Appendix C: Drought Management

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Throughout history droughts have had far-reaching effects on humans and their civilizations. Droughts have caused crop failures and the death of natural vegetation, livestock, wildlife and people. The World Health Organization estimates that droughts and their effects cause half the deaths worldwide due to all natural disasters. Economic losses from prolonged droughts often exceed those from other more dramatic natural hazards. Humans have choices: they can increase the adverse impacts of droughts or they can take measures to reduce them. Droughts are not going to be preventable. Humans need to learn how better to live with and manage them, as with all other types of natural events.

1. Introduction

Droughts are normal, recurrent, yet relatively infrequent features of climate. Their timing and severity are unpredictable. They can occur virtually anywhere that precipitation occurs. Arid and semi-arid areas where precipitation is minimal or nonexistent are indeed dry, but they are not considered to be in a perpetual state of drought. Droughts occur when water supplies are 'substantially below' what is usually experienced for that place and time. Just what is considered 'substantially below' is rather arbitrary, depending on the location and what features of a drought cause the most stress or loss. For an often-cited example, a drought on the coast of Libya would result when annual rainfall is less than 180 mm. In Bali a drought might be considered to occur after a period of only a week without rain! This is why it is difficult to define droughts in a consistent way that applies to all situations. However defined, droughts are larger and longer-lasting water supply deficits than those associated with the usual short-term variations of climate.

Droughts can be related to the timing of rainfall and/or the amount or effectiveness of the rains. Other climatic factors such as high temperature, high wind and low relative humidity can significantly aggravate their severity. Figure C.1 shows the drought susceptible regions of the world and the relative levels of stress that could occur should substantially less water be available than what is considered normal.

Some areas shown as having a relative low or negligible stress in Figure C.1 can experience droughts. Figure C.2 shows the areas of the world that experienced drought conditions in 1982 and 1983.

2. Drought Impacts

Droughts are characterized by dry, cracked soils on river beds and lakes, dust, and thirsty plants and animals. The Australian Bureau of Meteorology provides some pictures of these impacts, shown in Figure C.3.

Damage from droughts can exceed that resulting from any other natural hazard. In the United States their annual expected impacts are estimated to exceed $6 billion. Drought primarily affects agriculture, transportation, recreation and tourism, forestry and energy sectors. Social and environmental impacts are also significant, although it is difficult to assign a monetary value to them.

When a drought begins, the agricultural sector is usually the first to be affected because of its dependence on soil moisture, which can be rapidly depleted during extended dry periods. If precipitation deficiencies continue, then users dependent on other sources of water will begin to feel

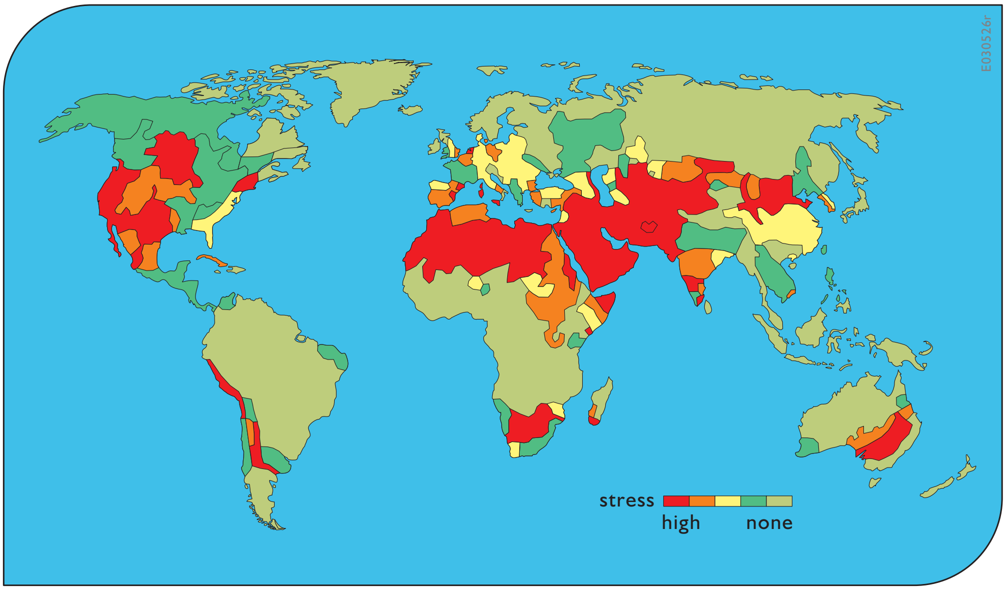

Figure C.1. Map showing the relative stress caused by water supply deficits should a prolonged drought occur in any of the drought-prone regions of the world.

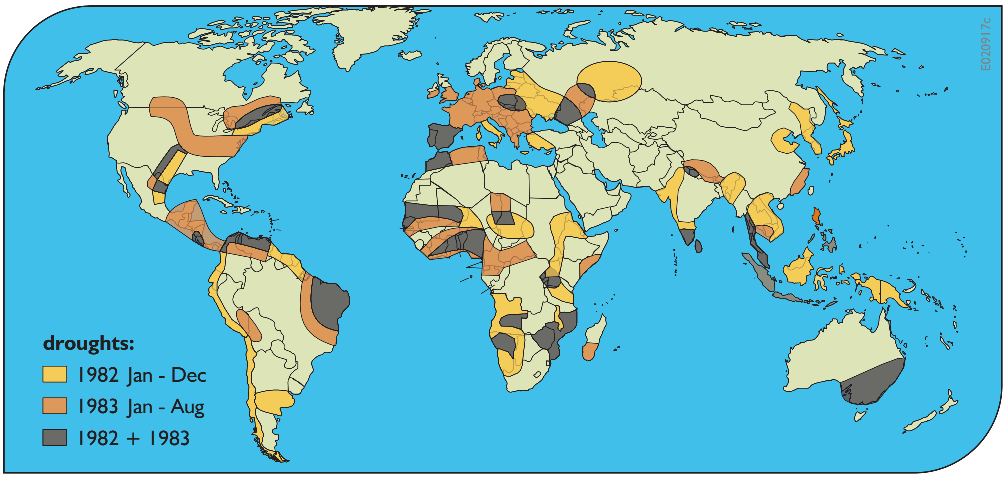

Figure C.2. Map showing areas of drought conditions in 1982–83 (National Drought Mitigation Center, 2000).

the effects of the shortage. Those users who rely on surface water (reservoirs and lakes) and groundwater, for example, are often the last to be affected. A short-term drought that persists for three to six months may have little impact on these water users, depending on the characteristics of the hydrological system and water-use requirements.

When precipitation returns to normal, the sequence is repeated for the recovery of surface and subsurface water supplies. Soil water reserves are replenished first, followed by streamflow, reservoirs and lakes, and groundwater. Drought impacts may diminish rapidly for agriculture because of its reliance on soil moisture, but can linger for months or even years for other users who are dependent on stored surface or subsurface supplies. Groundwater users, often the last to be affected by drought during its onset, may be the last to experience a return to normal water levels. The length of the recovery period is a function of the intensity of the drought, its duration and the quantity of precipitation received as the episode terminates.

The socio-economic impacts of a drought can follow all the other impacts just described. These impacts occur when the demand for an economic good exceeds supply. In Uruguay, for example, the 1988–89 drought resulted in significantly reduced hydropower production because power plants were dependent on streamflow rather than

Figure C.3. Signs of drought: dry dirt, thirsty animals and dust (courtesy of the Australian Bureau of Meteorology. http://www.k12.atmos.washington.edu/~gcg/RTN/Figures/adrought.html).

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location	major social impacts	costs	
Mexico & Central America	n/a	$ 600	million
Southern Peru & Western Bolivia	n/a	$ 240	million
Australia	71 dead, 8,000 homeless	$ 2.5	billion
Indonesia	340 dead	$ 500	million
Philippines	n/a	$ 450	million
Southern India, Sri Lanka	n/a	$ 150	million
Southern Africa	disease, starvation	$ 1	billion
Iberian Peninsula, Northern Africa	n/a	$ 200	million
United States	agricultural crop loss	$ 10-12	billion

Table C.1. Effects of the 1982–83 worldwide droughts (from the *New York Times*, 2 August 1983; data updated 7 February 1996).

storage for power generation. Reducing hydroelectric production required the government to use more expensive (imported) petroleum and implement stringent energy conservation measures to meet the nation's power needs.

Estimates of the economic impacts of the 1982–83 droughts, perhaps the most widespread drought event in recorded history (see Figure C.3), are given in Table C.1 (NOAA, 1994).

In North America one of the worst drought periods was from 1987–89. Economic losses from that drought in the United States exceeded $39 billion (OTA, 1993). This damage can be compared to that caused by the most costly flood, earthquake and tropical storm events.

The worst storm event in US history was Hurricane Andrew. On 24 August 1992, this 'costliest natural disaster', as it is called, hit South Florida and Louisiana. The storm killed sixty-five people and left some 200,000 others homeless. Approximately 600,000 homes and businesses were destroyed or severely damaged by the winds, waves and rain. Large parts of South Florida's communications and transportation infrastructure were significantly damaged. There was loss of power and utilities, water, sewage treatment and other essentials, in some cases up to six months after the storm ended. Andrew also damaged offshore oil facilities in the Gulf of Mexico. It toppled thirteen platforms and twenty-one satellites, bent five other platforms, and twenty-three other satellites, damaged 104 other structures and resulted in seven pollution incidents, two fires, and five drilling wells blown off location. The damage caused by Andrew in both South Florida and Louisiana totalled some $26 billion dollars.

