adaptation issues and integration of impacts across sectors, and it closes with a review of science and information needs.

7.2. State of Knowledge Regarding Climate Change Impacts on Human Populations

The TAR differs from the two previous assessments in that the literature has begun to quantify several of the climate-related risks to human settlements that previously were identified only in qualitative terms. Additional attention and research has been devoted to adaptation mechanisms that provide resistance to climate-related impacts and ability to recover from them. Several economic and social trends that are specific to development and change in human settlements will interact with the effects of climate change in the future and may exacerbate or mitigate the effects of climate change alone.

7.2.1. Nonclimate Trends Affecting Vulnerability to Climate

Population growth: Except for parts of Europe and the Russian Federation, most regions are expected to experience population growth. Although *Special Report on Emission Scenarios* (SRES) marker scenarios in Chapter 3 do not span the entire realm of possibilities and have not been assigned probabilities, they do show that under plausible conditions, future regional population growth rates will range from modest (Europe and North America, where projected rates are just above or below replacement) to 3% or more (portions of Latin America and especially Africa).

Urbanization (proportion of population living in urban areas) is expected to continue, especially in the developing world. Close to half of the world's population now lives in urban areas, and the likely trend toward a more urban world means that the impacts of climate change on human settlements, if they occur, increasingly will affect urban populations. The most rapid urban growth rates are occurring in the developing world, where urban populations are estimated to be growing at 2.7% yr^{-1}, compared to 0.5% yr^{-1} in more developed regions (UN, 2000). There also is a growing concentration of population in cities with more than 1 million inhabitants. The number of such cities worldwide grew from 80 in 1950 to more than 300 by 1990 and is expected to exceed 500 by 2010 (UNCHS, 1996; UN, 2000). Most cities with more than 1 million inhabitants are now in the developing world, although—as in more developed regions—they are heavily concentrated in its largest economies (UNCHS, 1996).

Cities also are reaching unprecedented sizes. However, the future world may be less dominated by "megacities" (cities of more than 10 million population) than previously predicted. Megacities are likely to be smaller than previously predicted and still contain a small proportion of the world's population—less than 4% in 1990, the last date for which there is census data for most nations (UNCHS, 1996; UN, 2000). Most of the world's urban population live in the 40,000–50,000 urban centers with fewer than 1 million inhabitants (UNCHS, 1996). In 1990, cities with more than 1 million inhabitants had just more than one-third of the world's urban population and just more than one-seventh of its total population (UN, 2000). Urban population increases were particularly sharp in the second half of the 20th century in some regions where urbanization had been held down by policy, such as China (Institute of Land Development and Regional Economy, State Planning Committee, 1998). Trends toward urbanization mean that the impacts of climate change on human settlements in most countries, if they occur, increasingly will affect urban populations, not rural or traditional settlements.

Poverty is becoming increasingly urbanized, as a growing proportion of the population suffering from absolute poverty lives in urban areas. In more developed regions and in much of Latin America (e.g., 36% in Latin America—ECLAC, 2000), poverty is concentrated in urban areas. In other regions, the number of rural poor still exceeds the number of urban poor, although the proportion of absolute poor living in urban areas is growing. In addition, the scale and depth of urban poverty frequently is underestimated, in part because official income-based poverty lines are set too low in relation to the cost of living (or the income needed to avoid deprivation) in most urban centers and in part because no provision is made to include housing conditions, access to services, assets, and aspects of social exclusion within most government poverty definitions (Satterthwaite 1997). Where it occurs, urban poverty reduces the capacity of urban populations to take action to adapt to climate change; poverty also may exacerbate many of its effects.

Market systems and privatization increasingly are being used to provide new infrastructure and maintain older systems (World Bank, 1994), giving government a smaller direct role in providing infrastructure for energy, environmental residuals, communications, and other key urban services. Governments that are trying to adapt settlements to climate change increasingly may have to work indirectly through markets and regulation of private providers to adapt buildings and infrastructure to climate change.

Energy systems are changing in some places, helping to determine which mechanisms are salient in human settlements impacts (Schipper and Meyers, 1992; Hall *et al*., 1993; World Energy Council, 1993a):

- Use of biomass fuels for cooking and space heating in many developing countries remains significant, which has added to deforestation and environmental destruction in some places but not others (Leach and Mearns, 1989; Tiffen and Mortimore, 1992). Biomass growth may be stimulated by warming, if precipitation remains adequate, but may fall otherwise.

- The increase in natural gas use in Europe and North America (and nuclear power in France) over the past 2 decades has held down the rate of use of coal and oil and has reduced coal use by 20% in western Europe. Accelerated coal use is expected in developing Asia (EIA, 1998). Much of the increase is related to increasing electricity demand, which would be compounded by climate warming.
- An increasing market share for electricity is occurring in new homes in all regions. Between 1995 and 2020, the world's annual consumption of electricity is projected to rise from 12 trillion to 23 trillion kWh. The greatest increases are expected in developing Asia and in Central and South America (EIA, 1998). Climate warming in these regions would increase the demand for space cooling, which is primarily fueled by electricity, at the same time that rapid electrification already is stretching capacity.
- Air conditioning in the commercial sector already accounts for a greater proportion of final energy demand than in the residential sector in developed countries. Commercial sector energy use also is increasing as a percentage of the total in developing countries. Some of this is a result of computerization of commerce.

Transportation activity and associated energy consumption are growing very rapidly in nearly every region. Except for economies in transition, the amount of goods traveling by road increased between 1990 and 1996. The increases were 50% or more, and total paved roadways worldwide rose from 39 to 46% of the total (World Bank, 1999). In all Organisation for Economic Cooperation and Development (OECD) countries, car ownership continues to rise steadily, but much of the growth in vehicle ownership is expected in developing countries and transition economies—especially in east Asia and the Pacific, and especially in urban areas (World Resources Institute, 1996). This trend contributes to local air pollution (which can be exacerbated by warm weather episodes) and to greenhouse gas (GHG) emissions.

A poleward intensification of agricultural, forestry, and mining activities is occurring, resulting in increased population and intensified settlement patterns in Canada's mid-north, for example, and even in arctic areas. Climate change could profoundly affect settlements in these regions, if climate change is greater toward the poles (Cohen, 1997). For example, some arctic and subarctic activities such as mining depend on snow roads, which would have to be replaced with more conventional transport.

Impact of urban wealth: Many of the worst city-level problems—such as sanitation and water supply—have been addressed in high-income cities such as those in Europe and North America, but not in many developing world cities (WHO, 1992; Hardoy *et al*., 2000; McGranahan and Satterthwaite, 2000). A wealthy city can more easily afford the public finance and administration required to regulate more perceptible forms of pollution than a poor one. However, although the ambient environment of high-income cities may be more benign in terms of health impacts of pollution, these cities exert a far greater toll on the regional and global environment (UNCHS, 1996).

7.2.2 Sensitivity and Vulnerability of Human Settlements to Direct and Indirect Impacts of Climate Change

This chapter highlights some of the key processes through which climate impacts could occur; individual regional chapters categorize settlements based on size, location, or complete coverage of the population.

As a result of research that has been done on settlements since the SAR and RICC, as well as additional interpretation of older research, it is becoming clearer where many of the key vulnerabilities of human settlements, energy, and industry occur, although it is still very difficult to provide more than qualitative guidance. Table 7-1 provides an overview of these vulnerabilities for the years between approximately 2050 and 2080; much of the available literature concentrates on the effects of climate change of a magnitude roughly corresponding to that time period. The table divides human settlements into general size categories and economic function in a hierarchy of settlements. The table emphasizes the most salient effects that appear to be characteristic of certain types of settlements and mechanisms that might make the settlements more or less sensitive to climate change.

Implications of climate change for development of settlements, energy, and industry are highly location-specific. For instance, as shown in Table 7-1, climate change is more likely to have important impacts on the development of settlements in resource-dependent regions or coastal or riverine locations. Most of the concerns are about possible negative impacts on development (e.g., on the comparative advantage of a settlement for economic growth compared with other locations), although impacts on some areas are likely to be positive. Impacts on sustainability depend very largely on how climate change interacts with other processes related to multiple stresses and opportunities—such as economic, demographic, and technological change—except in low-lying areas that may be subject to sea-level rise or polar regions whose physical conditions will be more directly affected by global warming. Equity effects are of considerable concern because the ability to cope with negative impacts or to take advantage of positive impacts is likely to be greater among advantaged groups than among disadvantaged groups, within regions and between regions. As a result, climate change has the potential to enlarge equity-related gaps in human settlements and systems.

In general, country studies that have been completed since the SAR was published have provided more specific regional details concerning sensitivities and vulnerabilities to climate

Table 7-1: *Impacts of climate change on human settlements, by impact type and settlement type (impact mechanism). Typeface indicates source of rating: Bold indicates direct evidence or study; italics indicates direct inference from similar impacts; and plain text indicates logical conclusion from settlement type, but cannot be directly corroborated from a study or inferred from similar impacts. Impacts generally are based on 2xCO_2 scenarios or studies describing the impact of current weather events (analogs) but have been placed in context of the IPCC transient scenarios for the mid- to late 21st century.*

	Type of Settlement, Importance Rating, and Reference												
	Resource-Dependent (Effects on Resources)				*Coastal-Riverine-Steeplands (Effects on Buildings and Infrastructure)*				*Urban 1+ M (Effects on Populations)*		*Urban <1 M (Effects on Populations)*		
Impact Type	Urban, High Capacity	Urban, Low Capacity	Rural, High Capacity	Rural, Low Capacity	Urban, High Capacity	Urban, Low Capacity	Rural, High Capacity	Rural, Low Capacity	High Capacity	Low Capacity	High Capacity	Low Capacity	**Confidence**
Flooding, landslides	**L–M**[1]	**M–H**[2]	**L–M**[1]	**M–H**[2]	**L–M**[1]	**M–H**[2]	**M–H**[1]	**M–H**[2]	**M**[1]	**M–H**[2]	**M**[1]	**M–H**[2]	H
Tropical cyclone	**L–M**[3]	**M–H**[4]	**L–M**[3]	**M–H**[4]	**L–M**[3]	**M–H**[4]	**M**[3]	**M–H**[4]	**L–M**[3]	**M**[4]	**L**[3]	**L–M**[4]	M
Water quality	L–M	M	L–M	M–H	**L–M**[5]	**M–H**[6]	*L–M*	*M–H*	L–M	M–H	L–M	M–H	M
Sea-level rise	**L–M**[7]	**M–H**[6]	**L–M**[7]	**M–H**[6]	**M**[8]	**M–H**[9]	*M*	**M–H**[6]	**L**[8]	**L–M**[6]	*L*	**L–M**[6]	H (L for resource-dependent)
Heat/cold waves	*L–M*	*M–H*	*L–M*	*M–H*	*L–M*[10]	L–M	**L–M**[10]	L	**L–M**[10]	**M–H**[11]	**L–M**[10]	**M–H**[11]	M (H for urban)
Water shortage	**L**[12]	*L–M*	**M**[12]	**M–H**[13]	*L*	*L–M*	*L–M*	*M–H*	*L*	*M*	**L–M**[12]	*M*	M (L for urban)
Fires	*L–M*	*L–M*	**L–M**[14]	*M–H*	*L–M*	*L–M*	*L–M*	*L–M*	**L–M**[15]	**L–M**[16]	*L–M*	*M*	VL (M for urban)
Hail, windstorm	**L–M**[17]	**L–M**[18]	**L–M**[17]	**M–H**[18]	*L–M*	*L–M*	*L–M*	*M*	**L–M**[17]	**L–M**[18]	**L–M**[17]	**L–M**[18]	L
Agriculture/ forestry/fisheries productivity	**L–M**[19]	**L–M**[20]	*L–M*	*M–H*	L	L	L	L	*L*	*L–M*	*L–M*	*M*	L
Air pollution	**L–M**[21]	*L–M*	L	L	—	—	—	—	**L–M**[10]	**M–H**[22]	**L–M**[10]	**M–H**[22]	M
Permafrost melting	L	L	**L–M**[23]	*L–M*	L	L	**L**[23]	L	—	—	*L–M*	*L–M*	H
Heat islands	L	L	—	—	L	L	—	—	**M**[24]	**L–M**[24]	**L–M**[25]	**L–M**[25]	M

change (e.g., IPCC, 1998; see Chapters 10–17). Because of variability in settlements across the world, it is virtually impossible to create rankings of impacts that do not contain numerous exceptions. However, the impact ratings in Table 7-1 provide a framework that can be adapted to local circumstances. Table 7-1 shows the author team's judgments, based on the available literature, about the vulnerability of different types of settlement to various aspects of climate change. The horizontal axis differentiates vulnerability according to type of settlement, capacity to adapt, and the mechanism through which the settlement is affected by climate change. For example, the resource base of settlements that are economically dependent on activities such as agriculture, forestry, fishing, hunting and gathering, or tourism may be affected; housing and infrastructure may be affected in coastal areas, riverine floodplains, islands that are sensitive to flooding, steeplands that are sensitive to landslides, and urban/wildland boundaries that are sensitive to fires; and the health and productivity of urban populations may be affected directly through air pollution, heat waves, and heat island effects. The vertical axis identifies 12 different types of climate change impact in descending order of global importance. Vulnerabilities are rated as low, medium, or high magnitude as described in Box 7-1. The information in Table 7-1 generally is presented as a range, reflecting the diversity of settlements within each broad class. The final column shows the level of confidence that the author team assigns to each type of climate impact. Table 7-1 depicts vulnerabilities for the years between approximately 2050 and 2080. Much of the available human settlements literature is silent on the timing of impacts; the choice of the years 2050–2080 in Table 7-1 is based on the size of the impacts or amount of climate change addressed in the literature reviewed by the author team. Table 7-1 takes into account the number and type of settlements affected worldwide and the likely strength of these effects by mid-to-late 21st century, as well as the financial, technical, and institutional capacity of settlements to respond. Figure 7-2 provides confidence scores for the impacts on individual scales described more fully in Box 7-1 (see also Moss and Schneider, 2000).

