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Adaptation to Climate Change: Options and Technologies

An Overview Paper

Richard J.T. Klein and Richard S.J. Tol

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IVM
Institute for Environmental Studies
Vrije Universiteit
De Boelelaan 1115
1081 HV Amsterdam
The Netherlands
Tel. +31 20 4449555
Fax +31 20 4449553
E-mail: secr@ivm.vu.nl

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Introduction and Background

This paper is aimed to provide the United Nations Framework Convention on Climate Change (UNFCCC) Secretariat and the Subsidiary Body for Scientific and Technological Advice (SBSTA) with an overview of current knowledge and understanding of climate-change adaptation, and of the availability and applicability of adaptation technologies. It may serve as an introductory paper to five focused papers, which will deal with adaptation technologies for climate change in relation to human health, agriculture, coastal zones, urban areas, and freshwater resources, respectively.

1.1 Context and Purpose of this Paper

The scope and outline of this paper were discussed at a meeting that was convened by the UNFCCC Secretariat and held—in conjunction with a meeting on adaptation organised by the Intergovernmental Panel on Climate Change (IPCC)—in Amsterdam on 20-22 March 1997. The meeting was triggered by a request by SBSTA to prepare a report on adaptation technologies. In 1995, SBSTA requested the Secretariat (FCCC/SBSTA/1995/3):

> "To prepare (...) an initial progress report relating to technology identification, assessment and development, as well as an inventory of state-of-the-art, environmentally sound and economically viable technologies and know-how conducive to mitigating and adapting to climate change."

An initial report on an inventory and assessment of technologies to mitigate and adapt to climate change has been provided by the Secretariat (FCCC/SBSTA/1996/4). It identifies what type of information on technologies and know-how would be most useful to the Parties to the UNFCCC. In doing so, it distinguishes between "soft" and "hard" technologies, whereby examples of soft technologies include capacity building, information networks, training, and research, while examples of hard technologies include equipment and products to control, reduce or prevent anthropogenic emissions of greenhouse gases in the energy, transportation, forestry, agriculture, and industry sectors, to enhance removals by sinks, and facilitate adaptation.

Given the predominant interest of many scientists and policy makers in *mitigation*, the initial report devotes little attention to technologies that could be employed for *adaptation* to climate change. The ten experts who participated in the Amsterdam meeting therefore urged the Secretariat to develop a work programme addressing a range of adaptation issues. The work programme is suggested to result in the following products (FCCC/SB/1997/3):

- An overview paper on adaptation;
- Focused papers, initially on technologies related to human health, agriculture, coastal zones, urban areas and freshwater resources;
- A long-term "vision paper" that would set out technological goals in different sectors.

This paper is the first of the above-listed products. It is intended to set the scene for the focused papers by identifying opportunities for adaptation and the application of technologies, and providing guidance as to the timing of adaptation and the use of criteria and decision tools[1]. Its main purpose is to provide SBSTA and other interested readers with a brief yet comprehensive

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[1] It is not the scope of this paper to provide a comprehensive overview of the projected impacts of climate change for each natural and socio-economic system. Reference is made to the IPCC Second Assessment Report and its Summary for Policy Makers (IPCC, 1996) for a detailed account.

overview of the issues involved in adaptation, and of the part that technology can play in contributing to adaptation.

1.2 Climate Change: Current Knowledge and Uncertainties

In its Second Assessment Report, the IPCC concluded that the increase of global mean surface temperature by between about 0.3 and 0.6°C since the late 19th century is unlikely to be entirely natural in origin. It stated that (IPCC, 1996):

> "The balance of evidence, from changes in global mean surface air temperature and from changes in geographical, seasonal and vertical patterns of atmospheric temperature, suggests a discernible human influence on global climate."

Thus, the uncertainty of the nature and origin of observed climatic alterations has been reduced. However, other uncertainties remain. Given the occurrence of global climate change, what will be the range and magnitude of impacts on natural and socio-economic systems? At which time scales will these become apparent? How will they interact with other, non-climatic stresses on the environment and the economy? Further, what can be said about climate-change impacts on regional and local scales? The larger the spatial scale of analysis (*i.e.*, the smaller the area of investigation), the greater the uncertainty associated with such analysis.

The fact that uncertainty increases as the scale of analysis increases is one of the major dilemmas for the climate-change impact and adaptation communities. Ideally, scientists would want to be able to predict exactly what will be the consequences of climate change for a given management unit (*e.g.*, a farming community, a river basin, a water-supply system) at a given point in time, and advise planners and decision makers as to the type and timing of adaptation actions. The current state of knowledge, however, does not allow scientists to provide such detailed advice, and it is highly unlikely that this situation will change within the next one or two decades. However, this is not to say that no advice can be given at all, but that it will be of a general nature and decision makers will have to recognise and use the elements that pertain to their situation when considering adaptation options.

Climate change is expected to be one factor among many that affect ecological systems and economic development. Other factors that interact with climate change could include air pollution, water availability and population growth. These other factors may make it more difficult for human and natural systems to cope with climate change. For example, coral reefs have the capacity—up to a certain threshold—to keep pace with sea-level rise. Under current projections, sea-level rise does not appear to pose a serious threat to healthy, unaffected coral-reef systems (Bijlsma *et al.*, 1996). However, many coral reefs are under pressure from increased sedimentation, overfishing, coral mining and other forms of non-sustainable resource use. In these places, the natural adaptive capacity of coral reefs has been diminished, and sea-level rise will pose a more serious problem than if the other stresses were not present.

2. Adaptation: Definitions and Framework

The term "adaptation" is applied in the climate-change literature to describe any actions taken to adjust to changing climatic conditions. It may refer to both natural and socio-economic systems. The various definitions of adaptation are discussed in this section.

2.1 What Is Adaptation?

As used in ecology, adaptation is defined as "an evolutionary process by which an organism becomes fitted to its environment" (Lawrence, 1995) and as "a change in an organism as a result of exposure to certain environmental conditions which makes it react more effectively to these conditions" (Abercrombie *et al.*, 1977). If in these definitions the word "organism" is replaced by the word "system" (either natural or socio-economic), the term takes on a broader meaning and can also be used in a climate-change context.

Definitions of climate-related adaptation found in the literature include the following:

- Adaptation to climate is the process through which people reduce the adverse effects of climate on their health and well-being, and take advantage of the opportunities that their climatic environment provides (Burton, 1992);
- Adaptation involves adjustments to enhance the viability of social and economic activities and to reduce their vulnerability to climate, including its current variability and extreme events as well as longer-term climate change (Smit, 1993);
- The term adaptation means any adjustment, whether passive, reactive or anticipatory, that is proposed as a means for ameliorating the anticipated adverse consequences associated with climate change (Stakhiv, 1993);
- Adaptation to climate change includes all adjustments in behaviour or economic structure that reduce the vulnerability of society to changes in the climate system (Smith *et al.*, 1996*a*).

Note that Burton's definition does not explicitly mention climate change, but pertains to climatic conditions in general. Perhaps for that reason it refers only to actions taken by humans, as natural systems may have been assumed to have already adapted to existing conditions and hence no need for adaptation arises so long as no change occurs. Thus, it remains closest to the above-quoted definitions of adaptation in ecology, be it that the only organism considered are humans.

Smit's definition refers to both climate variability and change, and includes what could be considered the primary goal of adaptation of socio-economic systems: to enhance the viability and reduce the vulnerability of social and economic activities.

While Burton's definition explicitly includes taking advantage of opportunities provided by climate and the definition by Smit can also be interpreted to include adaptation aimed at securing potential benefits, the definitions by Stakhiv and Smith *et al.* are limited to the adverse consequences of climate change. Stakhiv's definition distinguishes between three types of adaptation that relate to the nature and timing of implementation.

Building on the above and other definitions, IPCC (1996) has identified adaptability and adaptation as follows:

> "Adaptability refers to the degree to which adjustments are possible in practices, processes or structures of systems to projected or actual changes of climate. Adaptation can be

spontaneous[2] or planned, and can be carried out in response to or in anticipation of changes in conditions".

This definition is comprehensive in that it is not limited to either natural or socio-economic systems, it refers to both current and future changes in climatic conditions, and can be interpreted to include both adaptation to adverse and beneficial effects of climate change. In this paper, the terms adaptation and adaptability (or adaptive capacity) will be used in accordance to the definitions provided by IPCC (1996), although the paper focuses specifically on adaptation options to cope with adverse consequences of climate change.

2.2 Adaptation to What?

Before proceeding to design new technologies, it is important to identify the conditions and functions that will affect their use. When planning for adaptation it is often necessary to assess what aspect of climate change will have the most pronounced effect on a system. In this respect, it is important to distinguish between changes in long-term trends, such as mean temperature or sea level, and changes in variability and intensity of extreme meteorological and hydrological events, such as heatwaves and storm surges. In general, changing extremes are likely to cause the greatest impacts on natural and human systems, especially in the short term (Katz and Brown, 1992). However, projections of changing extremes are faced with considerable uncertainty.