The costliest earthquake in US history was the Loma Prieta earthquake. At 5 p.m. on 17 October 1989 the San Andreas Fault system in northern California had its first major quake since 1906. Four minutes later, as over 62,000 fans filled Candlestick Park baseball stadium for the third game of the World Series and as the San Francisco Bay Area evening commute moved into its heaviest flow, a Richter magnitude 7.1 earthquake struck. The Loma Prieta earthquake was responsible for 62 deaths, 3,757 injuries, and damage to over 18,000 homes and 2,600 businesses. About 3,000 people were left homeless. This 20-second earthquake, centred about sixty miles south of San Francisco, was felt as far away as San Diego in southern California and Reno in western Nevada. Damage and interruptions to business cost about $10 billion, with direct property damage estimated at $6.8 billion.

The most devastating flood in US history occurred in the summer of 1993. All large midwestern streams flooded, including the Mississippi, Missouri, Kansas, Illinois, Des Moines and Wisconsin rivers. The floods displaced over 70,000 people. Nearly 50,000 homes were damaged or destroyed and fifty-two people died. Over 31,000 km^2 (12,000 square miles) of productive farmland were rendered useless. Damage was estimated between $15 and 20 billion.

Hurricane Andrew, the Loma Prieta earthquake, and Mississippi flood events were sudden and dramatic. Droughts, on the other hand, are usually neither sudden nor dramatic; they are not given names. They can nevertheless be much more costly. As mentioned earlier, the cost of the 1988–89 drought exceeded $39 billion. Drought planning and implementing mitigation measures can help reduce those costs.

3. Defining Droughts

Operational definitions of droughts attempt to identify their beginning, end and degree of severity. Knowing exactly when a drought is beginning, so that water conservation measures can be implemented, is difficult since at the time it begins, whenever that is, the drought's severity and duration are unknown. Usually the beginning date is defined when some arbitrary drought index threshold is exceeded. Such a threshold might be, for example, observing less than 75% of the average precipitation in a two-year period. Alternatively, it could be based on the total volume of water in reservoirs used for water supply. The threshold or index that defines the beginning of a drought is usually established arbitrarily, depending on the hydrological characteristics of the basin and the specific demands for water in the region.

Meteorologists usually consider droughts in terms of their relative dryness and dry-period duration. What is considered abnormally dry will differ in different regions, since the atmospheric conditions that result in deficiencies of precipitation vary from region to region. Some measures of dryness identify the number of days with precipitation less than some specified threshold. This measure is appropriate for regions having a humid tropical or sub-tropical climate, or a humid mid-latitude climate characterized by year-round precipitation regimes. Examples are locations such as Manaus, Brazil; New Orleans, Louisiana (USA); and London, England. Regions such as the central United States, Europe, northeast Brazil, West Africa and northern Australia are characterized by seasonal rainfall patterns. Extended periods without rainfall are common in, for example, Omaha, Nebraska (USA); Fortaleza, Ceará (Brazil); and Darwin, Northwest Territory (Australia). In these cases a definition based on the number of days with precipitation less than some specified threshold is unrealistic. Actual precipitation departures from average amounts on monthly, seasonal or annual time scales may be more useful.

Farmers are mostly concerned about the susceptibility of crops to soil moisture deficits during different stages of crop development. Plant water demand depends on prevailing weather conditions, the biological characteristics of the specific plant, its stage of plant growth, and the physical and biological properties of the soil. Deficient topsoil moisture at planting may hinder germination, leading to low plant population densities and a reduced final yield. However, if topsoil moisture is sufficient for early growth requirements, deficiencies in subsoil moisture at this early stage may not affect final yield, provided subsoil moisture is replenished as the growing season progresses or rainfall meets plant water needs.

A drought threshold for farmers might involve daily precipitation values together with evapotranspiration rates that are used to determine the rate of soil moisture depletion and its effect on plant behaviour (growth and yield) at various stages of crop development. This measure of drought severity could be tracked over time, continually re-evaluating the potential impact of drought conditions on final yield.

Those who manage water for multiple uses at regional scales are primarily concerned about future water supplies. These hydrologists are interested in the effects of precipitation (including snowfall) shortfalls on surface or subsurface water supplies, as evidenced by streamflow, reservoir and lake levels, and groundwater table elevations. The frequency and severity of such a 'hydrological' drought is often defined on a watershed or river basin scale. Although all droughts originate with a deficiency of precipitation, hydrologists focus on how this deficiency affects the hydrological system.

Hydrological droughts usually occur some time after precipitation deficiencies show up in soil moisture. It takes longer for streamflows or groundwater and surface reservoir levels to react. It takes even longer for these effects to affect various economic sectors. For example, a precipitation deficiency may result in a rapid depletion of soil moisture that is almost immediately discernible to farmers, yet the impact of this deficiency on reservoir levels may not affect hydroelectric power production or recreational uses for many months. Also, water in lakes, reservoirs, and rivers is often used for multiple and competing purposes (irrigation, recreation, navigation, hydropower, wildlife habitat and so on), further complicating the sequence and quantification of impacts. Competition for water in these storage systems escalates during droughts, and hence conflicts among water users may increase as well.

Developing a history of drought frequency, severity, duration and impacts for a region provides a greater understanding of the region's drought characteristics and the probability of drought recurrence at various levels of severity. Even though these characteristics could be changing along with a changing climate, information of this type is beneficial in the development of drought response and mitigation strategies and preparedness plans. These plans need to be kept current as conditions change.

Figure C.4 summarizes the sequence and consequences of drought events, indicating which of these are of primary interest to meteorologists, agriculturalists and hydrologists.

4. Causes of Droughts

Understanding what causes droughts helps us predict them. This section briefly outlines the relation of droughts to normal variations in regional weather, and how weather is related to global climate patterns.

The immediate cause of droughts is the downward movement of air (subsidence). This causes compressional warming or high pressure that inhibits cloud formation and results in lower relative humidity and less precipitation. Most climatic regions experience high-pressure dominance, often depending on the season. Prolonged droughts occur when large-scale high-pressure anomalies in atmospheric circulation patterns persist for months or seasons (or longer). The extreme drought that affected the United States and Canada in 1988–89 resulted from the persistence of a large-scale atmospheric circulation anomaly. Regions under the influence of semi-permanent high pressure during all or a major portion of the year are usually deserts, such as the Sahara and Kalahari deserts of Africa and the Gobi Desert of Asia.

The ability to predict droughts is limited and differs by region, season and climatic regime. It is difficult to predict a drought a month or more in advance for most locations. Predicting droughts depends on the ability to forecast precipitation and temperature, which are inherently variable. Anomalies of precipitation and temperature may last from several months to several decades. How long they last depends on air–sea interactions, soil moisture and land surface processes, topography, internal dynamics, and the accumulated influence of dynamically unstable synoptic weather systems at the global scale.

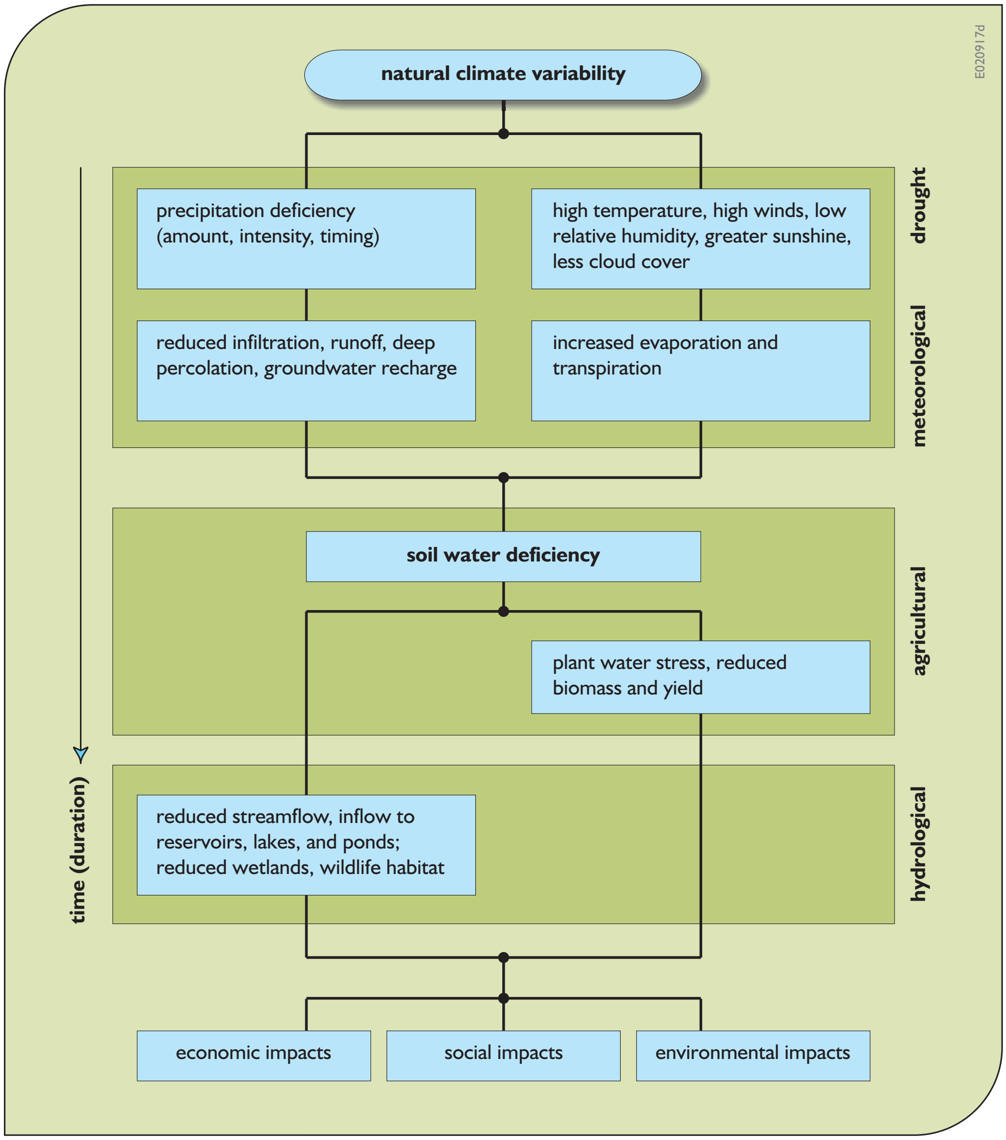

Figure C.4. A summary of the sequence and consequences of drought events, and the way meteorologists, agriculturalists and hydrologists view them.

