CHAPTER THREE

Climate and Agriculture

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INTRODUCTION

THE EARLIEST HUMAN form is dated some 25 million or more years ago. From the early hominids such as *Zinjanthropus,* it took many million years more for Homo sapiens to develop. In spite of the antiquity of the evolutionary processes resulting in the birth of modern man, the art of cultivating crops was developed only about 12,000 years ago. Until the era of settled cultivation, man met his calorific and other nutritional needs by gathering food from natural vegetation and by hunting and fishing. The transition from food gathering to food growing was marked by several important changes in human life, because the opportunities afforded by settled agriculture cradled culture.

Settled cultivation brought in its wake many new problems, such as the erosion of soil fertility, the dependence of crop yields on weather behaviour, and the incidence of pests and diseases. Through trial and error, early cultivators found answers to these problems. Shifting cultivation provided a means of restoring soil fertility. Total failure of crops due to moisture stress or moisture excess was avoided to some extent through mixed cropping and inter-cropping. Damage by pests and diseases was minimised by growing a mosaic of crop varieties, with considerable genetic variability in the material.

The birth of agriculture also gave rise to the introduction of various forms of energy, collectively referred to as cultural energy (Figure 3.1). Irrigation, an important component of the cultural energy forms introduced into agriculture, has been an important factor in elevating and stabilising crop production. In spite of the steps taken so far, it has not been possible to insulate agricultural fortunes from the vagaries of the weather.

The very process of change in the relationship between man and his environment initiated by agriculture has had several adverse effects in terms of long term production prospects. Shifting cultivation, soil erosion, indiscriminate deforestation, and other human activities, such as mining for minerals, have resulted in either the destruction or diminution of the biological potential of land in nearly one-third of the

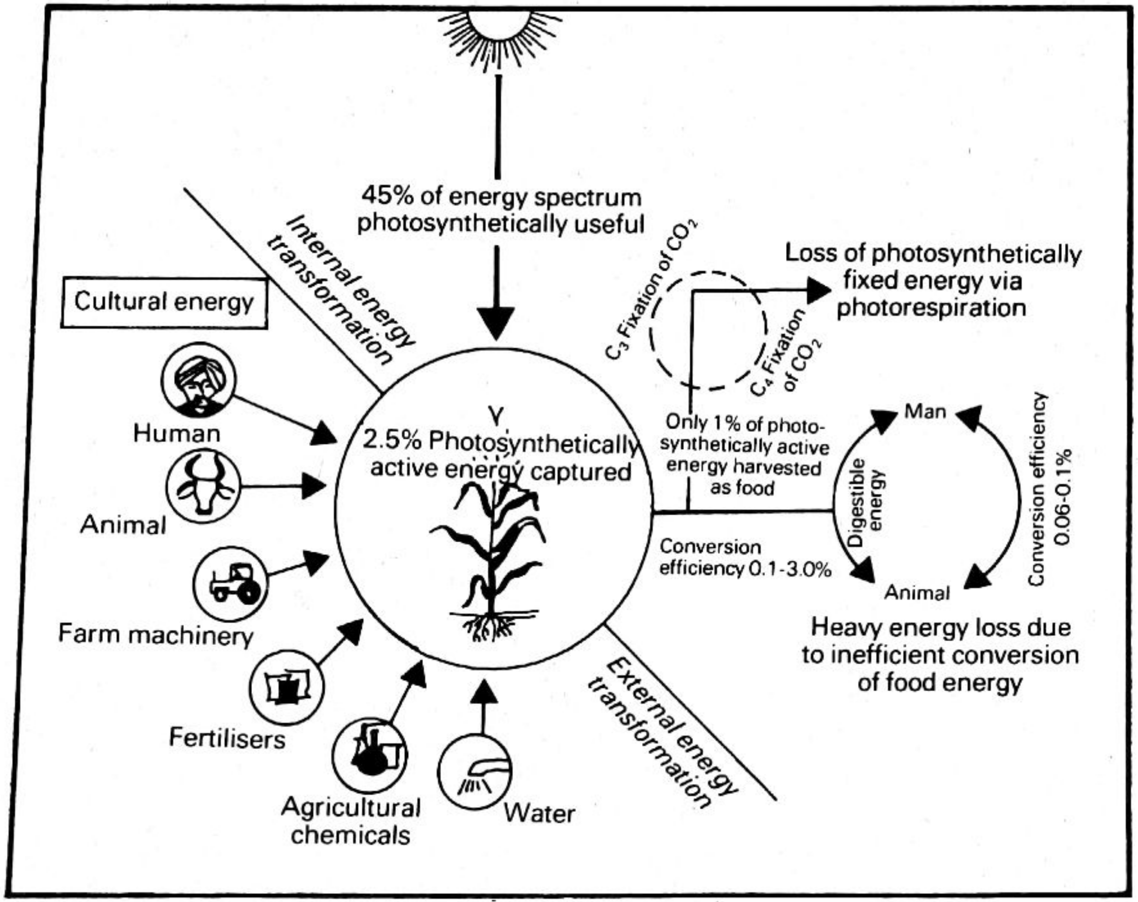


Figure 3.1. Solar and cultural energy input and output cycles in rice

world's surface. Today, several of the early centres of domestication are characterised by a high degree of desertification. Even in parts of the fertile crescent area in the Middle East, where the early domestication of crops occurred, desert conditions now exist.

The challenge lies in developing methods of sustainable agricultural growth. This is where a detailed study of the relationships between climate and agriculture assumes importance.

VULNERABILITY OF WORLD FOOD PRODUCTION SYSTEMS

Rapid increase in population, dependence on too few crops and animals for meeting global food needs, and dependence on too few countries for balancing the global food budget have led to a situation in which the conquest of hunger has become the most difficult as well as the most urgent task (Figures 3.2 to 3.5). Weather-induced

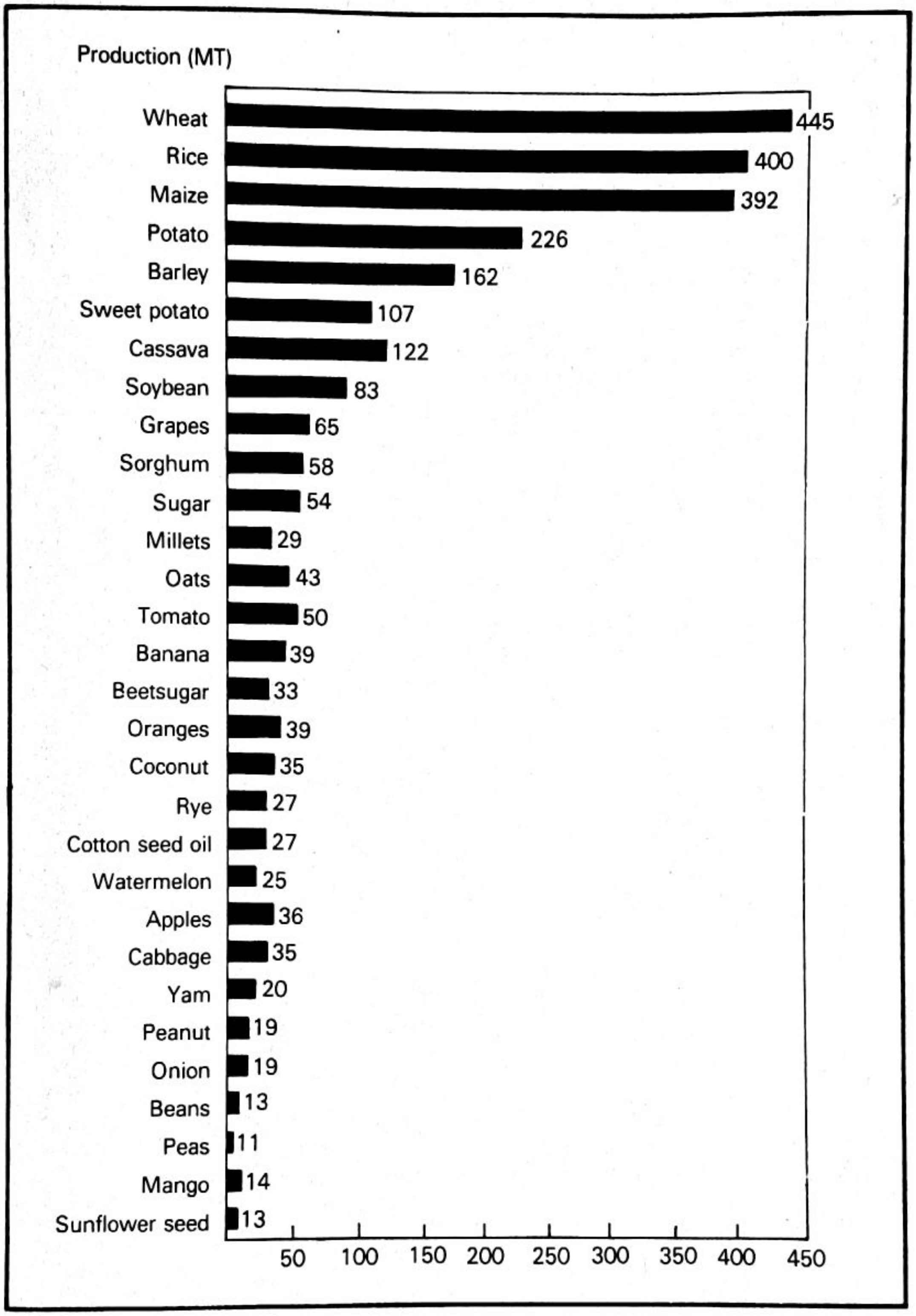


Figure 3.2. Annual production of the world's major food crops 1980 (SOURCE: FAO Production Yearbook, 1980)

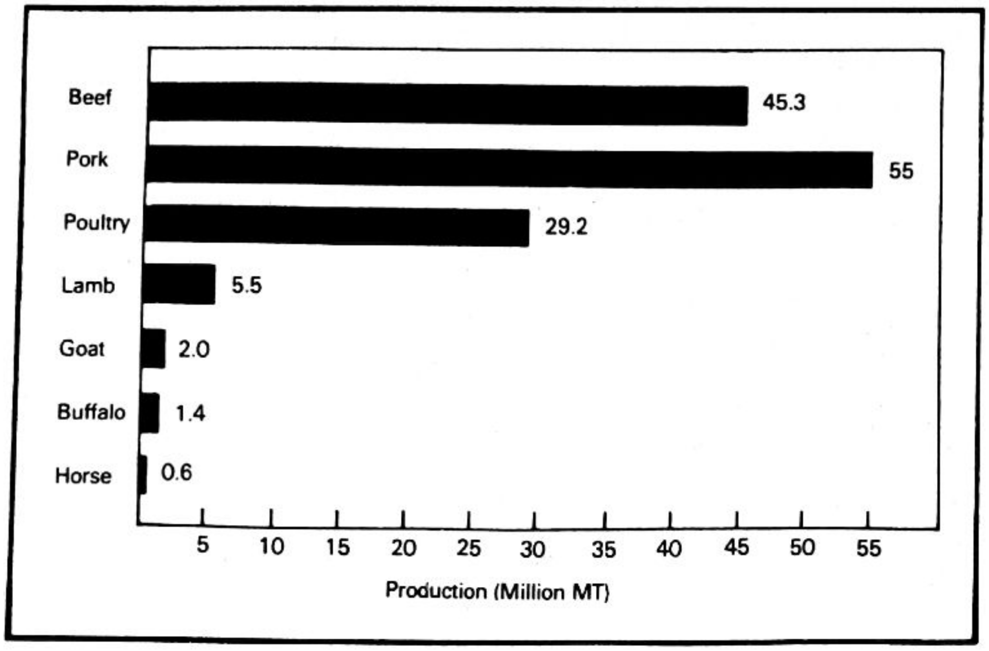
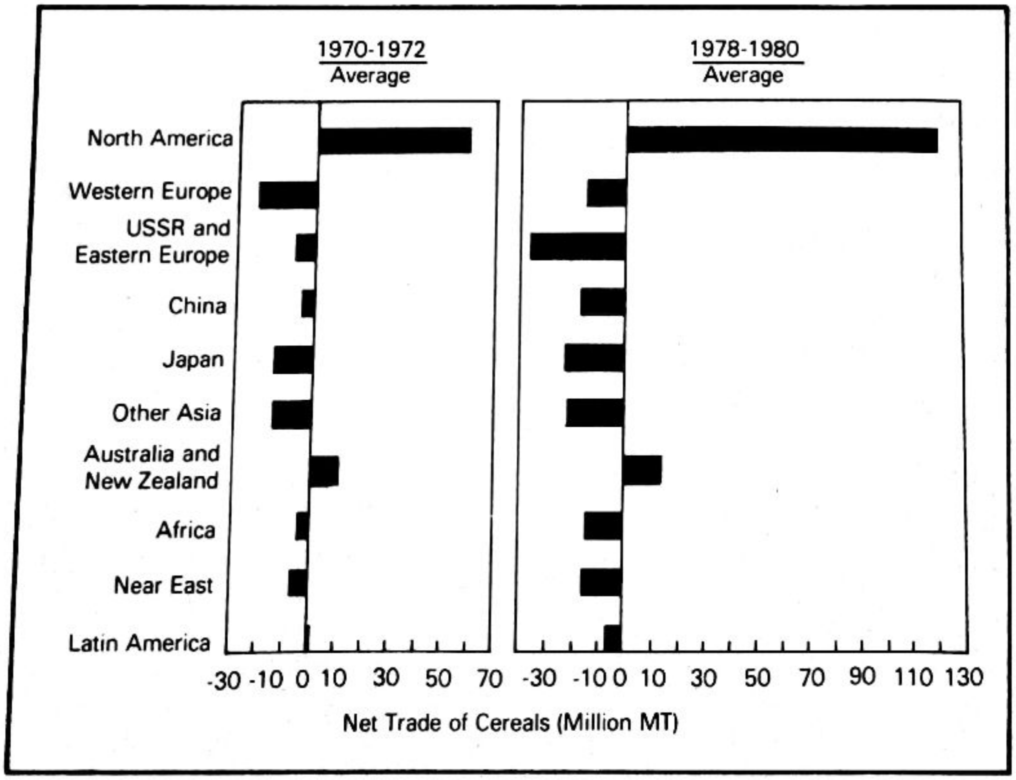


Figure 3.3. Annual production of the world's major animal products (SOURCE: FAO Production Yearbook, 1980)

Figure 3.4. World's increasing dependence on the grain exports of a few countries; USA and Canada supply most of the grain



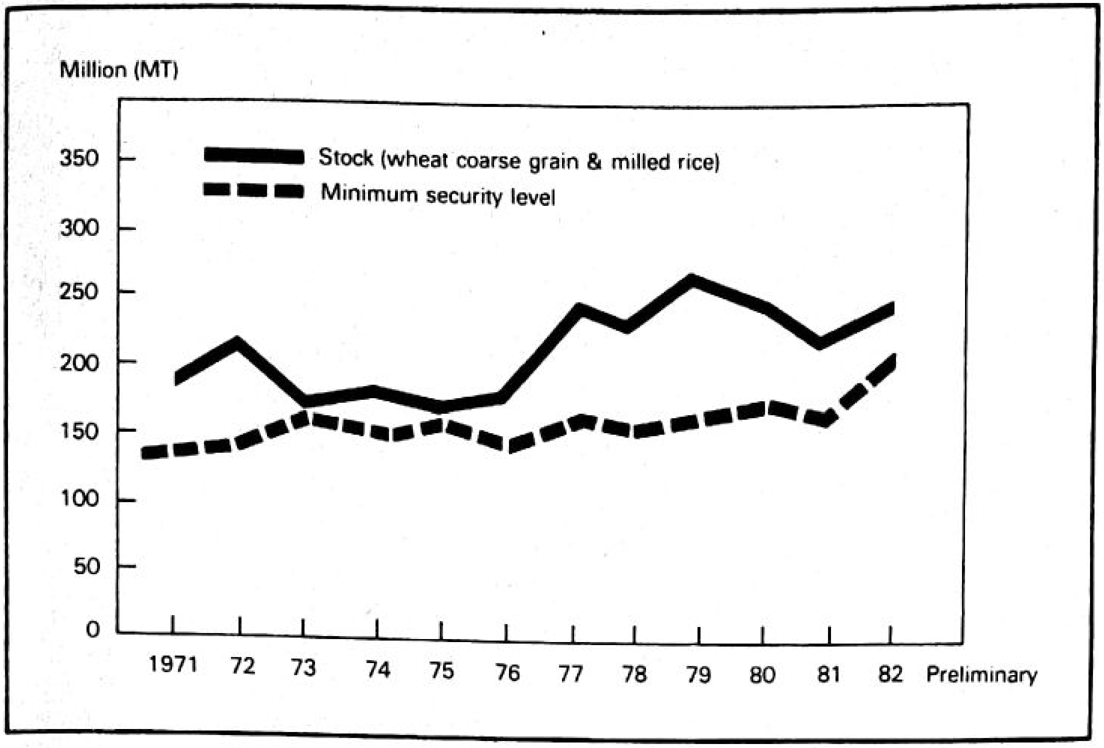


Figure 3.5. World carry-over stocks and minimum security levels of cereals (including China and USSR

fluctuations in production have led expectations for global food security to oscillate between hope and despair. A 5 to 10 per cent increase or decrease in production results in either an uncomfortable glut or an acute scarcity. Consequently, public policies in the matter of insurance, pricing, marketing and distribution of farm inputs and outputs have become important determinants in the control of production fluctuations. Weather, pest epidemics and public policies have important effects on stability of production.

According to FAO, world cereal production in 1981 exceeded expected global utilisation for the first time in three years, leading to a rise in carryover stocks at the end of the 1981-82 season and a definite improvement in the global food security situation.

The improvement in the overall supply situation was due to record crops in the main wheat and coarse grain exporting countries as well as in the major rice importing and exporting countries. This expansion reflected partly the higher prices prevailing in 1980 and partly the favourable growing conditions. Production of non-cereal foodstuffs also rose in developing countries. A rise in world cereal production of 7 per cent in 1981 exceeded the trend for the first time since 1978, despite lower harvests in Europe and the USSR. Output in the developing countries rose by 6 per cent, well above the average growth of the last decade.

As a result, global cereal stocks, which were drawn down heavily during 1979-80 and 1980-81, are provisionally forecast to rise to 270 million tonnes at the end of the

1981-82 season, representing nearly 18 per cent of world consumption. International prices of wheat and coarse grains have been substantially lower during the 1981-82 season. Prices of rice have declined by almost 40 per cent since mid-1981.

While there is an improvement in the overall global situation, the fact remains that the food import needs of many developing countries have increased dramatically in recent years. The cereal imports of developing countries as a whole have doubled in the past decade and are now close to 100 million tonnes a year.

Of considerable concern is the situation that had developed in low-income countries. According to an analysis made by FAO, as many as 37 low-income countries (with per capita incomes of US$730 or less in 1980) recorded negative growth rates in per capita production of cereals during the seventies; of these, 19 experienced a decline in total cereal output. Thus, far from achieving greater self-sufficiency, these countries are faced with a widening food gap. Food aid received by these countres has remained stagnant in recent years. The low-income countries as a whole now spend over US$7 billion a year to cover the value of commercial imports of cereals.

Food security in the world remains uncertain in the medium term. While international market prices of cereals have declined in 1982, following a rise for some years, costs of production have continued to rise. This has led to a concern in exporting countries that farmers' incentives will weaken and that this may have implications for growth in 1982 and even beyond. The US government limited the 1982 production of wheat, coarse grains, and rice through voluntary set aside programmes. According to the USDA, the initial projections of 1982-83 crops in the United States point to a decline of nearly 4 million tonnes of wheat and 16 million tonnes of coarse grains from 1981-82 production.

NATURAL RISKS IN AGRICULTURE

Agriculture is probably one of the riskiest professions in the world. Natural hazards affecting farm output include uncertainties of weather, such as deficiency of moisture or drought; excessive moisture, including flooding; excessive cold; hail; typhoons, tornados, cyclones, or windstorms; and natural fire and lightning.

These risks may be called meteorological risks. Schultz (1953), in a detailed analysis of the nature and factors of yield instability in the United States, stated with particular reference to west central regions, both north and south: "In this large area the hand of nature lifts and depresses yields despite all the efforts of farmers to counteract its influence." For example, in the drought year of 1936, wheat production in the United States fell to 526 million bushels, while production in the normal year of 1931 was 941 million bushels. Wide fluctuations in USSR food grain output are largely due to weather factors. Consequently, the USSR may import as much as 40 million tonnes of cereals in 1981-82, against 15 million tonnes three years ago.

The United Kingdom is considered to be relatively safe from exposure to severe weather hazards. But important exceptions occur now and then. For example, in 1976, alternate storms and drought dominated the agricultural scene. For many farmers, they caused havoc to buildings, equipment, crops, and production plans.