Uncertainty with regard to changing temperature and sea-level trends is relatively small: the sign of the change is often known with some level of confidence, and plausible projections exist of the magnitude of the change. Adaptation to these gradual changes is therefore less likely to pose a major problem, although opportunities should not be missed to make allowances and incorporate these changes into the designs of schemes that have a long turnover time, such as harbour and sewage facilities.

With respect to precipitation patterns and extreme weather events, the sign and magnitude of the changes are uncertain and the timing of the extreme events cannot be predicted. Given the low—but changing—probabilities of occurrence of extreme events it is as yet impossible to say whether or not a particular occurrence of an extreme is a manifestation of current weather or climate variability, or the result of climate change. However, one thing is certain: statistics currently used in hazard and risk management are becoming less reliable, and extremes could change in magnitude and frequency, already in the short term (Katz and Brown, 1992). Adaptation to changing extremes therefore deserves highest priority from scientists, planners and policy makers.

It is important to recognise that climate change does not occur in an otherwise non-changing environment. Climate change will interact with climate variability and non-climatic stresses, and it may not always be possible to distinguish clearly between the respective impacts. Thus, adaptation to climate change may also include addressing non-climate stresses[3]. Many strategies and technologies can be effectively employed for more than one purpose, thus yielding both climate and non-climate benefits.

Systems that are prone to natural hazards under current climate conditions may already have some form of adaptation in place. For example, levees may have been built to prevent river floods, irrigation systems installed to mitigate droughts, buildings equipped with air conditioning systems to prevent heat stress, and so on. As climate changes, floods, droughts and high-temperature

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[2] Note that in the remainder of this paper the term "autonomous" is preferred over the term spontaneous".

[3] For example, protection and rehabilitation of wetlands can help to reduce the vulnerability of coastal areas to storm surges (associated with climate variability but becoming more frequent and extreme as climate changes and sea level rises) as well as to enhance the assimilative capacity of pollution.

events would become more frequent and intense. Consequently, a revision of performance standards of existing adaptation technologies could be required to maintain current safety or comfort levels. In other words, levees have to be heightened, the capacity and efficiency of irrigation systems needs to be increased, and air conditioning systems need to be more accessible and widespread. Technological advances may be required to facilitate the upgrading of existing adaptation technologies to a level that would meet future demands at reasonable cost.

2.3 A Conceptual Approach towards Adaptation

Adaptation to climate change can be considered at three levels: the strategic level, the population level and the individual level. The strategic level focuses on the development and implementation of policies aimed at changing populations' and individuals' attitudes towards climate change. At the population level, adaptation can serve two purposes: to protect against or prevent impacts, and to facilitate adaptation by individuals. At the individual level, adaptation focuses on behavioural adjustments aimed at limiting dangerous exposures.

There are various ways to classify or distinguish between different adaptation strategies (see also Smit, 1993). Two fundamental distinctions are discussed here. First, depending on the timing, goal and motive of its implementation, adaptation can be either "reactive" or "anticipatory". Reactive adaptation takes place after impacts of climate change have become manifest, while anticipatory adaptation takes place before impacts are apparent. The boundary between reactive and anticipatory adaptation is not always clear, however. Adaptation activities are often implemented in response to an adverse event, aimed at preventing its recurrence or minimising future impacts. Moreover, it is difficult to define "before" and "after" in a continuously changing system.

Second, adaptation may be considered to be "autonomous" or "planned". Autonomous adaptation takes place without intervention of an informed decision maker, while planned adaptation requires informed and strategic actions. Most natural and socio-economic systems will undergo autonomous adjustments in response to changing climatic conditions. These adjustments are likely to occur both to gradual changes and more drastic events. Planned adaptation requires a strategic policy decision based on an awareness that climatic conditions have changed or are about to change, and that action is needed to return to or maintain a desired state. Thus, planned adaptation can be both reactive and anticipatory, while autonomous adjustments are always reactive. Adaptation by natural systems is always reactive and autonomous, whereas adaptation to socio-economic systems can be either reactive or anticipatory, and autonomous or planned. Note, however, that anticipatory planned adaptation could include enabling natural systems to adapt autonomously (*e.g.*, by establishing eco-corridors or nourishing beaches).

Box 2.1 suggests a framework in which the role of adaptation is considered in relation with other concepts and terms relevant to climate-change vulnerability[4]. This framework helps to define the various concepts involved in vulnerability assessment and shows how these are related. Also, it shows how adaptation can serve to reduce vulnerability, and thereby places the role of technology in adaptation in a broader context.

In accordance with Article 3.3 of the UNFCCC, anticipatory planned adaptation deserves particular attention from the international climate-change community. Anticipatory planned adaptation to climate change is aimed at reducing a system's vulnerability by either minimising

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[4] In the recent literature a number of conceptual frameworks have been suggested for climate-change impact and adaptation analysis, and the one presented above is only one of these. With the aim of improving consistency and facilitating discussion, relevant definitions and concepts will be further elaborated at an IPCC Workshop on Adaptation that will be held in 1998.

impact potential or maximising adaptive capacity. Four generic objectives of anticipatory planned adaptation can be distinguished:

- *Increasing robustness of infrastructural designs and long-term investments*—for example by extending the range of temperature or precipitation a system can withstand without failure, or changing the tolerance of loss or failure (*e.g.*, by increasing economic reserves or by insurance);
- *Increasing flexibility of vulnerable managed systems*—for example by allowing mid-term adjustments (including change of activities or location) or reducing economic lifetimes (including increasing depreciation);
- *Enhancing adaptability of vulnerable natural systems*—for example by reducing other (non-climatic) stresses or removing barriers to migration (including creating eco-corridors);
- *Reversing trends that increase vulnerability ("maladaptation")*—for example by introducing set-backs for development in vulnerable areas (*e.g.*, floodplains, coastal zones).

2.4 How Can Technology Contribute to Adaptation?

There are several approaches to anticipatory and planned adaptation, in both natural and socio-economic systems. These include economic, legal, institutional and technological approaches. Technological approaches may include both "soft" technology and "hard" technology. Soft technology—also called software or disembodied technology—concerns the knowledge of methods and techniques for the production of goods and services, or for choosing optimal courses of action. Hard technology—also called capital goods, hardware or embodied technology—refers to tools, machinery, equipment and entire production systems. The development and deployment of either type of technology requires the right economic, legal and institutional contexts. Therefore, an effective adaptation strategy will comprise a mix of various adaptation approaches.

Box 2.1 A conceptual and semantic framework for vulnerability assessment.

As shown in figure 2.1, one can distinguish between natural-system vulnerability and socio-economic vulnerability to climate change. Both types of vulnerability are clearly related, and proper analysis of socio-economic vulnerability requires prior understanding of how the natural system would be affected. Hence, analysis of coastal vulnerability always starts with some notion of the natural system's *susceptibility* to the biogeophysical effects of climate change, and of its natural capacity to cope with these effects (*resilience* and *resistance*). Susceptibility simply reflects the natural system's potential to be affected by climate change (*cf.* the potential effects of sea-level rise on a subsiding delta versus those on an emerging fiord coast), while resilience and resistance determine the system's stability in the face of possible perturbation. As applied in ecology, resilience describes the speed with which a system returns to its original state after being perturbed, while resistance describes the ability of the system to avoid perturbation in the first place. Susceptibility, resilience and resistance together determine a system's *natural vulnerability* to biogeophysical effects of climate change.

Resilience and resistance are functions of the natural system's capacity for *autonomous adaptation*, which represents the system's natural adaptive response to climate change. As opposed to susceptibility, which is—by definition—independent of human influences, resilience and resistance often are affected by human activities. The effect of human activities need not only be negative: *planned adaptation* can serve to reduce natural vulnerability by enhancing the system's resilience and resistance and thereby adding to the effectiveness of autonomous adaptation.

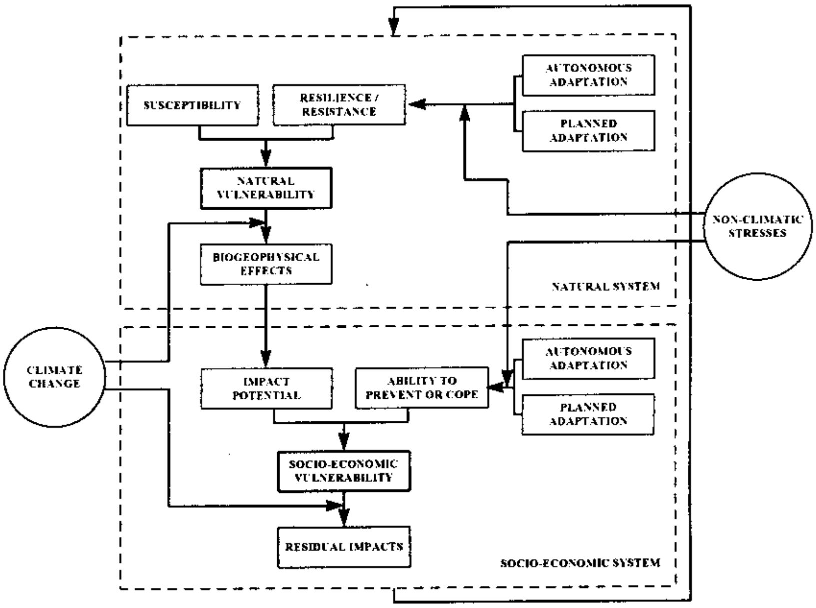

Figure 2.1 A conceptual and semantic framework for vulnerability assessment (source: Klein and Nicholls, 1996).