4.1. Global Patterns

Global patterns of climatic variability tend to recur periodically with enough frequency and with similar characteristics over a sufficient length of time to offer opportunities for improved long-range climate predictions. One such pattern is called El Niño/Southern Oscillation (ENSO). Off the western coast of South America every two to seven years, ocean currents and winds shift. This brings warm water westward to displace the nutrient-rich cold water that normally wells up from deep in the ocean. The invasion of warm water disrupts both the marine food chain and the economies of coastal communities that depend on fishing and related industries. Because the phenomenon peaks around the Christmas season, the fishermen who first observed it named it El Niño ('the Christ Child' or the little boy).

In recent decades, scientists have recognized that El Niño is linked with other shifts in global weather patterns. The upper half of Figure C.5 illustrates the El Niño conditions compared to normal conditions.

The intensity and duration of El Niño events are varied and hard to predict. They typically last anywhere from fourteen to twenty-two months, but they can be much shorter or longer. El Niño often begins early in the year and peaks between the following November and January,

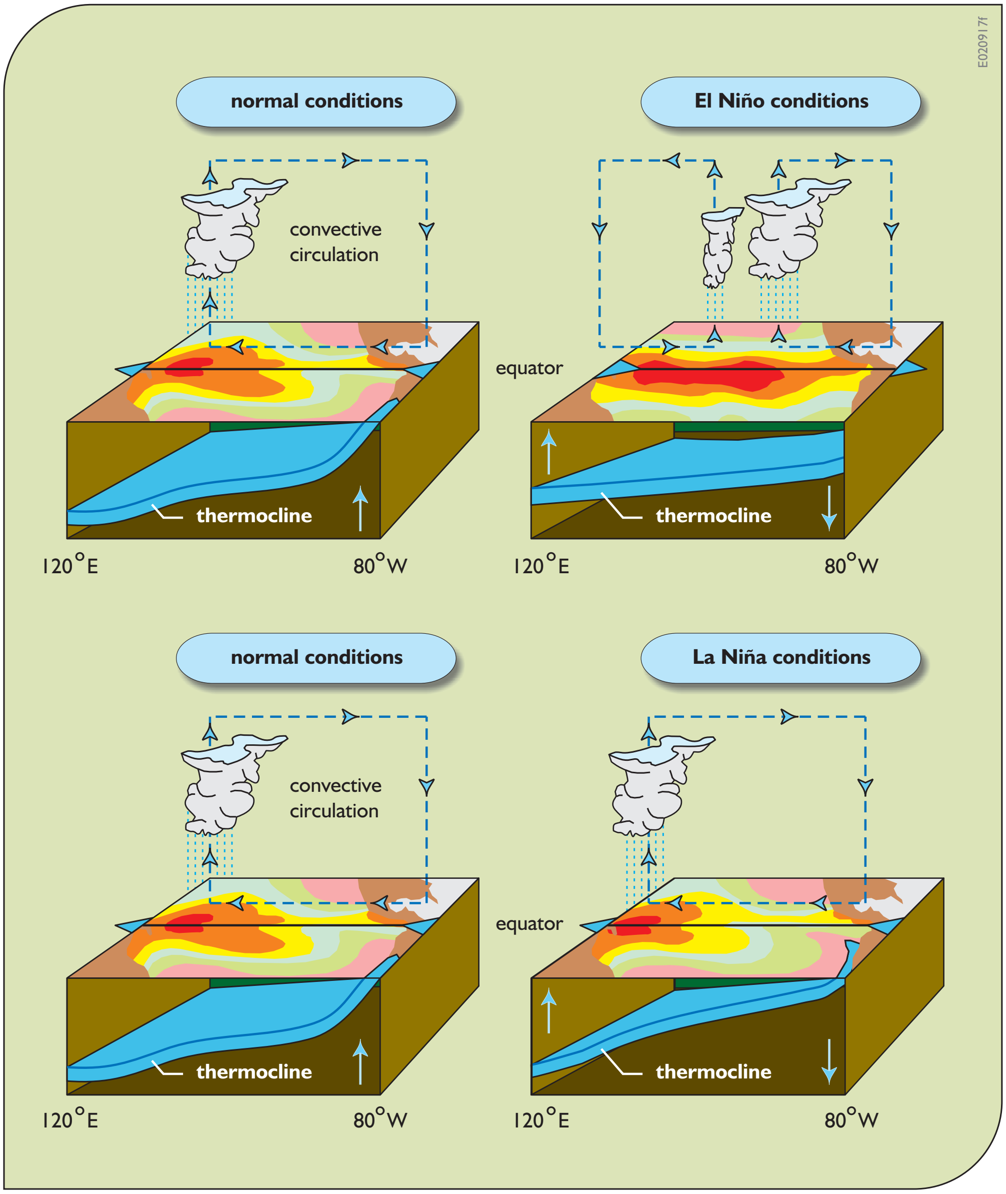

Figure C.5. Normal, El Niño, and La Niña conditions in the mid-Pacific Ocean.

but no two events in the past have behaved in the same way.

Often accompanying El Niño is the Southern Oscillation, a 'seesaw of atmospheric pressure between the eastern equatorial Pacific and Indo-Australian areas' (Glantz et al., 1991). The term Southern Oscillation refers to the atmospheric component of the relationship, shown in Figure C.5, and El Niño represents the oceanic property in which sea surface temperatures are the main factor.

During an El Niño/Southern Oscillation event, the Southern Oscillation is reversed. Generally, when pressure is high over the Pacific Ocean, it tends to be low in the eastern Indian Ocean, and vice versa (Maunder, 1992). ENSO events are those in which both a Southern Oscillation extreme and an El Niño occur together.

La Niña is the counterpart of El Niño and represents the other extreme of the ENSO cycle. In this event, the sea surface temperatures in the equatorial Pacific drop well below normal levels and advect to the west, while the trade winds are unusually intense rather than weak. La Niña cold event years often (but not always) follow El Niño warm event years. The lower half of Figure C.5 compares La Niña and normal conditions.

4.2. Teleconnections

Shifts in sea surface temperatures off the west coast of South America are just one part of the coupled interactions of atmosphere, oceans and land masses. Statistically, El Niño/Southern Oscillation can account at most for about half of the inter-annual rainfall variance in eastern and southern Africa (Ogallo, 1994). Yet many of the more extreme anomalies, such as severe droughts, flooding and hurricanes, have strong teleconnections to ENSO events. Teleconnections are defined as atmospheric interactions between widely separated regions (Glantz, 1994). Understanding these teleconnections can help in forecasting droughts, floods and tropical storms (hurricanes).

During an ENSO event, drought can occur virtually anywhere in the world, though the strongest connections between ENSO and intense drought are in Australia, India, Indonesia, the Philippines, Brazil, parts of eastern and southern Africa, the western Pacific Basin islands (including Hawaii), central America and various parts of the United States. Drought occurs in each of the above regions at different times (seasons) during an ENSO event and in varying degrees of magnitude.

In the Pacific Basin, Indonesia, Fiji, Micronesia and Hawaii are usually prone to droughts during ENSO events. Virtually all of Australia is subjected to abnormally dry conditions in these periods, but the eastern half has been especially prone to extreme drought. Bush fires and crop failures usually follow. India too has been subjected to drought through a suppression of the summer monsoon season that seems to coincide with ENSO events in many cases. Eastern and southern Africa also show a strong correlation between ENSO events and a lack of rainfall that brings on drought in the Horn region and areas south of there. Central America and the Caribbean islands are also abnormally dry during El Niño events.

ENSO events seem to have a stronger influence on regions in the lower latitudes, especially in the equatorial Pacific and bordering tropical areas. The relationships in the mid-latitudes are less pronounced and less consistent in the way El Niño influences wet or dry weather patterns. The intensity of the anomalies in these regions is also less consistent than those of the lower latitudes.

Incorporating some of these teleconnections within numerical computer models of global climate can improve their predictive capabilities. Predicting when an ENSO event might occur is much easier than predicting its duration and intensity, however. Predictive models are becoming more sophisticated and more effective in many respects due in part to the expanded data sets that are available for the equatorial Pacific region. Some models have predicted ENSO events a year or more in advance.

ENSO forecasts can help countries anticipate and mitigate droughts and floods, and can be useful in agricultural planning. Countries that are in latitudes with strong El Niño connections to weather patterns, such as Brazil, Australia, India, Peru and various African nations, use predictions of near-normal conditions, weak El Niño conditions, strong El Niño conditions or a La Niña condition to help agricultural producers select the crops most likely to be successful in the coming growing season. In countries or regions with a famine early warning system (FEWS) in place, ENSO forecasts can play a key role in mitigating the effects of floods or droughts that can lead to famine. Famine, like drought, is a slow-onset disaster, so forewarning may enable countries to substantially reduce, if not eliminate, its worst impacts.