Precise estimates of the crop losses caused by weather aberrations are virtually impossible because of the difficulties in separating the impact of components such as management, technology, and climate (Biswas, 1980). Nevertheless, crop-climate models can be constructed if adequate data are available. Biswas (1980) has cited the possibilities in this area. The establishment of crop-weather watch groups on the lines recommended by Swaminathan (1982) in the different agro-ecological regions of every country would help in studying the crop-weather interrelationships. Ray (1981) has described the difficulties currently experienced in the field of agricultural insurance due to gaps in the data base essential for assessing the insurability of agricultural risks.

In spite of these difficulties, it is clear that some regions, countries, and parts of countries are more prone to climatic variables than others. In Africa, apart from the Sahelian countries which face chronic food problems, many countries have experienced wide fluctuations in production arising largely from the vagaries of the weather in recent years. In the Philippines, the yearly losses in rice production caused by pests, drought, typhoons, and floods have been worked out by Pantastico and Cardenas (1980). Their data are reproduced in Figure 3.6. Stansel (1980) has worked out the likely deviations from average rice productions caused by changes in precipitation in the United States (Table 3.1). Temperature at the grain filling stage is an important determinant of total yield.

Figure 3.6. Yearly losses in Philippine rice production, 1968-77

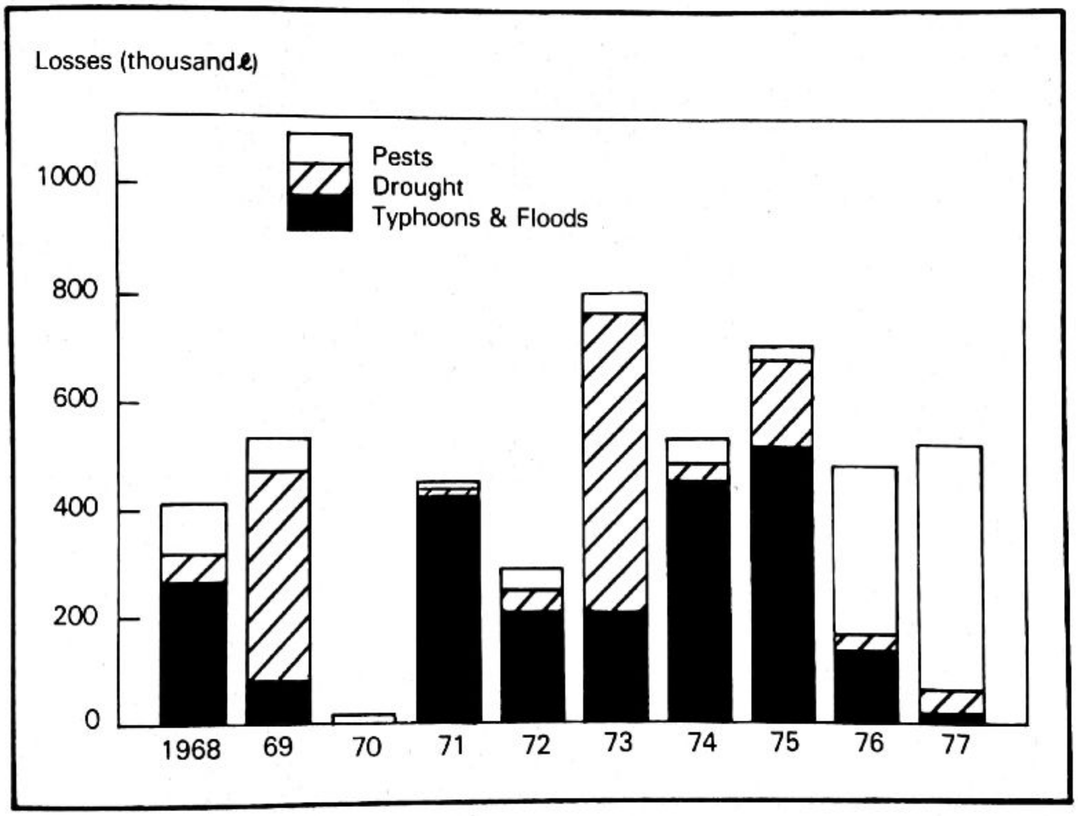


Table 3.1. Deviation from US average production of rice as influenced by changes in precipitation and temperature[1]

Precipitation change (%)	Deviation (%) at a temperature change of −2°C	−1°C	−.5°	0	+.5°C	+1°C	+2°C
−15	2	5	8	8	11	15	20
−10	−1	2	5	6	8	12	18
−5	−4	−1	2	2	5	9	14
0	−9	−4	−1	0	4	7	12
+5	−9	−6	−3	−2	0	4	9
+10	−14	−10	−7	−6	−3	0	6
+15	−18	−14	10	−9	−6	−2	3

1. Based on US production of 5 million t.

IMPACT OF DROUGHT ON AGRICULTURE

Drought, floods, cyclones, typhoons, hailstorms, frost, dew and snowfall all influence crop production to varying degrees. Of all these phenomena, widespread drought has historically had the most detrimental effect. Therefore, it would be useful to discuss the relationships between drought and agriculture in some detail.

Agricultural scientists and meteorologists tend to adopt different definitions of drought, the former in terms of crop behaviour and the latter in terms of rainfall. If, for example, the total rainfall over India (112 cm yr^{-1}) was evenly distributed in space and time, the water needs for the entire cultivated areas would be satisfied.

Agricultural droughts occur in particular areas because of erratic rainfall unrelated to crop needs. At a symposium on Meteorological Aspects of Tropical Droughts held in December 1981 at New Delhi under the sponsorship of the World Meteorological Organization, these conclusions on the relationship between drought and agriculture were drawn:

(a) The fundamental requirement for drought management in India is the collection and storage of water for utilisation in protective irrigation during dry spells (water harvesting).

(b) Food-grain storage measures taken to combat drought were extremely successful in 1979, the most severe meteorological drought this century. The result was no starvation and no need to import.

(c) Agricultural yield correlates poorly with annual rainfall, but well with a crop index based on crop need and soil water content. The latter may be included in the definition of the climatology of a particular region as a soil moisture index and used for agricultural drought evaluation.

(d) Refined predictions of rainfall are needed to match crops with expected weather, particularly now that so many hybrid varieties of crops are available.

The symposium participants recommended:

(a) Good forecasts of rainfall, both of quantity and distribution, are needed for agriculture in the short, medium, and long term, particularly during the monsoon season. Both probabilistic and dynamic forecasting methods should be further developed. Probabilistic forecasts should be issued until deterministic forecasts are demonstrably superior.

(b) The dialogue between meteorologists and agriculturalists and soil scientists must continue and FAO and UNDP should be encouraged to support this activity, e.g. by setting up special training programmes on meteorological applications for agriculturalists.

(c) Better communications and exchange of information in this area should be set up between developed (high technology) and developing countries, e.g. through exchange visits and symposia.

An integrated strategy to minimise the adverse impact of drought on crops, farm animals, and human population with short and long term action plans will have to be developed at the national level. In the long term strategy, the development of irrigation sources and scientific land and water use planning will have to receive attention. Also, the capability for making fairly accurate long term weather forecasts will have to be developed.

Fortunately, the various coordinated programmes of research sponsored by WMO, FAO, UNESCO, and national and international organisations are now providing valuable data. For example, Oldeman and Frère (1982) have provided detailed information on the agroclimatology of the humid tropics of Southeast Asia. Detailed data also are available for many other regions of the world, including the Sahel Region of Africa which underwent prolonged drought during the seventies. Several scientists such as Campbell and Bryson (1982) have been publishing year-in-advance forecasts of monsoon rainfall in India, USA, and other countries. Studies on crop yield and climate up to the year 2000 have been published by institutions in the USA as a part of their research on climate impact assessment (National Defense University and USDA, 1980).

Mooley *et al.* (1981) have compiled available information on the variability of annual rainwater availability in India. Their analysis reveals that water deficiency has had a much greater impact on agricultural production than water excess (Tables 3.2 and 3.3). Hence, developing countries have wisely stepped up their investments in irrigation (Table 3.4). This is particularly important because the only pathways open to many developing countries, particularly in Southeast Asia, for producing more food grains to meet the needs of the expanding population are higher productivity per unit area, water, and other cultural energy inputs and higher intensity of cropping through multiple and relay-cropping. This is because of the small land area available per capita population in Asia (Table 3.5). Arnon (1981) has recently discussed the resources, potentials, and problems in the modernisation of agriculture in developing countries.

An example of how crop production can be improved and stabilised through investment in irrigation is provided by the trends in crop production in India. The area under irrigation has been steadily improving (Table 3.6); hence the trough point in favourable years is also better (Table 3.7). Even during 1979, the most severe meteorological drought year of this century, food production was 30 million tonnes more than during the very favourable monsoon year of 1964-65 (Table 3.7). Swaminathan (1982) has shown how in areas such as the Punjab, where the pumping

Table 3.2. Percentage change in the yearly All India Index of food grain production in the year of marked annual rain-water deficiency over India

Year of marked deficiency	Percentage change in the index in the year
1904	–2.1
1905	–4.9
1911	–4.6
1918	–32.3
1920	–24.1
1941	4.5
1951	1.1
1965	–19.6
1966	1.7
1972	–8.2
1974	–5.4

Note: Values of the index of agricultural production are not available prior to 1900. Since 1965, 1966 are consecutive years of marked deficiency, there is little change in the Index of Agricultural Production in 1966.

Table 3.3. Years of marked rain-water deficiency over India (1871-1978)

Year	Percentage of the country's area under rain-water deficiency	Total annual rain-water deficiency over area under deficiency in km^3
1877	40.2	332.36
1899	75.1	901.21
1904	44.9	321.91
1905	47.1	401.70
1911	41.2	341.10
1918	60.0	649.18
1920	46.1	416.67
1941	55.0	432.45
1951	44.8	298.53
1965	52.0	447.65
1966	41.2	381.24
1972	63.5	571.93
1974	41.3	377.83

Table 3.4. Increase in areas under irrigation (million hectares) during the period 1961-65 (annual average to 1977 (FAO, 1978)

	1961-65	1977	Increase (%)
Africa	5.8	7.8	13.4
Asia	100.0	128.8	28.8
South America	4.9	6.5	32.6
All developing countries	110.0	144.9	31.7
All developed countries	39.0	52.9	35.6
World	149.0	198.0	32.9

Table 3.5. Arable land per head of population (calculated from data from FAO, 1978)

	Per capita agricultural population (ha)	Per capita total population (ha)
Africa	0.72	0.48
Asia	0.32	0.19
South America	1.40	0.46
All developing countries	0.42	0.26
All developed countries	4.39	0.59

of groundwater is the most important source of irrigation, energy management holds the key to reducing a drop in food output during a drought year. With effective energy management, the production of rice in the Punjab during the severe drought year of 1979-80 was maintained at about the same level as in 1978-79. Rainfall in 1978-79 was normal (Table 3.8). The Punjab has over 80 per cent of its cultivated area under irrigation, Madhya Pradesh and Orissa have less than 30 per cent.

Research on drought management in India

Drought is a recurrent phenomenon in the dry areas of India, as it is in all of the semi-arid and sub-humid areas of the world. In these regions, annual loss of water through evaporation and transpiration is greater than annual precipitation. In addition, annual rainfall in the semi-arid tropical areas usually is distributed unevenly. For instance, Hyderabad, Andhra Pradesh, receives over 80 per cent of its 780 mm rainfall between June and October. In Jodhpur, Rajasthan, almost all the annual precipitation (350 mm) falls between July and September.

With low precipitation relative to evaporation and transpiration, a short rainy season with uneven seasonal distribution of rainfall, a great interannual variability and small negative deviations in precipitation are all that is required to initiate drought. Small and large negative deviations are highly probable and even certain to

Table 3.6. Peak and trough points in foodgrain production during 1960-61 to 1978-79 (million tonnes)

Year	Foodgrains production. Adjusted actual production	Peak point	Trough point
1960-61	82.3		82.3
1961-62	82.4	82.4	
1962-63	80.3		80.3
1963-64	80.7		
1964-65	89.4	89.4	
1965-66	72.3		72.3
1966-67	74.2		
1967-68	95.1	95.1	
1968-69	94.0		94.0
1969-70	99.5		
1970-71	108.4	108.4	
1971-72	105.2		
1972-73	97.0		97.0
1973-74	104.7	104.7	
1974-75	99.8		99.8
1975-76	121.0	121.0	
1976-77	111.2		111.2
1977-78	126.4		
1978-79	131.4	131.4	
1979-80	109.0		109.0

Table 3.7. Variability in rice production in four states of India (Production in lakh tonnes)

State	1977-78	1978-79	1979-80	1980-81
Madhya Pradesh	44.4	35.6	18.3	40.0
Orissa	43.2	44.0	29.2	43.3
Punjab	24.9	30.9	30.4	32.2
Uttar Pradesh	52.0	59.6	25.5	54.4

occur in such regions. A survey reported by Ryan (1974) revealed that moderate or worse droughts are likely to occur in semi-arid India one year in every four.

There have been many definitions of drought. A simple definition of agricultural drought is given by Rosenberg (1980). Drought is a climatic excursion involving a shortage of precipitation sufficient to adversely affect crop production or grassland or horticultural productivity. The traditional farmer in the rainfed semi-arid tropics lives with the possibility of drought. He has learned by experience how to adjust to the inherent variability of climate. Each year he must decide what to plant, where and

Table 3.8. Disease and insect resistance reactions of varieties named by IRRI and named by the Philippine government

	Disease and Insect Reactions[1]							
	Blast	Bacterial blight	Grassy stunt	Tungro	Green Leaf-hopper	Brown Plant-hopper	Stem-borer	Gall midge
IR5	MR	S	S	S	R	S	MS	S
IR8	S	S	S	S	R	S	S	S
IR20	MR	R	S	MR	R	S	MR	S
IR22	S	R	S	S	S	S	S	S
IR24	S	S	S	S	R	S	S	S
IR26	MR	R	MR	MR	R	R	MR	S
IR28	R	R	R	R	R	R	MR	S
IR29	R	R	R	R	R	R	MR	S
IR30	MS	R	R	MR	R	R	MR	S
IR32	MR	R	R	MR	R	R	MR	R
IR34[2]	R	R	R	R	R	R	MR	S
IR36[2]	R	R	R	R	R	R	MR	R
IR38[2]	R	R	R	R	R	R	MR	R
IR40[2]	R	R	R	R	R	R	MR	R
IR42[2]	R	R	R	R	R	R	MR	R

1. S - Susceptible; MS - Moderately susceptible; MR - Moderately resistant; R - Resistant. Reactions based on tests conducted in the Philippines for all diseases and insects except gall midge. Screening for gall midge was done in India.
2. Named by the Philippine Government.

when. He will consider mainly what will survive until harvest to meet the needs of his family.

However, the Indian economy is largely dependent on agriculture. Experience indicates that agricultural drought can have ramifications to all sectors of the economy and society. The effects of drought on agricultural production in the Indian sub-continent are reasonably well understood — certainly in a qualitative sense. We also know the kinds and extent of the multiple effects of agricultural drought on the regional and national economies and the national and interregional food trade. The effects of drought on the social and political conditions of the affected regions and the nations are somewhat understood. Scattered information on the direct and indirect impacts of drought on urban life and urban society, and on the nutritional status of various segments of society is available.

Many specific technological drought-mitigating measures have been proposed, such as water storage and recycling, rainfall enhancement, evaporation suppression, alternative agronomic management techniques, proper selection of drought tolerant crops and their cultivars, and use of wind breaks. However, a thorough study and quantitative evaluation of the potential and practicality of these measures in regular and emergency use have not yet been attempted on any large scale. Similarly, it can be said that the efficacy of economic measures proposed to moderate drought effects, e.g. cost-sharing programmes, crop insurance, credit supports, and cooperative movements, also have not yet been fully evaluated.

There are examples of national planning for drought contingency or for response to drought once it occurs. In 1979, a serious drought developed in nearly half of the Indian sub-continent due to the failure of the south-west monsoon. The Government of India instituted a major programme of relief, major elements of which were described by Swaminathan (1979 and 1982).

Some of the components of this programme were: first, a *Food for Work* scheme, where farmers and others lacking work because of crop failure were employed by the government in the building of durable structures in rural areas for increasing agricultural productivity in normal rainfall years. Preference is given to construction of small irrigation structures, which should help provide relief in subsequent droughts; second, a *Food for Nutrition* programme to provide food to those who are unable to work, such as the aged and infirm, pregnant and lactating mothers, and children; third, a provision of *Water Security* of drinking water for man and animals; fourth, an especially innovative idea, the designation of certain districts as *Most Favourable Areas* which were more favoured in recent rainfall, and in which the greatest productivity of a post-rainy season crop can be achieved by diverting to them available resources of fertilisers, good quality seed and other requisites. By stepping up relief measures in the most seriously affected regions and by intensifying production effects in the most favourable areas, hardship to human and animal populations can be minimised. This provides one excellent example of a consistent national strategy.

Past approaches to resource development for increasing agricultural production in the rainfed semi-arid tropics have achieved very limited success because they have not recognised the basic climatological and soil characteristics of the region nor utilised natural watershed and drainage systems (Kampen and Burford, 1980). Better technologies are now being developed by the All India Coordinated Research Project for Dryland Agriculture (AICRPDA), State Agricultural Universities, and the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) to ameliorate the effects of drought, to increase food production per unit of land and capital, to assure stability, and to contribute directly to improving the quality of life. Some of the components of this technology are:

— improved soil management practices;
— use of improved and appropriate seeds;
— use of fertilisers;
— intercropping/double cropping;
— proportionate cropping;
— watershed management;
— supplementary life saving irrigation.

The researches conducted by AICRPDA and ICRISAT over the past decade or so at their research centres and in operational scale, village-level studies have shown that a technology for land and water management for a vast area of India (the black soil region) can substantially contribute to increased and stable crop production. Murthy (1981) has estimated that the area under such soils in India is 72.0 million hectares, which is about 22.2 per cent of the geographical area of the country. The area falls under two rainfall classes: dependable, in which stable dryland agriculture is feasible, and undependable, where risks to crop-based dry farming are high. Such areas are suited for range farming and silvi-pastoral systems.

The watershed-based management system for vertisols consists of bringing together several components of improved technology and recognises that the improvement of any one component may have small effect on crop yields. But the combination of all the components produces spectacular results. For any cropping system, the three components that have produced the most significant synergistic effect are:

- land management practices that reduce runoff and erosion and that give improved surface drainage with better aeration and workability of the soils;
- cropping systems and crop management practices that establish a crop at the very beginning of the rainy season, that make efficient use of moisture throughout both the rainy and post-rainy seasons, and that give high sustained levels of yields;
- implements for cultivation, seeding, and fertilising that enable the required land and crop management practices to be efficiently carried out.

The data from operational-scale field experiments on vertisols at ICRISAT Centre for a maize/pigeon-pea intercropping system under rainfed conditions show that the highest yields (2610 kg ha^{-1}) were obtained by a combination of all these factors. The effect became more marked when fertiliser, soil and crop management system, and high-yielding variety were combined (3.5 t ha^{-1}). Thus, for improving crop production from vertisols under rainfed conditions, improvement of soil fertility and soil management are crucial. There is considerable evidence that the situation under irrigated farming is similar (Kanwar *et al.*, 1981).

Action plan for drought management

Enough expertise should be developed to classify the regions affected by adverse weather into broad categories:

Most seriously affected areas (MSA): in these areas, the priority concern should be to provide adequate relief and rehabilitation measures to avoid distress to human and animal populations. The provision of safe drinking water in addition to emergency food and nutrition programmes will need attention.

Most favourable areas (MFA): in these areas, either assured irrigation facilities exist or adequate soil moisture is available because of normal rainfall. MFAs could receive added attention by initiating compensatory production programmes.

Briefly stated, a national agricultural strategy in a year characterised by widespread drought will have three major components:

- popularisation of crop-saving measures and risk distribution agronomy;
- alternative cropping strategies to suit different weather probabilities and mid-season corrections in crop planning;
- compensatory production programmes in areas with adequate soil moisture (MFA).

To implement that strategy, it will be necessary to build reserves of seeds of alternate crops and of fertiliser. Just as grain reserves are important for food security, seed and fertiliser reserves are necessary for the security of crop production.

Fortunately, considerable research has been done in recent years at the International Crops Research Institute for the Semi-Arid Tropics and All India Coordinated Research Project on Dryland Agriculture. Some examples of results of the All India Coordinated Project are:

Crop substitution: After identifying the environment in terms of both land and water (rainfall), these crops were found to be more efficient than the traditional crops:

Region	*Traditional crop*	*Substitute crop*
Deccan region	Cotton	Safflower
	Wheat	Safflower
Malwa plateau	Wheat	Chickpea Safflower
Eastern Uttar Pradesh	Wheat	Mustard
Uplands of Chotanagpur and Orissa region	Rice	Groundnut Greengram Ragi *(Eleucine corocana)*
Black soils of South-East Rajasthan	Maize	Sorghum

Such data help in introducing mid-season correction in crop scheduling.