The negative impacts in Table 7-1 generally would be less negative or even positive in some regions before 2050 but greater than shown and becoming more negative in more regions after 2100. The table is not intended to show that only specific types of settlements would be harmed (or helped) in certain ways by certain changes; it is intended to show that settlements of certain types probably are likely to be affected by certain impact mechanisms and are likely to be particularly vulnerable to certain types of climate changes or conditions.

Many of the effects in Table 7-1 are quite likely for some communities in some places; other effects are extremely uncertain, controversial, or inapplicable. Key articles that underlie the ratings are provided as footnotes to Table 7-1.

Confidence in the main conclusions of this chapter in Table 7-1 is rated in Figure 7-2 from very high (5) to very low (1) in four dimensions: support from theory, support from model results, support from data or trends in the existing environment, and the degree of consensus in expert opinion. Although these ratings reflect the subjective judgments of the chapter's authors concerning the weight that can be given to each element that increases confidence in the findings, the figure is useful in depicting the dimensions of the underlying literature that are particularly strong or weak in support of the chapter's conclusions. Confidence levels vary widely:

- Results that are very high on all dimensions, as in the expected vulnerability of at least some coastal settlements to sea-level rise
- Results that are very strong on most dimensions, such as local capacity being very important in practice for successful adaptation to environmental problems (even though the theory has not really been applied to climate change)
- Results that are very high on one or two dimensions, such as human health effects, where theory and model results are strongly supportive of the conclusion, whereas data are weaker or ambiguous and experts are somewhat divided
- Results for which there is some evidence, but most of it is only modestly supportive; one or two modestly

≺ Table 7-1 Notes

1. Changnon (1996b), Yohe *et al*. (1996), Evans and Clague (1997), FEMA(1997), Smith *et al*. (1999); **2.** Choudhury (1998), Rosquillas (1998), Magaña (1999); **3.** Landsea *et al*. (1996), Pielke (1996), Pielke and Landsea (1998); **4.** Yohe *et al*. (1996), Hurricane Mitch cost Honduras 80% of its GDPand Nicaragua 49% (FAO, 1999), Swiss Re (1999); **5.** in general, wealthier areas substitute new locations from which to draw water (WG2 SAR Section 10.5.4; Changnon and Glantz, 1996; Arnell, 1998); **6.** Meehl (1996), Nicholls and Hoozemans (1996), Nicholls and Mimura (1998); **7.** Mimura *et al*. (1998); **8.** FEMA (1991), Scott (1996), Rosenzweig and Solecki (2000); **9.** Ren (1994), Nicholls *et al*. (1999), see also Chapters 6 and 11; **10.** Phelps (1996), Chestnut *et al*. (1998), Duncan *et al*. (1999), Kerry *et al*. (1999); **11.** despite acclimatization, Indian cities have lost dozens to hundreds of people to heat-related deaths in recent years—more than 1,300 in 1998 (De and Mukhopadhyay, 1998); **12.** Wheaton and Arthur (1989), Rosenberg (1993), Lettenmaier *et al*. (1998), Gleick (2000); **13.** Meehl (1996), Scott (1996), Lewis *et al*. (1998); **14.** Hirsch (1999); **15.** the 1991 Oakland Hills and the 1994 Sydney fires are examples of losses sustained at urban interface in developed countries [in Oakland, a wildfire destroyed approximately 600 ha and more than 2,700 structures in the hills surrounding East Bay, took 25 lives, and caused more than US$1.68 billion in damages (see <www.firewise.org>, sponsored by the U.S. Forest Service); in the Sydney area, 800,000 ha burned, more than 200 houses—mostly in urban areas—were destroyed, and two firefighters and two civilians were killed (see Australian National University's FIRENET Web site)]; **16.** EEPSEA(2000), Wheeler (2000); **17.** Andrey and Mills (1999), Dorland *et al*. (1999), Changnon (2000); **18.** for example, on the Indian subcontinent on 26 April 1989, a single severe storm—locally known as "nor'westers" or kal'boishakhi—and a tornado north of Dhaka killed 1,300 and injured 12,000; **19.** Rosenberg (1993); **20.** Meltzoff *et al*. (1997); **21.** Scott (1996); **22.** WRI (1999); **23.** Cohen (1997), Andrey and Mills (1999); **24.** Quattrochi (1996), Chestnut *et al*. (1998); **25.** Jáuregui (1997), Chestnut *et al*. (1998), Lam (1999).

Box 7-1. Development of Scales forAssessing Potential Vulnerability of Human Settlements to Effects of Climate Change and Confidence in the Certainty of Impacts

Climate affects the stability of resources that support human systems. One way to assess the potential impact of climate change on human systems is by using a qualitative scale that expresses the vulnerability of settlements to various kinds of climate effects (e.g., floods) in terms of how potentially disruptive these climate effects are expected to be for various types of human settlements (based on differences in their economic base, location, size, and adaptability). The definitions in the rating system below are derived from standard environmental impact assessment language and are intended to apply to local climate impacts. However, the scale may be used nationally if the nation is small and homogeneous or if most of the population lives in settlements of a certain type.

Magnitude Ratings (Size of Impacts)

- *Low:* Impacts of changed climate are not distinguishable from normal background variability in weather impacts or there is little noticeable effect.
- *Moderate:* Resources or sectors are affected noticeably, even substantially, but the effect is not destabilizing and recovery is rapid.
- *High:* Impacts are large and sometimes catastrophic. Resources or settlements are destabilized, with little hope for near-term recovery.

A semi-quantitative approach is used with a 5-point confidence scale to indicate the certainty of the effects of climate change. The author team subjectively rated confidence on the basis of the literature in four dimensions: consensus among experts (*consensus*), the extent to which underlying theory and data is developed (*theory*), the quality of model results (*model results*), and the consistency of observational evidence (*observations*). The scores were used to create a four-sided polygon, as shown in Figure 7-2 on the facing page. All four dimensions were weighted equally to determine the area of the polygon and an overall confidence score.

$$\textit{Polygon Area} = 0.5 \bullet (\textit{Theory} \bullet \textit{Observations} + \textit{Observations} \bullet \textit{Model Results} + \textit{Model Results} \bullet \textit{Consensus} + \textit{Consensus} \bullet \textit{Theory})$$

The overall confidence score assigned was based on the area of the polygon. For example, to rate a 4 for “high confidence,” the polygon had to have an area between 16 and 25—the area of a polygon with ratings of greater than 4 but less than 5 on all four dimensions.

Confidence Rating (Certainty of Impacts)

1) *Very Low:* Impacts are extremely difficult to predict (confidence < 5%) (*Polygon Area* = 0–8).
2) *Low:* Impacts are regularly much greater or less than the median value (confidence < 33%) (*Polygon Area* = 8–18).
3) *Medium:* Impacts are regularly greater or less than the median value (confidence ≥ 33%) (*Polygon Area* = 18–32).
4) *High:* There is noticeable variation in the size of impacts (confidence ≥ 67%) (*Polygon Area* = 32–50).
5) *Very High:* There is little variation in impact among scenarios, within a settlement type (confidence = 95%) (*Polygon Area* = 50).

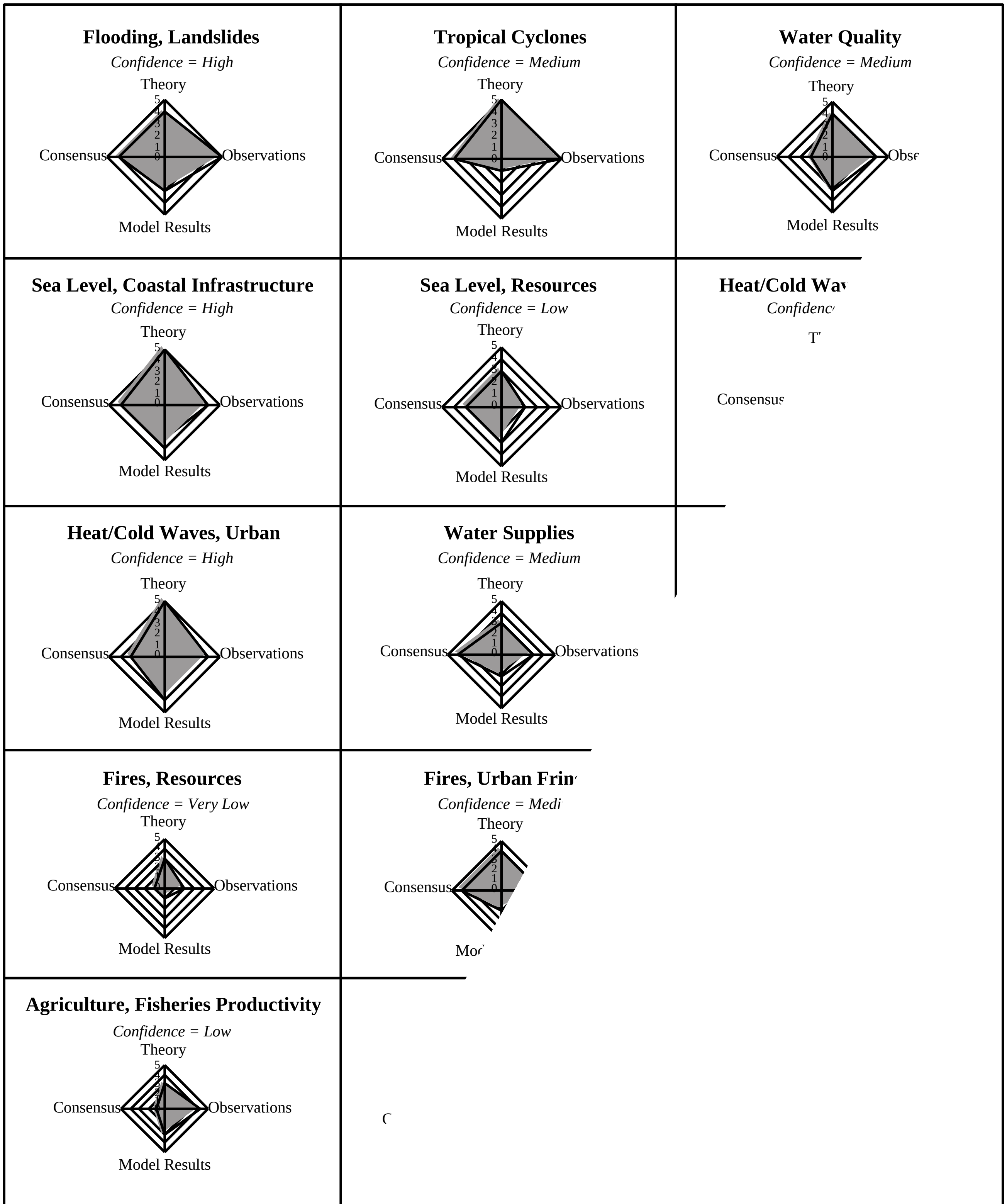
strong elements lead to the conclusion, but confidence is weak.

7.2.2.1. Resource-Dependent Settlements

What makes resource-dependent settlements unique is the extent to which they are dependent on and tuned to the natural resources of the region and the extent to which they are vulnerable to changes in these natural resources. Resource dependency emphasizes the impact of climate change on the economic livelihood of inhabitants. An extreme form of resource-dependent settlements are settlements of traditional peoples, including hunter-gatherer communities, subsistence agricultural settlements, artisanal fishing communities, and the like. The issues are somewhat different in different locations, as indicated below.