ENSO advisories are used to a lesser extent in planning in North America and other extratropical countries because the links between ENSO and weather patterns are less clear in these areas. As prediction models improve, the role of ENSO advisories in planning in mid-latitude countries will undoubtedly increase.

4.3. Climate Change

Climate change is associated with the greenhouse effect. The greenhouse effect is a naturally occurring phenomenon necessary to sustain life on earth. In a greenhouse, solar radiation passes through a mostly transparent piece of glass or plastic and warms the inside air, surface and plants. As the temperature increases inside the greenhouse, the interior radiates energy back to the outside and eventually a balance is reached.

The earth is in a greenhouse: its atmosphere is the 'piece of glass or plastic'. Short-wave radiation from the sun passes through the earth's atmosphere. Some of this radiation is reflected back into space by the atmosphere, some is absorbed by the atmosphere, and some makes it to the earth's surface. There, it is either reflected or absorbed. The earth, meanwhile, emits long-wave radiation outward. Gases within the atmosphere absorb some of this long-wave radiation and re-radiate it back to the surface. It is because of this greenhouse-like function of the atmosphere that the average global temperature of the earth is what it is, about 15 °C (59 °F). Without the atmosphere and these gases, the average global temperature would be a chilly −18 °C (0 °F). Life that exists on earth today would not be possible without these atmospheric greenhouse gases. They include carbon dioxide (CO_2), water vapour (H_2O), methane (CH_4), nitrous oxide (N_2O), chlorofluorocarbons (CFCs), and ozone (O_3).

Increasing concentrations of greenhouse gases will increase the temperature of the earth. Currently both are increasing. Carbon dioxide is responsible for approximately half of the greenhouse gas increase. Concentrations of CO_2 have been monitored at the Mauna Loa Observatory in Hawaii since 1958. Measurements of CO_2 concentrations from before 1958 are based on air bubbles within ice cores taken from around the world. In the middle of the eighteenth century, levels of CO_2 were around 270 parts per million (ppm). By the end of the twentieth century these levels were about 370 ppm. They are currently increasing at about 0.4% per year (IPCC, 2001). About 70–90% of the CO_2 added to the atmosphere is due to the burning of fossil fuels, and much of the rest is from deforestation (OTA, 1993). Methane, N_2O, and CFCs are increasing at similar rates. At these rates the concentration of CO_2 will double pre-industrial concentrations by about 2100 (IPCC, 2001).

Scientists incorporate this information within large-scale models of the atmosphere called general circulation models (also called global climate models, or GCMs). These models are designed to simulate global atmospheric conditions and make projections of the future climate. Although there are differences among the GCM projections, the models are in general agreement that, as a result of increasing greenhouse gas concentrations, the average global temperature will increase by about 1.4–5.8 °C (2.52–10.44 °F) by 2100 (IPCC, 2001). In the past century, the global average surface temperature has increased 0.60 °C (1.08 °F). This increase by itself is within the normal variability and, although it may be a result of climate change, it cannot be used as definitive proof that recent human activities have contributed noticeably to global warming. Between 1860 and 2000, however, the nine warmest years for the global temperature occurred after 1980 (IPCC, 2001).

With the projected global temperature increase, the global hydrological cycle could also intensify. GCMs indicate that global precipitation could increase 7–15%. Meanwhile, global evapotranspiration could increase 5–10% (OTA, 1993). The combined impacts of increased temperature, precipitation, and evapotranspiration would affect snowmelt, runoff, and soil moisture conditions. The global climate models (GCM) generally show that precipitation will increase at high latitudes and decrease at low and mid-latitudes. If this happens, evapotranspiration in mid-continental regions will be greater than precipitation. This could lead to more severe, longer-lasting droughts in these areas. In addition, the increased temperatures alone will expand ocean waters and this will lead to an estimated sea level rise of about half a centimetre per year (OTA, 1993).

One of the weaknesses of GCM climate change predictions is that they cannot adequately take into account factors that might influence regional and river basin climates, such as the local effects of mountains, coastlines, large lakes, vegetation boundaries and heterogeneous soils, or the ways that human activities affect those predictions. Thus, it is difficult to transfer GCM predictions to regional and basin scales. GCMs also cannot predict changes in the frequency of extreme events. Some believe the occurrence of extreme events such as droughts is increasing. Although the losses due to these events have increased worldwide, this is often the result of increased vulnerability rather than an increased number of events.

No one knows who will lose or who will benefit from a CO_2-induced climate change. Clearly, coastal regions will be likely to experience a slow rise in average sea levels. But some interior regions might benefit from gains in agricultural production resulting from the indirect effects of a warmer climate and adequate precipitation, especially in higher latitudes across Canada and Russia. The increased CO_2 might also directly increase plant growth and productivity as well. This is known as the CO_2 fertilization effect. Laboratory experiments have shown that increased CO_2 concentrations potentially promote plant growth and ecosystem productivity by increasing the rate of photosynthesis, improving nutrient uptake and use, increasing water-use efficiency, and decreasing respiration, along with several other factors (OTA, 1993). Increased ecosystem productivity could draw CO_2 from the atmosphere, thereby diminishing concerns about global warming (OTA, 1993). Whether any benefits would result from the CO_2 fertilization effect within the complex interactions of natural ecosystems is still unknown, however.

4.4. Land Use

Although climate is a primary contributor to droughts, other factors such as changes in land use (e.g. deforestation), land degradation and the construction of dams all affect the hydrological characteristics of a basin. Changes in land use upstream may reduce infiltration and thereby increase runoff rates, resulting in more variable streamflow, less groundwater retention and a higher incidence of hydrological drought downstream. Bangladesh, for example, has shown an increased frequency of water shortages in recent years because of land use changes that have occurred within its territory and in neighbouring countries.

Land use change is one of the ways human actions can alter the frequency of water shortage even when no statistical change in the frequency or intensity of precipitation has been observed.

5. Drought Indices

Drought indices combine various indicators of drought into a single index to help in identifying the onset as well as the severity of a drought. Different indices have been proposed and are used for different purposes. This section identifies a few of the more commonly used indices. No index is perfect for all situations. Hence, most water supply planners find it useful to track more than one index before making decisions that will affect people's welfare.

5.1. Percent of Normal Indices

The *percent of normal* indices are easily calculated and well suited to the needs of weathercasters and the general public. They can be associated with any hydrological variable, such as precipitation, soil moisture, groundwater level or reservoir storage volume. The percent of normal index based on precipitation is one of the simplest measurements of rainfall or snowfall for a location. Such analyses are effective when used for a single region or a single season. The index value is 100 times the actual value divided by the average value (typically considered to be a thirty-year mean). Normal for a specific location is considered to be 100%.

This index can be calculated for a variety of time scales. Usually these range from a single month to a group of months representing a particular season, to an annual or water year.

One potential disadvantage of using the percent of normal value is that the mean, or average, is often not the same as the median (the value exceeded 50% of the time in a long-term climate record). This is because most random hydrological values on monthly or seasonal scales are not normally distributed. Some people assume the use of the percent of normal comparison is based on median rather than mean values, and this can cause confusion. The long-term precipitation record for the month of January in Melbourne, Australia, can serve to illustrate the potential for misunderstanding. The median January precipitation is 36.0 mm (1.4 in.), meaning that in half the January months less than 36.0 mm has been recorded, and in the other half of the January months more than 36.0 mm has been recorded. However, a monthly January total of 36.0 mm would be only 75% of the historical mean, which is often considered to be quite dry (Willeke et al., 1994).

5.2. Standardized Precipitation Index

The realization that a precipitation deficit has different impacts on groundwater, reservoir storage, soil moisture, snow pack and streamflow led McKee et al. (1993) to develop the Standardized Precipitation Index (SPI). This index quantifies the precipitation deficit for multiple time scales that reflect the impact of drought on the availability of different sources of water. Soil moisture conditions respond to precipitation anomalies on a relatively short time scale. Groundwater, streamflow and reservoir storage reflect the longer-term precipitation anomalies. For these reasons, McKee et al. (1993) originally calculated the SPI for three, six, twelve, twenty-four, and forty-eight-month time scales.

The SPI calculation for any location is based on the long-term precipitation record fitted to a probability distribution. This distribution is then transformed into a normal distribution so that the mean SPI for the location and desired period is zero (Edwards and McKee, 1997). Positive SPI values indicate greater than median or mean precipitation, and negative values indicate less than median or mean precipitation. Because the SPI is normalized, wetter and drier climates can be represented in the same way, so wet periods can also be monitored using the SPI.

McKee et al. (1993) used the classification system shown in Table C.2 to define drought intensities resulting from the SPI. They also defined the criteria for a drought event for any of the time scales. A drought event occurs any time the SPI is continuously negative and reaches an intensity of −1.0 or less. The event ends when the SPI becomes positive. Each drought event, therefore, has a duration defined by its beginning and end, and an intensity for each month of the drought event. The absolute sum of the negative SPI for all the months within a drought event can be termed the drought's 'magnitude'.