Intercropping: Promising intercropping systems for various regions are:

Centre	*System*	*Ratio*
	Sorghum-based	
Hyderabad	Sorghum + pigeon pea	2:1
Akola	Sorghum + mung bean	1:1
	Sorghum + blackgram	1:1
	Sorghum + pigeon pea	2:1
Indore	Sorghum + pigeon pea	2:1
Udaipur	Sorghum + soyabean	2:2
	Sorghum + pigeon pea	1:1
	Pearl millet-based	
Solapur	Pearl millet + pigeon pea	2:1
Bijapur	Pearl millet + pigeon pea	2:1
Rajkot	Pearl millet + pigeon pea	2:1
	Maize-based	
Udaipur	Maize + pigeon pea	1:1
Indore	Maize + soyabean	1:1
Dehra Dun	Maize + soyabean	8:2
Bhubaneswar	Maize + horsegram	1:1
Ranchi	Maize + pigeon pea	2:1
Rakh Dhiansar	Maize + greengram	1:1

Centre	*System*	*Ratio*
	Rice-based	
Bhubaneswar	Rice + pigeon pea	4:2
Ranchi	Rice + pigeon pea	4:2
	Finger millet-based	
Bangalore	Finger millet + leucerne (as fodder)	3:1
Bhubaneswar	Finger millet + horsegram	2:1
	Peanut-based	
Anantapur	Peanut + pigeon pea	5:1
	Peanut + castor	5:1
Bangalore	Peanut + pigeon pea	4:1
Rajkot	Peanut + pigeon pea	6:1
	Peanut + castor	6:1
	Pigeon pea-based	
Varanasi	Pigeon pea + blackgram	1:1
Bijapur	Pigeon pea + setaria	2:1
Solapur	Pigeon pea + setaria	2:1
	Castor-based	
Jodhpur	Castor + cowpea (fodder)	1:1
Dantiwada	Castor + cowpea	1:1
	Castor + sorghum	1:2
Hyderabad	Castor + sorghum	1:1
	Fodder-based	
Jodhpur	Cenchrus + cluster bean (fodder)	2:2
	Cenchrus + cluster bean (grain)	2:2
Anand	Dicanthium + cluster bean/siratro	As a
	Cowpea(fodder)	mixture

Promising cropping sequences are:

1st crop	*2nd crop*	*Centre(s)*
	Cereal-based sequence	
Rice	Wheat	Dehra Dun, Rewa
	Gram	Dehra Dun, Rewa, Varanasi
	Rice	Bhubaneswar
	Linseed	Ranchi
Maize	Wheat + gram	Hoshiarpur, Rakh Dhiansar
	Barley	Dehra Dun

1st crop	*2nd crop*	*Centre(s)*
	Cereal-based sequence	
	Gram	Dehra Dun, Hoshiarpur, Varanasi
	Mustard/rape seed	Hoshiarpur, Rakh Dhiansar
	Safflower	Ranchi, Udaipur, Indore
	Linseed	Ranchi
Sorghum	Safflower	Indore, Akela, Udaipur
	Gram	Indore, Rewa
Pearl millet	Mustard/rape seed	Agra, Rakh Dhiansar
	Gram	Varanasi
	Safflower	Varanasi
	Wheat	Rakh Dhiansar
	Pulse-based sequence	
Mung bean	Mustard	Agra
	Safflower	Akola, Bijapur
	Pigeon pea	Akola
Cowpea	Ragi	Bangalore
	Safflower	Jhansi
	Mustard	Jhansi
Cluster bean	Safflower	Jhansi
	Mustard	Jhansi
Horsegram	Ragi	Bangalore
Blackgram	Mustard	Agra, Varanasi
Soyabean	Gram	Indore, Dehra Dun
	Barley	Dehra Dun
	Safflower	Indore
	Oilseed-based sequence	
Peanut	Safflower	Indore
Sesame	Gram	Varanasi
	Fodder-based sequence	
Maize (fodder)	Gram	Varanasi, Udaipur
	Mustard	Udaipur
Maize + cowpea (fodder)	Tobacco	Anand
	Cluster beans	Anand
Cowpea (fodder)	Safflower	Jhansi
	Barley	Jhansi
	Gram	Jhansi, Varanasi

1st crop	*2nd crop*	*Centre(s)*
	Fodder-based sequence	
Sorghum (fodder)	Mustard	Varanasi
	Gram	Jhansi
	Barley	Jhansi

Tillage: Off-season tillage helps to keep the soil open for better intake of rainwater and better weed control, particularly in the light-textured soils. In the USA, chemical tillage is often undertaken under conditions of moisture stress, to minimise evapotranspiration losses.

Fertilisers: Nitrogen should be placed in split doses for *kharif* (June-October) crops while phosphorus should be placed basally. For *rabi* (October-March) crops, deep placement of nitrogen is required. Introduction of a legume in the pre-season, either in a rotation sequence or in inter-cropping, would have a net gain of 10 kg N ha^{-1}. Since fertiliser is a costly input, farmers need training in more efficient use. Fertiliser and other external inputs must be made available at cartable distances for adopting dryland farmers to use.

Soil and water management: Soil conservation should be dovetailed with runoff management by providing dug-out ponds as well as waterways. Gully plugging and nalla (drain) building combined with checkdams have been shown to improve the water regime in a given area. This should be considered.

Agro-forestry: Marginal lands should be placed under forestry and sylvi-pastoral systems. *Luacaena leucocephalla* and *Stylosanthus* species have been found encouraging for that purpose.

Improved implements: Proven, bullock-drawn tools needs to be commercially manufactured. The over-riding requirement is quality control. Some examples are:

Implement	*Place of origin*
Bullock drawn ridger seed	Hissar
Seed drill	Anantapur
Serrated blade harrow	Akola
Bullock drawn bakhar-cum-fertiliser seed drill	Jodhpur
Bullock drawn seed-cum-fertiliser drill	Varanasi
Bullock drawn deep furrow seeder	Ranchi
Bullock drawn seed-cum-fertiliser drill	Bangalore

Use of such implements makes a large difference in plant population and fertiliser use efficiency.

FLOODS

Flood prone areas again can be classified, depending on the periodicity and fury of floods. In chronically flood-prone areas, steps should be taken not only for minimising flood incidence through appropriate civil engineering works but also for making the

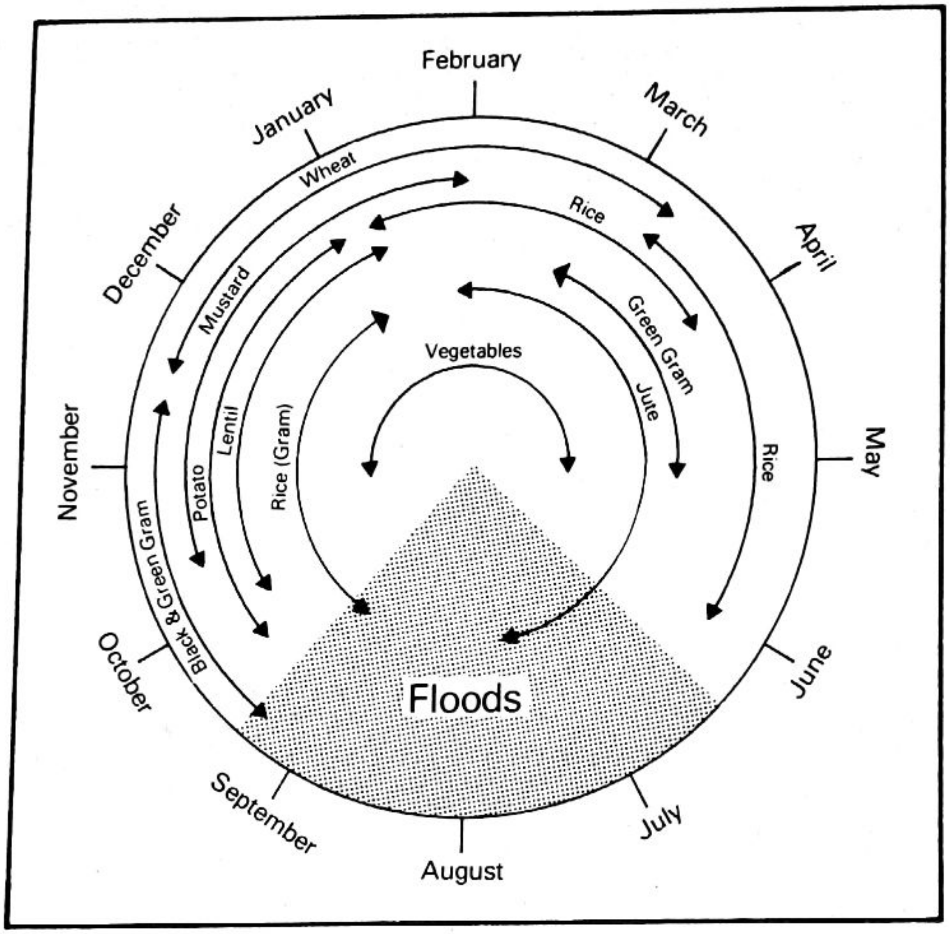


Figure 3.7. Restructuring the cropping patterns in flood-prone areas of Assam, India

flood-free season a major crop production season. The possibilities of undertaking a restructuring of crop patterns in the Brahmaputra Valley of Assam in India are shown in Figure 3.7.

BUILDING A NATIONAL FOOD SECURITY SYSTEM

A strong national food security system, integrating action to reduce the extent of crop production loss caused by unfavourable weather, can alone ultimately help to reduce the prospect of famine.

The steps involved in building an enduring national food security system have been described recently (Swaminathan, 1981). National food security means not only building grain reserves, but also paying concurrent and coordinated attention to:

Ecological security: Steps for achieving ecological security would include measures to protect the basic assets of agriculture and to minimise the liabilities. This can be achieved through the establishment of a National Land Use Board, which could foster, through appropriate scientific analysis and public policies, land and water use practices compatible with the concept of sustainable development. However, ecological security cannot be promoted by government alone. It has to be a joint sector activity involving the people and government agencies. Local level eco-development associations involving schools and colleges should be organised. Such associations could operate waste exchanges, to collect and recycle all organic waste. The economic benefits from eco-development and waste recycling could provide the motivation necessary for attracting public attention and participation. For example, in the United States it has been calculated that an estimated 300 million trees could be saved annually if the amount of paper recycled were trebled. Besides steps at the national level, regional and global level action plans to conserve our genetic and environmental heritage need to be developed. Some steps, such as the organisation of an International Bureau of Plant Genetic Resources, have already been initiated but many more are needed.

Technological security: Growth with stability should be the aim of agricultural development programmes. These would call for the breeding of high yield-cum-high stability crop varieties, with similar measures in animal husbandry and fisheries. The research system should be capable of promoting appropriate early warning-cum-timely action programmes. Pest survey and surveillance systems as well as soil, water, plant, and animal health care programmes will have to be developed. Here again, the total involvement of the local farming community will be necessary. Since, in the case of pest epidemics, political boundaries may not always provide the basis for appropriate early warning and control systems, it will be necessary for all the countries concerned with a problem to form regional control grids. The FAO-sponsored programme on locust control is a good example of the value of such cooperation.

Post-harvest technology and building grain reserves: A mismatch between production and post-harvest technologies frequently results in losses to both the producer and the consumer. Therefore, all operations after harvest, such as drying, storage, processing, transporting, and marketing will need to receive integrated attention. Depending upon possibilities, every country should maintain a reasonable grain reserve. For example, India derived immense benefit during the unprecedented drought year of 1979 from the grain reserve of about 20 million tonnes built by the government. A decentralised strategy of grain storage, under conditions of a free market economy, would also help to prevent panic purchases when conditions for crop growth are unfavourable and distress sales by poor farmers with no holding capacity when harvests are good. In fact, a decentralised plan for storing grain as well as water at appropriate locations all over the country, should be an essential element of the food security system of nations whose agricultural fortunes are closely linked to rainfall distribution.

Social security: In many developing countries, grain surplus and widespread hunger tend to co-exist. Even when there is food in the market, the lack of purchasing power leads to undernutrition and malnutrition. Therefore, in countries where agricultural production keeps ahead of population growth, the food and nutrition problem could be better stated in terms of mandays of employment rather than in metric tonnes of foodgrains. Right-to-work should become an integral part of a plan for food security. The integration of employment generation as an explicit aim in land and water use plans assumes relevance. Social security measures should include programmes such as "food for work" for able-bodied persons and "food for nutrition" for young children, pregnant and nursing mothers, and old and infirm persons. Rural development programmes should be designed to provide minimum needs in the fields of drinking water, education, health and environmental sanitation. In addition, there has to be a detailed manpower planning and employment generation strategy for rural areas based on a careful analysis of the possibilities for:

- land and water-based occupations, such as agriculture, horticulture, animal husbandry, fisheries and forestry;
- non-land occupations, such as small and village industries as well as agro-processing enterprises; and
- provision of relevant services.

In developed countries, the services sector tends to provide great opportunities for employment. In fact, as agriculture advances, more and more persons working on a daily wage status tend to be employed in the secondary and tertiary sectors of the economy. Historically, a rising standard of living has depended on the ability of agriculture to release manpower to other, more industrial pursuits.

Social security measures are needed as much for farmers and fishermen as for consumers. Suitable devices to insulate farmers against losses due to factors beyond their control will have to be developed. Old age pension and insurance measures to prevent the suffering of small farmers and agricultural labour when they become old and infirm are necessary.

Drinking water supply and nutrition education: Even when people have the requisite purchasing power, several forms of nutritional diseases arising from specific causes such as Vitamin A induced blindness, iron deficiency anaemia, goitre, etc., may still occur. Such nutritional disorders, attributable to well-identified causes, can be easily eliminated within a specific time frame through concerted efforts in nutrition education and intervention. Drinking water supply and mycotoxins in food need particular attention.

Population stabilisation: Depending upon the situation prevailing in each country with regard to the population-natural resources equation, an appropriate population policy will have to be developed and implemented. In countries like India, planning for economic development will be a futile exercise without the widespread adoption of the small family norm. Ecological security cannot be achieved, without arresting the rapid growth of both human and animal populations. Developments in preventive and curative medicine and improvements in environmental sanitation and safe drinking water supplies will lead to a continuous improvement in the average life span of humans. Family planning programmes will have to become an integral part of national food security systems. Livestock reform to regulate the pressure of cattle, sheep, goats, and other animals on the native vegetation is equally essential. In many developing countries, non-edible plants are becoming the dominant constituents of the local vegetation, since animals do not allow edible plants to survive. In some areas, non-edible shrubs are also cut for fuel. When this happens on a large scale, desertification results.

EMERGING SCENARIO

Specifications to the plant breeder

Detailed research on the interaction between climate and crop production is now gaining momentum. Considerable data are available on such crops as rice (IRRI, 1976 and 1980). We need similar studies on all major crops. More detailed characterisation of the environment in relation to the growing conditions for different crops is necessary. This will help in the formulation of more effective and appropriate research and development priorities and strategies. A rice weather project has recently been jointly sponsored by WMO and IRRI. Under this project, meteorological equipment will be installed at a number of selected sites of the IRTP irrigated nurseries. The locations selected will cover a wide range of climatic parameters, particularly with regard to solar radiation and minimum temperatures. The parameters to be measured on a daily basis are:

- solar radiation;
- maximum and minimum temperature;
- dry and wet bulb temperature;
- wind speed;
- rainfall.

Data from such studies will help provide detailed specifications to the plant breeder on the characteristics essential for better performance under conditions of moisture stress and moisture excess. An example of the power of modern plant breeding to develop varieties with wide adaptation and multiple resistance to pests is the history and characteristics of rice variety IR36, which now occupies over 10 million hectares in Asia and which has contributed to stabilising rice production to some extent.

Planning plant breeding programmes for stability of performance

(The history of IR36 was prepared by Dr. G. S. Khush of IRRI, under whose leadership the variety was developed).

History of Development of IR36 at IRRI

The initial crosses which led to the development of IR36 were made in June and July 1969. An early maturing line, IR579-48-1-2, from the cross of IR8/Tadukan, was crossed with another early maturing line, IR74B2-6-3, from the cross of TKM^2/TN1. These parents were selected because of their resistance to bacterial blight and stemborers and their excellent grain quality. In addition, IR747B2-6-3 is resistant to brown planthopper. The F_1 of this cross No. IR1561 was planted in July 1969 and the F_2 in December of the same year. F_3, F_4 and F_5 pedigree rows were grown in March, July, and November 1970, respectively. Many of the F_5 progenies were resistant to bacterial blight, stemborers, and brown planthopper but were susceptible to green leafhopper, tungro, and grassy stunt.

In May 1969, *Oryza nivara*, a wild species from India, was found to be resistant to grassy stunt. It was crossed to IR24 in July 1969. Since *O. nivara* is very poor agronomically, 3 backcrosses using IR24 as the recurrent parent were made, in October 1969, in June 1970, and in October 1970. Each generation of backcross progenies was screened for resistance to grassy stunt. Grassy stunt-resistant progenies from the third backcross (IR1737) looked essentially like IR24 and were flowering in the field in February 1971. F_5 progenies from IR1561 also were flowering in the field at the same time. A cross between IR1561-228-1-2 and a plant of IR1737 was made in February 1971. This cross was assigned IR2042. The F_1 seedlings of this cross were inoculated with grassy stunt and resistant seedlings were transplanted in the greenhouse in August 1971. An F_1 plant of this cross was topcrossed with gall midge resistant line, CR94-13, from CRRI, Cuttack, India. This line obtained in June 1971 was also found to be resistant to green leafhopper and tungro.

The F_1 seeds of this topcross were sown in January 1972 and seedlings were again inoculated with grassy stunt. Resistant seedlings were transplanted in the greenhouse and seeds from these plants were harvested in April 1972.

The F_2 population of this cross was grown without insecticide protection in July 1972 at Maligaya Rice Research and Training Center (MRRTC), Muñoz, Nueva Ecija, in Central Luzon, Philippines, because tungro disease pressure was very high in Central Luzon during 1971 and 1972. Moreover, stemborer populations at Maligaya in general are higher than at IRRI. The F_2 population was rogued at maximum tillering stage to remove tungro susceptible plants. Plants showing severe stemborer damage also were rogued. At maturity, 937 plant selections were made. These plant selections were grown at IRRI as F_3 progeny rows in the pedigree nursery planted in December 1972 without insecticide protection. There was severe build up of brown planthopper in the nursery and susceptible rows were killed.

All the F_3 rows were also inoculated with bacterial blight in the field at the maximum tillering stage. Susceptible rows were discarded and susceptible plants from the segregating rows were rogued. F_3 rows were also evaluated for blast resistance in the blast nursery and for resistance to green leafhopper and brown planthopper in the greenhouse. At maturity (March 1973), plant selections were made from the pedigree rows having multiple resistance to blast, bacterial blight, green leafhopper, and brown planthopper.

A special field screening technique was devised to screen F_4 progenies for resistance to grassy stunt. A field was planted to IR24, which is highly susceptible to brown planthopper and grassy stunt. No insecticides were used and the population of brown planthopper built up rapidly. Since there was a lot of inoculum of grassy stunt on IRRI farm, all the plants of IR24 were infected with grassy stunt. One-meter-wide strips of plants in this field were cut and a seedbed was made in the strips. F_4 progenies of IR2071 were sown in these seedbeds in May 1973. The young seedlings were inoculated with grassy stunt by the viruliferous insects abundant on the older seedlings of IR24 which moved to young seedlings in the seedbed. The seedlings were transplanted in the field in June 1973. Progeny rows which were susceptible to grassy stunt showed 100% susceptible plants. These F_4 rows also were inoculated with bacterial blight in the field and evaluated for resistance to blast in the blast nursery and for resistance to green leafhopper and brown planthopper in the greenhouse. An early maturing line numbered IR2071-625-1 appeared to be very vigorous and it was resistant to grassy stunt. Data in the field book showed that it was also resistant to blast, bacterial blight, green leafhopper, and brown planthopper. Seeds of this line were bulk harvested at maturity in early September along with many other lines of this cross.

A small seed increase plot of IR2071-625-1 was planted in September 1973. This also was entered in the replicated yield trials in January 1974. The seed increase plot planted in September 1973 matured in February 1974 and 400 individual plant selections were harvested. These plant selections were planted to headrow blocks at the end of February 1974. Plot No. 252 looked uniform at maturity and was bulk harvested in May 1974. It was labeled IR2071-625-1-252. This reselection from the original line was entered in the replicated yield trial in June 1974 and was tested in other coordinated trials.

By the end of 1973, tungro incidence in the Philippines declined and the breeding materials could not be screened for tungro resistance under field conditions. Therefore, seeds of F_5 lines of IR2071 cross, including IR297-625-1 and several thousand other breeding lines, were sent to

Indonesia in January 1974 for planting at Lanrang in South Sulawesi where tungro incidence was very high. IR2071-625-1 was found to be resistant to tungro in this trial.

Seeds of promising F_6 lines were planted without insecticide protection at CRRI, Cuttack, in July 1974 for screening for resistance to gall midge. Gall midge pressure at Cuttack during months of September and October is generally very high and these materials were exposed to heavy gall midge pressure. IR2071-625-1-252 was found to be resistant to gall midge. Meanwhile, F_6 lines were screened for resistance to stemborer in the screenhouse at IRRI during the July-October 1974 growing season. IR2071-625-1-252 was found to have best resistance to stemborer of all the lines of this cross.