7.2.2.1.2. Arid and semi-arid regions

Human societies have been developing by adaptation to the arid environment in desert regions for centuries. An example is the oasis water supply system called *karez*, *qanats*, or *foggaras*. For adaptation or mitigation, windbreaks are a powerful method to reduce the effects of the strong winds, dust storms, and sand dune movements (Du *et al*., 1996; Maki *et al*., 1997a,b). In addition, trees in windbreaks provide materials for



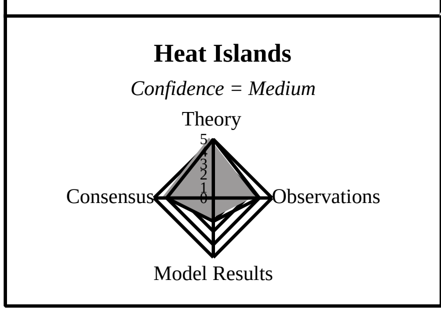


Figure 7-2: Confidence ratings for impacts of climate change on human settlements.

construction and firewood for people, keep a better hygienic environment in the settlements, and improve conditions for crops and livestock.

Social vulnerabilities in arid regions include low income among residents as a result of underdevelopment of industry in the oases, difficulty in telecommunication and transportation between oases, and growing human pressure on the limited land base, as illustrated by the scarcity of suitable irrigable land in oases in the Taklimakan Desert, northwest China (Yoshino, 1997c, 1998). On the northern rim of the Taklimakan desert, only 4–4.5% of the land is available for irrigation, and only about 2% on the south rim is available. Although these limit values vary from desert to desert because of the amount of available water, scarcity of suitable land is a vulnerable feature of settlements in all arid regions. In northern Africa, southwest Asia, and parts of the Middle East, there is a belt of entire countries that currently suffer from inadequate water supplies (see Chapter 4). Increasing temperatures and reduction in rainfall would further limit these settlements.

Climate change could reduce water availability in the semi-arid savanna ecosystem of tropical Africa, affecting farmers, herders, and tourist-industry workers, which in turn will impact human settlements. Conflict already occurs between herdsmen and farmers in this region, and the SAR discussed the impacts on major cities when people leave the land (see Chapter 10).

Small settlements in arid/semi-arid regions occasionally confront a higher risk of damage by flooding than their counterparts in more humid environments. This is usually because of the longer return periods or rarity of extreme rainfall. However, in a warmer world the frequency of these intense storms in semi-arid and arid regions may increase (Smith, 1996; Smith and Handmer, 1996; Smith *et al.*, 1999). During extreme rainfall events, houses, roads, irrigation systems, and other constructions are destroyed and human settlements in oases are isolated because telecommunication and traffic connections are broken. Because settlements have been adapted to dry conditions, the total numbers of deaths and the total amount of damages caused by drought and other impacts of dry conditions often are smaller than those caused by heavy rainfall.

7.2.2.1.2. Polar and subpolar settlements

There are two major types of polar and subpolar settlements: traditional indigenous communities that are based on hunting and gathering activities such as whaling, caribou hunting, and seal hunting and modern “outpost” settlements such as military, mining, and oil camps. The more traditional settlements are economically vulnerable to changes in the regional ecology that might occur as a result of climate change (changes in sea ice, migration routes, or abundance of game species). Although military and mining operations generally would not be concerned with game species, impacts of warming on permafrost areas, sea lanes, and flying weather could significantly improve or reduce the efficiency of resource extraction (Cohen, 1997). Infrastructure in both types of settlements is vulnerable to permafrost melting, desiccation during warming, landslides, and flooding (see Chapter 16).

7.2.2.1.3. Forest settlements

Traditional settlements of indigenous peoples still exist in (mostly tropical) portions of Africa, Asia and nearby islands, and Latin America. Although these societies engage in subsistence agriculture and some cash activities such as guiding tourists, much of their economy is based on subsistence hunting and gathering. Already under threat from growth in farming, mining, and commercial forestry activities (which may themselves be affected by climate change), under climate change the traditional forest communities would face the additional challenge of changed ecology, which could change the availability of key species and adversely affect the sustainability of these communities.

7.2.2.1.4. Agricultural and fisheries settlements and related industry

Agroindustry is considered to be among the more adaptable industries affected by climate change. Brown and Rosenberg (1996) and Brown *et al.* (1998) were able to show, for example, that growing switchgrass (*Panicum virgatum)* for biomass is an effective adaptation in the warmer, drier climates expected in central North America under climate change. Chapter 5 also describes agriculture as adaptable and discusses adaptive responses. However, the capacity to adapt varies significantly among regions and among groups of farmers within regions. Adaptability and sustainability of agriculture and agroindustry depend not only on resources such as favorable climate, water, soils, and amount of land but also on the adaptability of whole market chains, which in turn are influenced by wealth levels, technical and financial sophistication, and institutional flexibility and strength (Tweeten, 1995; Nellis, 1996).

Changes in ocean conditions from El Niño episodes have demonstrated that changes such as ocean warming have substantial impacts on the locations and types of marine species available (UNEP, 1989; Meltzoff *et al.*, 1997; Suman, 2001). Fishery-based settlements would be strongly affected as fishermen follow high-valued stocks to other locations, make do with lower valued stocks, or even abandon fishing altogether (see Chapters 6, 10, 14, 15, and 17). Other communities may benefit if high-valued stocks become more accessible.

What often is not appreciated about resource-dependent settlements is the complexity of the economic and social relationships among participants. Changes in the technology of farming, transportation, and communications have integrated farming communities into national and world markets as never before and increasingly have made farming a part-time activity in some parts of the developed world (e.g., Sakamoto, 1996; Sasaki, 1996) and the developing world. The complexity of interactions and the increasing degree of integration offer additional means of adaptation to climate change at the regional level, but these factors also mean that agriculture and agroindustry are being challenged from several directions at once, possibly complicating the impact of climate change alone (see, for example, Chapter 10).

To illustrate some of the complexities involved, in Japan agrarian structures have changed drastically during the past 30 years (Kumagai, 1996). Small farms have evolved through cooperative groups facing environmental requirements, double-cropping, cheaper imports, and high national economic growth (Sakamoto, 1996) into a regional system of farm households, hamlets, traditional villages, villages, and towns (Yoshino, 1997a,b), with significant part-time labor (Sasaki, 1996), and economics of large-scale production in farming, reductions in investment risks costs, diversification within farming, diversification between farming and other activities, and increases in nonfarm income.

Japanese rice-growing illustrates some constraints on adaptation and community sustainability. Inefficient agriculture (ironically) ties the younger generation to the rural community, where they play important roles in making the community active and viable. Provision of modern facilities and infrastructure does not lead to sustainable communities; more important, one must consider residents' pride or attachment to the community. Realization of a sustainable community requires investments in time, talent, and money for the future of the community (Tabayashi, 1996). Autonomous adaptation here, as elsewhere, might involve numerous social and economic dimensions that involve the entire settlement. It is unlikely to be simple or straightforward and may not result in sustaining every settlement.

7.2.2.1.5. Tourism and recreation

The SAR noted that tourism—a major and growing industry in many regions—will be affected by changes in precipitation patterns, severely affecting income-generating activities (IPCC, 1998). The outcome in any particular area depends in part on whether the tourist activity is summer- or winter-oriented and, for the latter, the elevation of the area and the impact of climate on alternative activities and destinations. For example, in spring 1997, when conditions in alternative destinations in the Alps were poor, the number of skiers in the High Atlas in Morrocco increased (Parish and Funnell, 1999). Scotland has been predicted to have less snow cover at its lower elevation ski areas with global warming but may have drier and warmer summers for hill-walking and other summer activities (Harrison *et al*., 1999) (see regional chapters for other examples).

The impacts of sea-level rise on coastal tourism are compounded by the fact that tourist facility development planning and execution in many cases has been inadequate even for current conditions, leading to environmental problems such as water shortages (Wong, 1998). Furthermore, tourism businesses, which usually are location-specific, have a lower potential than tourists themselves (who have a wide variety of options) to adapt to climate change (Wall, 1998). Small island states may find themselves especially vulnerable to changes in the tourism economy because of their often high economic dependence on tourism, concentration of assets and infrastructure in the coastal zone, and often poor resident population (see Chapter 17).

Whetton *et al.* (1996) quantified the effects of climate change on snow cover in the Australian Alps, which illustrates the problems of snow-based recreation activities. Under the best-case scenario for 2030, simulated average snow-cover duration and the frequency of more than 60 days cover annually decline at all sites considered. However, this effect is not very marked at higher sites (above 1,700 m). For the worst-case scenario, at higher sites, simulated average snow cover roughly halves by 2030 and approaches zero by 2070. At lower sites, near-zero average values are simulated by 2030.

7.2.2.2. Riverine, Coastal, and Steeplands Settlements—Impacts on Infrastructure

Riverine and coastal settlements are notable largely for the potential that flooding and especially sea-level rise can have on them; steeplands in many regions are expected to become more vulnerable to landslides. The mechanisms of these effects depend on the settlement being located in harm's way. River floods can arise from intense local rainfall events or rapid snowmelt, for which long-term probabilities are difficult to forecast (see Chapter 4; Georgakakos *et al*., 1998). Rapid snowmelt from rain-on-snow events or warm periods in the middle of winter is a potential threat in a warmer world in some heavily settled, snow-fed river systems such as the Rhine in Europe (see Chapter 13), whereas steeplands may suffer more landslides and snow avalanches (e.g., Evans and Clague, 1997). The mechanisms of adaptation are similar: defend against flooding or landslides with increasingly expensive protection structures; retreat from the floodplain and unstable areas to safe ground; or accommodate flooding and landslides in structure design, land-use planning, and evacuation plans (see also Chapters 9, 10, 11, 12, 13, 15, and 17).

The most widespread serious potential impact of climate change on human settlements is believed to be flooding. A growing literature suggests that a very wide variety of settlements in nearly every climate zone may be affected, although specific evidence is still very limited. Riverine and coastal settlements are believed to be particularly at risk, but urban flooding could be a problem anywhere storm drains, water supply, and waste management systems are not designed with enough system capacity or sophistication to avoid being overwhelmed. Urbanization itself explains much of the increase in runoff relative to precipitation in settled areas (Changnon and Demissie, 1996) and contributes to flood-prone situations.

In coastal regions (especially on river deltas and small islands), sea-level rise will be the most fundamental challenge of global warming that human settlements face. Some additional national and regional analyses of coastal vulnerability to sea-level rise have been published since the SAR. Many of these studies are summarized in Chapters 6 and 8 because of the importance of the issue to these sectors. In general, estimates of potential damages continue to increase because of increased movement of people and property into the coastal zone, even though the expected degree of sea-level rise has decreased. Worldwide, depending on the degree of adaptive response, the number of people at risk from annual flooding as a result of a 40-cm sea-level rise and population increase in the coastal zone is expected to increase from today's level of 10 million to 22–29 million by the 2020s, 50–80 million by 2050s, and 88–241 million by the 2080s (Nicholls *et al*., 1999). Without sea-level rise, the numbers were projected at 22–23 million in the 2020s, 27–32 million in the 2050s, and 13–36 million in the 2080s. The 40-cm sea-level rise is consistent with the middle of the range currently being projected for 2100 by Working Group I. In 2050, more than 70% (90% by the 2080s) of people in settlements that potentially would be flooded by sea-level rise are likely to be located in a few regions: west Africa, east Africa, the southern Mediterranean, south Asia, and southeast Asia. In terms of relative increase, however, some of the biggest impacts are in the small island states (Nicholls *et al*., 1999).

Although a 1-m sea-level rise is not considered likely before 2100, it often is used to calibrate many damage estimates. For example, a macroscopic analysis of coastal vulnerability, areas, population, and amount of assets at risk from sea-level rise and storm surges for Japan shows about 861 km^2 of land currently is below the high-water level, with 2 million people and 54 trillion Japanese yen in assets. A 1-m sea-level rise would expand the area at risk 2.7 times, to 2,339 km^2, and increase population and assets at risk to 4.1 million and 109 trillion Japanese yen, respectively (Mimura *et al.*, 1998). El-Raey (1997) identifies potential impacts on Egypt: 2 million persons and 214,000 jobs affected, US$35 billion in land value, property, and tourism income lost for a 50-cm sea-level rise. For a 100-cm rise, Zeidler (1997) identifies potential land losses of US$30 billion, plus US$18 billion at risk of flooding and as much as US$6 billion of "full protection" in Poland. (See also Nicholls *et al.*, 1999, for potential damages to settlements on the world's coasts; Adger, 1999, specifically for damages to human settlements in Vietnam; Weerakkody, 1997, for Sri Lanka; and Liu, 1997, for China.)

If sea-level changes occur slowly, economically rational decisions could be made to protect only property that is worth more than its protection costs. With foresight, settlements can be planned to avoid much of the potential cost of protection, given that between 50 and 100 years are expected to pass before a 1-m sea-level rise would be expected. Yohe and Neumann (1997) offer a method by which this planning might be applied. This method can reduce the costs of protection by more than an order of magnitude. Yohe *et al*. (1996) estimate discounted (at 3% yr^{-1}) cumulative U.S. national protection costs plus property abandonment costs for a 1-m sea-level rise by the end of the 21st century at US$5–6 billion, as opposed to previous estimates of $73–111 billion (Smith and Tirpak, 1989).