Using an analysis of stations across Colorado in the western United States, McKee determined that, as defined by the SPI, western Colorado is in mild drought 24% of the time, in moderate drought 9.2% of the time, in severe drought 4.4% of the time, and in extreme drought 2.3% of the time (McKee et al., 1993). Because the SPI is standardized, these percentages are expected from a normal distribution of the SPI. The 2.3% of SPI values within the 'extreme drought' category is a percentage that is typically expected for an 'extreme' event (Wilhite, 1995). In contrast, the Palmer index, to be discussed next, reaches its 'extreme' category more than 10% of the time across portions of the central Great Plains. This standardization allows the SPI to determine the rarity of a current drought, as well as the probability of the precipitation necessary to end the current drought (McKee et al., 1993).

SPI values	
2.0+	extremely wet
1.5 to 1.99	very wet
1.0 to 1.49	moderately wet
-0.99 to 0.99	near normal
-1.00 to -1.49	moderately dry
-1.50 to -1.99	severely dry
-2.00 and less	extremely dry

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Table C.2. Standardized precipitation index.

5.3. Palmer Drought Severity Index

The Palmer drought severity index (PDSI) is a soil moisture index designed for relatively homogeneous regions. Many US government and state agencies rely on it to trigger drought relief programmes. The index measures the departure of the soil moisture supply from demand (Palmer, 1965). The objective of the PDSI is to provide standardized measurements of moisture conditions so that comparisons using the index can be made between locations and between months. Complete descriptions of the equations can be found in the original study by Palmer (1965) and in the analysis by Alley (1984).

The PDSI responds to weather conditions that have been abnormally dry (or abnormally wet). It is calculated with the use of precipitation and temperature data, as well as the local available water content (AWC) of the soil. It does not consider streamflow, lake and reservoir levels, or other longer-term hydrological variable values that indeed may still show a drought (Karl and Knight, 1985). Human impacts on the water balance, such as irrigation, are also not considered.

Palmer developed the PDSI to include the duration of a dry or wet spell period. His motivation was as follows: an abnormally wet month in the middle of a long-term drought should not have a major impact on the index, and a series of months with near-normal precipitation following a serious drought does not mean that the drought is over. Therefore, Palmer developed criteria for determining when a drought or a wet spell begins and ends. Palmer (1965) described this effort and gave examples. It is also described in detail by Alley (1984).

In near-real time, Palmer's index is no longer a meteorological index but becomes a hydrological one, referred to as the Palmer hydrological drought index (PHDI). It is based on moisture inflow (precipitation), outflow and storage, and does not take into account the long-term trend (Karl and Knight, 1985).

A modified method to compute the PDSI was proposed by Heddinghaus and Sabol, 1991. This modified PDSI differs from the PDSI during transition periods between dry and wet spells. Because of the similarities between these Palmer indices, the terms Palmer index and Palmer drought index have been used to describe general characteristics of the indices.

The Palmer index varies between roughly −6.0 and +6.0. Palmer arbitrarily selected the classification scale of moisture conditions, shown in Table C.3, on the basis of his original study areas in the central United States (Palmer, 1965). Ideally, the Palmer index is designed so that a −4.0 in one region has the same meaning in terms of the moisture departure from a climatological normal as a −4.0 in another region (Alley, 1984). The Palmer index has typically been calculated on a monthly basis, and a long-term archive (from 1895 to present) of the monthly PDSI values for every climate division in the United States exists at the National Climatic Data Center. In addition, weekly Palmer index values (modified PDSI values) are calculated and mapped (Figure C.6) for the climate divisions during every growing season.

The Palmer index has been widely used for a variety of applications across the United States. It is most effective at measuring impacts sensitive to soil moisture conditions, such as agriculture (Willeke et al., 1994). It has also been useful as a drought-monitoring tool and has been used to trigger actions associated with drought contingency plans (Willeke et al., 1994). Alley (1984) identified

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Palmer classifications	
4.0 or more	extremely wet
3.0 to 3.99	very wet
2.0 to 2.99	moderately wet
1.0 to 1.99	slightly wet
0.5 to 0.99	incipient wet spell
0.49 to -0.49	near normal
-0.5 to -0.99	incipient dry spell
-1.9 to -1.99	mild drought
-2.0 to -2.99	moderate drought
-3.0 to -3.99	severe drought
-4.0 or less	extreme drought

Table C.3. The Palmer drought severity index.

three positive characteristics of the Palmer index that contribute to its popularity: it provides decision-makers with a measurement of the abnormality of recent weather for a region; it provides an opportunity to place current conditions in historical perspective; and it provides spatial and temporal representations of historical droughts. Several states in the USA, including New York, Colorado, Idaho and Utah, use the Palmer index as part of their drought monitoring systems.

The Palmer index has some limitations, and these are described in detail by Alley (1984) and Karl and Knight (1985). Also, while the index has been applied within the United States it has little acceptance elsewhere (Kogan, 1995; Smith et al., 1993). It does not do well in regions where there are extremes in the variability of rainfall or runoff, such as Australia and South Africa. Another weakness in the Palmer index is that the 'extreme' and 'severe' classifications of drought occur with a greater frequency in some regions than in others (Willeke et al., 1994). This limits the accuracy of comparisons of the intensity of droughts between two regions and makes planning response actions based on a given intensity more difficult.

5.4. Crop Moisture Index

Whereas the PDSI monitors long-term meteorological wet and dry spells, the crop moisture index (CMI) was designed to evaluate short-term moisture conditions across major crop-producing regions. It is not intended to assess long-term droughts. It reflects moisture supply in the short term across major crop-producing regions.

The CMI uses a meteorological approach to monitor week-to-week crop conditions. It is based on the mean temperature and total precipitation for each week within a climate division, as well as the CMI value from the previous week. The index responds rapidly to changing conditions, and is weighted by location and time so that maps, which commonly display the weekly CMI across a region, can be used to compare moisture conditions at different locations.

5.5. Surface Water Supply Index

The surface water supply index (SWSI, pronounced 'swa zee') is designed to complement the Palmer where mountain snow pack is a key element of water supply. It

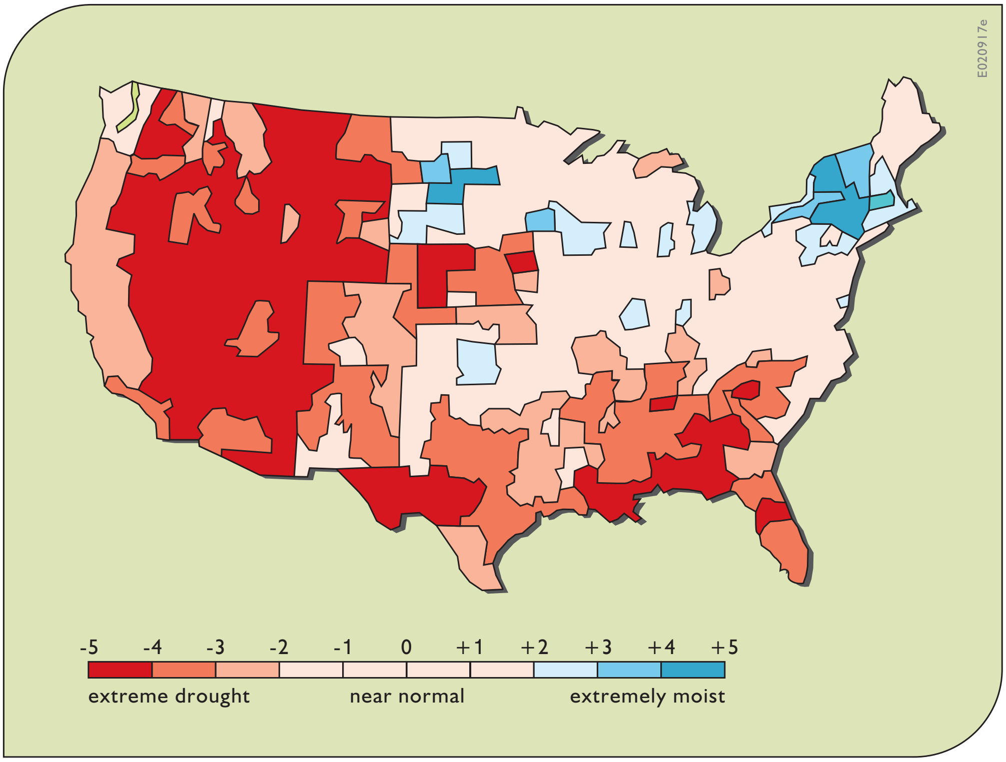

Figure C.6. Palmer index values for the United States during a week in August, 2000.

is calculated for river basins on the basis of snow pack, streamflow, precipitation and reservoir storage (Shafer and Dezman, 1982; Dezman et al., 1982). The index is unique to each basin, which limits interbasin comparisons.

Shafer and Dezman (1982) designed the SWSI to be an indicator of the conditions of surface water in which mountain snow pack is a major component. The objective of the SWSI was to incorporate both hydrological and climatological features into a single index value resembling the Palmer index for each major river basin in the state of Colorado. These values could be standardized to allow comparisons between basins. Four inputs are required within the SWSI: snow pack, streamflow, precipitation and reservoir storage. Because it is dependent on the season, the SWSI is computed with only snow pack, precipitation and reservoir storage in the winter. During the summer months, streamflow replaces snow pack as a component within the SWSI equation.

To determine the SWSI for a particular basin, monthly data are collected and summed for all the precipitation stations, reservoirs and snow pack/streamflow measuring stations over the basin. Each summed component is normalized using a frequency analysis gathered from a long-term data set. The probability of non-exceedance (the probability that subsequent sums of that component will exceed the current sum) is determined for each component on the basis of the frequency analysis. This allows comparisons of the probabilities to be made between the components. Each component has a weight assigned to it depending on its typical contribution to the surface water within that basin. These weighted components are summed to determine a SWSI value representing the entire basin. Like the Palmer index, the SWSI is centred on zero and has a range between -4.2 and $+4.2$.