By the end of 1974, multiple resistance of IR2071-625-1-252 to blast, bacterial blight, grassy stunt, tungro, green leafhopper, brown planthopper, stemborer, and gall midge was established. Two seasons' yield data in replicated yield trials during 1974 indicated that this line had very high yield potential. The analysis of grain quality showed that it had excellent, long, slender and translucent grains with high milling recovery. Therefore, IR2071-625-1-252 was entered in the Philippine Seedboard Lowland Cooperative Performance Trials in the 1st season of 1975. This line outyielded all the other entries in the early maturing group of these trials during two seasons of 1975. At its March 1976 meeting, the Rice Varietal Improvement Group of Philippine Seedboard recommended the naming of IR2071-625-1-252 as IR36. This recommendation was approved by the Philippine Seedboard at its 21st annual meeting in May 1976 and IR36 became a seedboard variety. It replaced IR26, the dominant variety at that time, within a year. More than 50 per cent of the total rice area of the Philippines has been planted to IR36 since 1978.

IR36 was first entered in the International Rice Yield Nurseries (IRYN-E) in 1975. It topped the list of 16 entries tested at 24 locations in nine countries. Similarly it was the highest yielding entry in the 1976 IRYN-E consisting of 20 entries tested at 37 locations in 16 countries. The test entries came from several national rice improvement programmes. IR36 has been used as an international check in the IRYN-E since 1977 and has consistently been among the three top yielding entries.

IR36 was entered in the All-India Coordinated Rice Improvement Project (AICRIP) trials in 1976 and was the top yielding entry among 16 entries tested at 56 locations throughout India in 1978. It was released for cultivation by the Central Variety Release committee of India in 1981.

To summarise, 13 varieties from 6 countries are involved in the ancestry of IR36. These parents contributed various traits for its genesis. Wide adaptation and high yield potential were contributed by Peta and IR8, respectively. Early maturity and superior grain quality came from TKM6 and Tadukan. Resistance to bacterial blight and stemborers also was inherited from TKM 6 and Tadukan. *Oryza nivara* contributed genes for resistance to grassy stunt and blast. Resistance to tungro, green leafhopper, and gall midge was inherited from Ptb 18 and Ptb 21. IR36 was the first improved variety of rice to have multiple resistance to all the major diseases and insects (Table 3.8).

Because of its wide genetic background, genes for tolerance to various problem soils, such as salinity, alkalinity, iron toxicity, zinc deficiency, iron deficiency, and aluminium toxicity (Table 3.9) were combined from different parents. It may have inherited drought tolerance from *Oryza nivara.*

The estimated area planted to IR36 in countries of Asia is given in Table 3.10.

That history of one recent variety of rice shows how a scientific programme for minimising fluctuations in yield caused by soil factors and pest incidence can be developed. Progress in biotechnology research should further enhance the power of scientific plant breeding because of the opportunities provided by tissue culture for screening and for alien gene transfer.

Table 3.9. Reaction of some IR varieties to adverse soil conditions (scale 0-9)[1]

	Wetland soils							Dryland soils	
	Toxicities					*Deficiencies*		*Toxicities*	*Deficiency*
	Salt	Alkali	Peat	Iron	Boron	Phosphorus	Zinc	Aluminium and manganese	Iron
IR5	4	7	0	6	4	5	5	5	4
IR8	3	6	5	7	4	4	4	4	4
IR20	5	7	4	2	4	1	3	4	4
IR28	7	5	6	4	4	3	5	5	6
IR36	3	3	3	3	3	7	2	4	2
IR42	3	4	5	3	2	3	4	5	6
IR48	4	7	5	6	0	5	5	3	4

1. 0: no information; 1: almost normal plant; 9: almost dead or dead plant.

Table 3.10. Estimated area planted to IR36 during 1981

Country(s)	Area (million hectares)
Indonesia	5.3
Philippines	2.3
Vietnam	2.1
India, Malaysia, Laos, Kampuchea, Sri Lanka, Bangladesh	>1.0
Total	>10.7

ISSUES RELATING TO ATMOSPHERIC CARBON DIOXIDE PROBLEM

There is also a need to look carefully at certain long term trends, for example the increase in carbon dioxide (CO_2) concentration in the atmosphere (Kellogg and Schware, 1981). By the middle of the next century, the continued burning of fossil fuels as a source of energy is likely to result in a doubling of the CO_2 content in the atmosphere relative to the amount present in 1860. The present CO_2 level of about 335 parts per million per volume (ppm) is expected to increase to about 380 ppm by the end of the century (Bach, 1981). Such an increase will have two types of consequences — on photosynthesis, because of the greater quantity of carbon available to plants from the atmosphere, and on climate. Computer models indicate that, on a global basis, average temperatures on the earth's surface will rise 2 to 3°C with a doubling of atmospheric CO_2. Both evaporation and precipitation may increase by about 9 per cent.

Given adequate solar radiation, soil nutrient availability, and irrigation, increased atmospheric CO_2 should act as a fertiliser for crop plants, raising both photosynthetic production and water-use efficiency. Greenhouse experiments have indicated that a doubling of CO_2 under good crop management can increase biomass yields by about 40 per cent. Structural adaptations in farming systems will be necessary, both to take advantage of the favourable consequences of CO_2 increase and to face its negative repercussions. The CO_2 effects should be especially important for such crop plants as rice, wheat, millet, and potato which have a C_3 photosynthetic pathway. Corn, sugarcane, and sorghum, with a C_4 pathway, are likely to be limited by solar radiation and nutrient and moisture availability rather than by CO_2.

Plant breeders in the tropics should aim at developing varieties that will have higher net photosynthetic production and use less water as atmospheric CO_2 content increases. The strains should not respond to a warmer atmospheric temperature by an increase in respiration that would cancel out the effect of CO_2 fertilisation. There is an opportunity for accelerating attempts to increase total photomass production in the major crop plants.

Herman Flohn (1981) recently estimated the changes in average surface temperature and precipitation that may occur in different latitude belts if atmospheric CO_2 goes up to 560-580 ppm (i.e., about twice the nineteenth century value) (Table 3.11).

If these estimates prove correct, major changes in surface and underground water supply due to altered precipitation and evapotranspiration patterns in several parts of the world could occur. Some of the agriculturally productive areas of the USA, Canada and USSR may be adversely affected. The USA, USSR and China have about 90 per cent of

Table 3.11. Probable effects of increased CO_2 content (Flohn, 1981)

Latitude	Average annual change in surface temperature (°C)	Change in precipitation (percentage)
60°N	+7.5	+18
50°N	6	+4
40°N	+6	−14
30°N	+4.5	0
20°N	+2.5	+20
10°N	+1.5	+20
Equator	+3	0
10°S	+4	−20
20°S	+4.5	−5
30°S	+4	+5
40°S	+4	+12
50°S	+3	+12
60°S	+2.5	+12

the world's coal reserves. Since higher CO_2 concentrations may affect these countries adversely, they may be unwilling to develop an export trade in coal. This in turn will have implications for the energy-short countries (Revelle, 1981).

The projections made by Herman Flohn would imply more rain in some of the drought prone areas and more floods along the Ganga and Brahmaputra rivers in the Indian sub-continent. Expansion in major and medium irrigation works as well as extensive denudation of vegetation may also influence weather, particularly the micro climate, in different ways. Hence, the plant breeder, with the help of climatologists and environmentalists, will have to assemble diverse genotypes which will profit from increased CO_2 and precipitation or, alternatively, withstand the adverse impact of higher temperature and enhanced evapotranspiration.

Anticipatory breeding in this area will include steps for:

- developing strains which can help to enhance productivity per day and per litre of water;
- breeding of varieties which can help to tap the production potential of flood-free seasons in flood prone areas;
- taking advantage of opportunities for external trade that may emerge in case the traditional bread basket areas of the world find it difficult to sustain production at high levels;
- developing genotypes which can derive advantage from enhanced CO_2 availability; and
- conserving genetic variability and maintenance of genetic diversity in crop populations.

FORECASTS OF PEST EPIDEMICS

Satellite photography of cloud movements and remote sensing techniques are aiding in the development of early warning systems against pest incidence. Cooperation between meteorologists and plant and animal health care specialists will be very beneficial in refining such techniques.

CLIMATE AND INLAND AND MARINE FISHERIES

Extensive data are now becoming available on the implications of weather patterns to aquatic productivity. This area of research is particularly important to countries which have a large, exclusive economic zone.

PREDICTION OF CLIMATE CHANGE

Huke and Sardido (1980) have pointed out that there has been a significant increase in weather variability in India since the early 1950s. It appears that the benign climate of the late 1930s and 1940s has started to change. Whether this change will be for the better or for the worse is not yet clear. Studies of this kind, with a deeper analysis of likely causes for climate change, are particularly important for countries with expanding populations and shrinking land resources for agriculture.

CONCLUSION

Among all the factors that influence agricultural output, climate is by far the most significant. This is particularly because, to a considerable extent, climate-induced production variations are beyond the control of man. However, early warning-cum-timely action programmes can be initiated based on predictions of likely weather patterns. Contingency plans and compensatory production programmes to suit different weather probabilities can become integral parts of crop production planning. By learning to live in harmony with nature, the benefits of favourable climatic conditions can be maximised and the risks associated with aberrant weather minimised.

Data from space exploration have shown that we have only our own planet to depend upon for the food we need. If we safeguard the basic agricultural assets of soil, water, flora, fauna, and the atmosphere, the chance of achieving freedom from hunger for present and future generations will correspondingly improve. To achieve the requisite blend of professional skill, political will, and people's action for promoting development without destruction, it will be necessary for every country to have effective tools for programme formulation and implementation.

Developing countries possessing a large, untapped agricultural production potential but faced with problems of chronic food shortage should consider the establishment of a suitable machinery for preparing and implementing these action codes —

- *good weather code:* this code should specify measures for maximising production during normal and favourable climatic conditions. This code also should specify the action to be taken in arid, semi-arid, and drought prone areas and the steps that should be taken during a good season for strengthening the ecological infrastructure of such areas. Only once in several years will such areas receive good rainfall. That year should be used fully for extensive tree plantation, sand dune stabilisation measures, and, where appropriate, aerial seeding, etc.;
- *unfavourable weather code:* this should have the components to deal with problems of drought, floods, typhoons, etc. on the lines earlier discussed.

Such measures will help countries to be prepared for different weather patterns and to initiate anticipatory action to mitigate the effects of aberrant weather rather than to be content with palliative action after misfortune has set in. Then even calamities can be converted into opportunities for further development.

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CHAPTER FOUR

Climate and Water Resources

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CLIMATE AFFECTS WATER resources most directly and immediately in terms of precipitation. Temperature and wind also effect water availability through the process of evapotranspiration. The principle of mass conservation can be successfully used to determine the amount of water available for use by the terrestrial ecosystem. This means that the rate of change of storage of water in water bodies, soil and groundwater in an area, over a specific time interval, is equal to the rate of water supplied from the sky in the form of precipitation minus the combined outflow from that area in terms of runoff and evapotranspiration. Continuous replenishment of water in surface-water bodies, both natural and man-made, and as groundwater is essential for long-term human survival.

It is not possible to design a sustainable development process within a region which can only use the annual replenishment of water for that specific year. This is due to the great variation in annual rainfall from one year to another. Thus, during a period of low rainfall, more water may have to be used than is being replenished, by using water stored during above-average rainfall years. If water consumption is continually higher than the surface and groundwater storage, it will eventually contribute to supply exhaustion.

History has many examples where water consumption patterns were higher than supplies available. When this happens, either development has to be abandoned in that area or consumption-supply ratio has to be brought into balance as quickly as possible, often at great hardship to the people of that area. Probably the best example of such a case is what happened to Akbar the Great, the most famous of the Mogul emperors of India, when he decided to establish a new capital for his vast empire. The best architects available were asked to design a magnificent palace at Fatehpur Sikri, not far from Agra, in the dry plains of Northern India. The cream of artisans worked for several years to complete the capital, and a vast amount of resources was spent on the realisation of the emperor's dream.

As any modern traveller to Fatehpur Sikri will attest, it is an excellent testimonial to Indian architecture. The completed palaces are still intact, untouched by the intervening centuries.

The history of the new capital, however, was not so auspicious. Akbar used it only for 15 years, and then he was forced to abandon it rather ignominiously to return to the old capital. The main reason for this unsustainable development was due to the fact that the rate of water consumption in such an arid climate was far higher than the rate of replenishment. Thus, when the available water resources of the area were exhausted, the emperor had no alternative but to abandon his expensively-built capital.

Thus, one of the main issues facing water resources planners is how to design water developments that are sustainable over the long-term. The reliability of precipitation, to some extent, depends on the climate. The problem is especially difficult in arid, semi-arid and monsoonal climates, which can have extraordinarily wide variations in precipitation from one year to another. The problem is further aggravated by the fact that areas of low precipitation are also areas where the variation is great. In contrast, year-to-year variation in areas having moderate marine climates could be fairly small. Figure 4.1 shows the global distribution of percentage variability of annual precipitation (Landsberg, 1975).

CLIMATE AND WATER DEVELOPMENT

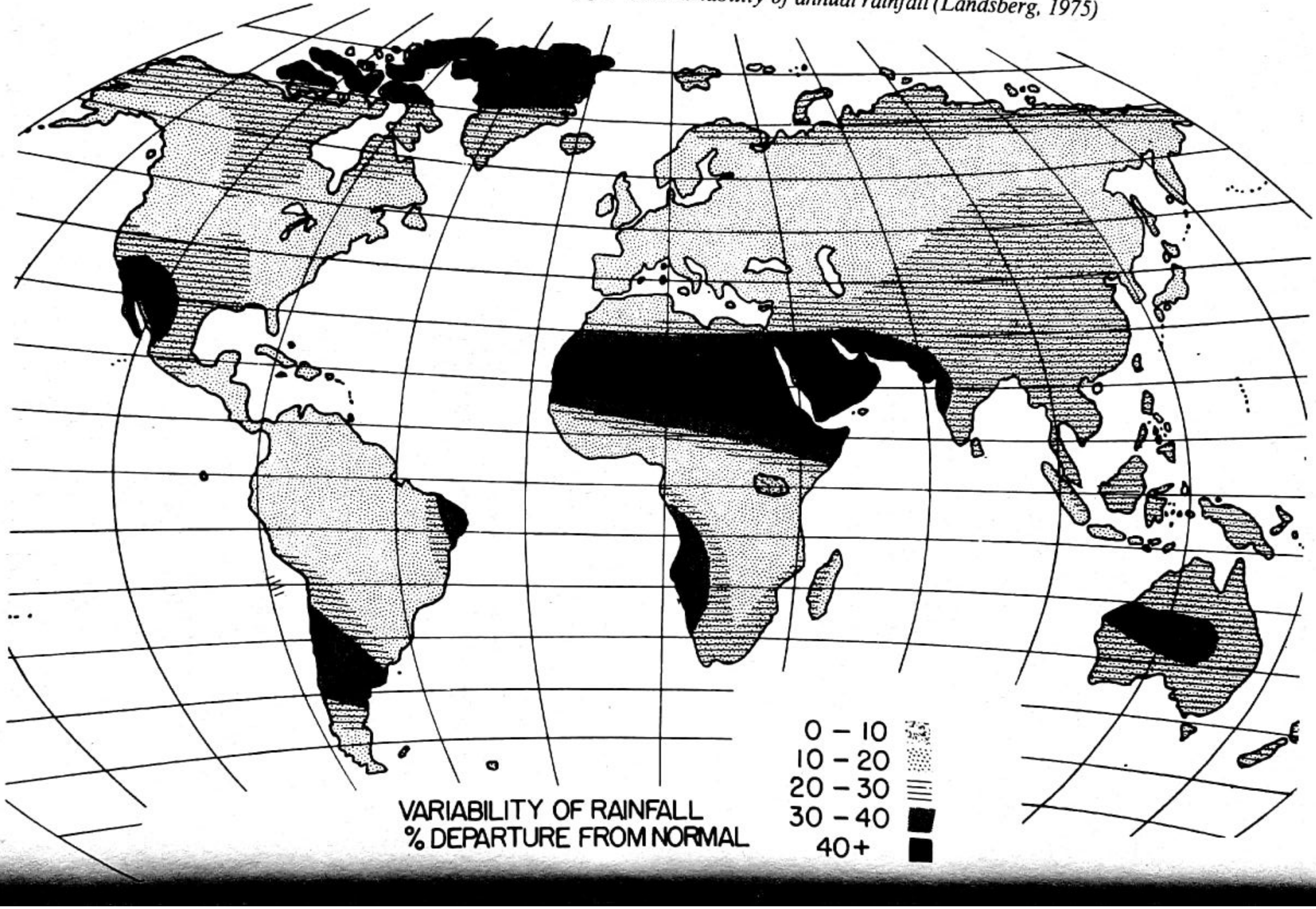
From a climate-water development viewpoint, there are four important issues which should be noted.

First, all water development projects are designed on the basis that climate of the recent past is also the key to the future, at least so far as the design-lives of projects are concerned. Generally, on the basis of 10 to 25 years of available data on hydrological variables such as precipitation, streamflow, etc., attempts are made to estimate probable extreme events in terms of low and high flows (droughts and floods). Water resources systems are then designed so as to minimise the impacts of the extreme events within an acceptable economic cost. It is thus implicitly assumed that the climatic and hydrologic regimes of the past will continue in the future.

The assumption of the constancy of the climatic regime, at least on a long-term basis, is incorrect. Climate has never been stable or constant throughout the earth's history, and there is absolutely no reason to believe that the situation will change. Thus, strictly speaking, the question of whether climatic change is taking place is tautological, since climate has continued to change as long as the earth has had an atmosphere, and will probably continue to do so even after man has disappeared from the earth, and thus no longer able to record those changes. Much uncertainty exists at present about the future climate since scientists cannot agree at present on causes, effects and trends.

Furthermore, human activities are becoming increasingly important, especially in terms of having perceptible impacts on climatic variables. For example, it has been conclusively proven that human activities can alter climatic norms on a meso-micro scale, but considerable uncertainty exists in making scientifically accurate estimates of potential climatic consequences due to man-made causes. Landsberg (1979) has provided an excellent view of the effects of human activities on climate.

Figure 4.1. Global distribution of per cent variability of annual rainfall (Landsberg, 1975)



It should also be noted that human activities can alter the hydrological regime as well. For example, large-scale deforestation or afforestation in the upper reaches of rivers may alter the patterns of runoff. Again it is not possible to make reliable estimates of what changes may occur in the flow regime due to changes in vegetative covers upstream.

Thus, even though the question of climatic change is tautological on a long-term basis, what needs to be considered within a water resources planning framework is the probability of such a change occurring within the design life of water resources systems. Normally, water resources systems are designed for an economic life, spanning over 50 to 100 years, though some large ones could be for as long as 500 years. In addition, often due to large investment necessary, and complexities arising out of the preparation of socially, economically, technologically and environmentally acceptable plans, an additional period of 10 to 30 years is often necessary to prepare adequate plans, have them accepted by appropriate decision-making processes, and then have the plan implemented. Thus, from a pragmatic, water resources development viewpoint, it would be desirable to have climatic forecasts, ranging from 60 to 130 years, depending on a variety of factors like the type and location of hydraulic structures, proximity to the centres of population, standard of safety necessary, development purposes etc. It is important, however, that for design and operational purposes, the climatic forecasts should be more site-specific, a point often forgotten in recent literature. Forecasts of global climatic "averages" or trends, while interesting, are of little value in the actual planning and design of water resources systems.

There are basically two schools of thought concerning the incorporation of climatic variability into water planning. The first school suggests that since the economic life of most water resources structures is between 50 to 100 years, and since there has been no evidence of climatic change during the past 200 years, the probability of a major change during the next 200 years is minimal, and therefore the whole question is somewhat academic. Thus, Chin and Yevjevich (1974) suggested that "since most systems have been built with the economic project life in the range of 40 to 100 years, the chances are minimal that the expected natural water supply would be significantly different during these life spans than in the past 200 years .... This question is, however, not crucial for the next several generations of contemporary earth population, but rather is more of an academic interest like many other human concerns with the long-term future." They further attempted to show that climatic fluctuations could be reduced to a deterministic component based on the Milankovich theory of astronomical cycles and a simple Markovian stochastic component.

Others have taken a contrary view, and have pointed out that climatic variability is an established fact. Accordingly, the variability should be recognised, and should be analysed and used in the water resources planning and management process. Mitchell *et al.* (1975) clearly state that "The lessons of history seem to be that climatic variability is to be recognised, and dealt with as a fundamental quality of climate, and that it should be potentially perilous for man to assume that the climate of future decades and centuries will be free from similar variability."

The importance of considering climatic variability has been clearly demonstrated, especially in terms of water resources management, by O'Connell and Wallis (1973).