Sea-level rise exacerbates beach erosion, changes sedimentation patterns, increases river floors in estaurine zones, and inundates wetlands and tidal flats. Groundwater salinization also is a serious problem in coastal zones and many small islands, where recharge does not keep up with usage even under current conditions (Liu, 1997). Higher sea levels are projected to further reduce the size of coastal fresh aquifers and exacerbate the problem. Directly, it causes drinking water quality problems for people in settlements; indirectly, it may limit agriculture in coastal zones (e.g., Dakar, Senegal—Timmerman and White, 1997). Groundwater pumping makes matters worse in many coastal zones by contributing to serious land subsidence. Examples of human settlements affected range from modern European cities (Venice) to large coastal settlements in developing countries (Alexandria, Tianjin, Jakarta, and Bangkok) (Timmerman and White, 1997; Nicholls *et al*., 1999).

Vulnerabilities of settlements in coastal regions to higher sea levels are compounded by severe wind damage and storm surge caused by tropical cyclones and extra-tropical cyclones. The possibility of increasingly frequent (in some regions) or more intense tropical cyclones also cannot be rejected (see Chapter 3). Even if cyclones do not increase in intensity or frequency, with sea-level rise they would be expected to be an increasingly severe problem in low-lying coastal regions (e.g., for settlements along the North Sea coast in northwest Europe, the Seychelles, parts of Micronesia, the Gulf Coast of the United States and Mexico, the Nile Delta, the Gulf of Guinea, and the Bay of Bengal—specific vulnerable regions are identified in the FAR, SAR, RICC, and regional chapters of this report). Infrastructure hardening costs can be high if a decision were made to protect everything: The costs of protecting port facilities and coastal structures, raising wharves and quays, and reconstructing water gates and pumping stations for a 1-m sea-level rise in 39 prefectures in Japan has been estimated at 22 trillion Japanese yen (US$194 billion), or about 7% of annual GDP (Mimura and Harasawa, 2000). In cases in which neither retreat nor defense is feasible, flooding can be accommodated through infrastructure that is designed to reduce damage and evacuation planning to reduce loss of life. Bangladesh, for example, provides hardened storm shelters (Choudhury, 1998).

When extreme weather disasters happen in these regions as a result of tropical or extra-tropical cyclones, the total costs of damages become very large and, where insured, often cause serious problems for insurance carriers (see Chapter 8). The United States' direct annual insured and uninsured costs for tropical cyclones (hurricanes), adjusting for inflation, averaged $1.6 billion (1995 US$) from 1950 to 1989 and $6.2 billion from 1989 to 1995 (Hebert *et al.*, 1996). Estimates of worldwide annual direct costs have been placed at $10–15 billion annually (Pielke, 1997). Increased losses in the United States and elsewhere have occurred during a period in which the number and intensity of tropical cyclones actually was declining (Landsea *et al*., 1996; Pielke and Landsea, 1998). Thus, any future climate change-induced increase in tropical cyclone frequency or intensity remains a matter of great concern to insurers and coastal facilities planners. A single US$50 billion storm is not considered unlikely (Pielke and Landsea, 1998).

7.2.2.3. Urban Settlements

Urban settlements feature many of the same impacts of climate change as other settlements—such as air and water pollution, flooding, or consequences of increasingly viable disease vectors. These impacts may take unusual or extremely costly forms in urban areas—for example, flooding that results not from river flooding but from overwhelmed urban storm drains and sewers during extreme rainfall events (which may become more common in the future). Urban settlements also experience the consequences of accommodating migrant populations, the unique aspects of urban heat islands (which affect human health and energy demand), and some of the more severe aspects of air and water pollution. To some extent, the effects of climate change anywhere in the world are integrated through world markets, social and political changes, and migration. Many of these social and economic effects appear in the world's cities, including some of the world's largest (Rosenzweig and Solecki, 2000).

7.2.2.3.1. Migration

The SAR discussed at some length the potential impact of population movement in response to environmental impact and attractions of large urban areas. Human populations show significant tendencies to adapt to interannual variability of climate via migration, although migration may be the last of a complex set of coping strategies (Meze-Hausken, 2000). For example, decreases in crop and rice yields as a result of a prolonged dry season under ENSO conditions in Indonesia causes farmers to leave the villages to work in the surrounding cities. Population subsequently recovers (Yoshino, 1996b; Yoshino *et al*., 1997). In some cases, immigration is more permanent and does not involve large urban areas. For example, after three successive typhoons hit Tau Island in American Samoa in 1987, 1990, and 1991, about one-third of the population abandoned their homes and moved to Pago Pago on Tutuila Island, putting more population pressure on the limited economic opportunities and services of that island (Meehl, 1996).

A school of thought based on observations of several ethnic conflicts in the developing world suggests that environmental degradation, loss of access to resources, and resulting human migration (including "environmental refugees") in some circumstances could become a source of political and even military conflict (see Chapters 10 and 11). The result is possible, but the many intervening and contributory causes of intergroup and intragroup conflicts allow only low confidence in predictions of increases in such conflicts as a result of climate change, even where environmental resources are scarce and threatened (e.g., Wolf, 1998).

7.2.2.3.2. Human health

The impact of climate change on human heath in settlements is a complicated mechanism that involves the interaction of physical attributes of settlements and precursors for direct effects of heat stress, vector-borne diseases such as malaria, and enteric diseases such as cholera (see Chapter 9). These impacts are common to all types of settlements, including traditional ones. The 1997–98 El Niño event provided a way to derive and test process models for the impacts of climate change. In Latin America, for example, outbreaks of malaria and Dengue fever appeared to be related to anomalously high nighttime minimum temperatures (Epstein *et al*., 1998). Settlements provide disease vectors and organisms with habitat in the form of standing water, garbage dumps, and space sheltered from the elements. Flooding can flush organisms into settlements' clean water supplies, causing disease outbreaks. Heavy rainfall in normally dry areas leads to rapid increases in rodent populations, in turn leading to increases in rodent-borne diseases such as hantavirus (Glass *et al*., 2000). Cholera-harboring marine plankton blooms also can be triggered by riverine flooding, which provides extra nutrients to the coastal environment (Colwell, 1996). Extremely dry conditions reduce the quantities and quality of water available for sanitary and drinking purposes, which also can trigger cholera and diarrheal outbreaks. Historically, this has been a problem on various Pacific islands during drought. Poverty, crowding, and poor sanitation in settlements add to these problems, as reported in the SAR.

7.2.2.3.3. Heat islands and human health

Warming of urban air increases in intensity and area as cities grow (Oke, 1982). This growing "heat island" tends to aggravate the risk of more frequent heat waves, as well as their impacts. Research indicates that variability in summer nighttime minimum temperature (temperatures above 32ºC at night)—combined with lack of acclimatization, high humidity, and poorly ventilated and insulated housing stock—may be the most important factor in urban heat deaths (Chestnut *et al.*, 1998). Elderly people, the very young, people in ill health, and poor people are most likely to be affected (see Chapter 9 for these and other health effects). Because climate change is expected to raise nighttime minimum temperatures more than daytime highs, urban heat islands would be a significant health concern in the largest human settlements.

Conversely, during the rainy season (except in a few cities, such as Cairo, where practically no rain occurs) the heat island enhances the intensity and frequency of rain showers (Changnon, 1992; Jáuregui and Romales, 1996), leading to higher risk of street flooding or mudslides where the urban poor live. Moreover, warmer and drier climates may aggravate air pollution seasonally because of wind erosion of bare soil areas in cities with semi-arid or arid climates (e.g., Mexico City, Beijing, Delhi, and cities located in sub-Saharan Africa). Blowing dust and high summer temperatures are likely to increase the incidence of heat stroke, respiratory illness, and transmission of disease by deposition of airborne bacteria in lungs and on food.

In warmer and drier climates, local minimum temperatures tend to be higher, which tends to attenuate the intensity (and depth) of temperature inversions formed by nocturnal radiation cooling and reduce the risk of poor air quality. However—and especially in large cities located in valleys (e.g., Mexico City, Santiago, Beijing, Delhi)—this attenuation effect could be compensated by a higher rate of radiation cooling to an air layer with less moisture content, aggravating the air pollution situation. Elevated subsidence inversions such as those on the descending branch of semi-permanent anticyclones and limiting vertical dispersion of pollutants in cities such as São Paulo, Los Angeles, or Tijuana are less likely to significantly change their thermal structure in a warmer world.

7.2.2.3.4. Water pollution

Despite massive investment in water treatment in the developed world and increasingly in the developing world over the past century, many settlements throughout the world (especially in rural areas) still are without adequate water treatment (UNCHS, 1999). In the case of drought, reduced water availability could force people to use polluted water sources in settlements at the same time that reduced flow rates reduce the rate of dilution of water contaminants. In the opposite case, flooding frequently damages water treatment works and floods wells, pit latrines and septic tanks, and agricultural and waste disposal areas and sometimes simply overwhelms treatment systems, contaminating water supplies.

7.2.2.3.5. Air pollution

Air pollution is a serious problem in many cities of the world, even under the current climate. The following issues emerge from a review of developing country cities that are members of the 69 urban agglomerations with population of more than 3 million in 1990 (UNEP, 1992):

- Population trends have not yet stabilized, which means cities will continue to extend their urban area (and urban heat island).
- Motor vehicles now constitute the main source of pollutants in most cities of the industrialized world. Although the rate of growth in the number of vehicles in some settlements in the developing world has been very rapid (Simon, 1996), cities in developing countries (with exceptions) exhibit greater variety in air pollution sources. This depends on the level of motorization and the level, density, and type of industry present. Cities in Latin America, for example, tend to have high vehicle densities and high vehicle-to-total pollution loads. The major sources of air pollution in Delhi are 2.8 million vehicles, thermal power plants, industries, and domestic

Box 7-2. **Air Pollution Problems of Large Cities in the Developing World—Update on the Case of Mexico City**

The SAR notes the complex air pollution problems of Mexico City and expresses concern that increases in air stability episodes under climate change could exacerbate an already difficult situation. Although these problems remain severe, as noted below, Mexico City also shows that adaptation (mitigation of air pollution) is possible and effective.

Mexico City is located in an elevated inland valley (approximately 2,250 m above sea level) in central Mexico. The climate is subhumid tropical, tempered by the altitude. Industrial activity contributes 20% of the city's air pollution; 3 million motor vehicles that consume 17.3 million liters of gasoline and 5 million liters of diesel daily (in 1997) generate 75% of the pollution (Office of the Environment Annual Report, 1997). Typical anticyclonic weather prevailing during the dry season contributes to frequent thermal inversions that prevent dispersion of pollutants. Moreover, abundant insolation prevailing during the dry warm period (March to May) favors activation of precursors [mainly oxides of nitrogen (NO_x) and hydrocarbons (HC)] to produce high levels of ozone. This also is the season for dust storms and blowing dust (Jáuregui, 1989). Although transport may generate 75% of the airborne pollutants by weight, estimates made in 1989 regarding transport's contribution to air pollution in terms of toxicity suggested its contribution was 42.4%. A considerable contribution also comes from vegetation and topsoil (12% of all airborne pollutants by weight in 1994) (see Connolly, 1999).

The Mexico City Ministry of the Environment subsequently found that ozone—one of the most serious threats to health—was still above acceptable levels on 300 days in 1999 but that some progress had been achieved. During the worst days from 1990 to 1992, pollutants hit emergency levels on as many as 177 days annually. Emergency levels occurred on 5 days in 1999. This achievement was considered to be a result of anti-pollution efforts by the local government. For example, in the early 1990s, lead was removed from gasoline sold in the Valley of Mexico; laws restricted the use of cars without catalytic converters to 4 weekdays; and inspections of factories to reduce pollution doubled in 1999, to 152. The average ozone reading fell from 197.6 to 144, where the air quality norm is 100 points of ozone—equivalent to exposure to 0.11 ppm for 1 hour (Mexico City Ministry of the Environment, 2000). This progress in improving air quality suggests that even huge developing world cities can begin to reduce pollution.

fuel combustion. The problem has been compounded by unplanned development, inadequate public transport, poor road conditions, lack of traffic management, inadequate vehicle/engine maintenance, use of old vehicles, and poor fuel quality. Many developing countries' vehicle fleets tend to be older and poorly maintained (and not easily replaced because of the low incomes of their owners)—a factor that will increase the significance of motor vehicles as a pollution source (UNEP, 1992).

- Cities with seasonally warm, calm air and sunny weather with high traffic densities tend to be especially prone to the net formation of ozone and other photochemical oxidants, although it is not yet clear whether such conditions will be more or less prevalent under climate change. Volatile organic carbons (VOCs) from biogenic and anthropogenic sources such as automobiles increase at high temperatures, and thermal decomposition of peroxyacetyl nitrate (PAN) also increases (Samson *et al*., 1989).
- Atmospheric and air-shed modeling exercises suggest that higher temperatures and more stable air episodes under global warming of 4ºC could lead to 1–20% increases in peak urban ozone concentrations in the United States (Morris *et al*., 1989; Penner *et al*., 1989) and increased violation of clean air standards (Morris *et al*., 1995). See Chapter 9 for the health effects of elevated ozone levels.