The biogeophysical effects of climate change are likely to give rise to a range of potential socio-economic impacts. This *impact potential* is the socio-economic equivalent of the natural system's susceptibility (see above), although now it clearly does depend on human influences. In parallel with a system's natural vulnerability, which is a function of susceptibility and resilience/resistance,

socio-economic vulnerability is determined by the impact potential and society's technical, institutional, economic and cultural *ability to prevent or cope* with these impacts. As with the natural system's resilience and resistance, the potential for *autonomous adaptation* and *planned adaptation* determines this ability to prevent or cope.

Finally, it is important to acknowledge the dynamic interaction that takes place between natural and socio-economic systems. Instead of being considered as two separate systems that exist independently of each other, natural and socio-economic systems are increasingly viewed as developing in a co-evolutionary way. This co-evolution is shown in figure 2.1 by the feedback loop from the socio-economic system to the natural system.

Many technologies have been used to adapt to contemporary climate variability and extremes. Examples of existing adaptation technologies include air conditioning, flood-defence systems and irrigation, but also monitoring, forecasting and early-warning systems for natural hazards. These technologies can also be used to adapt to climate change, although they may need to be improved and new technologies may need to be developed because climate change is likely to exact new and higher standards of reliability and performance.

With respect to the four generic objectives of anticipatory planned adaptation discussed in section 2.3, it appears that the contribution of technology is particularly important for the first two of these categories, while the latter two categories may be better served by non-technological adaptation options. This may be linked to the fact that the latter two categories assume a greater reliance on the role of natural systems in adapting to climate change.

However, in addition to enhancing the robustness and flexibility of managed systems, technology can also be employed to help natural systems to cope better with actual or anticipated pressures. Examples of technologies aimed at enhancing the adaptability of natural systems include beach nourishment and the creation of eco-corridors.

3. Opportunities for Adaptation Technologies

In the context of climate change, much attention has been given to mitigation strategies, including technology to limit atmospheric greenhouse-gas concentrations by reducing emissions and enhancing sinks. These mitigation technologies have been catalogued, including their costs, potential and availability (Streets *et al.*, 1996). Technologies for adaptation to climate change, however, are much more diverse, and no comprehensive catalogue of adaptation technologies exists as yet.

The following sections identify adaptation opportunities for five sectors: human health, agriculture, coastal zones, urban areas and freshwater resources. These sectoral overviews should not be regarded as exhaustive lists of all potential adaptation options and technologies. Rather, they provide illustrative examples of adaptation options and technologies and thus represent a starting point for more elaborate inventories, which could be conducted in the context of the sectoral focused papers that may follow up this overview paper. Note that no attempt has been made to distinguish technologies from other, more strategic, adaptation options.

The examples of currently available adaptation options and technologies are complemented with a number of boxes that take a more imaginative and speculative approach towards possible future roles of technology in adaptation. The aim of these boxes is primarily to stimulate discussion and generate awareness of and interest in the potential future contribution of technology to climate-change adaptation[5].

The need for innovation and new development of adaptation technologies provides important new challenges and opportunities to research laboratories, industry and other groups involved in research and development. However, many such groups may not yet be aware of these opportunities, simply because they have never considered their activities as being relevant in the context of climate change.

3.1 Human Health

For both the population level and the individual level, table 3.1 provides examples of currently available adaptation opportunities aimed at protection against or prevention of direct and indirect human-health impacts of climate change[6]. Note, however, that the feasibility of adaptation would be constrained for many of the world's populations by a lack of resources (McMichael *et al.*, 1996*a,b*).

In general, adaptation aimed at reducing vulnerability to health impacts of climate change cannot be seen independent of public health-care efforts. Nonetheless, there are great opportunities for improvement of currently available technologies that are particularly relevant to climate change. For example, air conditioning systems can be further improved to allow larger parts of the world's population access to this technology (see also section 3.4), and vaccines and antibiotics may be improved or developed to protect against diseases that may become more important as climate

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[5] No attention has been given to the emerging field of nanotechnology in view of the many uncertainties involved and the diversity of claims that are made to its favour and its detriment. However, this technology, which is based on manufacturing at the molecular level, could be promising not only in the context of climate change but also to other environmental problems.

[6] These adjustments could complement any physiological adaptation that might occur spontaneously through acclimatisation (to heat stress) or acquired immunity (to infectious diseases).

changes (see box 3.1). Further, the usefulness and applicability of monitoring and early-warning systems can be increased as climate-change projections improve.

Table 3.1 Examples of adaptation opportunities to protect against or prevent climate-change impacts on human health (adapted from Lancet, 1994; McMichael et al., 1996a).

Health impact	Population level	Individual level
Heat stress	- Air conditioning - Adjustment of building designs (insulation, blinds, ventilation) - Tree planting in urban areas	- Protective clothing (hats, sunglasses, light fabrics) - Domestic cooling
High-wind extremes	- Strengthening of buildings and other structures - Early-warning systems - Disaster-preparedness programmes	
High-water extremes (see also sections 3.3 and 3.5)	- Flood-defence systems - Increased mobility - Set-backs - Improved run-off facilities	- Domestic protection
Vector-borne diseases	- Vector-control approaches (*e.g.*, fumigation) - Primary health care, including vaccinations and medicines - Public health surveillance and control programmes - Environmental management	- Mosquito nets and repellents - Wire gauze (door and window screens)
Water/food-borne diseases	- Improved water-supply systems - Water purification - Improved sanitation - Primary health care, including vaccinations and medicines - Public health surveillance and control programmes - Environmental management	- Personal hygiene
Plant aero-allergens	- Allergy warning systems	- Anti-allergens and other drugs

The development of entirely new technologies is of course more difficult to predict, but one could think of new means for water-quality control, based on "smart bacteria" (see also section 3.5). Also, the protection against natural hazards (particularly coastal and riverine floods) may be improved by new, mobile and easy-to-adjust defensive structures (see section 3.3).

When implementing adaptation technologies to reduce vulnerability to direct or indirect health impacts, care may be needed to prevent the occurrence of secondary impacts, that is, new health or ecological hazards created by the application of technologies. For example, air conditioning systems may increase the urban heat-island effect, and coastal flood protection in tropical regions may result in an increase of the area of stagnant water and thereby of the habitat for malaria-transmitting mosquito species. Hence, there is a clear challenge for planners, policy makers and the industry alike to consider the full range of effects of application of existing and new technologies, and minimise any potential secondary impacts.

Box 3.1 Opportunities for improved vaccines against tropical diseases.

Climate change is likely to increase the number of people exposed to tropical diseases such as malaria. People who have not been previously exposed to such diseases are particularly vulnerable since they have had no opportunity for physiological adaptation by means of acquiring immunity. Hence, these people will rely strongly on technological adaptation options.

One of the most effective ways to prevent a disease is by means of vaccination. However, vaccines are not yet available against every disease. Given the current significance of malaria and other tropical diseases, and their increasing importance as climate changes, Western commercial pharmaceutical companies may wish to increase investments to develop vaccines against these diseases. The notion of malaria and other diseases expanding to new areas, including developed countries, may be an added incentive for Western companies and governments to attach higher priority to the development of vaccines and make these available at affordable costs.

In resource-poor areas, introducing public health-care facilities is likely to have a positive effect on a population's vulnerability to health hazards in the short term. Hence, trade-offs need to be made between general short-term development goals and reducing medium- to long-term vulnerability to climate-related hazards. Clearly, priorities need to be set based on the local circumstances of affected populations. It may then well appear that vulnerability to climate change is best dealt with by taking measures that are also justifiable in the absence of climate change (see also section 5).

3.2 Agriculture

In general, agriculture is a flexible system because of the short-time span of management decisions affecting living resources relative to the time-frame over which impacts of climate change become manifest. However, non-climate stresses may have reduced this flexibility. Moreover, timely planning and preparation of adaptation is essential as the vulnerability of agriculture is not so much related to changing trends but to the rate of climate change, including extreme events. Critical thresholds, such as frosts, winter-chill requirements and maximum temperature limits, also play an important part.

Given the climate-dependent nature of agriculture and the importance of other external factors such as technological development and changes in demand for food, farmers generally have been used to adapting to changing conditions. It is frequently assumed that if climate change is gradual, it may be a small factor that goes unnoticed by most farmers as they adjust to other changes. However, as argued by Smit *et al.* (1996), agricultural systems do not evolve in response to changes in average conditions, but to changes in variable and largely unpredictable conditions, including extreme weather events. Therefore, adaptation to climate change cannot be considered independent of current and on-going adaptation to climate variability.