They showed that the reservoir firm yield, assuming a 50-year design life, could have different estimates even when Markov and other persistent generating mechanisms used yielded samples having identical expected values for the mean, variance and lag-one correlation. In other words, the analysis clearly indicated that it is not only important for hydrologists and water planners to understand the nature of climatic variability and persistence but also imperative that such considerations be incorporated in the planning process. In another paper, Wallis and O'Connell (1973) showed that statistical analyses of hydrologic data of average period of years would usually lead one to believe that a Markov generating mechanism adequately represents the streamflow pattern in a real world. Such analyses could instill a false sense of security amongst water resources planners, since they are likely to be erroneous. This is because various statistical tests carried out do not have the power to distinguish between samples of such lengths taken from Markovian and more persistent generating mechanisms.

In addition to the above consideration, there could be another factor which could enhance the economic uncertainty, especially in terms of available future water supply, much of which will be necessary to increase agricultural production through irrigation and better water control. As the National Research Council (1977) of the United States has noted, the uncertainty is due to the "threat of climatic change, real or imagined, which can alter what farmers will plant, as well as what economists think they will plant. At present, we do not know whether climatic change will result in more or less water available behind a proposed dam. Further, we do not know what the net effect of a postulated average annual global temperature change may be on the future water requirements within an actual specific project area. It would appear that rather than global averages, the climatic-change estimates that might actually influence projections of water use are estimtes of changes in frequency and severity of extreme periods. Climatologists may find reliable, nonstationary, extreme value forecasting beyond their ability."

The second important issue is that while there may be major fluctuations in precipitation in an area from year to year, changes in runoff generally tend to be more pronounced than precipitation in dry years. Since most evapotranspiration requirements have to be met prior to surface runoff and groundwater recharge, and evapotranspiration tends to be relatively constant from one year to another, any downward drift in precipitation often tends to result in even more reduction in surface runoff. Thus, in the areas that depend exclusively or primarily on water supply from rivers, the problem of water shortage could be more serious than the low precipitation figures may indicate.

Changnon (1977) has provided an example of this issue by analysing 55 years of streamflow data for the Illinois River basin. He considered the lowest flow periods for five distinctly separate 30-month periods during 1915-70. He assumed evapotranspiration to be constant by using an average figure. The analysis indicated that the lowest 30-month rainfall, 173 cm, was associated with the lowest streamflow, 13 cm, but whereas the precipitation figure was a 24 percent departure from normal, the corresponding departure for streamflow was 79 percent (Table 4.1).

The third important issue is the fact that water development projects are generally designed to operate under a wide range of climatic fluctuations. It is a common

Table 4.1. Comparison of precipitation and runoff during 30-month dry periods in Central Illinois River Basin, 1915-70 (Changnon, 1977)

Rank	Precipitation (cm)	Runoff (cm)	*Percent of normal*		*Percentage departures below normal*	
			Precipitation	Runoff	Precipitation	Runoff
1	173	13	76	21	24	79
2	183	15	80	27	20	83
3	201	28	89	46	11	54
4	208	33	91	55	9	45
5	213	36	93	57	7	43

practice amongst water planners to estimate maximum probable flood so that the hydraulic structures designed can withstand them, and also to determine lowest flows to be expected over a specific period of time, generally 3 to 5 years, during which required water can be supplied from the system. The final decision as to the ranges of the extreme climatic regime within which the system can function effectively is dependent on economics, institutional and legal requirements and societal concern. Thus, it can be argued that because of this built-in flexibility, water development projects can better withstand not only climatic fluctuations but also some modest changes in climatic and hydrological regimes, either natural or man-made, than many other areas of human activities like agricultural production, which have been discussed in other chapters, where such changes or fluctuations could have catastrophic effects.

It should, however, be remembered that while much scientific progress has been made during the last two decades in estimating extreme climatic events, both in terms of magnitude and probability of occurrence, we still cannot predict them with any significant degree of confidence (Biswas, 1971). Thus, considerable uncertainty still exists in the design of water resources systems to withstand extreme events.

Equally, it should be noted that continuing population growth, increasing urbanisation, and expansion of agricultural development into marginal areas in recent years, have generally tended to increase the potential socio-economic impacts of variations of water availability compared to similar impacts in the past. For example, comparatively small changes in climatic variables, especially in terms of precipitation and temperature, could mean the difference between abundant agricultural production or failure in marginal areas. Thus, in many cases, the flexibility available to decision-makers or range of errors permissible are diminishing, which means the potential for social and economic vulnerability to specific segments of society is increasing. Such considerations are especially important in the arid and semi-arid areas of developing countries. In the future, with further increases in population, urbanisation and use of marginal land, the socio-economic impacts of variability of water sources are likely to be even more serious and crucial than at present (Biswas, 1979).

The fourth important consideration is the fact that there are important differences due to climatic factors in different parts of the world so far as water development activities are concerned. Some of these differences are serious and others may be subtle, but together they may require different design, planning and operational practices for water resources systems from one area to another, often within the same country. The environment and institutional processes within which water development takes places could also be different. Consequently, water management process can differ from one climatological area to another.

Some of the major implications of climate-development interrelationships have already been discussed in Chapter 1, many of which are also relevant for water resources development. In this section some of the different aspects of lake and reservoir management in the tropics and temperate regions will be considered as an example of variable management requirements in such areas.

Tropical and temperate zone rivers may differ widely in such factors as flow rate, turbidity, pollutants present in water and temperature. Naturally the quantity and quality of water flowing into lakes or reservoirs determine many of their characteristics. For example, sedimentation is a major concern in most tropical reservoirs. Heavy tropical rainfall, the onset of rain after the summer when vegetative cover is generally at its least, and the soil is very dry and loose, and steep valley slopes all contribute to high sedimentation rates. Poor management of upland watersheds due to deforestation and overgrazing further aggravates the situation. As the silt-laden river water enters the reservoir, the velocity of flow is reduced and thus the rate of sedimentation increases. Accordingly, special attention needs to be given for sedimentation management.[1]

Sedimentation reduces storage capacity, and hence the useful life of a reservoir. It also results in the loss of nutrients, which otherwise may have reached agricultural and aquatic ecosystems downstream. Clear water coming out from the reservoir often increases erosion of the river banks and deltas. High rates of sedimentation also can have adverse effect on the spawning of fish and distribution of biota. Presence of suspended materials increases turbidity, thus significantly reducing photosynthesis, which in turn reduces productivity of higher trophic levels (NRC, 1982).

If trees and vegetation within a reservoir are not cleared prior to inundation, water quality implications could differ between the tropics and temperate climates. Decay of organic material is much faster in the tropics than in temperate climates, and rates of oxygen consumption during biochemical degradation and nutrient release have different impact magnitudes on water quality in the two regions. In cold temperatures, submerged trees can last a long time. For example, in the Gounin Reservoir in Canada, tree trunks show very little deterioration after being flooded for some 55 years (Biswas, 1982).

Infestation of aquatic weeds is often a serious problem in the tropics and semi-tropics. Major problems with aquatic weeds have been observed in places as diverse as Aswan, Kariba, Nam Pong (Thailand) and Brokopondo (Surinam). Once infestation starts, growth of aquatic weeds can be very fast. For example, *Eichornia crassipes*, commonly known as water hyacinth, covered an area of about 50 square kilometres in Lake Brokopondo within the short period of February to December, 1964. In little

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[1] For a comprehensive review of reservoir sedimentation problems from different parts of the world, see Biswas, 1982.

over two years, by April 1966, it had covered more than 50 per cent of the surface of the reservoir, an area of about 410 square kilometres. Similarly, in Egypt, weeds were not a problem until 1964. However, in 1965, water hyacinth started to spread prolifically in Middle Egypt and the Nile Delta area. By the beginning of the spring of 1975, various types of aquatic weeds, sometimes mixed with dense algae, had invaded more than 80 per cent of all the watercourses and a great part of the Nile itself. Experience in the Congo Basin has been somewhat similar. Between 1952, when the weeds were first observed, and 1955, they spread a distance of some 1,600 kilometres, covering large areas of the Congo River. The problem of aquatic weeds is further aggravated by the presence of irrigation and drainage channels.

Weeds create several problems. First, water losses are greatly increased by their evapotranspiration process. If irrigation is practised, more water has to be released to ensure adequate water availability in the lower reaches. These two factors often account for a tremendous amount of water loss. Thus, at Aswan it has been estimated that 2,875,000,000 cubic metres of water are lost per year due to the preceding two factors alone. A better perspective can be obtained if it is considered that at present prices, 2,875,000,000 cubic metres of annual over-year storage on the upper reaches of the Nile at Aswan will cost some 216,000,000 US dollars, which is a not insignificant figure.

Weeds also tend to increase the incidence of diseases such as malaria and schistosomiasis by providing a favourable habitat for invertebrate vectors and intermediate hosts (mosquitoes and aquatic snails) for disease-causing agents. They create further problems by interfering with the operation and maintenance of hydroelectric generation and pumping stations, and by competing with fish for space and nutrients.

Control of aquatic weeds in the tropics and semi-tropics, especially after invasion, is a difficult and expensive task. Mechanised or manual clearing of weeds, especially in shallow waters, has been quite successful, but in deep waters it is not a very viable alternative. Weeds thus removed can be used to produce animal feed, biogas or manure. In certain countries, e.g. China, aquatic plants are specially cultivated as animal feed.

Chemical herbicides have been used extensively to control weeds, but chemical control is not very effective for submerged weeds. In addition, herbicides often pose a major environmental hazard to aquatic organisms and deteriorate water quality; their long-term effects on aquatic ecosystems and human health are little understood.

Another type of control is biological: fish, snails or aquatic grasshoppers are introduced to control weeds. There is still much to be learned about the use of biological controls. Naturally, the three control measures are not mutually exclusive; they are often used in various combinations for optimal weed control. The type of control measures to be used depends on various local situations such as the type of weed, density of infestation, depth and width of the channel, time of application, water-use pattern, proximity of crop areas sensitive to herbicides, availability of material from local or foreign sources and availability of skilled manpower.

Water-development schemes have often enhanced or created favourable ecological environments for parasitic and water-borne diseases such as schistosomiasis, dengue and dengue haemorrhagic fever, liver-fluke infections, bancroftian filariasis, and malaria. These diseases are not new; for example, schistosomiasis was known during

Pharaonic times. However, the incidence of these diseases is much higher if extensive perennial irrigation is practised. Schistosomiasis is currently endemic in over 70 countries, and affects over 200 million people. The same number are at present infected with malaria in the tropics and subtropics, and another 250 million are infected with bancroftian filariasis. Similarly, plant growth around reservoirs provides a suitable habitat for tsetse fly to transmit trypanosomiasis to humans and domestic animals (M.R. Biswas, 1979).

In contrast to the diseases mentioned, water resources developments tend to reduce the incidence of onchocerciasis. The intermediate host, the *Similium* fly, tends to breed in fast-flowing waters, which are often drowned by the construction of dams. Thus, the construction of the Volta dam destroyed the breeding ground of the *Simulium* fly that existed upstream. However, adequate measures should be taken to ensure that new breeding places do not develop, especially in the fast-flowing water near spillways.

Water quality considerations are also somewhat different in tropical reservoirs when compared to their temperate counterparts. Higher average daily temperature and thermal discharges from thermal or nuclear power plants, if present, can have adverse water quality impacts. This is because of two reasons. First, dissolved oxygen levels in water decrease with increases in temperature. For example, oxygen solubility from air into water is 16 per cent lower at 30°C compared to 20°C, and is 29 per cent lower at 40°C than 20°C. Second, the rates of biological processes increase with temperature, and accordingly biochemical oxygen demand (BOD) increases as well. The net result of these two effects could be a significant reduction in the dissolved oxygen level in water, which may have deleterious effects on fisheries and other components of an aquatic ecosytem (Biswas, 1980). Thus, both reservoir and fisheries management may need to be more finely-tuned in the tropics than in temperate climates.

Climate fluctuations and water resources planning and management

Considering the significant potential impacts of climate on water resources planning and management, it is really surprising that not much work is being done in this important area. Recent activities in the area of water resources planning and management will be discussed under the following three headings: study of cycles, synthetic hydrology and other techniques.

Study of cycles: If the present methods and techniques for water resources planning and management are critically reviewed, it soon becomes evident that one of the most important basic philosophies, albeit somewhat implicit, is that the recent past is the key to the near future. It is relatively simple to consider the near future, the length of which is the design life of the proposed system. However, problems start to arise when a review of the past is attempted — since the techniques for doing so have not been universally agreed to, and thus have resulted in some controversy.

The situation becomes even more complicated when one tries to predict the near future on the basis of limited data on the past, a common occurrence in most of the developing countries and in many instances in the developed world. Often hydrologists consider themselves to be lucky to have reliable data for only 10 to 15 years. Considering the inherent problem of sampling errors in such short records, it is indeed difficult to make predictions for the future. The problem becomes even more complex if it is assumed that the climatic and/or hydrological regimes have changed to a new state in recent years. In this case, it would mean that the observed data of the past belong to one statistical population, and the events of the near future will belong to another. This means that one of the fundamental assumptions of hydrology becomes immediately invalid, and the recent past could no longer be considered to be the key to the future.

Facing these types of difficult problems, some scientists have considered the possibility of using cycle analysis as a basis for climatic forecasts. The technique is a little more sophisticated than trend analysis. Basically, cycle analysis is an empirical method wherein reasonably long periods of observed data of different phenomena are analysed to determine the existence of cycles. These cycles are then used as a form of forecasting algorithm to predict the future. Cycle analysis has always been popular among certain scientists and they have often used it as a forecasting tool. In fact, this form of analysis has been popular enough to support its own society, devoted to the study of cycles, and sponsor its own speciality journals, e.g. *Interdisciplinary Cycle Research.* In all cycle analysis, non-cyclic independence of data is implicitly assumed. This, as Mandlebrot and Wallis (1969) have pointed out, is somewhat unlikely for climatic data.

In the area of climatic analysis, considerable emphasis has been placed in recent years to the study of solar cycles, and their apparent correlation to water availability. These studies range from the precipitation characteristics of Addis Ababa and Asmara, to variations in the water levels of Lake Victoria, to droughts in the high plains of the United States. In each of these cases, attempts were made or are being made to correlate certain climatic events with sunspot cycles, with inconclusive results.

Attempts to correlate water-related phenomena with sunspot cycles have been made for decades. However, without scientific explanation of interrelationships between sunspots and climatic events, it is rather easy to get into trouble. For example, as early as 1937, Stetson wrote a book on *Sunspots and their Effects*, in which he shows some "interesting" correlation between sunspot numbers with Dow Jones Stock market averages, rabbit population, building contracts or number of automobiles. These are shown in Figure 4.2. Without a physical understanding of the interrelationships between the events being correlated, statistical analyses could often easily result in spurious correlation.

One could argue that even between seemingly unrelated events such as sunspot numbers and rabbit population, one could find some physical linkages. For example, the output of the sun obviously has some effect on the climate, though precisely what it is, is difficult to say. If, as some researchers have claimed, there is some relation between sunspot numbers and droughts, sunspots could have some impact on vegetation, and through vegetation on the rabbit population. Such linkages, however, are hypothetical, and have yet to be proved with any degree of confidence. In the absence of any realistic scientific theory, such speculations are interesting conjunctures at best, and nonsense at worst.

Thompson (1973) has analysed double sunspot cycles with droughts in the state of

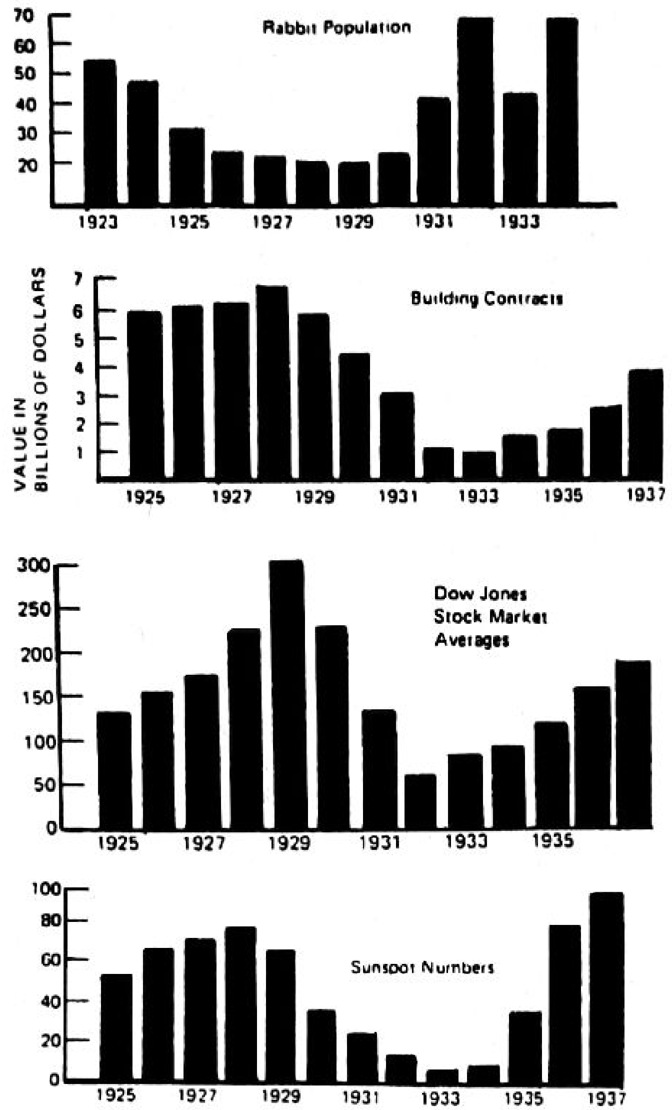


Figure 4.2. Correlation between sunspots, rabbit population, building and the Dow Jones index (from Stetson).

Nebraska in the United States. It appears that droughts have occurred in Nebraska during alternate minima of the double sunspot cycle. If the result is to be taken at its face value, it would seem that the droughts occur in 22-year cycles, centred near the minima of that circle.

There are many questions to be answered before the 22-year cycle of droughts in Nebraska can be taken seriously. For example, why do such cycles occur in the plains of the United States, but not elsewhere? Why do the droughts not affect the entire plain? It seems that they occur in different parts of the plain, and the cycles do not necessarily affect the similar parts of the plain each time. Nor does their timing of occurrence coincide exactly with alternate sunspot minima. Without reasonable explanations of such anomalies, the 22-year cycle is likely to remain an interesting speculation.

With regard to cycle analysis, it is interesting to note that in 1960, an attempt was made to forecast precipitation, for the period 1961 to 1970, for 32 locations within the United States. This was done by developing an algorithm based on solar cycles of 91, 46 and 23 years, and 91, 68, 55, 44¼, 38½, 34, 30⅓, 25½, 21, 11.87, 11.29, 9.79 and 8.12 months (Abbot, 1960; Abbot and Hill, 1967). A similar algorithm was used to predict temperature in ten locations for the 1962 to 1967 period (Abbot, 1961) of the United States.

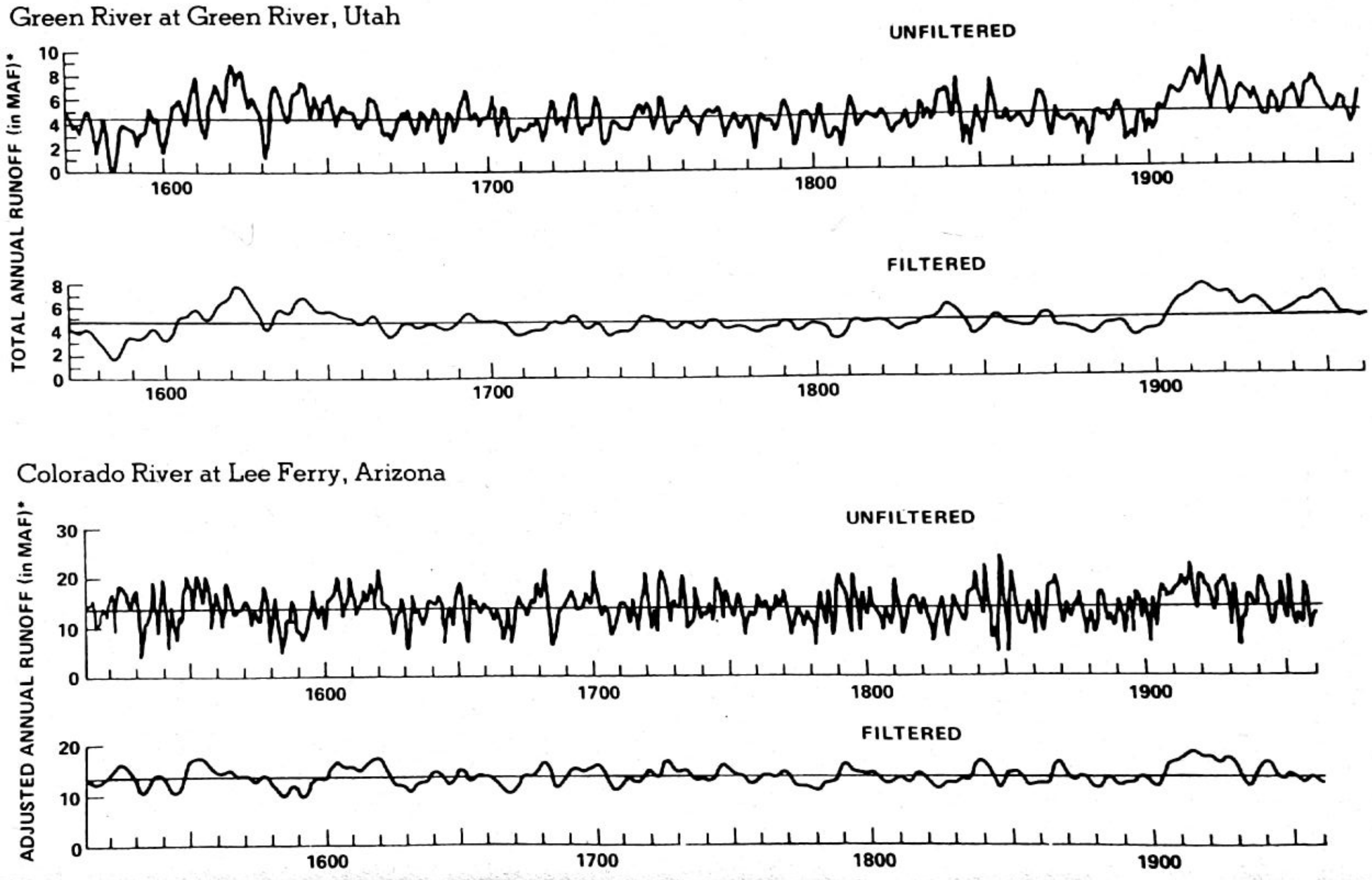
The advance ten-year forecasts for precipitation were then compared with actual figures. Using Spearman's rank correlation coefficient to determine the accuracy of the advance forecasts, it was found that nearly half of the correlations were positive and the balance was negative. This means that forecasts were no better than random. An analysis of the forecast temperatures was not much better.