Box 7-2 shows that adaptive measures can be effective in reducing many of the precursors to adverse air quality under current climate. These measures also would help in the context of unfavorable atmospheric conditions as a result of climate change.

7.3. Energy, Transportation, and Other Climate-Sensitive Industry

7.3.1. Energy Supply and Demand

The SAR notes that climate change would impact energy supply and demand. Subsequent studies confirm this sensitivity. Hydropower generation is the energy source that is most likely to be impacted because it is sensitive to the amount, timing, and geographical pattern of precipitation as well as temperature (rain or snow, timing of melting) (see Chapter 4). Where reduced streamflows occur, they are expected to negatively impact hydropower production; greater streamflows, if they are timed correctly, might help hydroelectric production. In some regions, change of streamflow timing from spring to winter may increase hydropotential more in the winter than it reduces it in the spring and summer, but there is a question of whether the electric system can take advantage of the increase in winter flows and whether storage would be adequate. Hydroelectric projects generally are designed for a specific river flow regime, including a margin of safety. Projected climate changes are expected to change flow regimes—perhaps outside these safety margins in some instances (see Chapter 4). Although it is not yet possible to provide reliable forecasts of shifts in flow regimes for world river systems as a consequences of climate change, what is known suggests more intense rainfall events (which would require more conservative water storage strategies to prevent flood damage), greater probability of drought (less hydroelectric production), and less precipitation falling as snow (less water available during warm months). All three factors point to less (or, at least, less flexible) hydroelectric capacity at current powerhouses. Reduced flows in rivers and higher temperatures reduce the capabilities of thermal electric generation (Herrington *et al*., 1997); high temperatures also reduce transmission capabilities.

Some advanced energy technologies also may be affected. For example, the United States and Japan are trying to learn how to exploit the potential of methane hydrates. If global warming leads to warmer oceans or warms areas that currently are permafrost regions, these compounds are likely to become less stable, making it more problematic to attempt to recover methane from them (Kripowicz, 1998).

Increased cloudiness can reduce solar energy production. Wind energy production would be reduced if wind speeds increase above or fall below the acceptable operating range of the technology. Changes in growing conditions could affect the production of biomass, as well as prospects for carbon sequestration in soils and forest resources. Climate change could worsen current trends in depletion of biomass energy stocks in Africa, which is expected to become drier (see Chapters 3 and 10). The impact on biomass elsewhere is less clear; it may include enhancement of growth because of higher rainfall in Africa as well.

The portion of total energy supply from renewable energy sources varies among countries, developed and developing. In the United States in 1998, renewable sources provided roughly 7% of gross energy consumption—about half of that as hydroelectric energy (EIA, 1999a). In other countries, developed and developing, the percentages vary. For example, biomass accounts for 5% of north African, 15% of south African, and 86% of sub-Saharan (minus South Africa) energy consumption; in Cote d'Ivoire, the Democratic Republic of Congo, Ethiopia, Mozambique, and Zambia, the vast majority of on-grid electricity generation comes from hydropower (EIA, 1999b). Hydroelectricity represents the primary source of electricity in Canada and most South and Central American countries, with the highest reliance in Paraguay and Brazil (99 and 87% of generating capacity, respectively) (EIA, 1999c). Although renewable energy sources may be adaptable to new climate, larger percentages of renewables (especially hydroelectricity) in a country's energy supply might make the country relatively more sensitive to climate (see Chapters 10, 11, and 12). However, fossil fuel extraction may be adversely affected by increased wind and wave action, heavy precipitation, shoreline erosion, and permafrost melting in regions where this applies (see Chapter 16). In addition, thermal power plants can be adversely affected by loss of cooling water as a result of low flows (see Chapter 12).

If a warmer climate is characterized by more extreme weather events such as windstorms, ice storms, floods, tornadoes, and hail, the transmission systems of electric utilities may experience a higher rate of failure, with attendant costs (see, however, Chapter 3 and TAR WGI Chapter 10) These failures can be extremely costly, as illustrated by the great eastern Canada ice storm of January 1998, which toppled hundreds of transmission towers and downed 120,000 km of power lines—in some cases for a month to 6 weeks—and cost CDN$3 billion in economic damage (only half of which was insured) (Kerry *et al.*, 1999). A 5-week power failure in the central business district of Auckland, New Zealand, occurred in February–March 1998 when four high-voltage transmission cables failed (Ministry of Commerce of New Zealand, 1998). Hot weather contributed to high demand and less-than-optimal operating conditions of these cables as a result of high soil temperature and dryness, although it was not ruled the direct cause. Transmission and distribution systems can be hardened to respond to greater risk, but only at substantial cost.

The SAR notes that on the demand side, space-cooling demand would increase and space-heating demand would decrease. Electrical system expansion (generation, transmission, and distribution) may be required to meet greater summer peaks. In warmer areas, it is expected that the demand for electricity will certainly increase, as may the demand for energy overall. Urbanization, rising incomes, and warmer climates could combine to increase energy used for space cooling—already a major concern in tropical and subtropical cities, most of which are in developing countries (e.g., as much as 60% of total electricity use in the commercial sector in Hong Kong, 60% of all electric energy in Riyadh—see Al-Rabghi *et al.*, 1999; Lam, 1999, 2000). Besides having a major impact on the energy sector, air conditioning would tend to enhance heat island effects because of the energy used. At the same time, research has found that air conditioning, where available and affordable, is a statistically significant factor in reducing the chances of hot-weather-related mortality (Chestnut *et al.*, 1998).

The heat island phenomenon may have a positive impact in cities with seasonally cool to cold winters. For example, during the 20th century, the long-term impact of the urban heat island has been to reduce potential energy demand for space heating by as much as 50% in the central quarters of megacities such as Tokyo and Mexico City (Jáuregui, 1998). Urban warming and increased demand for cooling is expected, even though urban aerosol production (e.g., from power plants) does have a cooling effect (*Science News*, 1992; Jáuregui and Luyando, 1999).

Additional studies that have been published since the SAR continue to show that whether *net* energy consumption will increase or decrease as a result of climate change depends very much on location—in particular, whether energy consumption includes larger heating loads or cooling loads. The north-south orientation of Japan provides some insight into this question. Ichinose (1996) (quoted in Mimura *et al*., 1998) has shown for Japan that reduction in heating would be about 30% in Sapporo on the northern island of Hokkaido, whereas it would be only 10% in Tokyo on the central island of Honshu. On the other hand, electricity consumption for cooling would increase hardly at all on Honshu and several percent in Naha on the southern island of Okinawa. The direction of net change also is sensitive to the future market penetration of air conditioning and to energy prices. In one Japanese study (Hattori *et al.*, 1991, summarized in Mimura *et al*., 1998) the sensitivity of peak electric power demand to air temperature was shown to have increased 2.3 times during the 15 years between 1975 and 1990, largely as a result of the increase in the market penetration and unit size of air conditioners. Amano (1996, summarized in Mimura *et al*., 1998) points out that a decline in energy prices contributed to the increase in the sensitivity of electricity consumption to climate.

Belzer *et al.* (1996) is among the few studies since the SAR that has estimated the effect of climate change on energy demand by the commercial sector. The study projects the change in demand at the national level for the United States in 2030. Accounting for changes in the building stock, a 4°C increase in average annual temperature, holding other loads constant, leads to an estimated 0–5% reduction in total energy consumption by the commercial sector in the year 2030 (note that 4°C was then considered possible at mid-latitudes if worldwide temperatures increased 2.5°C; now it is probably at the upper end of potential increases).

The SAR notes that energy used for irrigation would increase. Peart *et al.* (1995) studied the effects of climate change on energy efficiency in agriculture (including irrigation) in the southeastern United States. Results indicate that climate change would cause an increase in energy inputs required to produce a given amount of maize, soybeans, and peanuts.

Only a handful of studies since the SAR have looked at the effects of climate change on overall energy demand. Mendelsohn and Schlesinger (1999) estimated climate response functions and economic welfare for the entire energy sector in the United States, based on the cross-sectional study of household and firm energy expenditures in Mendelsohn and Neumann (1998). Two approaches were used: laboratory experiments coupled with process-based simulation models, and cross-sectional studies to substitute for impacts of climate change over time. Economic welfare associated with energy was found to have a quadratic relationship with temperature, with a maximum at 10°C. Although the experimental method succeeded in isolating the effect of climate from other variables, it failed to fully incorporate adaptive responses. The cross-sectional studies found that annual energy expenditures were minimized with an annual temperature of 12.8°C in the commercial energy sector and with 11.7°C in the residential energy sector. The cross-sectional approach, of course, does not allow for the transient response of the climate system or the actual dynamics of the energy sector in response to climate. It substitutes static history for a dynamic future and cannot deal with irreversibilities, higher moments of climatic changes such as alterations to diurnal or seasonal cycles, synergic responses (see Section 7.6), or extreme events. (e.g., Schneider, 1997).

7.3.2. Transportation

Changnon (1996a) studied the effects of potential shifts in summer precipitation on transportation in Chicago, using data for 1977–79 and assuming continued use of current modes of transport. The study suggests that a future climate with more summer rainy days, somewhat higher rain rates, and more rainstorms would increase total vehicular accidents and total injuries in vehicular accidents, reduce travel on public transportation systems, and cause more aircraft accidents and delays. A drier climate probably would experience fewer moderate to heavy rain events, but results show that rain events during drier conditions produce a greater frequency of accidents and injuries per event than during wetter conditions. If high-heat events became more common with warmer climate, they also could become a problem. They have been known to soften asphalt roads, "explode" or buckle concrete roads, warp railroad rails, close airports because of lack of "lift" in extremely hot air, and increase mechanical failures in automobiles and trucks. On the other hand, there might be fewer mechanical failures resulting from extreme cold (Adams, 1997). Floods are costly to transportation systems, as they are to other infrastructure. Although the effect of climate change on flying weather is not clear, transportation by air is known to be sensitive to adverse weather conditions; major systemwide effects sometimes follow from flight cancellations, rerouting, or rescheduling. For example, one diverted flight can cause anywhere from 2 to 50 flight delays, and one canceled flight can result in 15–20 flight delays. The cost of a diverted flight can be as much as US$150,000, and a cancellation can cost close to US$40,000. The corresponding direct annual costs to 16 U.S. airlines are US$47 million and US$222 million, respectively (Qualley, 1997). Several additional examples of impacts on transportation are cited in Chapter 13.

7.3.3. Construction

Flooding and other extreme weather events that damage buildings and infrastructure could cost the world's economies billions of dollars under climate change simply to replace the damage—a cost that could divert funds from other needed investment (see Chapter 8). However, Mimura *et al.* (1998) note that cost increases for disaster rehabilitation and countermeasures against natural calamities could expand the market for the construction industry. Although no direct studies have been done, it is likely that a greater incidence of summer heat waves would reduce the productivity of this sector, but a lower incidence of cold waves and snowy conditions would increase the amount of year-round construction that could be accomplished in climates that currently have long, cold winters. Changes in design requirements for infrastructure, leading to additional requirements for construction, are discussed in the SAR.

7.3.4. Manufacturing

Manufacturing industries that are not directly dependent on natural resources generally would not be affected by climate unless key infrastructure is destroyed by flood or landslides, or unless shipments of inputs and outputs are affected (e.g., by snow blocking roads, airports, and train tracks; flooding or low flow that make river transportation untenable; or low water supplies that make process cooling and environmental activities more difficult). However, manufacturers are influenced by climate change in two other ways. First, they would be affected through the impact of government policies pertaining to climate change, such as carbon taxes (thereby increasing the cost of inputs). Second, they could be affected through consumer behavior that in turn is affected by climatic variations. For example, less cold-weather clothing and more warm-weather clothing might be ordered. Manufacture that depends on climate-sensitive natural resources would be affected by impacts on those resources. For example, food processing activity would follow the success of agriculture. Very little is known concerning the effects of warming on industry, and most information is highly speculative.

7.3.5. Financial Services and Insurance

Climate change increases risks for the insurance sector, but the effect on profitability is not likely to be severe because insurance companies are capable of shifting changed risks to the insured, provided that they are "properly and timely informed" on the consequences of climate change (Tol, 1998). For example, during the great storms in the early 1990s, the insurance sector reacted to increased risk and large losses by restricting coverage and raising premiums. Tucker (1997) also shows that increased climatic variability necessitates higher insurance premiums to account for the higher probability of damages. However, insurance companies still can be destabilized by large losses in a major weather-related catastrophe in a region where actuarial tables and estimated risks do not adequately reflect true weather risk (including greater variability), and companies therefore may not have made adequate provision for losses. See Chapter 8 for a description of impacts on financial services.