Table 3.2 Examples of adaptation opportunities to climate-change impacts on agricultural systems (adapted from Smit, 1993).

Response strategy	Adaptation options
Change land topography to reduce runoff, improve water uptake and reduce wind erosion	- Subdivide large fields - Grass waterways - Land levelling - Waterway-levelled pans - Bench terracing - Tied ridges - Deep plowing - Roughen land surface - Use windbreaks
Introduce artificial systems to improve water use and availability and control soil erosion	- Low-cost pumps and water supplies - Dormant season irrigation - Line canals or install pipes - Use brackish water where possible - Concentrate irrigation water during peak-growth period - Level fields, recycle tailwater, irrigate alternate furrows - Drip-irrigation systems - Diversions
Change farming practices to conserve soil moisture and nutrients, reduce runoff and control soil erosion	- Conventional bare fallow - Stubble/straw mulching - Minimum tillage - Crop rotation - Contour cropping to slope - Avoid monocropping - Chisel up soil clods - Use lower planting densities
Change timing of farm operations to better fit new climatic conditions	- Advance sowing dates to offset moisture stress during warm period
Use different crops or varieties to match changing water supply and temperature conditions	- Conduct research to develop new crop varieties. - Improve distribution networks

Many adaptation opportunities suitable for climate change have already been applied by some farmers. Table 3.2 provides a list of currently available adaptation opportunities that can be applied at the farm or farmer community level[7]. Most available options take advantage of the general flexibility of agricultural systems related with the short management cycles involved. It is likely that autonomous adjustment by farmers will continue to be important as climate changes, provided that farmers have access to the right information and tools. However, some agricultural systems are less flexible, for example because they are constrained by soil quality or water availability or because they face economic, technological, institutional or cultural barriers. In such cases, autonomous adjustments may not be implemented in time because of lack of awareness (of

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[7] Note that this list originates from a Canadian study and therefore may be biased to higher-latitude agricultural systems. However, many of the options are equally applicable to lower-latitude farming. The reader is referred to Smit (1993) for a more elaborate discussion.

both problem and solution), and anticipatory planned adaptation would be required to provide the right conditions (*i.e.*, information and tools) to farmers for autonomous adjustment.

Anticipatory planned adaptation to climate change and climate variability aims to increase flexibility so as to allow the type of adjustments shown in table 3.2 to be made. For example, increasing the variety of crops may require the introduction of new knowledge and machinery to a farming community. However, as climate changes, the technologies listed in table 3.2 may not be sufficient, and the need may arise for the development of new technologies to allow farmers to cope better with anticipated climate-change impacts, and to reduce the costs of adaptation. The use of biotechnology is discussed in box 3.2, while box 3.3 presents a case for improved irrigation systems that minimise evapotranspiration. Opportunities for improved long-term weather and short-term climate forecasting capabilities are discussed in box 3.4.

Box 3.2 Opportunities for biotechnology in seed development.

One of the ways by which the agricultural sector has traditionally adapted to changing environmental conditions and maximised its profits is by selecting, combining and cultivating plants with a particular characteristic (*e.g.*, giving large fruits). These plants can be cross-fertilised with plants that have a different characteristic (*e.g.*, pest-resistant fruits) in order to form new and more successful varieties.

Modern biotechnology can now take over the role of these traditional methods. By combining the genetic material of different plants at the level of the cell, different hereditary characteristics can be combined into one new subspecies. The advantages of this new technique are manifold: yields can be increased, crops can be made less susceptible to pests, flavour and appearance can be adjusted to meet human preferences, *etc.* Similarly, biotechnology may be used to develop crops that perform better under changing climatic conditions, for example by being able to cope better with heat stress and droughts.

However, public acceptability of biotechnology is an important issue in many countries, for a number of reasons. An important reason is the fear that biotechnology will have unanticipated and undesirable consequences (*e.g.*, while new varieties or subspecies will be resistant to pests, they may transmit diseases to other, non-engineered plants), or to over-dependence on a few genotypes. Another reason for the lack of public acceptability is the fact that it is not consider ethical for humans to change the genetic material that has evolved over millions of years.

Box 3.3 Opportunities for improved irrigation.

In many parts of the world, irrigation is both a necessity and a problem. It is a necessity because lack of precipitation is, at least at some time during the growing season, a common concern to many farmers. At the same time, however, irrigation is a problem because it may cause shortages of water to nature and other socio-economic sectors. Both groundwater and surface water levels may drop substantially, and in the worst cases this process may be irreversible and lead to desertification. Alternatively, saltwater may surface, thus rendering the land unusable.

The main cause of water losses is evapotranspiration. Hence, in order to address the desiccation problem there is a need for irrigation systems that use water more efficiently. Important steps have already been made with the development of drop-irrigation systems; new developments may include closed irrigation systems, whereby water is released from subsurface water conduits. This would reduce evaporation to a minimum, although water loss would still occur owing to transpiration from plants. Water efficiency could be further reduced by closing the cycle completely, which would involve covering the land, for example by greenhouses.

Box 3.4 *Opportunities for improved long-term weather and short-term climate forecasting.*

Thus far, farmers cannot rely on climate-change projections because these do not provide detailed information on relevant temporal and spatial scales. However, predictive capacities of climate change are increasing fast at regional scales. Also, important progress has been made with developing predictive skills of weather conditions over a period of months based on statistical regularities and teleconnections. Long-term weather and short-term climate forecasting can be of crucial importance in helping farmers to take the right decisions in the face of climate variability and climate change.

As knowledge and understanding of the climate system increases, predictions can be further improved so that they become of increasing importance at the farm level. A computerised network linking all farms in a region to a central computer from which relevant and up-to-date information can be obtained may be developed. Such a forecasting and information tool would combine meteorological, climatic, hydrological and land-use data in a geographical information system. Similar technology would also be highly useful for natural-hazard assessment and water-resources management.

Governments and international organisations can play an important part in promoting research and development activities directed at technological innovation for climate-change adaptation in agriculture. However, they need to ensure that technologies and information reaches farmers in time and that farmers are able to interpret the information correctly and draw conclusions that are relevant to their farming practices. This will require awareness programmes by which farmers are informed of the potential implications of climate change and of the opportunities that exist to adapt to climate change. Technology that could be of use to such awareness programmes include educational software packages and other—non-computerised—demonstration tools. Networks of regional agricultural and agrometeorological research and farmer-support centres could contribute greatly to capacity building and utilisation.

In addition, governments and international organisations can facilitate adaptation by farmers by providing incentives, by regulation and by improving existing or setting up new institutions. For example, farmers need to be given stronger incentives to adapt to changing environmental conditions. Income subsidies and other distortions of agricultural markets have made farmers less susceptible to the effects of fluctuations in yield and price, but also less sensitive to the first effects of climate change.

3.3 Coastal Zones

Three generic strategies can be distinguished to respond to climate change in coastal zones: (planned) retreat, accommodate and protect (IPCC CZMS, 1990; Bijlsma *et al.*, 1996). The first strategy involves retreat from or the prevention of future major developments in coastal areas that will be impacted. The second includes adaptive responses such as elevation of buildings, modification of drainage systems, and land-use changes. Both strategies are based on the premise that increases in land loss and coastal flooding will be allowed to occur and that some coastal functions and values will change or be lost. On the other hand, these strategies help to maintain the dynamic nature of coastal ecosystems and thus allow them to adapt naturally. The third strategy involves defensive measures and seeks to maintain shorelines at their present position by either building or strengthening protective structures or by artificially nourishing or maintaining beaches and dunes. This strategy could involve the loss of natural functions and values.

IPCC CZMS (1990, 1992) has identified the environmental, economic, cultural, legal and institutional implications of the three response strategies. Vulnerability assessments have since made clear that the extreme options of retreat and full protection could overestimate the potential losses and costs from climate change and sea-level rise. Yet adaptation options in low-lying island countries (*e.g.*, the Marshall Islands, the Maldives) and for countries with large deltaic areas (*e.g.*, Bangladesh, Nigeria, Egypt, China), which have been identified as especially vulnerable, are problematic because the options appear limited and potentially very costly. Innovative technologies could help to protect vulnerable regions at a considerably lower cost, while preserving ecosystem values (see box 3.5).

As shown in table 3.3, there is a wide array of available adaptation options that can be employed within the three strategies (planned) retreat, accommodate and protect. Some options under (planned) retreat and accommodate are not technological, while a protective strategy relies more strongly on technological options. The ideal combination of adaptation options clearly depends on local natural conditions and socio-economic development objectives. In view of the many other stresses with which coastal zones are faced, it is important to consider anticipatory planned adaptation in the context of an integrated coastal zone management programme (WCC'93, 1994; Tol *et al.*, 1996).

Table 3.3 Adaptation technologies within the three types of response strategies to sea-level rise (sources: IPCC CZMS, 1990; Bijlsma et al., 1996).