In the absence of better scientific explanation and documentation, hydrologists should realise that forecasts based on cycle analysis, like many other climatic forecasts, are often based on "poor foundations, apparent similarities, parallel-looking curves and analogous trends" (Gani, 1975). Further, it can be experimentally verified that "stochastic processes with low-frequency components can yield sample functions with numerous 'significant' cycles are often induced into the analysis of moving average manipulations to smooth what are otherwise noisy data" (National Academy of Sciences, 1977; Slutzky, 1927).

Use of paleoenvironmental indicators: Some progress has been made in recent years in estimating long-term climatic fluctuations on both global and hemispheric scales. Since such estimates are of little direct value to water resources planning, it is necessary to interpret and translate past climatic variability in terms of regional hydrologic variables like streamflow.

Not much work in this area has been carried out thus far. Among the few scientists working in this area, Stockton (1975, 1977) and Stockton and Jacoby (1976) have successfully reconstructed total annual runoff data, by using tree-ring information for the Upper Colorado Basin. Figure 4.3 shows reconstructed hydrographs for total annual runoff for two rivers: Green River — a tributary river within the Upper Colorado River Basin, at Green River, Utah; and the Colorado River at Lee Ferry, Arizona. From the reconstructed hydrographs, several important points emerge. For example, if a hydrologist were to analyse only the streamflow data of the two rivers, based on actual observations, then it is highly likely that rather high estimates of mean annual flow and variance would be obtained. This is because during the early part of the present century, both the rivers experienced high flows — over a prolonged period — which, as the reconstructed records indicate were the longest for the 450 years of reconstructed history. In other words, without such reconstruction of streamflow data, one would have obtained much higher water availability from both rivers, than would have been actually the case. Furthermore, analysis of the long-term hydrograph of the Colorado River indicated that the series is significantly different from random and can be best modelled by a mixed autoregressive-moving average scheme

Figure 4.3. Reconstructed hydrographs for total annual runoff for Green River at Green River, Utah, and Colorado River at Lee Ferry (Stockton, 1975)



*Million Acre Feet

(Stockton, 1977). Also, the Colorado did not exhibit the long-term persistence found in the reconstructed history of the Green River.

Similar reconstructions of hydrological time series data are not readily available, but Landsberg *et al.* (1968) have reconstructed annual temperature and precipitation totals along the eastern seaboard of the United States, centred in Philadelphia, for the period 1738 to 1968. The preliminary reconstruction of this 230-year data shows an anomalous wet period for about 50 years during 1830 to 1880, and a trend in the annual temperature data caused primarily due to the "lack of cold years since the turn of the 20th century".

Use of paleoenvironmental indicators for actual water resources planning is still in its infancy, and much work remains to be done to develop new techniques and refine the existing ones. There is, however, no doubt that this is a promising area of work, and expenditure of further resources is likely to pay rich dividends.

Synthetic hydrology: There are a few studies that are being currently conducted in the area of synthetic hydrology, with regard to climatic fluctuations.

In some pioneering work, the Harvard University Water Group used in 1962 synthetic lag-one Markov generating mechanism of the type:

$$x_1 = p_1 x_{i-1} + E_i$$

where E_i are independent random variables scaled to preserve the observed means, variances and lag-one correlations, P_1. The problem with such a generating mechanism is that it tends to give lower critical flow values than those of the observed sequences rather than providing values that are equally likely to occur. In order to improve analytical process, there has been a tendency to introduce incremental changes like elimination of biases in the parameter-estimating procedures, or even use of multi-lag models. These changes, however, have not solved the basic problem.

Some attempts have been made to introduce certain aspects of climatic changes in the lag-one Markov model. For example, Schwarz (1977) assumed that variations of monthly streamflow can be represented by a skewed logarithmic lag-one Markov model, and that four parameters, mean, standard deviation, and coefficients of skewness and serial correlation, can define such a model. These parameters were then changed according to a long-term climatic change model, which gave some indication of the system response due to effects of climatic changes.

Schwarz used this concept to see how the streamflow records of the Potomac River at the Points of Rock gauge may be affected. The drainage area at that locale is 24,996 square kilometres. He used 75 years of streamflow data (1897-1970) to estimate the logarithmic mean, standard deviation and coefficients of skewness and serial correlation for each month. From these parameters, a 1,000 year synthetic flow record was generated. One set of statistics was then varied to generate eight alternative "climatically-changed" 1,000 year records.

From this analysis, Schwarz concluded that climatic change does not seem to "radically alter the water-supply planning process". Based on this analysis, Schwarz has also provided a speculative impact matrix of climatic change as shown in Table 4.2.

Schwarz's attempt to generate synthetic streamflow, as a surrogate for climatic change, is a valiant effort in a view direction, and it could possibly give planners a

Table 4.2. *Speculative Impact Matrix of Climatic Change (Schwarz, 1977)*

Attributes of water supply systems	Parameters of Climatic Change				
	A Decrease in mean streamflow	B Increase in variance of streamflow	C Increase in skew of streamflow	D Increase in persistence of streamflow	E Speed with which change occurs
1. Yield from unregulated streams	Some effects, but likely not very large except if change in mean is large or combined with other changes	Severe effects; however, generally short term	Significant effects because number of days of low flow increase relative to few very high flow periods	Significant effects more through duration of low flows than severity	Not applicable
2. Yield from reservoirs	Significant to severe effects particularly if reservoirs develop a high percentage of the average flow	Medium to no effects depending on the size of the reservoir in relation to drainage area; larger reservoirs will suffer smaller effects	Medium to no effects depending on the size of the reservoir in relation to drainage area; larger reservoirs will suffer smaller effects	Significant to severe effects especially if reservoir long-term storage is limited	Not applicable
3. Yield from groundwater	Significant in the long run, especially if draft on aquifer is near average recharge	Little if any significance	Little if any significance	Effects severe and of long duration	Not applicable
4. System reliability	Some effects, other than effects accounted for under 1-3	Some reduction due to constant change in flows in addition to effects under 1-3	Little or none, other than effects under 1-3	Little or none, other than effects under 1-3	Sudden changes severely affect reliability, slow ones less or not at all
5. Magnitude and control of demand	No significant effect	No significant effect; often recurring short-term restrictions may reduce their effectiveness	No significant effect	No significant effect; emergency restrictions likely to become less effective over long droughts	Significant and visible effects, relatively fast changes could force major steps toward conservation and demand control
6. Cost of operation of water system	No significant effects except for additional construction that might eventually ensue to alleviate long-term shortages	Possible increase due to turbidity, increased pumping between systems if applicable; possible additional reservoir construction	No significant effects likely	No significant effects except search for new sources	No effects
7. Pressure on and ability of the water system to respond to change	Pressure for expansion would be created if shortages occur repeatedly; ability to respond would not be affected by hydrologic event	Pressure for expansion would be created, but rapid return to normal may for some time inhibit expansion	Pressure for expansion would be created if shortages occur repeatedly; ability to respond would not be affected by hydrologic event	Pressure for expansion would mount over time and increase likelihood of action; however, long high flow periods may inhibit development	Sudden or relatively near future changes could increase action; long-term changes (20 years+) even if known would likely be ignored by existing institutions

"feeling" of the system sensitivity to change. Such analyses have many major disadvantages, some of which have been pointed out by Schwarz himself. First, the relation between climatic variations and streamflow at a specific site is still largely undefined. Second, no estimate of likely climatic change, even on a global basis, is available at present. The situation could be even more difficult to construct a site-specific master long-term climatic change model, based on the physical and meteorological levels, which could then dictate changes that are to be analysed. Thus, in the study mentioned, the investigators were forced to make arbitrary variations in the parameters, without having much information on the probability of occurrence of such changes. Third, it is difficult to select a good generating algorithm. Currently, several models exist, but each have their own advantages and disadvantages. Schwarz's approach was a nonlinear, non-stationary, synthetic hydrology, which is theoretically interesting but not very useful for water resources planning purposes.

Other techniques Not many new concepts have been put forward to incorporate the effects of possible climatic change in water resource planning and management in recent years. In fact, after an extensive literature search and a questionnaire survey of leading research institutions, only one technique was found that could be termed relatively "new". This is the introduction of the concept of robustness and resilience within the context of mathematical modelling of water resources systems.

Literally hundreds of models have been developed in recent years in most parts of the world to transfer climatic functions such as precipitation and temperature to streamflow. Use of such climatic transfer functions, which implicitly assume that climate will continue to be as before in the real world, has not been all that successful. For example, the World Meteorological Organisation carried out an evaluation of the performance of ten models on up to six watersheds for a period of two years. The results were often greatly in error, even when recorded daily precipitation and temperature values were used for the basins considered. Individual events sometimes showed little or no correlation between observed and forecast values, and the sum of the forecast flows for the 2-year period ranged in excess of 40 per cent. This, of course, is not surprising, especially when the inherent uncertainties associated with hydrological techniques currently being used for parameter estimation are considered. Thus, there is a hierarchy of uncertainties, in depending on which parameters are being estimated. For example, there is some uncertainty associated with the determination of streamflow, more uncertainty with the estimation of the standard deviation and even more uncertainty with the higher moments of the low probability density functions.

If this is the state of the art for climatic transfer function models, all of which are constructed with the explicit assumption that model parameters are time invariant, i.e. streamflow is a stationary process, the situation is far worse, when the development of a realistic model with time variant parameters is considered. Matalas and Fiering (1977) have addressed to some of these problems.

Matalas and Fiering have attempted to introduce the concept of robustness and resilience in hydrological analyses. None of these two concepts is new: they came from statistics and ecology respectively. Robustness is defined as "the insensitivity of the system design to errors, random or otherwise, in the estimates of those parameters affecting design choice." It was suggested that some designs have built-in buffering, and consequently are more robust than others in that they are applicable over a wider range of population mean values. In contrast, some designs could be optimal over a narrow range of the population mean. Normally, as a rule, it can be said that large systems have substantial robustness built-in, in that they are technologically and institutionally capable of adopting to larger stresses. Matalas and Fiering suggest:

> Part of the design problem is to identify the types of climatic shift that might be anticipated and to determine if they are sufficiently precipitous with respect to flow characteristics to dictate a change in system design. It is not necessary for this purpose to know or to try to determine whether there is a true climatic shift. This may be an interesting scientific question, important in its own right, but it is virtually meaningless for the design of water-resource systems. It is also unimportant to know if the population moments of the flow distribution are modified, because, again, while this might be an important hydrologic matter, it is important for water-resource design if, and only if, the changes, when coupled with economic criteria, lead to new design.

If a water resources system has been designed to perform at an optimal level, and has adequate built-in buffering, it should be capable of being operated at another system level. Such a deviation of the system from an optimal level will undoubtedly mean some economic loss, but this can be constrained for design purposes at a certain percentage — which can then be referred to as the resilience at that level. Such a design will not be optimal — in the standard sense of the term — but could possibly be the operational choice, which can be expected to perform reasonably well under changing climatic conditions. In other words, a system designed for a specific climate can be modified to operate under a different set of climatic norms, at a certain economic cost. This flexibility then becomes the resilience of the system. It should be noted that resilience so defined cannot only be enhanced by changes in structural measures, but also by using other means like zoning, insurance, subsidies and price structures.

The technique proposed by Matalas and Fiering seems to have considerable future potential. However, from a strictly water resources planning viewpoint it is unlikely to be used at present. Much work needs to be done before the technique can be considered for actual use in the planning of water systems.

In another development, WMO and UNEP cooperated in evaluating climate and water resources for agricultural development, for the Sudano-Sahelian zone of Africa (WMO, 1976). These studies are important in the sense tht they provide comprehensive analysis of the available data on different climatic variables — precipitation, temperature, wind speed and direction, vapour pressure, solar radiation and evapotranspiration. They point out some of the problems of analyses of climatic data. For example, thirty years of records at a single station may not be a good parameter for rainfall for planning considerations, especially in the northern half of the Sudano-Sahelian zone. Such averages of annual rainfall, even when considered over a long period of years, may provide insufficient and unreliable information. Throughout this zone, monthly averages or averages over even shorter periods, often show considerable inconsistencies that can probably be explained by the randomness of the local rainfall. For these reasons, it was suggested that median was a more useful parameter of rainfall rather than normal.

CLIMATE AND WATER QUALITY

Concern about dispersal of pollutants through climatic factors has continued to increase since the late 1960s. Air pollutants are dispersed far and wide through the atmosphere. While such dispersal reduces the concentration of pollutants as they are transported from the point of origin, they may nevertheless precipitate in the form of acid rain, often as far as hundreds or even thousands of kilometres away from the sources, depending on the strengths of prevailing wind. Thus, the water quality of precipitation has increasingly become an important concern during the last decade, especially in developing countries.

Many pollutants have been observed to have been precipitated. They range from metals such as zinc and lead to various chemicals such as pesticides. The concern with acid rain, however, has centred on two man-made compounds — sulphur oxides (SO_x) and oxides of nitrogen (NO_x). These compounds react in the atmosphere to form sulphuric acid and nitric acid, which then precipitate on the earth's surface in both rain and snow.

Emissions of sulphur oxides can be controlled, but such controls are expensive. Control requirements differ radically from one country to another. Technology that can be applied for removing oxides of nitrogen from industrial stack gases does not exist at present. A direct result of such emissions has been lower pH values of rainfall, which indicates higher acidity. For example, the pH values of rainfall over large areas of southern Sweden and Norway have been observed to have fallen from a normal value of 5.7 to around 4.5-4.2.

Acid rain can have adverse effects on aquatic ecosystems, terrestrial biota and soil. A survey of over 1,500 lakes in south-western Norway indicated that over 70 per cent of the lakes having a pH value lower than 4.3 contained no fish (Barney, 1980). Similar results have been noted in Sweden, Canada and the United States. Forest growths in some areas have also suffered from acid rain. Soil acidification may also result from acid rain, depending on the amount of calcium present in the soil. Growing acidification of soil can only reduce agricultural yield. Lime needs to be applied to the soil to neutralise its acidity.

OTHER CONSIDERATIONS

Extreme climatic events such as floods and droughts have serious social and economic impacts on countries. For example, according to WMO (1975), 22 countries in the Asia and Pacific region sustained a damage of 9.9 billion US dollars only from typhoons and floods, an amount which was almost as large as the World Bank loans to these countries during the same period.

For efficient operation and management of water resources systems, it is essential to have more information on the magnitude and probability of occurrence of extreme climatic events. This means it is essential to monitor climatic variables on appropriate time and space scales to develop a better data base for both design and management purposes, and to develop better theoretical basis for such designs. It is equally necessary to ensure that the information collected is available not only to water resources' planners and managers, but also to other people who need to use it, e.g. farmers. If it can be predicted with some degree of reliability that a growing season is likely to be dry, farmers can substitute some crops that can better withstand dry seasons than others. Under such circumstances, sorghum can be a good substitute for corn. However, if the prediction turns out to be wrong, and the season turns out to be average, farmers will incur economic losses for having planted sorghum instead of corn. In other words, it does not pay to play guessing games with climate: the results could be either excellent or catastrophic.

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CHAPTER FIVE

The Effect of Climate Fluctuations on Human Populations: a Case Study of Mesopotamian Society[1]

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IN NEARLY ALL human-environment systems there is a tendency for population growth to press against the limits established by technologically exploitable resources. Few systems are so stable in their population dynamics that variation in population level does not occur. Historically, there is evidence for slow, progressive growth in total global population, a trend that has accelerated dramatically in the last three centuries. Yet in contrast to this cumulative expansion of global population is the evidence for periodic collapse of populations in particular areas. The remains of these defunct civilisations litter the archaeological landscape, and arouse speculation as to the causes that produced such catastrophic results.

One recurrent conjecture for such collapses has been exogenous environmental causes. In the case of Mycenean civilisation, Bryson and Murray (1977) invoke shifts in the average position of winter storm tracks, which makes less moisture available to the cities of the Peloponnesus, as an explanation for the decline and ultimate collapse of Mycenae. McNeill (1977) indicts the transport of disease from one ecological setting to another as an important population destabilising variable whenever previously isolated disease pools are brought into contact. The unfamiliar infectious disease that crippled Athens in 430-429 BC during the Peloponnesian War, the possible outbreak of measles and smallpox in the Antonine plague of AD 165-180 and its successor in AD 251-266, and the weakening of Byzantine and Persian empires as a consequence of repeated outbreaks of bubonic plague after AD 542 before the Muslim Arab invasions are intriguing examples of the interaction between disease, population dynamics and history. A similar argument for population decline in the Islamic portions of the Middle East during the fourteenth century due to the Black Death is made by Dols

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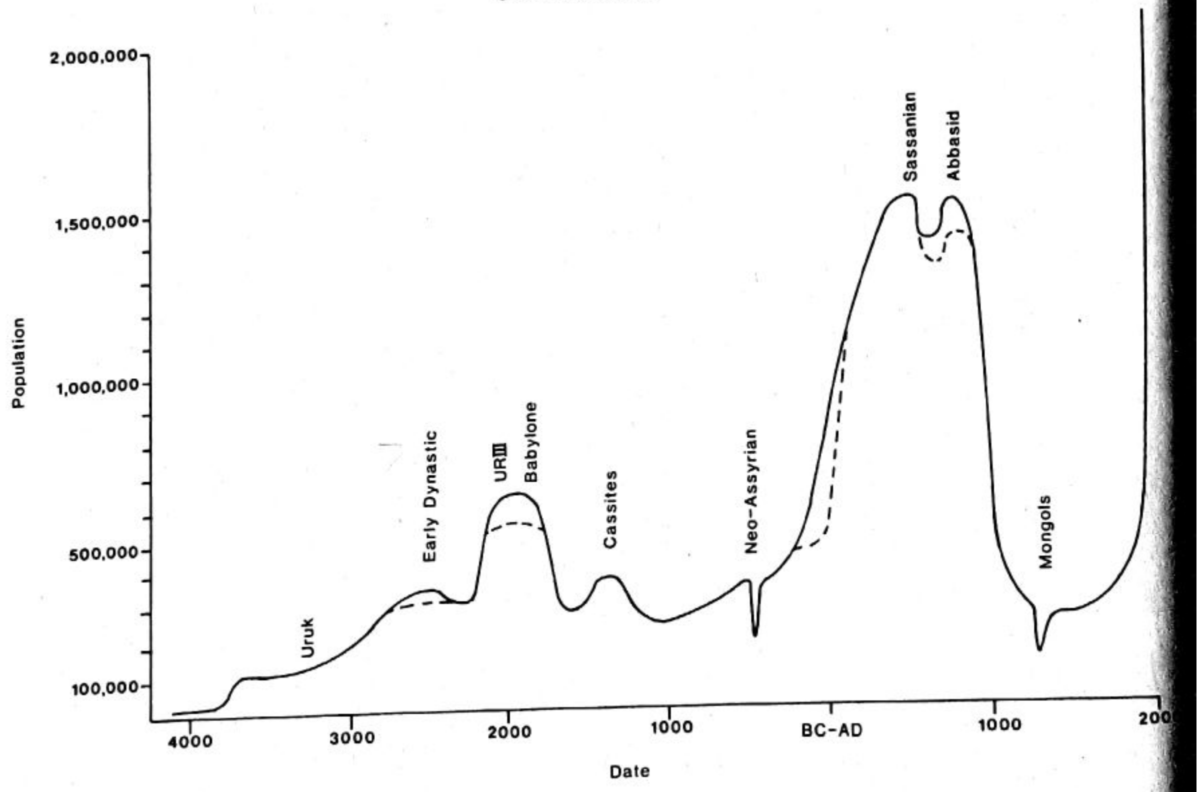
(1977). Another example of exogenous causation is the decline of urban civilisation in the Indus Valley after 1800 BC. This decline may have been due to destructive flooding caused by geomorphological changes (Wheeler, 1968) as well as the removal of vegetation in the foothills of the Himalayas.