5.6. Reclamation Drought Index

Like the SWSI, the reclamation drought index (RDI) is calculated at the river basin level, incorporating temperature as well as precipitation, snow pack, streamflow and reservoir levels as input. By including a temperature component, it also accounts for evaporation. It is used by the US Bureau of Reclamation as a trigger to release drought emergency relief funds. The RDI classifications are listed in Table C.4.

The RDI was developed as a tool for defining drought severity and duration, and for predicting the onset and end of periods of drought. The impetus to devise it came

RDI classifications	
4.0 or more	extremely wet
1.5 to 4.0	moderately wet
1 to 1.5	normal to mild wetness
0 to 1.5	normal to mild drought
-1.5 to -4.0	moderate drought
-4.0 or less	extreme drought

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Table C.4. RDI classifications.

decile classifications		
deciles 1 - 2:	lowest 20 %	much below normal
deciles 3 - 4:	lowest next 20 %	below normal
deciles 5 - 6:	middle 20 %	near normal
deciles 7 - 8:	highest next 20 %	above normal
deciles 9 - 10:	highest 20 %	much above normal

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Table C.5. Decile classifications.

from the US Reclamation States Drought Assistance Act of 1988, which allows states to seek assistance from the US Bureau of Reclamation to mitigate the effects of drought.

The RDI differs from the SWSI in that it builds a temperature-based demand component and duration into the index. The RDI's main strength is its ability to account for both climate and water supply factors.

5.7. Deciles

This index groups monthly precipitation occurrences into deciles so that, by definition, 'much lower than normal' weather cannot occur more often than 20% of the time. These deciles are shown in Table C.5.

Arranging monthly precipitation data into deciles is another drought-monitoring technique. Developed by Gibbs and Maher (1967), it removes some of the weaknesses in the 'percent of normal' approach. The technique divides the distribution of occurrences over a long-term precipitation record into tenths of the distribution. Each of these categories is a decile. The first decile is the rainfall amount not exceeded by the lowest 10% of the precipitation occurrences. The second decile is the precipitation amount not exceeded by the lowest 20% of occurrences. These deciles continue until the rainfall amount identified by the tenth decile is the largest precipitation amount within the long-term record. By definition, the fifth decile is the median; it is the precipitation amount not exceeded by 50% of the occurrences over the period of record. The deciles are grouped into five classifications, as shown in Table C.5.

The decile method was selected as the meteorological measurement of drought within the Australian Drought Watch System because it is relatively simple to calculate and requires fewer data and assumptions than the Palmer Drought Severity Index (Smith et al., 1993). In this system, farmers and ranchers can only request government assistance if the drought is shown to be an event that occurs only once in twenty or twenty-five years (deciles 1 and 2 over a 100-year record) and has lasted longer than twelve months (White and O'Meagher, 1995). This uniformity in drought classifications, unlike a system based on the percent of normal precipitation, has assisted Australian authorities in determining appropriate drought mitigation responses.

5.8. Method of Truncation

The method of truncation uses historic records of streamflow, precipitation, groundwater drawdown, lake elevation and temperature (Chang and Kleopa, 1991). The historic data are sorted in ascending order, and trigger levels are determined from the truncation level specified (Figure C.7).

For example, if stage 1 drought is defined as the 70% level, this corresponds to streamflows that are less than 70% of all flows. When using this method, drought events of higher severity are 'nested' inside drought events of lower severity: that is to say, a 90% drought implies the occurrence of a 70% and 80% drought (if those are the trigger levels selected). The highest level of severity determines the decisions to make, as a water management system must deal with the most severe shortage that occurs.

5.9. Water Availability Index

The water availability index (WAI) relates current water availability to historical availability during periods of drought by measuring the deviation-from-normal rainfall

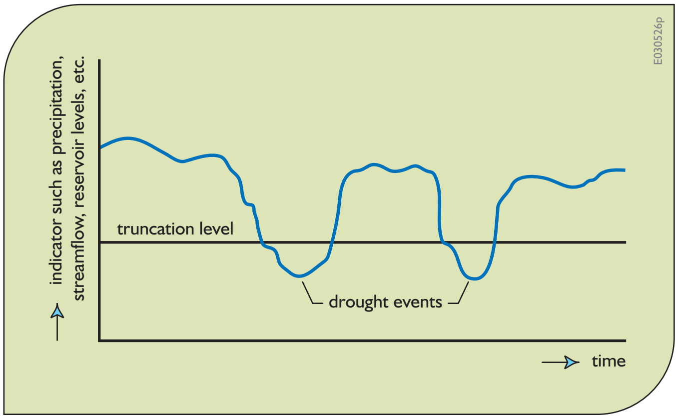

Figure C.7. Method of truncation to define drought conditions (Fisher and Palmer, 1997).

week	**beginning storage** volume	**inflow** volume per week	**demand** volume per week	**ending storage** volume	**demand met?**	**DSR** days
begin	100	40	40	100		7
+ 1	100	60	40	120		14
+ 2	120	20	40	100		21
+ 3	100	20	40	80		28
+ 4	80	0	40	40		35
+ 5	40	20	40	20		42
+ 6	20	10	40	-10	no	
+ 7	-10	60	40	10		

Table C.6. Calculation of DSR index value based on weekly time steps and forecast inflow and demands (from Fisher and Palmer, 1997).

over the prior four months (Davis and Holler, 1987). The WAI is multiplied by a constant to make the index fall between 0 and 10, with zero representing normal conditions and ten a severe drought. Hoke (1989) included a factor for minimum and maximum desirable reservoir pool elevation, and Raney (1991) included volume and drainage area factors to account for multiple reservoirs within one watershed.

5.10. Days of Supply Remaining

The days of supply remaining (DSR) index includes current reservoir storage, forecast future inflows from precipitation and snowmelt, and predicted demands for municipal supply and instream flows (Fisher and Palmer, 1997). It provides an objective and easily understood measure of the supply of water. As new sources of supply or new demands occur, the index remains appropriate.

DSR is calculated by predicting future inflows and demands and determining when the inflows and existing supply will no longer be adequate to meet demands. A simplified example shown in Table C.6 illustrates this calculation.

The DSR values are calculated at the beginning of each time step, for example, a week. At that time, forecasts are made of the subsequent weeks' inflows and demands. Inflows are added and demands subtracted for each successive week until the remaining supply is less than the demand.

In the example shown in Table C.6, there are 100 units of storage currently available. Forecasts show that the projected demand cannot be met after six weeks from now. There is adequate supply for the current week plus the following five weeks. Thus, only forty-two days of supply remains. A water management agency presented with the data in this example could implement restrictions to try to reduce demand by 5%. If successful that would maintain adequate levels of storage until the expected reservoir refill begins in seven weeks. Alternatively, a new supply source could be sought, or other demand and supply management options could be analysed. Determining just what actions one should take (given the uncertainty of supply and demand forecasts) can be based, in part, on such analyses, including simulations of alternative actions given supply and demand situations experienced in the past.

Palmer et al. (2002) describe doing this for the City of Atlanta in southeastern United States. Determining in advance what actions are appropriate under what specific conditions or values of DSR and getting them accepted makes drought management substantially easier when under the stress of an actual drought.

The particular values of DSR or any other index value that trigger management decisions are called drought triggers.

6. Drought Triggers

Drought management is tricky. Without knowing just how severe a drought may become, it is difficult to know what actions are best to take, if any, when a drought is likely to have begun. Water managers must take appropriate action to reduce future losses and not increase them by imposing unnecessary restrictions when they are not needed (Wright et al., 1986). Taking actions that impose hardships on the public and the water utility when it later turns out they were unnecessary is not likely to engender compliance with water saving actions the next time they are ordered. One way to make drought management easier is to establish a sequence of increasingly strict conservation measures based on a sequence of drought triggers, and seek the public's approval.

A drought trigger is the specific value of a drought indicator that activates a management response. For example, a drought trigger could be a reservoir decreasing below 50% of its active storage capacity. In a drought contingency plan, trigger levels can be varied to alter the sensitivity of the response and the effectiveness of the plan. Defining drought triggers can be difficult. Trigger levels change over time: that is, an appropriate trigger level for a particular system may change dramatically if that system's infrastructure is expanded or if water demands change dramatically. Urban water triggers are often quite different from agricultural drought triggers, as the urban infrastructure can often mitigate the impacts of short-term droughts.

Short-term responses may include the initiation of outdoor water use bans, an increase in the price of water or the use of printed media to inform the public of water supply problems. Drought management plans for many urban areas are often developed with four to five levels of responses, all of which encourage different levels of demand reduction or supply augmentation. The appropriateness or effectiveness of particular drought measures is dependent upon the type of user. An outdoor water ban, for instance, may be effective for a residential community but not for a heavy industrial complex.

Specific values of any of the drought indices just reviewed in the previous section could be used for a drought trigger. Since each has its limitations, triggers based on multiple indices appropriate for the region will probably be the most reliable and robust (Alley, 1985; Dracup et al., 1980; Johnson and Kohne, 1993; Mather, 1985; Titlow, 1987).

Numerous utilities and government organizations in many countries have explored the use of triggers. Those using triggers to support decision-making in the United States include the Massachusetts Water Resources Authority (which serves the Boston area), Northern New Jersey, the Interstate Commission on the Potomac River Basin (which facilitates supply operations in Washington, D.C., northern Virginia and southern Maryland), the Bureau of Water Works for the City of Portland, and the Seattle Water Department and Denver Water (Fisher and Palmer, 1997; Hrezo et al., 1986; Nault et al., 1990; USACE, 1991).