Response strategy	Adaptation options
(Planned) retreat	- Preventing development in areas near the coast - Conditional phased-out development - Withdrawal of government subsidies
Accommodate	- Advanced planning to avoid worst impacts - Modification of land use and building codes - Protection of threatened ecosystems - Strict regulation of hazard zones - Hazard insurance
Protect	Hard structural options: - Dikes, levees and floodwalls - Seawalls, revetments and bulkheads - Groynes - Detached breakwaters - Floodgates and tidal barriers - Saltwater intrusion barriers (see also section 3.5) Soft structural options: - Periodic beach nourishment (beach fill) - Dune restoration - Wetland creation - Littoral drift replenishment - Afforestation

Traditionally, the emphasis of adaptation to coastal dynamics has been on engineering responses to combat coastal erosion and protect against flooding, with action often being triggered in response to an extreme event. Now the range of options has expanded to include non-structural and non-technological adaptation, consisting primarily of zoning, building codes, land-use regulation and flood-damage insurance, with more emphasis on a precautionary approach. In part this shift of emphasis is related to the anticipated costs involved with coastal protection using hard structures, and with the environmental impacts that may be caused by stabilising the coastline.

Box 3.5 Opportunities for coastal protection technologies that preserve ecosystem values.

An important problem associated with coastal protection is the fact that fixing a coastline by hard structures alters the sediment balance of the coast, which often results in the loss of important environmental values. Moreover, fixing a coastline may even be counter-productive in that the off-shore coastal morphology steepens, which makes the coast more vulnerable to storm surges. Further, adjacent coastal areas may be supplied with less sediment, which can lead to erosion.

It is desirable to combine the safety provided by coastal protection with the natural dynamics of a pristine coastline. This may be achieved by providing protection only when it is necessary, *i.e.*, when the natural coastline is anticipated to be unable to withstand expected high-water levels. This would require mobile, easy-to-install protection technology, that can be dismantled again once the hazardous situation has gone. One opportunity by which this could be established is by means of inflatable protection. Clearly, such a technology can only be implemented in combination with an effective and reliable monitoring and early-warning system (see box 3.4).

All options listed in table 3.3 can be considered as part of an anticipatory planned adaptation strategy, while some can also be implemented autonomously (*e.g.*, by landowners). These options include modification of land use, and construction of dikes, levees, floodwalls, seawalls, revetments, bulkheads and groynes (Klein and Nicholls, 1996).

3.4 Urban Areas

Important urban systems that could be affected by climate change include infrastructure, water supply and human health. Many adaptation options are available to address the potential direct and indirect impacts of climate change on these urban systems. However, the variety of urban areas and the complexity of their environmental circumstances suggest that many options will need to be tailored to specific locations.

Many other factors, largely independent of climate change, also play a crucial part in planning for adaptation. These factors include population growth, urbanisation and industrialisation, air pollution, technological change, and government policies (Scott *et al.*, 1996). In order to be most effective, adaptation to climate change therefore needs to be an integral part of holistic urban management plans that primarily address non-climate factors (White, 1994).

Infrastructure

Infrastructure (such as buildings, roads, bridges, port and harbour facilities, utility systems) often has *potential* physical lifetimes of several decades if not centuries. Also, it is often designed with little flexibility to make mid-term adjustments. However, the *actual* lifetimes of infrastructure are often shorter as urban areas undergo renewal for a variety of reasons (Scott *et al.*, 1996). In this continuous process of urban renewal, opportunities exist to incorporate changing climatic conditions into the design of new infrastructure. This includes making allowances for uncertainty regarding potentially extreme events, and increasing flexibility to allow for adjustments as knowledge increases. Flexibility can also be increased by increasing depreciation, which diminishes the economic lifetime of an infrastructural project.

An example of infrastructure that could benefit from adaptation are sewage and other water-discharge systems that depend on gravity-based flows and which can be affected by rising sea or river levels. Increasing the discharge height is likely to be considerably cheaper when incorporated as a safety factor in the system's original design than when implemented in a reactive manner to an existing and operating system (*i.e.*, after some damage has already occurred). Similar considerations are valid for port and harbour facilities, and land reclamations.

Extreme events are particularly important in determining the vulnerability of urban infrastructure. Based on records of past river levels it can be calculated what are the water heights that—on average—occur once every 50, 100, 250 years and so on. Thus, levees can be designed and constructed that protect the adjacent land from flooding up to a certain safety standard, below which no damage occurs. Climate change, however, reduces the reliability of these statistics. It may well be that, as extreme precipitation events become more frequent, a discharge that was considered to be a once-in-100-years event would now—on average—occur every 20 years. Therefore, in order to continue to provide the same safety standards as climate changes, changing precipitation and run-off patterns will have to be incorporated in the design of flood-protection works. In view of the uncertainties involved with climate-change projections on local and regional scales, trade-offs are required between minimising risk (possibly by taking a precautionary approach) and minimising costs.

Adaptation technologies that can be employed to reduce the vulnerability of infrastructure to climate change are very diverse, depending on the type of infrastructure, its location, and the climatic variable in question. In spite of this diversity, however, most technological options have in common that they are aimed at increasing robustness of the infrastructural scheme. A second commonality is that many technologies are already being employed—in a reactive manner—to reduce vulnerability to contemporary natural hazards. For example, following a number of very destructive hurricanes in the Caribbean, stricter building codes are being maintained.

Box 3.6 Opportunities for new road-surface technology.

Recent new developments in road-surface technology could be of great importance in the context of climate-change adaptation. First, materials are being developed to make road surfaces more heat resistant. Second and more importantly, road surfaces are being developed that are permeable and thus allow rainwater to percolate through the road rather than form puddles. In addition to the clear advantages to traffic, these new road surfaces could also be an important contribution to improved management of catchment areas.

Extreme peak discharges of rivers have been observed to become more frequent and intense over the past decades. In part, this may be the result of climate change, but urbanisation of river basins is probably a more important factor. Precipitation that falls on urbanised parts of a catchment area is immediately removed by drainage and sewage systems and then transported to the river, whereas in an undeveloped river basin it is first stored in the soil. Permeable road surfaces may be combined with techniques that use the storage capacity of soils to discharge the water that has percolated through the road. Thus, the peak discharge associated with a high-precipitation event can be stretched over a longer period, thereby making it less pronounced.

The need for new technologies needs to be examined on a case-by-case basis. For some types of infrastructure adaptation to climate change does not appear to be impeded by technological constraints, but by a lack of information on future climatic conditions, including extreme events. For example, the introduction of light-coloured roofing materials to reduce the heat-island effect in some cities is limited more by information than by technology. In other cases, effective adaptation may depend on the introduction of new designs and materials. One such innovation concerns the development of new road surfaces (see box 3.6). For most infrastructure, however, incremental improvements and more robust designs should be adequate to adapt to climate change, provided that knowledge on extreme events and regional effects of climate change increases. Hence, as for all other sectors, monitoring and forecasting capabilities need to be improved.

Urban effects on human health

Conditions prevailing in many urban centres are likely to exacerbate a number of impacts of climate change on human health. Owing to the heat-island effect, the impact of heat stress will be more pronounced in urban areas as poor air quality interacts with high temperatures to increase mortality and morbidity from cardio-vascular and respiratory diseases. Poor waste management and sanitation in combination with warmer and possibly more humid conditions may also lead to higher occurrences of infectious diseases.

Some technologies to adapt to potential human-health impacts of climate change have been discussed in section 3.1. All of these technologies will be applicable in urban areas, although some are particularly important. Among the adaptation measures to increased heat stress are early-warning systems, public education, light-coloured surfaces, the planting of trees, and air conditioning. Trees reduce the urban heat-island effect by providing shade, and they also contribute to clean air. Air conditioning is another effective way of limiting exposure to heat stress, although studies in the United States have shown that some heat-related death will persist even if adaptation measures are applied (Kalkstein, 1993). Box 3.7 discusses opportunities to improve air conditioning technology.

Box 3.7 Opportunities for improved air conditioning technology.

Air conditioning is a very effective way of reducing heat stress. However, there are a number of constraints that would make the wider implementation of current air conditioning technology problematic. First, air conditioning is energy-demanding, which means that, if the required energy is generated with fossil fuels, it is an important contributor to atmospheric greenhouse-gas concentrations and thereby exacerbates the problem of climate change. Second, by releasing warm air to the urban environment, air conditioners contribute to the urban heat-island effect, which is likely to worsen as air conditioning technology becomes more widespread.

Hence, there is a great need for new air conditioning technology, which should be much more energy efficient and have a reduced heat output. In temperate areas, a reduced heat output may be achieved by seasonal storage of heat, to be used for space heating in winter. Looking to the future and anticipating a world-wide increase in demand for cooling, engineers may need to consider the use of new materials. Also, they will have to ask themselves if the design and capital costs of systems can be substantially reduced, as well as energy demands.

3.5 Freshwater Resources

A change in the volume and distribution of freshwater will affect all of a region's water uses. The impacts, however, will depend in part on the actions of water users and managers, who will not only respond to climate change but also to population growth and changes in demands, technology, and economic, social and legislative conditions. Optimal effectiveness of adaptation measures is most likely to be achieved when combined in one integrated strategy that also addresses these non-climate factors that influence demand, supply and quality of freshwater resources, and includes measures related to other sectors.