External causation is only one part of the process of environmental and social change over long time periods. Internal causes also play a major role, and it is important to emphasise the interactive and multi-causal nature of environmental change. In this chapter, our intention is to explore a case study situation in which not only internal and external causal factors can be differentiated, but also in which changes can be observed over a long time sequence of human occupation. In many areas it is possible that important relationships between climate and society are concealed simply because the period of historical observation is too limited. Moreover, identifying an area in which both internal and external causal factors appear to operate increases the interest and application of the case study. With these considerations in mind, various possible regions were reviewed and the Tigris-Euphrates Valley was selected (Figure 5.1). There are three reasons for this choice:

(a) it is best documented of all possible regions because the existence of clay tablets and the world's first writing system yields direct, although fragmentary, information about society back to 3000 BC;

(b) a major effort in reconstructing the population of the region provides a careful record of population dynamics for 6,000 years. Moreover, much of the spatial extent

Figure 5.1. Historical population levels on the Tigris-Euphrates floodplain (a speculative reconstruction). Dashed lines show plausible alternative reconstructions (Adams, pers. comm., 1979)



of the society is mapped; this reveals the centrality of irrigation, and thus of water supply and climate, to human life;

(c) sophisticated ecological analysis is central to the theories of archaeologists and anthropologists most knowledgeable about the region, and provides a rich base from which to construct hypotheses.

The decision to study this long historic period suggests that a simulation modelling approach, which emphasises the qualitative relationships between the major system components, would be useful. Such an approach makes it possible to bridge gaps in the historic record and to examine the long-term relationships of social and environmental components. Section 1 examines the pattern of population growth and the development of the irrigation system in the study area. In Section 2 we develop a simple model to illustrate the nature of the methodology and functional interrelationship of major system components. A more complex model is described in Section 3. Basic model runs are presented in Section 4 and discussed in Section 5.

1. POPULATION GROWTH AND IRRIGATION IN THE TIGRIS-EUPHRATES LOWLAND

Unlike most parts of the world, where reliable population data are a recent phenomenon, the floodplain of the Tigris and Euphrates rivers, ancient Mesopotamia, possesses a settlement record that can be reconstructed for six millenia. This historical record is the product of a literate, urban civilisation that was based on skilful manipulation of a sophisticated irrigation system. Much of the data base is archaeological in character, and is preserved as a result of the region's arid climate. Mud brick buildings and clay tablets have accumulated layer by layer as settlement has succeeded settlement on the same site, depositing a chronologically dateable network of refuse heaps into which archaeologists have delved for the last hundred years.

The result is a mass of information about society and polity. While more details are known about political events than about social and economic developments, the emerging data base permits a tentative reconstruction of the broad outlines of social history and demography. These reconstructions of population dynamics show that the Tigris and Euphrates lowland has experienced two and a half cycles of population growth and collapse. The population curves reconstructed by Adams (Figure 5.1) depict a series of oscillations of increasing amplitude that indicate decreasing system stability over time. This long-term record of increasingly large population fluctuations makes the Tigris and Euphrates a particularly interesting historical contrast to contemporary visions of exponential population growth.

Rainfall in the Tigris and Euphrates lowland is insufficient to provide a secure agricultural base, and the potential productivity of the fertile alluvial soils of the riverine lowland can only be realised by means of irrigation technology. This technology emerged slowly over the course of centuries as local groups gradually learned to manipulate the water resources available to them. Eventually, local leadership in organising local labour to carry out small-scale irrigation projects was supplemented by temple-based religious leaders who used their religious pre-eminence to coordinate secular activities. The temple storehouse emerged gradually as a central repository for surplus agricultural products. The development of a central storage function increased the importance of a specialised managerial population and its associated mercantile and military groups. These groups assumed a crucial coordinating function in the expansion of the irrigation system and the growth of the population. Over time, fully developed states emerged led by religious or kingly figures with a propensity for conspicuous consumption. This tendency was offset by the bureaucratic role played by the managers of the crucially important, increasingly integrated regional irrigation system (Walters, 1970).

Despite existence of a temporally long record, many lacunae exist. The survival of artifacts is spotty, events are imperfectly recorded, and much of the experience of everyday life is untransmitted to the present. Many events, significant in their cumulative effect but unexceptional individually, pass by unnoted. It is for these reasons that an effort to recreate comprehensively and understand a past society would be illusory.

Our effort is directed toward developing a better understanding of the qualitative aspects of the floodplain's irrigation civilisation. For both social and environmental processes and changes reliance must be placed on data at a scale of a century or longer. Direct physical evidence for the impact of shorter-term events is unavailable (Larsen *et al.*, 1978; Vita-Finzi, 1978), although the last several decades of instrumental records can be used as a basis for establishing the likely magnitude and recurrence interval of such extreme events as droughts and floods (Clawson *et al.*, 1971; al-Khashab, 1958; Rosenan, 1963; Ubell, 1971). Only political events can be dated with some confidence, and even for these there are difficulties (Bottero *et al.*, 1967), such as in the synchronisation of dynastic lists. It is not possible to specify precise quantitative measures for such variables as population growth rates, population size, and variation in stream flow. Rather, it is necessary to rely on fragments of literary data and environmental proxy information for much of our knowledge of events (Kay and Johnson, in press). For this reason, we have chosen a system dynamics type of modelling (discussed in Section 2) that emphasises the qualitative interaction of key variables.

There are a number of possible explanations for societal changes in the Tigris and Euphrates, some of which we have been able to examine explicitly. These explanations can be grouped into two broad categories: (a) those that rely on change derived from forces exogenous to Mesopotamia; and (b) those produced by internal causes. One possible external cause is climatic change. Evidence for climatic change in the last five millenia is scanty, and little direct evidence of the climate history of the Tigris and Euphrates has emerged from the lowland itself. The best data currently available is a recent review by Neumann and Sigrist (1978) of recorded barley harvest dates. This study indicates that harvesting began as much as thirty days later in 600-400 BC than it had a millenium previously. This combination of warmer, drier conditions might have encouraged over-irrigation and accounted for the first archaeologically identifiable case of salinisation. But for most of our climatic reconstruction, we must rely on environmental proxy data widely scattered across the highlands of Anatolia where the Tigris and Euphrates rivers have their headwaters.

Another possible external cause of population decline is invasion by neighbouring groups (Davis, 1949). Both organised states (e.g., Hittites c. 3500 BP) and tribal confederations (e.g., Gutians 4200 BP) episodically contributed to the destabilisation of Mesopotamian society. Often accompanied by the introduction of disease, frequently associated with internal disorganisation and civil unrest, invasions were a significant factor in Mesopotamian history.

Internal factors have also been touted as mechanisms causing collapse. Gibson (1974) has suggested that violation of fallow cycles would quickly lead to increased salinisation and a vicious cycle of lower yields, pressures for shorter fallow cycles, and ultimately collapse of the irrigation system. Since the basic agricultural regime is constructed around fallowing fields in alternate years in order to lower the water table below the plant root zone, any practice that reduced the period in fallow would encourage a rise in the water table. Once salts are no longer leached from the root zone, rapid loss of productivity takes place. The result is a progressive deterioration because declining yields encourage further shortening of the fallow cycle in order to replace the lost production. A crash inevitably ensues.

A second explanation argues for bureaucratic inefficiency as the primary explanation for collapse. In this scenario, leaders and bureaucrats either are ineffectual or excessively demanding. Leadership that can no longer organise labour to counteract siltation and extend the irrigation network, or a king so incompetent that revolt and civil war develop, could destroy the integration upon which the irrigation system depends. Alternately, rapacious demands for taxes to satisfy the aspirations of a privileged class could lead to destructive intensification practices on the part of the primary producers (Waines, 1977). With parts of the system no longer able to receive the water and logistic support upon which they have come to depend, extensive population collapse is initiated.

A third explanation stresses the role of conflict between settled and nomadic society. In this view, it is the conquest of settled folk by pastoral communities that leads to catastrophic collapse. These pastoralists may either be herders who normally exist on the margins of the irrigation system, linked to the settled communities symbiotically through patterns of seasonal grazing and trade, or coalitions of nomads both local and regional. Relations between the two groups have at times been so hostile that the irrigation areas have attempted to defend themselves by the Mesopotamian equivalent of a Great Wall dividing the desert from the sown (Barnett, 1963; Jacobsen, 1953). Any change in the power relationships of the two groups that reduces the ability of the settled population to defend itself effectively could result in conquest by a nomadic group which has only limited interest in maintaining an integrated irrigation system. Thus, nomadic conquest would result in population losses due to both combat and drastically reduced crop yields consequent on a disrupted and poorly maintained post-conquest irrigation network.

These explanations for population fluctuation are examined in IRRIG, our system dynamics simulation model of the Tigris-Euphrates irrigation society. In particular, the impact of climate fluctuations, especially drought, and fallow violation resulting in salinisation are the primary foci of the modelling effort. This exploration of the interaction of population dynamics, environment and technology begins with a simple two level model that establishes the basic relationships between components of the

Tigris and Euphrates irrigation system. Once these relationships are determined, the model is expanded in IRRIG to include a greater array of variables in a more realistic fashion. IRRIG then provides the framework within which we consider several of the major explanations for population change.

2. A SIMPLE TWO LEVEL MODEL

The cyclical growth and collapse of the Mesopotamian population is intriguing, and encourages us to seek a causal explanation. One way of understanding possible causes for this pattern is to develop a model in which all assumptions are made explicit. We adopt a system dynamics methodology which assumes that the persistent dynamic tendencies of a complex system arise from its internal causal structure rather than external disturbances of random events. In this section we summarise the basic ideas of system dynamics[2] and apply them to a simple two level model.

From the point of view of system structure, systems with the same structure exhibit the same behaviour patterns. Since a number of well-known ecological models yield cyclical growth and collapse, it is instructive to study first a simple model which yields this qualitative behaviour. Consider a system for which the total population and the carrying capacity are the two state variables or "levels". The carrying capacity need be only loosely defined as the ability of the society to sustain a corresponding level of population. This definition differs from that normally employed in ecology, where carrying capacity is defined as the ability of the physical environment to sustain a population. Viewed from a more social perspective, ecological carrying capacity is redefined whenever technology devises new ways of deriving support for human populations. In this context, carrying capacity aggregates quantities such as the size of the irrigation system, the amount of available water, the level of stored food, and the organisational abilities of society.

One possible, inherently Malthusian, interpretation of the observed behaviour pattern in the Mesopotamian population is that at low levels of population the society is able to increase carrying capacity at a rate faster than population growth. However, at higher levels of population, growth in the carrying capacity can no longer keep up

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[2] The central concept used in system dynamics is the principle of feedback. Feedback exists whenever there is a closed chain of causal relationships. In a positive feedback process a change in a variable leads to further change and produces exponential growth or collapse. A negative feedback process counteracts a change, and moves the system toward equilibrium or a specific goal. System dynamics models link together many such positive and negative feedback loops. Implicitly associated with this feedback structure are time delays, nonlinear relationships that are also assumed to be important in determining system behaviour. A nonlinear relationship causes the feedback loop to vary in strength depending on the state of the system. Hence, different combinations of feedback loops might be dominant and shift the system's behaviour. A model composed of several feedback loops that respond to each other nonlinearly, and with significant time delays, can exhibit a wide variety of complex behaviour patterns. Since the consequences of such relationships are difficult to understand analytically or intuitively, it is convenient to study such models using computer simulation. Although system dynamics models are frequently written in Dynamo, they can also be written in a general purpose language such as Fortran or Basic.

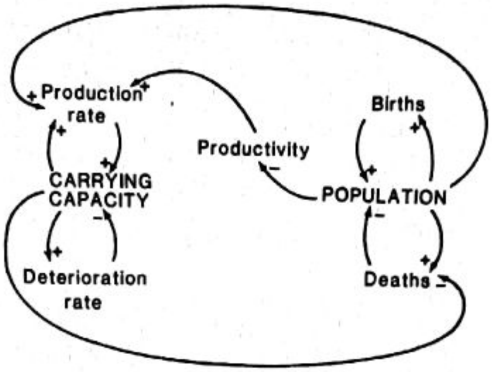


Figure 5.2. Causal loop diagram of simple ecological model

with the growth in population. It then might be conjectured that the society cannot sustain this high level of population and the population falls to a much lower level from which it eventually recovers and begins another cycle.

Possible causal feedback relationships which are consistent with the above description of Mesopotamian society are shown in Figure 5.2. These relationships include positive and negative feedback loops relating births, deaths and population. If the positive feedback loop dominates, the population exhibits exponential growth. The level of population is linked to the carrying capacity by the latter's influence on the number of deaths. Carrying capacity is determined by its production and deterioration rate. For simplicity, we assume that the production rate is proportional to the population. Productivity (increment in carrying capacity per person input) is assumed to decrease with increasing population, and the carrying capacity deterioration rate is assumed to be a constant fraction of the carrying capacity.

A computer simulation model was constructed to make these qualitative causal relationships more explicit. Normal conditions are arbitrarily assumed to correspond to the ratio of population to carrying capacity being near unity. Typical behaviour of the population and carrying capacity is shown in Figure 5.3a. Inspection shows that the growth in the carrying capacity initially exceeds that of the population and that both increase exponentially. However, after about 200 years, the population exceeds the carrying capacity and then falls to a sustainable level. This qualitative behaviour mode, similar to sigmoidal or logistic growth, arises from the linked positive and negative feedback loops that respond to each other nonlinearly, but with no significant time delays.

To understand the observed oscillatory population behaviour mode, we look for the important time delays in the system. Time delays are ubiquitous in dynamic systems and play an important role in stabilizing or destabilizing the system. For our example, it is easy to identify time delays between a change in the carrying capacity and the number of deaths, and a change in the population and the productivity of the resource base. If we assumed that these delays are on the order of ten and twenty-five years respectively, the population and carrying capacity do exhibit oscillatory behaviour as shown in Figure 5.4a. Note that the period of the oscillations (the time between relative

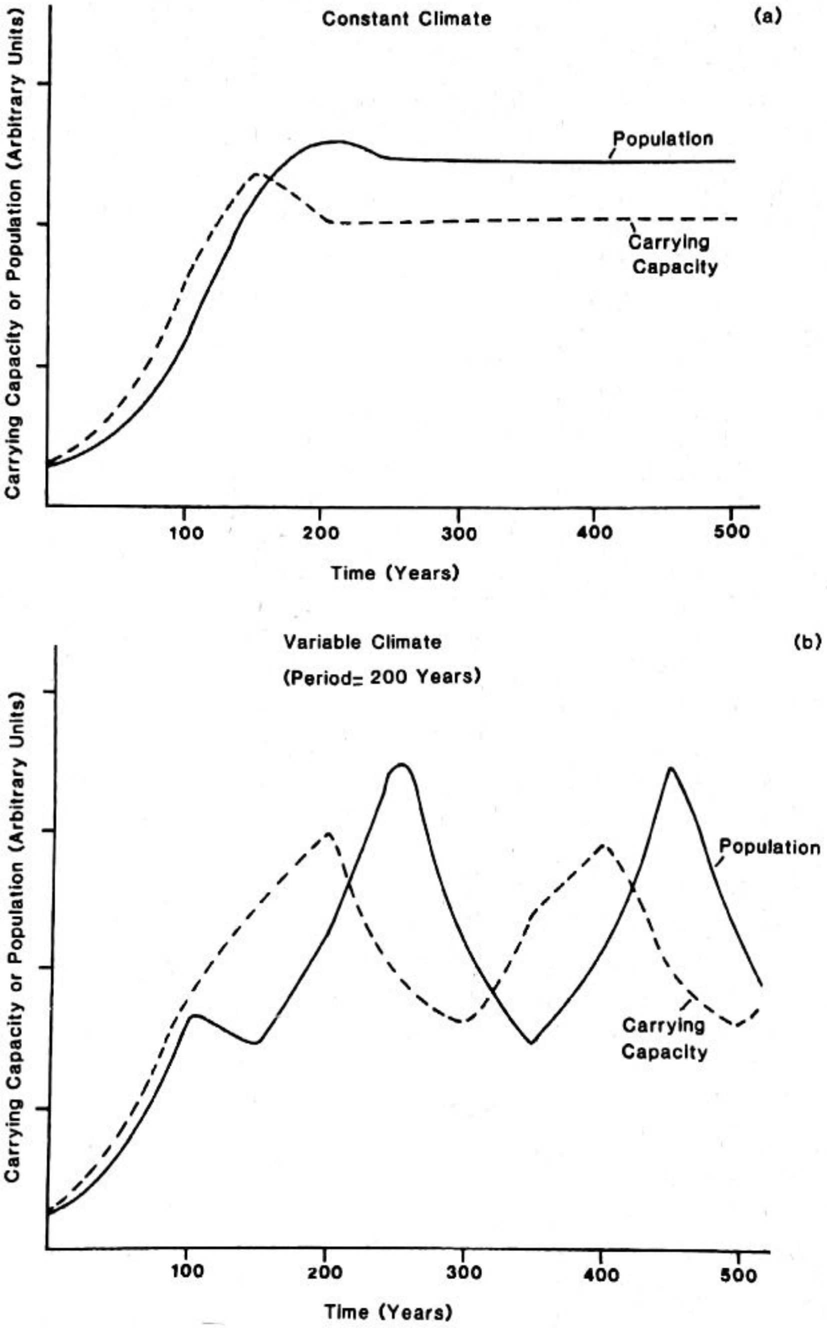
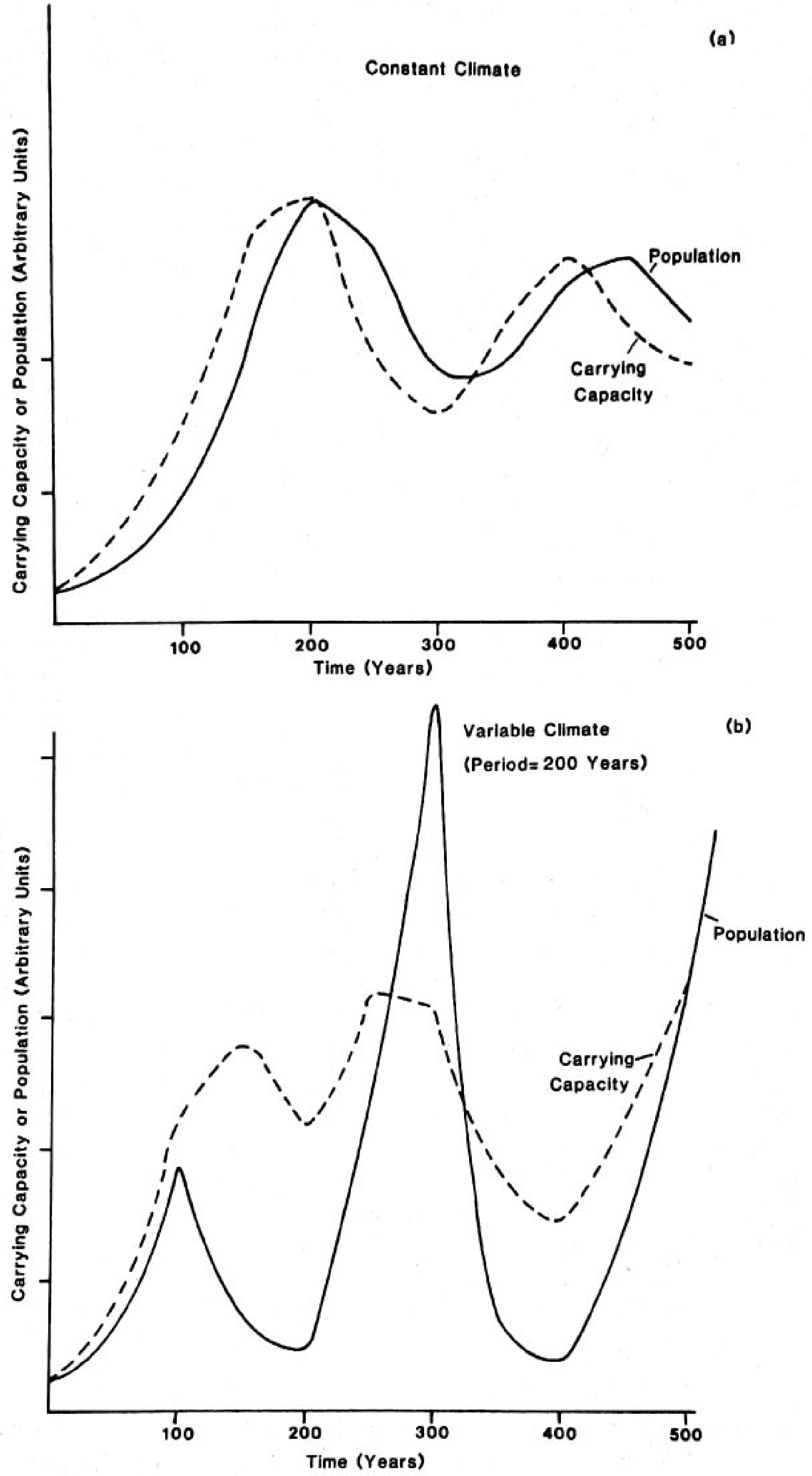


Figure 5.3. Behaviour of the population (solid line) and carrying capacity (dashed line) in ecological model with no time delays: (a) constant climate, (b) variable climate

maxima or minima of the population) is approximately 200 years for the particular values chosen for the numerical constants in the model.