7.3.6. Estimating and Valuing Effects

Valuation of climate impacts remains difficult on three grounds. The first is uncertainty associated with determining physical changes and responses to these changes. The second is economic valuations of these changes that vary across regions. Fankhauser *et al.* (1998) show that damage cost estimates are sensitive to assumptions made on the basis of valuation (willingness to pay versus willingness to accept), accountability for impacts, differentiation of per unit values, and aggregation of damage costs over diverse regions. A third problem can be expressed as follows: "Which metric?" Five popular metrics are used: market costs, lives lost, species lost, changes in the distribution of costs/benefits, changes in quality of life (loss of heritage sites, environmental refugees, etc). Schneider *et al.* (2000) conclude that when aggregation exercises are undertaken, disaggregation of all estimated effects into each of five numeraires is needed first, followed by a traceable account of any aggregation so others holding different weighting schemes for each numeraire can re-aggregate. This is done rarely, if ever.

The Workshop on the Social and Economic Impacts of Weather at the National Center for Atmospheric Research, 2–4 April 1997, in Boulder, CO, estimated that property losses from extreme weather of all types currently costs the United States about \$15 billion yr^{-1} (\$6.2 billion related to hurricanes), as well as about 1,500 deaths (about half resulting from cold events); the worst flood and hurricane years yield about \$30–40 billion in property losses.

Smith (1996) standardized estimates of climate change damages for the United States for a 2.5°C warming, a 50-cm sea-level rise, 1990 income and population, and a 4% real rate of return on investments. Total damage estimates are slightly less than 1% of United States gross national product (GNP) in 1990. Within individual sectors such as agriculture and electricity, however, standardized damages differ by more than an order of magnitude. This level of uncertainty appears to apply among experts as well. For example, Nordhaus (1994) surveyed experts, and their damage estimates ranged over more than an order of magnitude.

Yohe *et al*. (1996) calculated the cost of a 50-cm sea-level rise trajectory for developed property along the U.S. coastline. Transient costs in 2065 were estimated to be approximately \$70 million (undiscounted and measured in constant 1990 US\$). These costs are nearly an order of magnitude lower than estimates published prior to 1995 (e.g., Fankhauser, 1995). This is because Yohe *et al*. (1996) incorporated the cost-reducing potential of market-based adaptation in anticipation of the threat of sea-level rise. In addition, they assumed efficient discrete decisions to protect or abandon small tracts of property, based on their economic merit. Some work since suggests that maladaptation may cause the costs of sea-level rise to be somewhat higher (West and Dowlatabadi, 1998).

7.3.7. Tools/Methods/Approaches/Models Used in Developing New Knowledge, including Assumptions, Sensitivities, and Scenarios Used in Models

Current impact assessment methods focus on comparing current conditions to a single alternative steady state—that associated with doubling of GHGs. Mendelsohn and Schlesinger (1999) attempt to estimate climate response functions for market sectors in the United States that reflect how damages change as climate changes through a range of values. Impacts are generated by using national climate values, rather than global values, and the timing of climate change is included in the modeling of capital-intensive sectors such as coastal resources and timber, which cannot adjust quickly. Empirical estimates of climate response functions are based on laboratory experiments coupled with process-based simulation models and cross-sectional studies (Mendelsohn and Neumann, 1998). Both methods indicate that agriculture, forestry, and energy have a bell-shaped relationship to temperature. Similarly, an increase in precipitation is likely to be beneficial to some agriculture, forestry, and water sectors, although this effect is reversed at sufficiently high levels. However, this work captures neither the transient response of the climate system nor the actual dynamics of the energy sector in response to climate (e.g., Schneider, 1997).

7.4. Infrastructure

7.4.1. Water Supply and Demand

Increases in average atmospheric temperature accelerate the rate of evaporation and demand for cooling water in human settlements, thereby increasing overall water demand, while simultaneously either increasing or decreasing water supplies (depending on whether precipitation increases or decreases and whether additional supply, if any, can be captured or simply runs off and is lost). Shimizu (1993, quoted in Mimura *et al*., 1998) showed that daily water demand in Nagoya, Japan, would increase by 10% as the highest daily temperature rose from 25 to 30°C. Boland (1997) looked at several climate transient forecasts for the Washington, DC, metropolitan area for the year 2030 and estimated increases in summertime use of 13 to 19% and annual use of –8 to +11% relative to a future increase from 1990 without climate change of approximately 100%. In China, using four GCMs for the year 2030, water deficiency under normal (50%) and extreme dry (95%) hydrological conditions for various basins was predicted as -1.6×10^8 to 1.43×10^9 m^3 in the Beijing-Tianjin-Tangshan area and -1.1×10^8 to 121.2×10^8 m^3 in the Yellow River Basin (China Country Study Team, 1999).

Estimates of effects on water supply mostly have dealt with linking atmospheric and hydrologic models in an attempt to produce more plausible forecasts with statistical variability. Although they do not directly forecast water supplies to human settlements, Kwadijk and Rotmans (1995) do show an increase in variability of supply in the Rhine River with climate change, but little change in estimated annual flow. The study is unusual in that it attempts to directly link impacts to mitigation policy. Amore conventional study that still links water supply (directly for a municipal water system) and climate scenarios is Wood *et al*. (1997).

7.4.2. Buildings, Transportation, and Other Infrastructure

Additional research since the SAR seems to have added to concerns about increased intensity of rainfall and urban flooding (e.g., for the highly urbanized northeast United States—Rosensenzweig and Solecki, 2000). Increases in intensity are projected by Fowler and Hennessy (1995) and Hennessy *et al*.

(1997). Smith *et al.* (1999) have performed a series of four case studies that combine climate and hydrological modeling to directly model flood frequency and magnitude and economic losses under enhanced greenhouse rainfall intensities. The study concludes that there would be little change in forecast flood damage by the year 2030 but that there would be substantial increase in flood risk (shortened average return interval) and flood damage (as a result of building inundation and failure) by the year 2070. The estimation technique was an improvement over earlier studies that assumed that changes in intensities of rainfall events would be associated with changes in flood frequency (e.g., Minnery and Smith, 1996).

Generally speaking, climate change will change the level and type of climatic effects that need to be covered by infrastructure design codes. This could affect infrastructure durability and energy usage. Potential changes in humidity and climate may change distribution in factors such as termites, for example—with potential degradation of structures and more serious impacts from given extreme events. There also could be adverse effects of storms, heat, and humidity on walls and insulation, though perhaps less winter damage.

7.4.3. Estimating and Valuing Infrastructure Effects

There still are relatively few reports that estimate the impact of global warming on the value of economic losses resulting from effects on infrastructure. However, Smith *et al*. (1999) and Penning-Powswell *et al.* (1996) provide estimates that show that increases in damages from urban riverine flooding probably would be substantial. See also the discussion on sea-level rise in Section 7.2.2.2.

7.5. Management and Adaptation of Human Settlements

Social and natural sustainability are important for sustainable development of human settlements (Yoshino, 1994). Coping with flooding and drought; getting potable water, breathable air, and a stable environment; and so forth have been prime concerns of urban planners, engineers, governments, and citizenry for thousands of years (Priscoli, 1998). Climate change simply adds to the challenge. Some of the adaptations probably would take place autonomously, but some adaptations may be much improved by taking climate into account explicitly (Wood *et al*., 1997).

7.5.1. Adaptation

Questions such as "adapt to what?", "who or what adapts?", and "how does adaptation occur?" (Smit *et al*., 1998) are still difficult to answer in a strict sense. Management, adaptation, and vulnerabilities have been discussed for settlements in coastal (Fukuma, 1999/2000), arid, agrarian (Douguédroit, 1997; Douguédroit *et al*., 1997; Le Treut 1997), and urban regions (Maunder, 1995). To be successful, adaptations must be consistent with economic development, they must be environmentally and socially sustainable over time, and they must be equitable (that is, not have significantly deleterious effects on disadvantaged groups) (Munasinhge, 2000).

7.5.2. Adaptation to What and Why?

In most cases, human settlements have designed into them the ability to withstand most of the consequences of some environmental variability. In most regions, climate change would change the probability of certain weather conditions. The only effect for which average change would be important is sea-level rise, under which there could be increased risk of inundation of coastal settlements from average (higher) sea levels. Human settlements for the most part would have to adapt to more or less *frequent* or intense rain conditions or more or less *frequent* mild winters and hot summers, although individual days'weather may be well within the range of current weather variability and thus not require exceptionally costly adaptation measures. The larger, more costly impacts of climate change on human settlements would occur through increased (or decreased) probability of extreme weather events that overwhelm the designed resiliency of human systems.

Much of the management of urban centers as well as the governance structures that direct and oversee them are related to reducing environmental hazards, including those posed by extreme weather events and other natural hazards. Most regulations and management practices related to buildings, land use, waste management, and transportation have important environmental aspects. So too do most public and private investments in infrastructure. A significant part of health care and emergency services exists to limit the health impacts of environmental hazards. Local capacity to limit environmental hazards or their health consequences in any settlement generally implies local capacity to adapt to climate change, unless adaptation implies particularly expensive infrastructure investment.

An increasing number of urban centers are developing more comprehensive plans to manage the environmental implications of urban development. Many techniques can contribute to better environmental planning and management including: market-based tools for pollution control, demand management and waste reduction, mixed-use zoning and transport planning (with appropriate provision for pedestrians and cyclists), environmental impact assessments, capacity studies, strategic environmental plans, environmental audit procedures, and state-of-the-environment reports (Haughton, 1999). Many cities have used a combination of these techniques in developing "Local Agenda 21s." Many Local Agenda 21s deal with a list of urban problems that could closely interact with climate change in the future. Examples of these problems include (WRI, 1996; Velasquez, 1998):

- Transport and road infrastructure systems that are inappropriate to the settlement's topography (could be

damaged by landslides or flooding with climate change)
- Dwellings that are located in high-risk locations for floods, landslides, air and water pollution, or disease (vulnerable to flood or landslides; disease vectors more likely)
- Industrial contamination of rivers, lakes, wetlands, or coastal zones (vulnerable to flooding)
- Degradation of landscape (interacts with climate change to produce flash floods or desertification)
- Shortage of green spaces and public recreation areas (enhanced heat island effects)
- Lack of education, training, or effective institutional cooperation in environmental management (lack of adaptive capacity).

7.5.3. Sustainable Cities Activities

The following generic lessons from Curitiba, Brazil—which come from the context of "sustainable cities" under *existing* conditions—may be applicable to future adaptation responses (Rabinovitch, 1998):

- Top priority should be given to public transportation rather than to automobiles and other light-duty vehicles, and to pedestrians and cyclists rather than to motorized vehicles. This reduces air pollution and some other forms of pollution. It was noted that some alternative fuels such as hydrogen are particularly attractive for reducing local air quality problems, as well as mitigating GHG emissions.
- There can be an action plan for each set of urban problems, but solutions within a city are connected, not isolated.
- Action plans must be participatory, with partnerships involving all responsible parties [government, private sector, nongovernmental organizations (NGOs), individuals].
- Creativity can substitute for financial resources (labor-intensive and creative ideas can substitute for capital).
- Even during rapid demographic growth, physical expansion can be guided by integrated road planning, investment in public transportation, and enforcement of appropriate land-use legislation.
- Technological solutions and standards for everything from public transit to recycling should be chosen on the basis of affordability (cost-effectiveness, combined with sensitivity to total cost).
- Public information and awareness are essential.

The most effective pathways for adaptation that result in sustainable development are likely to arise out of an informed evolution of existing institutions. Several authors emphasize the importance of the support and will of local public officials in developing successful environmental solutions (e.g., Gilbert *et al.*, 1996: Foronda, 1998). Others emphasize the need in traditional societies to build from and integrate modern techniques into traditional management practices and kinship and community networks, to effectively collect and disseminate data needed for assessing impacts, to open public participation processes for formulating policy, and to provide a process for strengthening financial, legal, institutional, and technical elements (Huang, 1997).

7.5.4. Adaptation Options

Adaptation to climate changes involves planning of settlements and their infrastructure, placement of industrial facilities, and making similar long-lived decisions to reduce the adverse effects of events that are of low (but increasing) probability and high (and perhaps rising) consequences. The adaptation response consists of planning to reduce the sensitivity of key assets, designing resilience and flexibility into the public and private infrastructure on appropriate time scales, and managing settlements and institutions in a climate-resilient manner. The following discussion of example options and strategies is divided into Planning and Design, Management, and Institutional Frameworks (see Table 7-2 for a summary):

- *Planning and Design*
  - Take advantage of rapidly increasing populations in many regions. Growing populations and cities provide economic advantages, not just costs (Satterthwaite, 1998). In the case of infrastructure, growing populations provide an opportunity for new construction that can be designed for increased resilience and flexibility with respect to climate change. With good planning and building practices in new construction, considerable energy and environmental cost can be saved at relatively small incremental construction costs compared with later retrofit or protection (Rabinovitch, 1998). It can be less costly to design and build flood works "oversized" in the beginning than to rebuild them later to add capacity (this is not a foregone conclusion and depends on local uncertainties; see Wood *et al*., 1997).
  - Take advantage of replacement schedules. Many short-lived assets such as consumer goods, motor vehicles, and space heating/cooling systems will be replaced several times in the course of a few decades, offering considerable opportunities for adaptation. Even medium-life assets such as industrial plants, oil and gas pipelines, and conventional power stations are likely to be completely replaced over such a time scale, though there will be less opportunity for adaptation through upgrades and relocation.
  - Community design tools such as floodplain and hillside building practices and landscape design (zoning in developed countries; perhaps land-use planning in developing countries) can be improved to limit damage. Reducing heat islands (through judicious use of vegetation and light-colored surfaces, reducing motor transportation, and taking advantage of solar resources) also should be included in the package of possibilities.