Deciding on what the trigger indices should be, what the trigger values of those indices should be, and what decisions to make when those trigger index values have been reached is not a trivial exercise. Performing simulations of alternative actions given supply and demand situations experienced in the past can help identify the possible range of likely impacts associated with any particular set of trigger values and associated decisions (Palmer et al., 2002). Performing these analyses in a real-time virtual drought simulation exercise involving all relevant agencies and decision-makers may be even more effective.

7. Virtual Drought Exercises

Drought management requires more than just a plan. Its implementation needs public support and financial resources. The plan needs to be kept up to date. People who are going to be implementing it need to be ready to do that when a drought comes. Virtual drought exercises are one way to accomplish and maintain a state of readiness.

A virtual drought is a fire drill, a test during which water managers, public health officials and other stakeholders put a drought management plan into practice using a hypothetical, computer-generated drought event. A good virtual drought exercise will raise important issues and provide experience that can be applied in real droughts. It will also keep those from different agencies who must work closely together during times of droughts in closer contact with each other.

For over twenty years, the Interstate Commission on the Potomac River Basin (ICPRB) has been conducting

Box C.1. A Recent History of the Potomac River

In 1963, the US Army Corps of Engineers conducted a comprehensive study of the Potomac River basin to identify solutions to the anticipated demand deficits during low river flows. They proposed the construction of sixteen large multipurpose reservoirs in the Potomac River basin. This proposal was not accepted by the public, nor by Congress who would pay the bill. Flow shortages in which unrestricted water use would cause the river to run dry, coupled with increasing population in the 1960s and 1970s, underlined the need to continue to look for solutions. One of the sixteen proposed reservoir projects was built: Jennings Randolph Lake (originally called Bloomington Lake).

Other structural solutions were examined. Interbasin transfers were analysed. A pilot treatment plant and an emergency pumping station were constructed.

Concurrently, an academic study was being conducted that combined distribution areas of the three major Washington metropolitan area utilities into a single regional demand centre. Through simulation modelling, the study investigated the benefits derived from the coordinated operation of all the resources then available to all three utilities. The study showed that coordinated management of the water resources from a total integrated systems perspective led to gains in the reliability of the water resource. The results of the latter analysis and its lower cost non-structural features led to the adoption of its results with the signing of the Water Supply Coordination Agreement in 1982.

The management objectives embodied in the agreement are to keep the reservoir storage volumes balanced while meeting environmental requirements and municipal demands for water. The coordinated operations of each utility are expected to meet the expected demands without imposing restrictions through the year 2015 even under a repeat of the drought of record. This is possible because of synergistic gains in total yield realized under the cooperative management strategies. Each utility gives up a small measure of autonomy in order to gain the substantial benefits of reduced capital costs through coordinated cooperative operations of its individually and jointly owned resources. A committee of the water utilities and the Interstate Commission on the Potomac River Basin oversee the coordinated operations.

annual virtual drought exercises for the Washington metropolitan area. During a drought, the Commission coordinates water supply operations of three major water utilities in Washington, D.C., and the adjacent suburbs in the states of Maryland and Virginia. In the drought exercises, the Commission and the utilities practise the operations of the system as they would during an actual drought. Box C.1 gives a history of how this began.

Virtual drought exercises typically have three stages: briefing, gaming and debriefing. During the briefing, the objectives of the exercise are stated, the rules of the exercise are described, and the initial conditions of the simulated drought scenario are introduced. During the gaming, participants discuss management strategies and negotiate decisions to respond to the simulated drought conditions as they progress. Finally, during debriefing, the outcomes of the exercise are evaluated and drought management plans are modified if and as appropriate.

The briefing portion of the exercise provides a foundation for the day, establishing a common understanding of the objectives and how the gaming will take place. Briefing materials are distributed in advance of the exercise to give participants time to clarify questions or misunderstandings. Typically the briefing will:

- define the objectives of the exercise
- introduce participants
- review the roles of participants
- clarify the format of the exercise
- specify the rules for decision-making
- explain the background information
- demonstrate the virtual drought process.

During the gaming portion of the exercise, the participants manage the water resources system during a drought scenario. This requires discussion among the participants and joint decision-making. Guidelines are provided to define options and modes of decision-making, but the negotiation and acceptance of decisions is one of the by-products of this drought rehearsal. Typical responses include water use restrictions, modifying instream flow requirements, revising water pricing, emergency source acquisitions, modifying surface and groundwater system operations, public involvement and regional coordination measures.

During the gaming, the drought event unfolds over time. The participants intervene with actions when necessary to manage the drought. Information to support and/or influence decision-making is provided throughout the exercise. Such information can include the existing drought plan, forecasts of future conditions, system status reports, results of technical analyses, media news briefs and legal actions.

Debriefing is the reflective and evaluative portion of the exercise. The participants' actions and perceptions are discussed and translated into 'lessons learned'. Specific insights on how the participants managed the drought are brought out and recommendations are made. A facilitated group discussion is the best form of debriefing, providing the participants an opportunity for self-observation.

There are clear links between the general drought planning and preparedness process and virtual drought exercises. Virtual drought exercises test a group's abilities to resolve conflicts and make decisions; they allow participants to experience a drought event and practise its management without the dangers of a real event, and they provide an effective means of evaluating a drought plan's likely effectiveness.

The more realistic the virtual drought exercise is, the more beneficial it will be. It is important that those individuals who are responsible for drought management participate, that the participants represent a wide range of perspectives, that the objectives of the exercise are clear to all, and that the exercise be made as realistic as possible. This makes it possible to capture a true sense of how the resource is likely to be managed during the stress of an actual drought.

Virtual drought exercises should be viewed as natural complements to traditional drought planning activities. If properly designed and implemented, these exercises can keep plans up to date, stakeholders informed and water managers' skills current.

8. Conclusion

Droughts are unusually severe water shortages. We cannot predict when they will occur or how long they will last, but they will happen and when they do the economic as well as social costs can be substantial. Being prepared for droughts can help to mitigate some of those costs and damages. It costs money to plan, but planning to be prepared for droughts in advance of when they occur saves much more that it costs.

Society's vulnerability to droughts is affected by population density and growth (especially in urban regions), changes in water use trends, government policy, social behaviour, economic conditions, and environmental and ecological objectives. Changes in all of these factors tend to increase the demand for water, and hence society's vulnerability to droughts.

Although droughts are natural hazards, society can reduce its vulnerability and therefore lessen the risks associated with drought events. The impacts of droughts, like those of other natural hazards, can be reduced through planning and preparedness. Drought management is decision-making under uncertainty. It is risk management. Planning ahead to identify effective ways of mitigating drought losses gives decision-makers the chance to reduce both suffering and expense. Reacting without a plan to emergencies in a 'crisis mode' during an actual drought generally decreases self-reliance and increases dependence on government services and donors.

Planning for droughts is essential, but it may not come easily. There are many constraints on planning. For example, it is hard for politicians and the public to be concerned about a drought when they are coping with a flood – or any other more immediate crisis. Unless there is a drought emergency, it is often hard to get support for drought planning. There are always more urgent needs for money and people's attention. Where coordination among multiple agencies can yield real benefits, it is not easy to get it to happen until it becomes obviously essential, for example during a severe drought. Multi-agency cooperation and coordination must be planned for, and perhaps practised in virtual drought management exercises, in advance of the drought. Getting multiple agencies to work together only in a crisis mode is never efficient. Crisis-oriented drought response efforts have been largely ineffective, poorly coordinated, untimely, and inefficient in terms of the resources allocated.

Drought planning will vary from one city or region to another, simply because resources, institutions and populations differ. Although drought contingency plans may vary in detail, they all should specify a sequence of increasingly stringent steps to either augment supplies or reduce demand as the drought becomes more severe – that is, as the water shortage increases. This should happen in such a way as to minimize the adverse impacts of water shortages on public health, consumer activities, recreation, economic activity and the environment in the most cost-effective manner possible.

Drought plans provide a consistent framework to prepare for and respond to drought events. The plans should include drought indicators, triggers, and responses. They should also include provisions for forecasting drought conditions, monitoring and enforcement (Werick and Whipple, 1994). Drought plans should consider a wide range of issues and be compatible with the political and social environments that can affect just what measures can be implemented.

Developing a drought plan and keeping it current is a continuing process that should include an informed public. Drought plans should also include measures to educate the public and keep them aware of the potential risks of droughts, and the measures that will be implemented to mitigate those risks. A comprehensive public information programme should be implemented to achieve public acceptance of and compliance with the plan. At the same time, enforcement measures are often necessary to encourage the public to abide by the water-use restrictions. Enforcement measures traditionally include penalties for noncompliance. They can also include economic incentives such as rebates on low flow showerheads and faucets, and cheaper water rate charges for lower consumption rates.

9. References

ALLEY, W.M. 1984. The Palmer drought severity index: limitations and assumptions. *Journal of Climate and Applied Meteorology*, No. 23, pp. 1100–9.

ALLEY, W.M. 1985. The Palmer drought severity index as a measure of hydrological drought. *Water Resources Bulletin*, Vol. 21, No. 1, pp. 105–14.

CHANG, T.J. and KLEOPA, X.A. 1991. A proposed method for drought monitoring. *Water Resources Bulletin*, Vol. 27, No. 2, pp. 275–81.

DAVIS, P.C. and HOLLER, A.G. 1987. Southeastern drought of 1986: lessons learned. In: A.D. Feldman (ed.), *Proceedings of the Engineering Hydrology Symposium*. Williamsburg, Va., 3–7 August 1987. New York, ASCE, pp. 616–21.