Reduced supply and increased demand

As water supplies are reduced and demand for water increases, a new balance between these two must be found. Water-resources management is a combination of demand management and supply development and management (Ballentine and Stakhiv, 1993). Demand management is essentially concerned with influencing water users' behaviour so as to increase efficiency as well as to encourage the use of simple technologies currently available for this purpose. Adaptation to climate change from a demand-management perspective thus involves the use of economic, legal and policy instruments, such as water pricing and allocation of property rights (Frederick, 1993). Examples of simple technologies to increase efficiency are water-efficient shower heads and leak-proof tap washers. Further, technology can contribute to awareness building, for example by means of demonstration tools that illustrate the potential ecological and societal consequences of water shortages.

Supply development and management is aimed at securing the provision of sufficient water to all potential users under all possible conditions. Climate variability—especially low-precipitation extremes—has always been one of the key factors to be taken into account by water-supply managers. A wide variety of tools and techniques exist to cope with water shortages, the most important of which include increasing water-storage capacity (*e.g.*, by building reservoirs or marginally increasing reservoir size) and reducing losses to evaporation, seepage and leakage. Interbasin transfer of water may also be an option, as may the treatment and subsequent use of waste-water. Technological innovation may serve to improve desalination processes (see box 3.8).

Box 3.8 Opportunities for improved desalination technology.

A technology currently used in a number of dry coastal locations to produce freshwater is desalination of seawater. There are various processes in use to desalinate seawater, including membrane separation processes (*e.g.*, reverse osmosis, electrodialysis reversal), thermal processes (*e.g.*, distillation), vacuum freezing, membrane distillation, and solar humidification. Membrane separation and thermal processes are commercially available.

Desalination is the most expensive way of producing freshwater, and is therefore only used when other sources of water are not available. Moreover, it requires much electricity, thereby contributing to global warming. Hence, as climate changes and the need for desalination technology increases, there is a need for the technology to become more energy efficient and inexpensive.

In order to respond better and more effectively to anticipated water shortages, it is important to improve predictive capacities, for example of streamflow and water usage. Highly sophisticated models are available to predict streamflow conditions in rivers, using geographical information systems and combining remote-sensing with on-site measurements and meteorological information. As the reliability of regional climate projections increases, the linking of these models with climate models becomes feasible, allowing for longer-term projections and adaptation.

Increased runoff

Flood protection works and land-use plans in floodplains are usually based on either a risk analysis to determine the most effective level of protection or on some legislative or institutional guideline for design standards. A change in flood-frequency characteristics can have a very significant effect on flood risk and hence design standards. Similar to adaptation in coastal areas to sea-level rise, adaptation to increased risk of riverine flooding can comprise measures aimed at retreat, accommodation and protection.

As already indicated in section 3.4, climate change will make existing statistics on peak discharges and safety standards less reliable as spatial and temporal precipitation patterns change and extreme precipitation events could become more frequent. In view of the high capital values potentially at risk, continued protection is likely to be the most feasible—albeit costly—option in urban areas. In lesser populated areas, however, adaptation could also include retreat from the floodplain and accommodation to changing conditions (*cf.* adaptation to sea-level rise in coastal zones—section 3.3, table 3.3).

Retreat and accommodation can be combined with technologies to rehabilitate nature and create wetlands, which will increase the storage capacity of the riverbed and the catchment area. An increased storage capacity will result in peak discharges being stretched out over larger periods of time, thus causing smaller extremes. Current nature rehabilitation efforts are relatively primitive and experimental, and deployed at a small scale. Innovative technologies may need to be developed to rehabilitate larger areas. However, the creation of wetlands as buffers may conflict with development objectives in river basins. Sound river basin management is required to cope with the anticipated effects of climate change on river discharges while taking advantage of the many economic opportunities offered by riverine locations (see also box 3.6).

Water quality

Pollution prevention and control will be the most effective strategy to deal with climate-related pressures on water quality. One possible adaptation technology is to increase river flow so as to increase the river's capacity to dilute pollutant concentrations. Another, more speculative, technology is based on the use of so-called "smart bacteria" that could be developed to make pollutants harmless.

Saltwater intrusion in estuaries and groundwater aquifers as a result of sea-level rise is a more direct impact of climate change, and could threaten freshwater resources in many coastal areas. For many countries, the prevention of saline intrusion in coastal estuaries and groundwater aquifers may require skills and technologies not yet available. In principle, technological options to adapt to increased salinity in estuaries include (Rijsberman, 1991):

- Build barriers across rivers;
- Tune (minimum) discharge of rivers to keep the salt wedge at the river mouth in dynamic equilibrium;
- Build sluices to allow outflow but not inflow;
- Switch to salt-resistant crops or other activities less impacted by saline intrusion;
- Move freshwater inlets further upstream.

However, experience with these options is as yet limited, not in the least because they are expensive and require detailed knowledge of coastal hydrology. Hence, there is a clear challenge to develop inexpensive technologies that are more generically applicable to combat saltwater intrusion in estuaries and groundwater aquifers.

3.6 Implementation Considerations and Cross-Cutting Adaptation Technologies

Proper, effective and timely implementation of any of the above-presented anticipatory planned adaptation options can be facilitated by the following accompanying, cross-cutting measures:

- Improving awareness of potential implications of climate change among all parties involved (from grassroots level to decision makers);
- Increasing knowledge and understanding of climate change and variability, including long-term weather and short-term climate forecasting;
- Enhancing research, development and demonstration efforts of adaptation technologies.

In part these measures involve the development of soft technologies, for example to educate individual farmers and enable them to make the right decisions concerning crop variety and sowing dates. Helpful in capacity building and utilisation are simulation tools, which can be highly sophisticated graphics-supported computer models, but also simple board games. The aim of simulation tools is to help people to develop and increase the understanding of complex cause-and-effect-relationships, including the risk of non-linear responses. Such tools could be used to establish behavioural adjustments, but also to inform policy makers of the potential consequences of their decisions.

4. The Issue of Timeliness

The timing of adaptation is an important aspect. Some suggest that climate change is an uncertain feature of a remote future and that, therefore, adaptation is something for later generations (*e.g.*, Ausubel, 1995). However, given past emissions of greenhouse gases and the resulting commitment of the atmosphere to some climate change, many chapters of the IPCC Second Assessment report suggest that it may be prudent to start preparing for the adverse effects of climate change now, even though it may take a few decades for impacts associated with changing climate trends to become manifest.

4.1 The Timing of Action

It has been established by the IPCC (1996) that humans are discernibly influencing global climate. Climate change affects current infrastructure, agriculture and other managed and unmanaged systems. More climate change will occur in the future, affecting investments that are already in place now or are being planned or made at this moment. For such activities, the time to adapt has come, provided that the impact of climate would otherwise be substantial.

There are four important arguments that support taking action now. First, impacts are primarily driven by changing patterns of extreme weather events and by the rate of climate change, which will increasingly become apparent in the shorter term. Second, cost-effective opportunities exist to incorporate climate-change projections in large infrastructural projects that are currently being planned and implemented and which will still be in place fifty to a hundred years from now. Third, a number of adaptation technologies will take a considerable time to be planned and implemented. For example, new varieties of crops, more flexible water-supply infrastructure and legislations, and integrated coastal zone management plans require a considerable lead time of scientific and technological study and consultation with stakeholders. Finally, society's vulnerability to climate change largely depends on its economic, technical, institutional and socio-cultural capabilities to cope with the adverse effects. These capabilities can only be substantially and gradually improved in the longer term, starting now.

For other activities the urgency to adapt now may be less great, or adaptation may be very costly and not (yet) justified by remaining uncertainties. Examples include technological adaptation to climate-change impacts on fisheries, and protection against saline intrusion of coastal groundwater aquifers. However, in view of the often serious nature of potential impacts, it is crucial to enhance research efforts and take any other measures that would enable society to act timely and effectively.

As indicated before, much preparatory action can already be undertaken. In addition to the three accompanying measures listed in section 3.7, such action could also include the development of appropriate economic, social, institutional and legal settings and resources to create the proper conditions for adaptation to climate change, including implementation of adaptation technologies.

When deciding on the timing of implementation, one may be inclined to favour those adaptation options that produce the greatest benefits, not only in the long run but already at the short term. However, as climate change is a gradual process, this implies that the benefits these adaptation options would yield at the short term have to be associated with other, non-climate stresses. This also implies that if climate change would not take place at all, such options would still be worthwhile to implement in view of these other stresses. For this reason, these options can be termed "no-regret" measures and benefits not related to climate change can be referred to as "secondary benefits". Examples of no regret-measures include pollution control, early-warning systems, nature and biodiversity conservation, and protection of watersheds and wetlands. Box 4.1 provides a discussion on the role of no-regret adaptation and the significance of secondary benefits.

Box 4.1 Secondary benefits of adaptation.