***Table 7-2**: Planning and design, management, and institutional frameworks actions for human settlements, by type of settlement.*

	Resource-Dependent Settlements	**Coastal, Riverine, and Steeplands Settlements**	**Urban Settlements**
Planning and Design	– Increase economic diversification – Oasis development – Windbreaks – Develop irrigation and water supply – Rural planning – Redevelop tourism and recreation industry – Take advantage of replacement schedules for buildings and infrastructure	– Zoning in developed countries; perhaps land-use planning in developing countries – Better building codes to limit impact of extreme events, reduce resource use – Soft and hard measures to reduce risk of floods: • Reconstruction of harbor facilities and infrastructure • Flood barriers • Managed retreat (acquisition of properties; fiscal and financial incentives) • Hazard mapping • Tsunami damage-prevention facilities – Take advantage of rapidly increasing populations for sizing infrastructure – Take advantage of replacement schedules for buildings and infrastructure – Use community design tools such as floodplain and hillside building practices, public transportation – Improve sanitation, water supply, electric power distribution systems – Employ design practices to prevent fire damage (development densities and/or lot sizes, setbacks, etc.)	– Site designs and building materials and technologies that moderate temperature extremes indoors – Improve infrastructure and services, including water, sanitation, storm and surface water drainage, and solid waste collection and disposal – For higher temperatures: • Building and planning regulations and incentives that encourage building measures to limit development of “heat islands” – Take advantage of rapidly increasing populations for sizing infrastructure
Management	– Employ countermeasures for desertification – Increase environmental education – Improve landscape management – Develop agricultural and fisheries cooperatives to reduce risk – Preserve and maintain environmental quality – Institute emergency preparedness and improve neighborhood response systems	– Provide warning systems and evacuation plans; salvage; emergency services; insurance and flood relief – Better implement/enforce existing building codes – Employ special measures to promote adaptation and disaster preparedness in sites or cities at high risk from such events – Institute market-like mechanisms and more efficient management of water supplies (e.g., fix leaks) – Institute neighborhood water wholesaling and improve delivery	– Institute neighborhood water wholesaling and improve delivery systems – Improve sanitation and waste disposal – Create and enforce pollution controls for solid, liquid, and gaseous wastes – Efficiently operate public transportation systems – Institute emergency preparedness and improve neighborhood response systems – Improve health education

Table 7-2 (continued)

	Resource-Dependent Settlements	Coastal, Riverine, and Steeplands Settlements	Urban Settlements
Management (continued)		– Institute emergency preparedness and improve neighborhood response systems – Improve health education	
Institutional Frameworks	– Build institutional capacity in environmental management – Create partnerships between all responsible parties (government, private sector, NGOs, individuals) – Regularize property rights for informal settlements and other measures to allow low-income groups to buy, rent, or build good quality housing on safe sites – Improve technology of farm machinery, herbicides, computers, etc.	– Build institutional capacity in environmental management – Create partnerships between all responsible parties (government, private sector, NGOs, individuals) – Regularize property rights for informal settlements and other measures to allow low-income groups to buy, rent, or build good quality housing on safe sites	– Build institutional capacity in environmental management – Create partnerships between all responsible parties (government, private sector, NGOs, individuals) – Regularize property rights for informal settlements and other measures to allow low-income groups to buy, rent, or build good quality housing on safe sites

- Improved sanitation, water supply, and electric power distribution systems can be planned in an integrated manner, with sensitivity to the location of air sheds and water sheds and efficient utilization of plant (e.g., properly price water to reflect scarcity and reduce leakage in water supply systems) (Wood *et al*., 1997; Lettenmaier *et al*., 1998; Tindleni, 1998). In some cases, this requires "hardening" the system. In other cases, it requires flexible approaches to plans for cleanup and movement of waste facilities in the flood zone throughout the watershed and, for example, sanitation (Bartone, 1998). There are more opportunities to do this in developing countries, which are still acquiring their basic urban infrastructure. According to the United Nations Center for Human Settlements (UNCHS) Global Urban Indicators Program Web site in 1999, which developed city data collection systems in 237 cities in 110 countries, about 38.5% of African urban households were connected to water systems, 15.4% to sewerage, 46.9% to electricity, and 14.1% to telephones; in Asia the corresponding connection rates were 52.4, 33.2, 82.5, and 26.5%, respectively, and in the industrialized countries the percentages were 99.4, 95.8, 99.2, and 78.2% (UNCHS, 1999).
- Measures can be taken by governments to anticipate floods (Smith and Handmer, 1984), including "hard" engineering measures such as dams, levees, diversions, channels, and retarding basins and "soft" or "nonstructural" methods such as acquisition of properties, fiscal and financial incentives, regulations such as zoning and building regulations, information and education campaigns, forecasts/warning systems/evacuation plans, salvage, emergency services, insurance, and flood relief. "Designing with nature" is an effective strategy for curbing flood losses even with current climate (Rabinovitch, 1998). In some cases, this may require cleanup and movement of waste facilities in the flood zone throughout the watershed, an issue also discussed in the SAR. FEMA (1997) has concluded that the process of establishing and implementing state and community comprehensive development and land-use plans provides significant opportunities to mitigate damages caused by natural hazards. Losses from floods in the upper Mississippi valley in 1996 (after some of these actions had been taken) were two orders of magnitude lower than in 1993 for similar-sized floods. Albergel and Dacosta (1996) propose analyzing runoff patterns from non-normal storm events as a basis for more sustainable water resource management in the specific instance of Senegal to deal with extreme events more effectively. Colombo, Sri Lanka, has an ambitious plan to redesign and rebuild its flood management system, incorporating improved maintenance of the existing system, development of flood retention areas, cost-effective defined flood safety margins, movement of people out of flood-prone lands immediately adjacent to canals, and even a plan to move industries and public organizations out of Colombo to hold constant the amount of unbuilt lands in the face of increased urbanization (Gooneratne, 1998).

- Put key infrastructure in less vulnerable areas and (as appropriate) harden against fire. Urban/ wildlands interface fires at locations such as Oakland/East Bay Hills in California and Sydney, Australia, have yielded examples of design practices to prevent such occurrences, including limiting development densities and/or requiring large lot sizes; setting buildings back from flood, landslide, and fault hazard zones; requiring adequate minimum paved street widths and grades; requiring second access points; restricting the lengths of cul-de-sacs; developing adequate water supply, flows, and redundant storage; and using open space easements for fire breaks, equipment staging, and evacuation areas (Topping, 1996). Wildlands fires also may affect settlements at a distance. In 1997, health and haze effects of wildfires alone cost Indonesia US$1 billion (EEPSEA, 1999; Wheeler, 2000). Total costs were about US$4.5 billion.
- Diversifying economic activity could be an important precautionary response that would facilitate successful adaptation to climate change for resource-dependent settlements.
- Use suitable design techniques to reduce cooling demand in many buildings. For example, the U.S. Department of Energy's Building America Program uses a systems engineering approach and works with the home building industry to produce quality homes that use 30–50% less energy without increasing building costs, that reduce construction time and waste by as much as 50%, and that improve builder productivity. Eliminating inefficiencies is not strictly an adaptation option, but these improvements also would have the benefit of reducing the impact of warming on energy use. Adaptive measures that can effectively reduce energy use relating to space cooling include better design of building envelopes (which can cut cooling energy consumption by more than one-third in current subtropical conditions or 5–30% under current European conditions—see Chan and Chow, 1998; Balarus *et al*., 2000); high-albedo roofs (field tests in Florida show savings of 2–40%—Akbari *et al*., 1999); and development of urban trees and other greenery (Avissar, 1996; Spronkensmith and Oke, 1998; Upmais *et al*., 1998), reducing summertime urban cooling loads by 3–5% (Sailor, 1998). See also Angioletti (1996) for criteria for sustainable building practices. Low-income energy assistance and weatherization can play a role in assuring equity (Miller *et al*., 2000).

- *Management*
  - To stretch water supplies further, especially in high-income parts of developed countries, institute market-like mechanisms and more efficient management of water supplies. Experiments with market systems in the United States have yielded water surpluses during drought in California, but such schemes must consider distribution and equity effects when water consumption is very low already (Hardoy *et al*., 2000), as well as external environmental effects on third parties (Frederick, 1997). In some urban water systems, a significant percentage of water put into the system is lost through leakage (e.g., 23%—or about eight times the expected increase in demand resulting from climate change—in the case of the southern part of Britain). Urban water systems may lose as much as 40–60% of their water in distribution (Cairncross, 1990; Daniere, 1996; Rahman *et al.,* 1997). Simply fixing leaks in cases such as this would go a long way toward making sure that supplies are available (Arnell, 1998). Boland (1997) found that mandating and widely promoting conservation measures in the Washington, DC, area (such as a 50% increase in tariff level, industrial/commercial water reuse and recycling, and a moderate conservation-oriented plumbing code) could cut the increase in baseline water use in the year 2030 from 100% to about 45%. This would more than offset any increase in use resulting from climate warming. In developing-world cities' poor neighborhoods, where water use already may be below levels that are conducive to good health, a mixed response involving improving pipes, instituting neighborhood water wholesaling, and improving water vendors and kiosks may be effective and affordable, if coordinated with organized liquid waste disposal (Hardoy *et al*., 2000).
  - Provide flood control and other forms of property assurance (not necessarily insurance). On the insurance side, Germany and France have taken very different approaches, with Germans adopting private insurance and minimal flood assistance and the French adopting compulsory extended coverage under the "cat 'nat" system. Neither system has proved to be able "to provide sufficient coverage at reasonable cost (Gardette, 1997). The United States has been able to provide flood insurance through a national system—at the cost of not controlling losses. Much more activity is now going into loss prevention in the United States (FEMA, 2000). The FEMA Hazard Mitigation Grant Program (HMGP) provides grants to states and local governments to reduce loss of life and property from natural disasters and to enable mitigation measures to be implemented during the immediate recovery from a disaster (FEMA, 2000). Some authors argue that loss prevention could be anticipatory (Miller *et al*., 2000).
  - Institute emergency preparedness and improve neighborhood response systems and mutual assistance. This strategy is featured in many of

the local initiatives cataloged by the International Council for Local Environmental Initiatives (ICLEI). Increasing access to cooling stations and city heat emergency response plans for urban heat island effects are an example. Plans for extreme events have improved considerably in the past 50 years, especially in developed countries, and can be very effective against some of the anticipated consequences of climate change. For example, preparation of disaster prevention organization in Japan, including forecast techniques and information systems between weather bureau/meteorological offices and individuals through local government/offices, has resulted in a dramatic decrease in the number of deaths and houses destroyed, especially for middle-sized typhoons (Class III) in the past 4 decades. This trend suggests that disaster prevention systems such as river improvement, establishment of information systems, improvement of typhoon forecasting, and so forth were most effective for middle-sized typhoons (Fukuma, 1996; Yoshino, 1996a). In most developing countries, local governments are particularly weak and ineffective at environmental management and have little capacity to integrate disaster preparedness into their current tasks and responsibilities. For example, no significant change has been found in deaths per violent hurricane in Bangladesh (Fukuma, 1999/2000), whereas there has been a significant decline in the United States (Pielke, 1997). However, some of the differences may be partly a result of a reduction in violent hurricanes making landfall in populated areas. U.S. property damages increased while the incidence of hurricanes fell (see Pielke and Landsea, 1998). Analysis of 15 years of simulation and observations show that typhoon frequency has decreased off the Philippine Islands and that the location of their generation shifts toward the east during El Niño years (Matsuura *et al.*, 1999). If similar conditions in typhoon regions also occur under global warming, more effective prediction and tracking of tropical typhoons in the 21st century could reduce typhoon disasters.

- Improve health education. Because the consequences of flood and drought on water quantity and quality are fairly straightforward to predict, concerted public awareness campaigns can significantly reduce adverse heath consequences on populations from water-borne enteric diseases. For example, in the Marshall Islands in 1997–1998, a public awareness campaign to boil all water supplies was triggered by public health officials' concerns over dwindling water availability. The number of hospitalizations for diarrheal disease was lower than normal (Lewis *et al*., 1998).