DEZMAN, L.E.; SHAFER, B.A.; SIMPSON, H.D. and DANIELSON, J.A. 1982. Development of a surface water supply index: a drought severity indicator for Colorado, In: A.I. Johnson and R.A. Clark (eds.). *Proceedings of the International Symposium on Hydrometeorology*, 13–17 June 1982, Denver, Colorado. Bethesda, Md., American Water Resources Association, pp. 337–41.

DRACUP, J.A.; LEE, K.S. and PAULSON, E.G. 1980. On the definition of droughts. *Water Resources Research*, Vol. 16, No. 2, pp. 297–302.

EDWARDS, D.C. and MCKEE, T.B. 1997. *Characteristics of twentieth century drought in the United States at multiple time scales*. Fort Collins, Colo., Colorado State University, Department of Atmospheric Sciences (Climatology Report Number 97–2).

FISHER, S.M. and PALMER, R.N. 1995. Managing water supplies during drought: the search for triggers. In: M.F. Domenica (ed.), *Proceedings of the 22nd Annual National Conference*, 7–11 May 1995, Cambridge, Mass. Cambridge, Mass., Water Resources Planning and Management Division of ASCE, pp. 1001–4.

GIBBS, W.J. and MAHER, J.V. 1967. Rainfall deciles as drought indicators. *Bureau of Meteorology Bulletin*, No. 48. Melbourne, Commonwealth of Australia.

GLANTZ, M. (ed.). 1994. *Usable science: food security, early warning, and El Niño*. Proceedings of the Workshop on ENSO/FEWS, Budapest, Hungary, October 1993. Nairobi and Boulder, Colo., UNEP and NCAR.

GLANTZ, M.; KATZ, R. and NICHOLLS, N. (eds.). 1991. *Teleconnections linking worldwide climate anomalies*. Cambridge, Cambridge University Press.

HEDDINGHAUS, T.R. and SABOL, P. 1991. A review of the Palmer drought severity index and where do we go from here? In: *Proceedings of the Seventh Conference on Applied Climatology*, 10–13 September 1991, Salt Lake City, Utah. Boston, Mass., American Meteorological Society, pp. 242–6.

HOKE, J.P. Jr. 1989. Savannah River Basin drought contingency planning. In: *Proceedings of the ASCE National Water Conference*, pp. 188–95. Newark, Del., 17–20 July 1989. New York, ASCE.

HREZO, M.S.; BRIDGEMAN, P.G. and WALKER, W.R. 1986. Managing droughts through triggering mechanisms, *Journal AWWA*, Vol. 78, No. 6, pp. 46–51.

IPCC (Intergovernmental Panel on Climate Change). 2001. Climate change 2001: the scientific basis. In: J.T. Houghton, Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, X. Dai, K. Maskell and C.A. Johnson (eds.). *Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, Cambridge University Press.

JOHNSON, W.K. and KOHNE, R.W. 1993. Susceptibility of reservoirs to drought using Palmer index. *Journal of Water Resources Planning and Management*, Vol. 119, No. 3, pp. 367–87.

KARL, T.R. and KNIGHT, R.W. 1985. *Atlas of monthly Palmer hydrological drought indices (1931–1983) for the contiguous United States*. Asheville, N.C., National Climatic Data Center (Historical Climatology Series 3–7).

KOGAN, F.N. 1995. Droughts of the late 1980s in the United States as derived from NOAA polar-orbiting satellite data. *Bulletin of the American Meteorological Society*, Vol. 76, No. 5, pp. 655–68.

MATHER, J.R. 1985. Drought indices for water managers. *Publications in Climatology*, Vol. 38, No. 1, pp. 1–77.

MAUNDER, W.J. 1992. *Dictionary of global climate change*. New York, Chapman and Hall.

MCKEE, T.B. and DOESKEN, N.J.; KLEIST, J. 1993. The relationship of drought frequency and duration to time scales. In: T.B. McKee, N.J. Doesken and J. Kleist (eds.). *Preprints, 8th Conference on Applied Climatology*, pp. 179–84. 17–22 January 1993, Anaheim, Calif. Boston, Mass., American Meterological Society.

NAULT, R.J.; GAEWSKI, P. and WALL, D.J. 1990. *Drought indication and response: optimizing the resources for water management*. In: R.M. Khanbilvardi and T.C. Gooch (eds.). *Proceedings of the 17th Annual National Conference*, 17–21 April 1990, Fort Worth, Texas. New York, ASCE, pp. 720–25.

NOAA. 1994. *El Niño and climate prediction: reports to the nation on our changing planet*. A publication of the University Corporation for Atmospheric Research pursuant to National Oceanic and Atmospheric Administration Award No. NA27GP0232–01. Boulder, Colorado, UCAR.

OGALLO, L.A. 1994. Validity of the ENSO-related impacts in Eastern and Southern Africa. In M. Glantz (ed.). *Usable science: food security, early warning, and El Niño*, Proceedings of the Workshop on ENSO/FEWS, Budapest, Hungary, October 1993. Nairobi and Boulder, Colo., UNEP and NCAR, pp. 179–84.

OTA (Office of Technology Assessment). 1993. *Preparing for an uncertain climate*, Vol. I. OTA-O-567. Washington, D.C., US Government Printing Office.

PALMER, R.N.; KUTZING, S.L. and STEINEMANN, A.C. (eds.). 2002. *Developing drought triggers and drought responses: an application in Georgia*. Proceedings of the EWRI Symposium in Water Resources Planning and Management, 19–22 May, Roanoke, Va.

PALMER, W.C. 1965. *Meteorological drought*. Washington, D.C., US Department of Commerce Weather Bureau (Research Paper No. 45).

RANEY, D.C. 1991. A water availability index for reservoir management. In: P.A. Krenkel (ed.), *Proceedings of the Environmental Engineering Conference*, 10–12 June 1991, Reno, Nev. New York, ASCE, pp. 686–91.

SHAFER, B.A. and DEZMAN, L.E. 1982. Development of a surface water supply index (SWSI) to assess the severity of drought conditions in snowpack runoff areas. In: *Proceedings of the 1982 Western Snow Conference*, 1982, Reno, Nev. Fort Collins, Colo., Colorado State University, pp. 164–75.

SMITH, D.I. HUTCHINSON, M.F. and MCARTHUR, R.J. 1993. Australian climatic and agricultural drought: payments and policy. *Drought Network News*, Vol. 5, No. 3, pp. 11–2.

TITLOW, J.K. III. 1987. A precipitation-based drought index for the Delaware River Basin, *Publications in Climatology*, Vol. 40, No. 2, p. 68.

USACE (US Army Corps of Engineers). 1991. *The national study of water management during drought: a research assessment*. Alexandria, Va., Institute for Water Resources (IWR Report 91-NDS-3).

WERICK, W.J. and WHIPPLE, W. Jr. 1994. *National study of water management during drought: managing water for drought*. Alexandria, Va., USACE, Water Resources

Support Center, Institute for Water Resources (IWR Report 94-NDS-8).

WHITE, D.H. and O'MEAGHER, B. 1995. Coping with exceptional droughts in Australia. *Drought Network News*, Vol. 7, No. 2, pp. 13–17.

WILHITE, D.A. 1995. Developing a precipitation-based index to assess climatic conditions across Nebraska. Lincoln, Nebr., final report submitted to the Natural Resources Commission.

WILLEKE, G.; HOSKING, J.R.M.; WALLIS, J.R. and GUTTMAN, N.B. 1994. *The national drought atlas*. Alexandria, Va., USACE (Institute for Water Resources Report 94-NDS-4).

WRIGHT, J.R.; HOUCK, M.H.; DIAMOND, J.T. and RANDALL, D. 1986. Drought contingency planning. *Civil Engineering Systems*. Vol. 3, No. 4, pp. 210–21.

Additional References (Further Reading)

BLAIKIE, P.; CANNON, T.; DAVIS, I. and WISNER, B. 1994. *At risk: natural hazards, people's vulnerability, and disasters*. London, Routledge.

DAVIS, C.P.; WATSON, R.M. III and HOLLER, A.G. 1989. Southeastern drought of 1988: a federal perspective. In: T.A. Austin (ed.). *Proceedings of the National Water Conference*, 17–20 July 1989, Newark, Del. New York, ASCE, pp. 172–9.

FISHER, S. and PALMER, R.N. 1997. Managing water supplies during drought: triggers for operational responses. *Water Resources Update*, Vol. 3, No. 108, pp. 14–31.

HAYES, M. 1998. *Drought indices*. Lincoln, Nebr., National Drought Mitigation Center. www.drought.unl.edu/whatis/indices.htm (accessed 15 November 2004).

KNUTSON, C.; HAYES, M. and PHILLIPS, T. 1998. *How to reduce drought risk: a guide prepared by the Preparedness and Mitigation Working Group of the Western Drought Coordination Council*. Lincoln, Nebr., National Drought Mitigation Center. www.drought.unl.edu/plan/handbook/risk.pdf (accessed 15 November 2004).

PALMER, W.C. 1968. Keeping track of crop moisture conditions, nationwide: The new crop moisture index. *Weatherwise*, No. 21, pp. 156–61.

PHILANDER, S.G. 1990. *El Niño, La Niña, and the Southern Oscillation*. San Diego, Calif., Academic Press.

WILHITE, D.A. and VANYARKHO, O. 2000. Drought: pervasive impacts of a creeping phenomenon. In D.A. Wilhite (ed.). *Drought: a global assessment*, Vol. I, Ch. 18. London, Routledge.