Many options to adapt to climate change will yield non-climatic, secondary benefits. The term secondary benefits has been widely applied in the context of climate-change mitigation. From both an efficiency and effectiveness viewpoint, mitigation strategies are considered particularly desirable when, in addition to their global benefit in limiting atmospheric greenhouse-gas concentrations, they provide local or regional benefits. For example, a fuel switch from coal to gas does not only lead to lower emissions of carbon dioxide but also helps to reduce acidification.

For mitigation strategies, the potential of secondary benefits now forms an important justification for their implementation and the provision of financial support. For adaptation strategies there are, however, a number of difficulties involved. The most important of these concerns the question of where to draw the line between primary climate benefits and secondary non-climate benefits. In principle, the best way to prepare for the impacts of climate change (or any other potentially disrupting phenomenon) is to be well-informed, well-endowed and flexible, as this is how vulnerability can be reduced most effectively. Does this mean, however, that general development programmes aimed at alleviation of poverty and enhancing economic opportunities can be considered as adaptation to climate change?

4.2 Uncertainty in Decision Making

A complicating factor in climate-change adaptation is that the future in general and future climate in particular are uncertain. Planners and decision makers are used to coping with the fact that the world is an uncertain place. In most cases, they develop a number of scenarios of possible states of the world and choose a strategy that would perform reasonably well for most possibilities (perhaps weighted by their likelihood), whilst minimising the spread in outcomes between possible states. Also, decision makers will avoid getting locked in one action when the situation may call for another. In some cases, particularly those where stakes are low and potential gains high, one may choose to gamble on a strategy that would yield large gains in one situation and minimal losses in other situations. In other cases, one may need to be cautious and choose a strategy that seeks to avoid the severely negative consequences of one situation while tolerating minimal losses in other situations.

Appraisals as described above are informally made on a routine basis, often embedded in habits, encoded in procedures or even enshrined in religious prescripts. The outcome varies from person to person and case to case, depending on available information and attitudes to risk and uncertainty. New situations call for new appraisals or reappraisals; if the stakes are high or the situation is complex, this may be done formally, using decision tools as described in section 6. Note that the formality only extends to the quantification of options, outcomes and probabilities; attitudes to risk aversion that primarily drive decision rules will still—to a large extent—be based on the attitude of the decision maker.

Climate change is a new situation; at least, the speed and prolonged uniform direction of the change in climate as projected for the coming two centuries is unprecedented in human history. This implies that, even in formal decision analyses, the assumption that climate will be as it has been over the instrumental record must be replaced by assumptions on a changing climate that is rather uncertain in its manifestations. This uncertainty underscores the need to increase robustness and flexibility of technological designs and projects. The need to develop new and improve existing adaptation technologies to a new but uncertain climate presents new challenges and opportunities for technology developers.

5. Criteria for Selecting Adaptation Technologies

In view of the limited resources available, a number of criteria, priorities and trade-offs need to be made by governments and industries regarding the selection and timing of implementation of adaptation technologies. Among the important criteria are efficacy, efficiency and equity, as applied to procedures to reach a decision, for example on whether research and development should be enhanced or a technology should be implemented, as well as to evaluate the consequences of a decision.

In addition, specific criteria can be used for decisions to be made within a research and development context, and for those to be made at a project level. Criteria that are relevant to research and development include:

- Number of people or countries affected by the impact;
- Likelihood of impact;
- Generic applicability of the adaptation technology;
- Nature of the industry;
- Situation of the market.

As regards decisions at a project level, Smith (1997) suggests that adaptation technologies most in need of immediate implementation should meet at least one of the following criteria:

- Address irreversible or costly impacts;
- Reverse (maladaptive) trends that make adoption of the measure more difficult over time;
- Address long-term decisions, such as building infrastructure.

Other criteria that may be considered when planning adaptation include flexibility, equity, environmental sustainability, social and political acceptability, and economic efficiency. Economic efficiency may be the single most important criterion in decision making. Usually, two forms of efficiency are distinguished. In its first form, resources are allocated in an optimal manner. This means that the costs of adaptation are balanced with the benefits of adaptation so as to ensure maximisation of welfare. A weaker form of efficiency seeks to accomplish a given target at the least cost. An example of the former is to set the marginal costs of building a dike equal to the marginal benefits of increased flood safety. An example of the latter is to set a flood safety standard and achieve it as cheaply as possible.

Smith (1997) proposes a four-step method to identify and analyse anticipatory planned adaptation technologies, and assess to which extent they meet the above three criteria:

- Analyse system's susceptibility or impact potential to climate change (see also box 2.1);
- Select resources where adaptation would be a high priority;
- Analyse sensitivities of current policies to climate change;
- Examine the relative effectiveness of anticipatory planned adaptation technologies.

6. Decision Tools for Adaptation

The planning of adaptation and the setting of priorities is not easy, since criteria and interests may be conflicting. For example, the economically most efficient path of technology implementation may not be the most equitable one. Moreover, decisions have to be made in the face of uncertainty. Decision makers need to consider a range of plausible "futures", and take decisions that would optimise each of these scenarios while minimising both costs and risks.

A number of tools and techniques are available to assist decision makers in evaluating consistently the outcomes of suggested alternative policy options. These tools and techniques form the second category of cross-cutting adaptation technologies. They are already being used for many other climate and non-climate policies, and will also be helpful when deciding on the type of adaptation technologies, and the timing of their implementation.

Decision tools (sometimes referred to as evaluation frameworks), assess the performance of a number of alternative policy strategies on a set of pre-defined criteria. Economic efficiency is almost always one of the most important of these criteria, but depending on the overall policy of a country, sector or company, trade-offs can be made with other criteria. Decision tools make these potential trade-offs explicit, and evaluate the overall result of a suggested policy.

The decision tools that are most relevant for climate-change adaptation are cost-benefit analysis, cost-effectiveness analysis, multi-criteria analysis and risk-benefit analysis. This section provides a brief discussion on each of these tools. Practical examples in the context of climate-change adaptation are presented in Appendix I.

Cost-benefit analysis

Cost-benefit analysis (CBA) is based on the balancing of gains and losses of alternative policies, and thus identifies the policy that offers the greatest net gain to society. Gains and losses, or rather, benefits and costs, are defined according to the satisfaction of society's needs, or preferences. A benefit is something that meets a need, while a cost is something that detracts from it. More generally, anything that increases human well-being is a benefit, and anything that reduces human well-being is a cost.

Benefits and costs associated with a particular policy are generally expressed in terms of society's willingness to pay for goods and services to be gained or lost. Thus, a monetary unit is used to compare alternative policies. With respect to priced goods and services, these gains or losses can be easily expressed in monetary terms. However, benefits and losses that pertain to non-monetary values, such as environmental resources, are more difficult to assess. Valuation techniques exist to express non-market values in monetary terms (*e.g.*, contingent-valuation method, travel-cost method, hedonic-price method), but these are generally laborious and expensive to apply.

CBA is not only concerned with identifying the costs and benefits of alternative policies, it also needs to consider the time at which these costs and benefits occur. For climate-change adaptation this is particularly important, as investments in adaptation need to be made now in order to prevent major damages in the future. When costs and benefits occur at different points in time, this can be accounted for by discounting. By means of a discount rate, all future costs and benefits are discounted to their net present value, after which they can be compared. The role of CBA is to identify the policy with the highest net present value.

Cost-effectiveness analysis

As opposed to CBA, which is aimed at maximising net present value of a range of possible futures, cost-effectiveness analysis (CEA) is directed at identifying the most economic way of achieving a particular pre-defined policy goal if more than one option is available. These policy goals often take the form of standards—ambient environmental quality, flood-protection levels, fisheries quota, nature reserve designations, *etc.*

CEA is a reduced form of CBA, that is, in CEA the benefits are not measured in monetary units, but the costs are. It comes into use whenever the monetary valuation of the benefits is thought to be inappropriate or undesirable. Hence, CEA does not provide information on the appropriateness of the prior policy goal. However, CEA is an important decision tool for ensuring the rational use of limited resources in meeting this goal.

Multi-criteria analysis

Both CBA and CEA rely on economic efficiency as the single criterion for evaluating alternative policies. However, more criteria can be used to determine the appropriateness of policy options. When more than one criterion is used to describe the potential benefits of policies, systematic appraisal of these policies is done by using multi-criteria analysis (MCA). Unlike in CBA and CEA, costs and benefits to be evaluated by MCA do not need be expressed in a single, monetary unit.

The basis of MCA is formed by a set of matrices that combine alternative policy options with a range of decision criteria. MCA methods require two types of information, in the form of:

- An effect-score matrix: the numerical assessment of all relevant impacts of a set of alternative options, each of them measured in its own units;
- A preference or weight vector: the numerical assessment of the relative priority attached to each of the decision criteria considered in the effect-score matrix.

The primary purpose of MCA is to reduce the diverse available information to either a set of single-number scores, yielding a single "best" solution, or to produce a complete or partial ranking of alternatives following a series of pairwise comparisons. It clearly shows the multiple objectives generally available to decision makers, and, if the importance weights can be derived, it enables diverse objectives to be integrated. Compared to CBA, the fundamental difference lies in the recognition that economic efficiency often is not the sole objective of policy.