- *Institutional Frameworks*
  - An institutional framework can be put in place that is more "friendly" for adaptation strategies. Some key features of such a strategy include regularizing property rights for informal settlements and other measures to allow low-income groups to buy, rent, or build good-quality housing on safe sites. Much of the poor-quality settlement infrastructure in the developing world in particular is traceable to the questionable legal status of housing in these settlements (e.g., Jaglin, 1994; Acho-Chi, 1998; Perlman, 1998). Thus, the occupants of such housing units can be reluctant to spend much on quality construction and may have little legal standing to demand municipal government services such as piped water, sewerage, or waste collection. Perhaps more important, even if they are financially able to do so, governments may be unable or reluctant to extend services to households and communities lacking legal standing, especially if such extension of service thereby "validates" the settlement.
  - Build institutional capacity in environmental management. Capacity to adapt to climate change, as with other environmental problems, will be realized only if the necessary information is available, enterprises and organizations have the institutional and financial capacity to manage change, and there is an appropriate framework within which to operate. In this respect, autonomous adaptation cannot necessarily be relied on. Governments may have a role in terms of disseminating information (Miranda and Hordijk, 1998) and in any case should not stand in the way through indifference, hostility, or inefficient or corrupt management (Foronda, 1998). Building efficient environmental institutions requires coherent policy, planning, mechanisms for implementation, procedures for monitoring and corrective action, and a means for review. Mechanisms include use of market-based regulatory instruments to limit contributory pollution and to organize land use; development of appropriate roles for central and local governments; involvment of communities and civil societies in adaptive strategies (including traditional environmental knowledge and informal regulation as appropriate); and expansion of the scope for international cooperation (World Bank, 1999).

7.5.5. Barriers and Opportunities for Adaptation

Most urban authorities in developing regions have very little investment capacity despite rapid growth in their populations and the need for infrastructure. Problems arise from inadequate and inappropriate planning for settlements. Yet the need for planning becomes even more pressing in light of increased social, economic, and environmental impacts of urbanization; growing consumption levels; and renewed concern for sustainable development since the adoption of Agenda 21 (UNCHS, 1996). Environmental management tends to be more difficult in very large cities (WRI, 1996). Although there are commitments from developed countries in Article 4.4 of the United Nations Framework Convention on Climate Change (UNFCCC) to assist particularly vulnerable countries with adaptation, the financial resources needed to provide services to tens of millions of people are daunting.

Increasingly, settlements are exchanging ideas concerning methods and experiences for community design and management to improve sustainability and livability. For example, ICLEI is an association of local governments dedicated to prevention and solution of local, regional, and global environmental problems through local action. More than 300 cities, towns, counties, and their associations from around the world are members of the Council (ICLEI, 1995).

Environmentally sound land-use planning is central to achievement of healthy, productive, and socially accountable human settlements within societies whose draw on natural resources and ecosystems is sustainable. The challenge is not only how to direct and contain urban growth but also how to mobilize human, financial, and technical resources to ensure that social, economic, and environmental needs are addressed adequately (UNCHS, 1996).

7.6. Integration

There are multiple pressures on human settlements that interact with climate change. The discussion in this chapter shows that these other effects are more important in the short run; climate is a *potential* player in the long run. For example, urban population in the least-developed countries currently is growing at about 5% yr^{-1}, compared with 0.3% yr^{-1} in highly industrialized countries.[1] Providing for this rapidly urbanizing population will be much higher on most countries' agendas than longer term issues with climate change.

Other environmental problems will tend to interact with climate change, adversely affecting human settlements. For example, 25–90% of domestic energy supply in the developing world is met by biomass resources, especially in small urban centers (Barnes *et al*., 1998). In some countries, 11–20% of all deforestation may be attributable to charcoal production (Ribot, 1993), much of it to meet urban needs. If biomass growth is slowed via climate change effects, the impacts on biomass may be compounded.

Deforestation and cultivation of marginal lands can compound the effects of extreme events. For example, floods resulting from Hurricane Mitch, though not caused by climate change, illustrate the fact that poor watershed management can contribute to flooding and landslides—which, in turn, causes loss of life and destroys infrastructure and the means of livelihood. Mitch cost Honduras 80% and Nicaragua 49% of one year's GDP (FAO, 1999). Poor watershed management and technical failures has contributed to loss of life in landslides in Sri Lanka, Peru, Brazil, several European countries, and the United States (Katupotha, 1994)

Urban water resources already are in extremely short supply in 19 Middle Eastern and African countries (IPCC, 1998) and in cities in many parts of the world, where as many as 60% of poorer residents may not have access to reliable water supplies (Foronda, 1998). Poor urban water management may be responsible for losses through leakage of 20–50% in cities in the developing world and even in some cities in the industrialized world (WRI, 1996). If climate change makes water more scarce—by increasing demand (even in regions that currently are not particularly short of water, such as Great Britain—see Arnell, 1998) or by reducing supply (reduced surface runoff, exacerbation of water quality problems as a result of warmer temperatures and reduced flows, or salinization of coastal aquifers resulting from sea-level rise)—water supply problems would be exacerbated.

Liquid waste disposal is a significant problem in urban areas as diverse as Chimbote, Peru (Foronda, 1998); Buenos Aires, Argentina (Pirez, 1998); Cotonou, Benin (Dedehouanou, 1998); and Chicago, USA (Changnon and Glantz, 1996). There are two ways in which climate could interact with this problem: reductions in supplies of water with which wastes are diluted and the impact of more severe flooding episodes that overtop sewer systems and treatment plants (Walsh and Pittock, 1998). Where most inhabitants rely on pit latrines and wells, flooding spreads excreta from pit latrines everywhere and contaminates wells (Boko, 1991, 1993, 1994). Land-use changes associated with urbanization also have reduced the absorptive capacity of many river basins, increasing the ratio of runoff to precipitation and making flooding more likely (Changnon and Demissie, 1996).

Large urban areas, especially in the developed world, depend on extended "linkage systems" for their viability (Timmerman and White, 1997; Rosenzweig and Solecki, 2000). They depend on imports from the local area, region, nation, and even the world for everything from raw material and food, to product and waste exports and communications. These linkage systems often are vulnerable to severe storms, floods, and other severe weather events. Management, redundancy, and robustness of these interlocking systems is a top priority for developed world settlements especially, but increasingly so for the developing world (Timmerman and White, 1997).

7.6.1. Key Vulnerabilities

Key climate-related sensitivities in urban areas of the world include water supply and the effects of extreme events (primarily

[1]See <www.sustainabledevelopment.org>, which provides data on growth for 237 world cities by development level, based on the UNCHS (Habitat) Global Urban Indicators database.

flooding) on infrastructure in river floodplains and coastal zones. These areas should be considered sensitive to climate change. To the extent that sensitive settlements coincide with conditions of poverty and lack of technical infrastructure, these settlements also will be particularly vulnerable to climate change.

7.6.2. Potential for Nonlinear Interactions and Synergistic Effects

Because of their role as centers for administration and commerce, urban areas integrate all of the environmental effects that visit a society and to some extent buffer their human occupants from natural environmental fluctuations. However, these urban areas still may be affected by several stresses that interact with each other in a nonlinear fashion (Rosenzweig and Solecki, 2000; Wilbanks and Wilkinson, 2001). Whatever cash economy there is in a country tends to reside in its biggest cities, and trade routes also focus on these areas. These are two very important coping mechanisms. Thus, for example, climate-related food shortages are more likely to be experienced in urban areas as an increase in migrants from the countryside or loss of business in agriculture-related business rather than as famine *per se*.

Once populations are housed in urban settlements, there are other potential interactions among climate effects that lead to nonlinear impacts on them. Flooding events that are beyond the designed capacity of settlement infrastructure are a case in point, especially in cases in which systems already may be degraded. Urban flooding can overwhelm sewage treatment systems, thereby increasing the risk of disease at the same time that water treatment systems are compromised, health services are disrupted, disease vector species are driven into close contact with people, and people are exposed to the elements because of lost housing. Outbreaks of epidemics are always a risk under such circumstances, whereas the breakdown of any single one of the affected systems might be merely inconvenient. Although all of these effects and mechanisms are well understood, however, it is not possible to predict impacts *quantitatively* at this time.

Table 7-3 shows the primary synergistic effects between climate-related factors that may affect human settlements and the primary types of settlements or industries affected. Each cell identifies a synergistic effect between the climate impact featured in the row and another effect shown in the column. For example, climate-related impacts of flooding, landslides, and fire are compounded when they occur in settlements that also might be crowded by migration. Likewise, flooding in particular exacerbates water pollution and human health impacts and probably would compound problems in obtaining drinking water and transportation. In addition, the agricultural base and energy supplies could be affected in regions that already are water-deficient.

Air and water pollution effects of climate change would be worse if the health of human populations already is compromised (e.g., asthma attacks may be more severe or prolonged in a weakened population). Charlot-Valdieu *et al.* (1999) argue for reducing some stresses in a multiple-stress context to handle other stresses in a more sustainable manner.

Access to energy, clean water, sanitation, and selected other resources is essential to maintain human settlements and the health of the populations within. Flooding, landslides, or fire resulting from extreme weather could compound the shortage of resources by destroying critical infrastructure (floods in Honduras in 1998 and Mozambique in 2000 are examples of the phenomenon under current climate) and, in the case of water, polluting the sources. Similarly, water pollution reduces the effective water supply by making some sources unusable.

7.7. Science and Information Needs

Our ability to answer questions about climate change, vulnerability, and adaptation on the basis of research evidence is very limited

***Table 7-3**: Matrix of synergistic effects, by type of effect and settlement and industry type.*[a,b]

Primary Impact Mechanism	Synergistic Impact Mechanism, Settlement Type or Industry: Migration	Flooding, Landslides, Fire	Air and Water Pollution	Human Health	Energy, Water, Other Resources
Migration	—	U,RCS	U,RCS	U,RCS	U,E,A
Flooding , Landslides, Fire	U,RCS,TR	—	U,RD,RCS	U,RD,RCS	U,RD,RCS,TR
Air and Water Pollution	U,RCS	U,RD,RCS,RE	—	U,RD,RCS,RE,A	RE
Human Health	U	U,RD,RCS	U,RC,RE	—	U
Energy, Water, Other Resources	U,RD,RCS,A	U,RD,RCS	U,RD,RCS	—	—

[a] Settlement types: RD = resource-dependent, RCS = riverine, coastal, steeplands, U = urban.
[b] Industry types: A = agroindustry, E = energy, TR = transportation, RE = recreation.

for human settlements, energy, and industry. Energy has been regarded mainly as an issue for Working Group III, related more to causes of climate change than to impacts. Industry generally has been considered relatively insensitive to most primary climate change impacts, although some sectors (e.g., agroindustry) are dependent on supply streams that could be vulnerable to climate change impacts. Impacts of climate change on human settlements are hard to forecast, at least partly because the ability to project climate change at an urban or smaller scale has been so limited. As a result, more research is needed on impacts and adaptations in human settlements. Several activities also have been developed by governments in the area of "sustainable communities," which are designed primarily to reduce the impact of human settlements on the environment. Many of the actions recommended also reduce the vulnerability of settlements to global warming. Some areas of information required to support these programs have been identified by organizations such as the United Nations' International Decade for Natural Disaster Reduction (IDNDR Secretariat), the ICLEI, and the U.S. President's Council on Sustainable Development. Others were identified during preparation of the FAR, SAR, RICC, and this report.

The highest priority needs for research on impacts, adaptation, and vulnerabilities in human settlements are as follows:

- A much larger number and variety of bottom-up empirical case studies of climate change impacts and possible responses in settlements in the developing and industrialized world
- More reliable climate change scenarios at the scale of urban and even smaller areas
- Improved understanding of how climate change interacts with integrated multiple-stress contexts in human settlements, including possible ramifications of global urbanization
- Improved understanding of adaptation pathways, their costs and benefits, and what can reasonably be expected from them, especially in resource-constrained developing regions (includes autonomous and planned adaptation, as well as traditional and local adaptation; for example, analysis of water demand lags analysis of energy use in most countries)
- Improved understanding of the effects of climate on human migration and the effects of migration on source and destination settlements
- Improved understanding of critical climate change vulnerabilities in settlements, including conceivable low-probability, high-impact effects of climate change (need for continuing research and capacity-building efforts to improve preparedness and strengthen early warning and other mitigation aspects; establishment of a tropical cyclone landfall program is regarded as a logical vehicle for carrying research and development initiatives into the 21st century)
- Better understanding of the particular vulnerabilities of livelihoods and settlements of low-income and marginalized groups
- Improved understanding of the implications of climate variability and change for the well-being of human settlements as they relate to other sectors, other places, and the broader sustainable development process
- Improved understanding of the cascading of climate change through primary, secondary, and tertiary impacts within human settlements (a conclusion of the RICC, but not yet addressed effectively)
- Improved analytical capability to incorporate uncertainty, ambiguity, and indeterminacy in assessments of impacts and response strategies, at least partly by strengthening the science base for integrating quantitative and qualitative analysis, including undertakings such as scenario development and stakeholder participation.

Other key challenges to be faced include development of essential scientific and technical capacity in vulnerable regions, establishment and maintenance of adequate meteorological and hydrological monitoring networks, and improvement of seasonal and interannual prediction.

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