Risk-benefit analysis

- The application of decision tools to policy areas that involve risky events has led to the emergence of risk-benefit analysis (RBA). Instead of looking at the costs and benefits of a risk-reducing policy, RBA considers the costs and benefits of taking no action to reduce risks. The risks of such a policy would be the associated increase in morbidity and mortality, while the benefits are the avoided costs of reducing the risks. As such, RBA is an application of CBA in the context of risk, where some of the costs are expressed in a probabilistic form.

7. Conclusions

Technologies could be used now and could play an increasingly important part in adaptation to climate change. Many opportunities exist for the application of both hard and soft technologies to complement economic, legal and institutional adaptation options. In spite of the many uncertainties that still surround climate change, technology can already be employed in a cost-effective manner to enhance the robustness and flexibility of human systems, and the adaptability of natural systems.

Many technologies that could be used to adapt to climate change have been used successfully as a means of adapting to contemporary climate variability and extremes. Examples of existing adaptation technologies include air conditioning, flood-defence systems, irrigation, monitoring, forecasting and early warning systems for natural hazards. However, it may well be that climate change will exact new and higher standards of reliability and performance of technological options, at significantly lower costs.

Innovation and new technologies are required in order to improve access to all countries at reduced costs. This provides new challenges and opportunities to research laboratories, industry and other groups involved in research and development. Many such groups may not yet be aware of these opportunities, simply because they have never considered their activities as being relevant in the context of climate change.

Adaptation to climate change can be autonomous. It can take place without the intervention of the decision maker and should be planned following informed and strategic actions. Adaptation can also be reactive. It may be undertaken in response to an observed change. It can be anticipatory, that is, in advance of climate change. Planned adaptation can be both reactive and anticipatory, while autonomous adaptation is always reactive. In view of the suggested discernible human influence on global climate and in accordance with Article 3.3 of the UNFCCC, anticipatory planned adaptation deserves particular attention from the international climate change community.

Anticipatory planned adaptation is particularly important to reduce vulnerability to climate change. Anticipatory planned adaptation can have a number of objectives. It may aim, for example, to increase the robustness of infrastructure designs and long-term investments; increase the flexibility of vulnerable managed systems; enhance the adaptability of vulnerable natural systems; and reverse the trends that increase vulnerability ("maladaptation").

Anticipatory planned adaptation can be beneficial to a number of important sectors and systems. Examples of sectors that could benefit from anticipatory planned adaptation are infrastructure, such as, port and harbour facilities, flood-defence systems, water supply systems, sewage systems, and urban systems. Fragmented industries, such as those that are not part of a larger network of governmental and industrial organizations may also benefit as well as human health through vaccine programmes and early-warning systems.

The arguments in favour of implementing some adaptation measures now are as follows:

(a) The impacts of changing weather extremes may become apparent well before the impacts associated with changing trends;

(b) Large projects, currently being planned and implemented, could factor climate change into their designs and be cost effective. Many of these projects will be in place for 50 to 100 years; and

(c) Vulnerability to climate change in the long-term is a function of a society's experience in coping with current problems by means of economic, technical, institutional and socio-cultural measures. These capabilities can only be improved by virtue of experience.

Many technologies that can be used to adapt to climate change also have other, non climate, benefits. These non-climate benefits are termed secondary benefits. Sometimes the secondary benefits of adaptation measures are sufficient to justify them in their own right, even in the absence of climate change. Such adaptation measures can be considered "no-regret" measures. Examples of these include technologies for increasing efficiency of water use, improved land-use planning, ecosystem and biodiversity protection, and monitoring, forecasting and early-warning systems.

Some decision tools to evaluate alternative adaptation strategies, based on a number of criteria, are available. Others are undergoing further research. The decision tools that are most relevant for climate change adaptation are cost-effectiveness analysis, multi-criteria analysis, risk-benefit analysis and cost-benefit analysis. A few of these decision tools have been incorporated into decision-support systems, which provide an important technology to assist planners and decision makers.

Further activities to promote the development and application of innovative technologies could include:

(a) Building awareness among planners and decision makers of the need to adapt to climate change, the part that technology can play in adaptation and the benefits of adaptation;

(b) Assessing the current and future availability, accessibility, potential, costs, environmental impacts and implementation requirements of technologies for climate change adaptation, as well as opportunities for innovation;

(c) Co-operating with research laboratories and industry to encourage research and development of adaptation technology;

(d) Creating a demand for climate change adaptation technology, for example, by setting standards that incorporate climate change projections or via the market by requirements of the insurance industry;

(e) Establishing design and performance goals for adaptation technology; and

(f) Ensuring institutional coherence with related issues, such as those of national programmes for national disaster reduction or relief.

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Appendix I. Practical Examples of Decision Tools

A number of practical examples exist that illustrate the use of decision tools for climate-change adaptation. These examples range from generically applicable decision matrices to highly sophisticated and site-specific simulation models. A common characteristic, however, is that they all use multi-criteria analysis as the underlying evaluation framework. This section discusses two examples. They serve to indicate the usefulness of decision tools, and to highlight the potential role and importance of these cross-cutting adaptation technologies.

A decision matrix for water-resources development

In the context of the United States Country Studies Programme, Smith (1996) developed a decision matrix that combines cost-effectiveness analysis with multi-criteria analysis. It is generically applicable for evaluating climate-change adaptation technologies for a range of socio-economic sectors. Published examples of its application include water-resources management (Smith, 1996) and forestry (Smith *et al.*, 1996*b*). Below the example for water-resources management is discussed.

Table I.1 A decision matrix for adaptation in water-resources management, combining multi-criteria analysis and cost-effectiveness analysis (source: Smith, 1996).

		Objectives							
		Drinking water	Irrigation	Water quality	Flood control				
	Weights	3	1	2	3				
Measures	Scenario					Score	Total score	Cost of measure	CER[1]
Current policy	Wet	3	4	3	3	28	50	N/A	N/A
	Dry	2	2	1	4	22			
Marginal increase in size	Wet	4	5	2	4	33	62	$20m	1.67
	Dry	3	3	1	5	29			
Water conservation	Wet	4	4	4	3	33	60	$5m	0.50
	Dry	3	2	2	4	27			
Market allocation	Wet	5	2	3	3	32	59	$2m	0.22
	Dry	4	1	1	4	27			

[1] Cost-effectiveness ratio

For a hypothetical freshwater reservoir, current policy and three alternative adaptation measures are examined in the decision matrix shown in table 6.1. Using expert judgement, the performance of the four policies is ranked (on a scale from 1 to 5) under two scenarios for each water-resources management objective. In this example, the eight scores per policy are simply added to a total score, with weights attached to the objectives but not to the scenarios (for the scenarios weight could reflect probability of occurrence). Next, the costs of each alternative policy are estimated and divided by the respective incremental score (*i.e.*, total score for the alternative minus total score for current policy). Thus one arrives at a cost-effectiveness ratio (CER), which reflects the costs of a measure per incremental unit of benefit. The lower this ratio, the more efficient the policy measure.

This decision matrix can be easily adjusted for any natural and socio-economic system, and any technological and non-technological adaptation option can be considered. However, once the most cost-effective option has been established, additional analysis would be required, for example to identify any barriers to implementation (Smith, 1996).

A simulation model for coastal management and adaptation to sea-level rise

For the World Coast Conference 1993, held in The Netherlands, a computer-based simulation model was developed of a hypothetical coastal area that faces multiple stresses, including climate change and sea-level rise. The initial goal of this model, called COSMO, was to create awareness among the high-level policy makers present at the conference of the need to make trade-offs and of the importance to take climate-change concerns into consideration in coastal management (CZMC and RA, 1993).

COSMO is an interactive tool that demonstrates the main steps in the preparation, analysis and evaluation of coastal zone management plans in an area where pressures for industry and tourism development conflict with each other and with environmental protection measures. As a particular feature, COSMO facilitates the analysis of impacts of present-day actions on the region's vulnerability to climate change and sea-level rise. The principal objective of COSMO is to ensure the sustainable development and use of coastal resources by enhancing economic development and improving environmental quality, while minimising necessary capital investment and reducing vulnerability to climate change.

The development scenarios that are created by the operator of COSMO are eventually evaluated using multi-criteria analysis. The criteria against which the scenarios are scored include economic development (adjusted regional income, income per capita, employment, balance of trade), environmental quality (number of polluted locations, violation of standards, establishment of marine park), capital investments (port, tourist, residential and agricultural developments), and long-term vulnerability (people at risk, capital at risk, protection and relocation costs).

Since 1993, COSMO has been successful in highlighting the importance of integration in coastal zone management. COSMO-related simulation models are now being developed for real coastal locations, based on real data. The objective of such models is not only to create awareness, but to make a distinct contribution to the decision-making process and guide planners and managers in making the right decisions with respect to both contemporary issues as well as climate change. However, there is a clear constraint in that the integration of various data sources, stemming from different scientific disciplines and pertaining to different time scales is difficult to achieve. At the same time, however, it provides a major scientific and technological challenge and opportunity.

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