Since we are interested in the effect of climatic fluctuations on society, it is instructive to study the response of our two models to climatic fluctuations. We

Figure 5.4. Behaviour of the population and carrying capacity in ecological model with time delays: (a) constant climate, (b) variable climate



associate climatic fluctuations with a variable streamflow and hence with an externally imposed variation in the carrying capacity. This variation is in addition to the changes in the carrying capacity due to the internal dynamics of the system. Let us assume that streamflow varies sinusoidally, that is, it is characterised by its period and amplitude, and that the amplitude of the riverflow variation is such that it changes the carrying capacity by a maximum of 50 per cent. (The form of the streamflow variation and the magnitude of its amplitude are chosen only for illustrative purposes.) Taking the period of the streamflow to be 200 years, and assuming no time delays, Figure 5.3b shows that the population and carrying capacity oscillate with the same period as the externally imposed climatic fluctuations and that their maxima coincide with the peaks in riverflow. If we reduce the climatic periodicity to 25 years, the population and carrying capacity exhibit unperturbed behaviour modes.

A variable riverflow of 200 year periodicity imposed on the system with time delays, yields the oscillatory population and carrying capacity behaviour shown in Figure 5.4b. Note that population maxima do not coincide with peaks in riverflow. If the riverflow period is reduced to 25 years, there is little effect on the system.

One general observation drawn from these results is that the cause of the observed fluctuations in a state variable such as population may be internal or external to the system. Since frequently the cause is a combination of the two, the peaks in the population do not necessarily coincide with peaks in the external forcing variable. Changes in the streamflow that occurred over a 200 year period were reflected in significant changes in the population. However, changes in climate periodicity that occurred over a much shorter time scale had no significant long-term effect. Such a conclusion is valid in general as long as the external perturbations are small enough in magnitude so as not to cause major changes in system structure.

3. THE TIGRIS AND EUPHRATES MODEL

Our initial success with a simple model encourages us to develop more sophisticated models of an irrigation-based society. In this model (IIRIG), we place our emphasis on internal factors that promote change. The only external causal factor explicitly considered is climatic variation and change. Treating the Tigris and Euphrates as a closed political and economic system is an unrealistic simplification of historical reality. Trade and tribute from non-irrigated areas provided important resources to the sustenance of Mesopotamian life in many epochs. Denial of access to those resources could have serious implications for the stability of the central government, certainly a factor in the long decline of the Abassid Caliphate before its destruction by the Mongols in AD 1258. Similarly, invasions by ephemeral nomadic confederations or by hostile states could, and did, contribute to the disruption of Mesopotamian irrigation systems and the decline of the population dependent upon them. While recognising the role played by such factors, we hold their specific exploration in abeyance for future iterations of the model.

As a first step in developing IRRIG, our model of the Tigris and Euphrates irrigation system, we show some of the basic feed-back loops in Figure 5.5. Most of these are self-

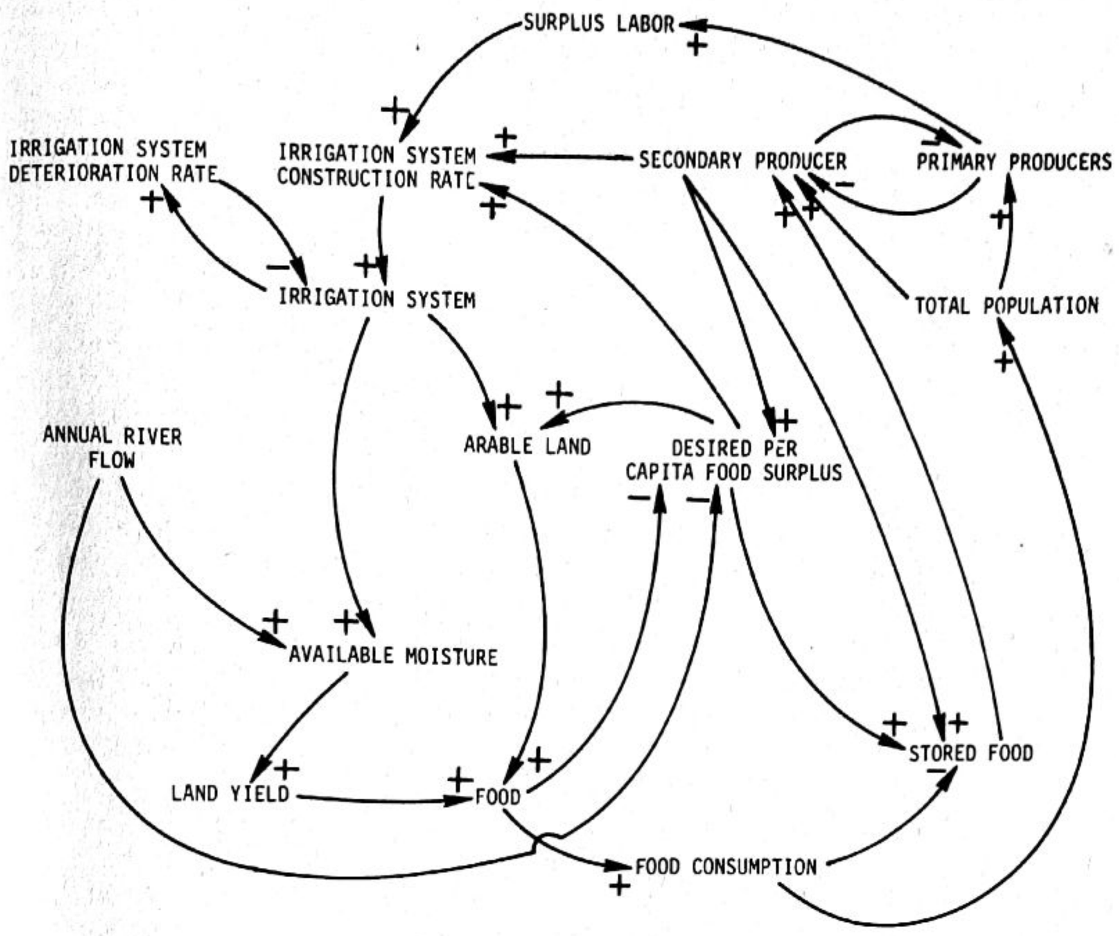


Figure 5.5. Causal loop diagram of IRRIG. a system dynamics model of the Tigris-Euphrates irrigation scheme

explanatory at this qualitative level. The important state variables are population, size of the irrigation system, level of stored food, and the size of the harvest. The latter is affected in part by the available moisture for agriculture and the salinity of the soil. Since the causal loop diagram of Figure 5.5 only includes some of the qualitative relationships, we give in the following paragraphs a more detailed outline of IRRIG. A discussion of the limitations of IRRIG is reserved for Section 5.

The total population is divided into two groups, primary producers who are mainly involved in agriculture, and secondary producers who are engaged in trade, irrigation system organisation, extension and maintenance, the performance of religious functions, specialised artisanal enterprises, and military activities. The irrigation system can exist in either of two states: (a) *disaggregated,* characterised by a discrete series of locally managed units localised along meandering natural stream channels, each unit comprising a small total population; and (b) *aggregated,* where artificially constructed, centrally managed canals integrate local cultivation units into a larger system and larger population totals can be maintained. As indicated below, this division of the population and the irrigation system into two basic types is useful in examining the mechanisms involved in irrigation system expansion.

Two of our fundamental assumptions are that both population growth and the need for a stored food reserve (due to the ever-present danger of variation in available moisture) are mechanisms that promote construction of a more sophisticated and integrated irrigation system. The assumption of these two mechanisms makes it convenient to conceptually separate the total irrigation system into locally- and centrally-managed components. The former is extended and maintained by the primary producers who extend the local irrigation system at a rate that keeps population growth and available food supply in a rough balance. That is, the primary producers increase the irrigated area in small increments at the margin of existing cultivation. Such increases are small in scale, and locally available labour, organised and controlled consensually by local leadership, is sufficient to extend and maintain the local irrigation system independent of the size and of the existence of the secondary producers.

When the expansion of the local irrigation system approaches its technological and managerial limits, there is increasing incentive for the growth of a specialised group in the population. These secondary producers (and the other specialised groups who serve and/or are associated with them) organise and centrally manage an expanded irrigation system. In the Tigris and Euphrates, this specialised elite developed in urban settlements where priests, the servants of the major local diety, performed mediatory and organisational functions that transcended the boundaries of local kin groups. In IRRIG the strength of this central authority at any point in time is represented by the ratio of specialised to primary producers in the total population.

A paramount function of this specialised elite was the development of stored food reserves that buffered the community from the vicissitudes of short-term environmental fluctuation. The existence of such reserves also served as an attractive magnet for peripheral populations whose movement toward the better-endowed centre augmented urban population growth and increased the demand for larger and more secure food supplies. Although only a small proportion of this migration flow would cease to be primary producers, it is by means of such spatial redistribution of population as well as social and economic change that primary producers can be transmuted into secondary and specialised producers or, under altered circumstances, *vice versa.*

In IRRIG, it is assumed that the main goal of the secondary producers is to expand the central irrigation system in order to keep the stored food reserve above a desired minimum level. Their ability to do this is determined by the percentage of specialised producers in society, and by the amount of surplus food already available. The central bureaucracy also has the option of investing the surplus food in more self-indulgent uses rather than in increased food consumption, surplus storage and the extension of the irrigation system.

Feedback between the population and the irrigation system loops is positive since an increase in the irrigation system construction rate due to population growth expands the available cultivated land, makes it possible to tap a greater percentage of water from the main rivers, and hence to increase yields, the size of the harvest and the level of stored food. These increases lead to further increases in population which further spur the rate of irrigation system construction.

In addition to these positive feedback loops, there are several important negative feedback loops in the system. An increase in available moisture can, in the absence of careful control of its application at the field level, set in motion a rise in the water table and an increase in salinity. A substantial increase in soil salinity has a negative impact on crop yields, an environmental management problem well documented in ancient Iraq (Jacobsen and Adams 1958). A decrease in the amount of stored food can also have a negative impact on yields by encouraging violation of fallow (Gibson, 1974). Farmers in the Tigris and Euphrates traditionally have followed an alternate year fallowing pattern that depends on deep-rooted shrubs acting as natural tube wells to draw down the water table. Should prolonged drought reduce the stored food supply below the desired minimum, or should rapacious taxation affect the same result, intensified cropping that kept fields in production for longer periods before being fallowed would be the farmer's only alternative. Higher salinity levels and lower yields would be the inevitable consequence of such practices. These degradational tendencies are likely to appear first in the older, more established components of the irrigation system that have been in production longest. This process of degradation in core areas could contribute both to the search for new technological solutions to water management and to the extension of the irrigation system at its margins into new areas. The consequence of shortened fallow cycles would be the development of a treadmill effect analogous to that afflicting many irrigation systems today (Worthington 1977; White, 1978), where expansionary gains at the margins of the system are offset by losses in the older core areas.

Increases in the amount of cultivated land due to irrigation system expansion not only increase food supply, but they also increase land development costs. Because the best and most easily developed land will be brought into production initially, the cost of developing new land at greater distances from the source river will rise. Such cost acts as a brake on the irrigation system construction rate. Other constraints also act to slow construction. One is the greater labour costs required to dig longer canals from river to undeveloped land with consequent increases in the drain on stored food needed to pay for such labour. Another constraint is the finite amount of water that can be extracted with existing technology from the available water supply. Because we base IRRIG on conditions characteristic of the first cycle of population growth, we hold constant the level of technology available. Subsequent epochs did develop new technologies for increasing the amount of water extracted from the river system, and this represented an important condition for later growth cycles.

Also important is the increased proportion of available surplus stored food that must be channelled from construction into maintenance of the existing canal infrastructure as the irrigation system grows. The model assumes that the deterioration rate can be controlled as long as central authority remains intact and population density remains high enough to provide sufficient labour. It is also clear that the larger the system the more maintenance expenditures become competitive with, and have a negative impact on, the irrigation system construction rate (Adams, 1974).

Since rainfall in the alluvial lowland is insufficient for agriculture without irrigation, streamflow is based on precipitation occurring in the adjacent highlands. Streamflow can be regarded as a surrogate for climatic fluctuation, since any variation in regional climate will produce a concomitant change in available moisture for irrigation. The twenty-five years of instrumental record do not encourage confidence that the full range of streamflow variability is contained in existing data. It is possible to incorporate random variation about the mean into the model to simulate the effect of extreme events. The model also permits testing of the impact of short-term but more persistent variation.

4. MODEL RESULTS

We describe in this section some typical runs of our computer model IRRIG. Because of the assumed finite resource base of the system, an important dynamical question is whether the population will be able to reach a final equilibrium state of maximum size or collapse after a period of initial growth. Of particular interest is the behaviour of IRRIG under constant and variable climate conditions.

Constant climate

The total amount of water flowing in the river per year or the "water supply" is the surrogate for climate in IRRIG. As one test of the relationships in IRRIG, we made a "standard" run for which the water supply does not fluctuate. An established mean streamflow of 6.2×10^9 cubic metres per year is employed, a figure that is consistent with the known instrumental record (al-Khashab, 1958; Ubell, 1971). The behaviour of the total population is shown in the solid line in Figure 5.6. The population and the total irrigation system (not shown) exhibit similar behaviour, and both achieve equilibrium after an approximately one thousand year period of sustained growth. Yields are limited only by the amount of water available for irrigation and not by salinisation. Further growth in the population is constrained by the finite resource base rather than by salinisation or some other internal cause. The model society is able to support a large population by lowering its per capita consumption by approximately 20 per cent from the desired amount. The irrigation system is overextended and hence less than the optimum amount of water is delivered to the fields. Although fallow is violated, salinisation does not develop since the fields are underirrigated. The organisational structure of the society shifts increasingly away from local control to centralised management of irrigation system construction and maintenance.

Variable climate

Several runs of IRRIG were made with a variable water supply which is assumed to vary randomly about its mean with a persistence time of approximately 50 years. The mean value of the water supply is equal to that assumed in the constant water supply run described above; the standard deviation from the mean is assumed to be thirty per cent of the mean. These values for persistence time and standard deviation are taken for

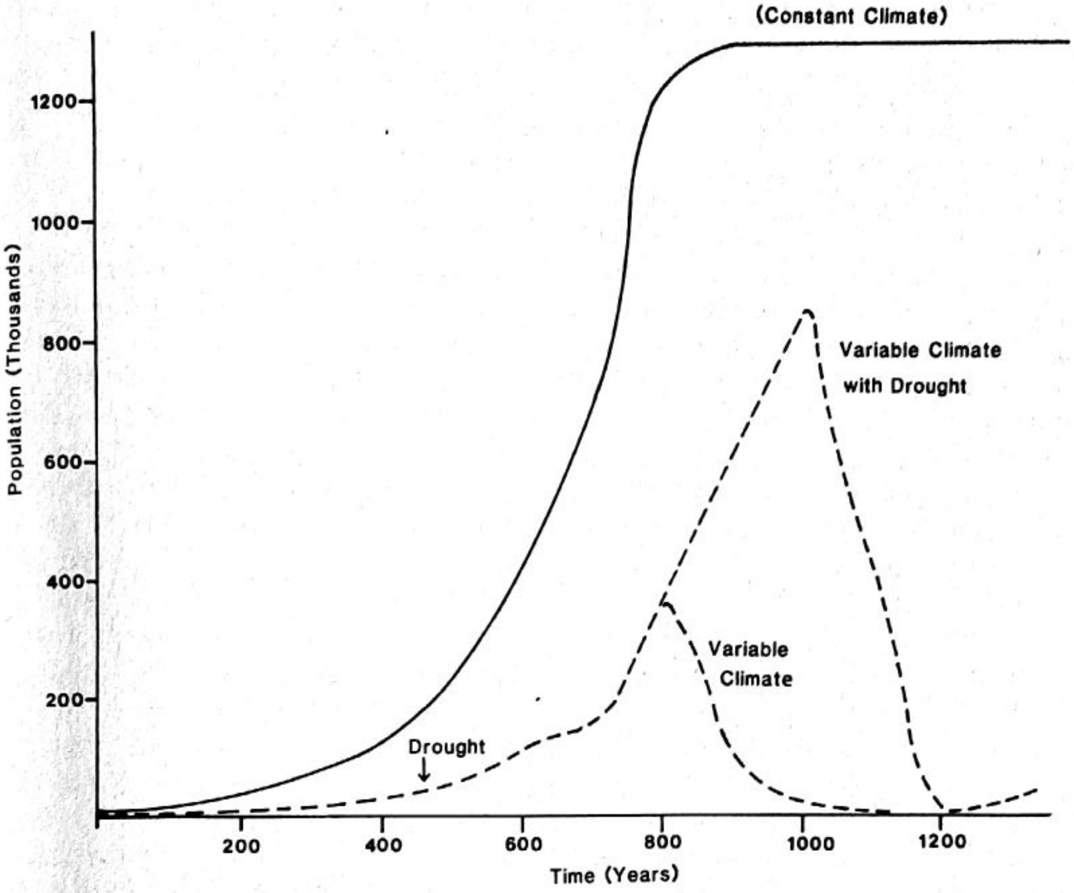


Figure 5.6. Behaviour of the population in IRRIG *under varying climatic assumptions*

illustrative purposes only, since the period of instrumental record is too short to produce meaningful data.

Two representative examples of the behaviour of the population for different variable climates are shown in Figure 5.6 (dotted lines). In the "non-drought stressed" case the climate varies as discussed above. In contrast, the water supply in the "drought stressed" example has a ten-year drought imposed at year 500 in addition to the fluctuations in the water supply that occur in the non-drought stressed case. Hence the differences in the water supply between the two examples occur during the years 500-510. The water supply is at least 30 per cent below the mean in all ten years of the drought stressed run, but is below the mean in only seven out of the ten years of the non-drought stressed run. Note that the drought occurs during a period of population growth.

The behaviour of the population in both variable climatic runs (Figure 5.6) is similar — a period of growth followed by a rapid collapse. The behaviour of the irrigation system, which is now shown in the figures, is similar. The population and irrigation system behaviour mode of growth and collapse for variable climate is in contrast to the sigmoidal behaviour mode obtained for constant climate. Clearly the addition of variability in the water supply is enough to change the system's behaviour dramatically. In addition to the different behaviour modes, the rate of initial growth of the population is, as might be expected, less for the variable climate than the constant climate runs.

Although the population does exhibit similar qualitative behaviour in both variable climate runs, the population does show a longer period of sustained growth in the drought stressed case. Population in the drought stressed run rises to a maximum of 960,000 people at year 1025 rather than the maximum of 270,000 people at year 800. The explanation for this result is that the drought was imposed at a time when sufficient food resources were available. Thus, although the food resources were lowered by a factor of two in the following twenty-five year period in order to maintain adequate consumption, there were sufficient reserves remaining to allow the central bureaucracy to expand the irrigation system and to replenish the depleted food resources. At year 800 when the non-drought stressed population shown in Figure 5.6 begins to collapse, the population of the drought stressed run has 50 per cent greater food resources and is better able to sustain itself.

We now determine the specific scenario for the collapse of the population and the associated infrastructure. As can be seen from Figure 5.6, the non-drought stressed society at year 800 had a population maximum of 370,000 people, a population much below the resource-limited maximum of one million people assumed in the model. Not shown in Figure 5.6 is the fact that at this time there were approximately 2.5 years equivalent of stored food, although the stored food resources had decreased slightly for the previous 100 years. The water supply is slightly greater than normal during the 200 years before year 800 and dips to slightly below normal during the succeeding 25 years. This slight change is not sufficient to cause a collapse in the population by itself. However, the decrease in the water supply is sufficient to cause the food resources to decrease further and to cause the strong central bureaucracy to extend the central irrigation system (now about 80 per cent of the total system) to maintain reserves. This extension of the irrigation system lowers the food reserves even further and causes the primary producers to violate fallow. Unfortunately, this violation of fallow leads to rapidly developing salinity, decreased yields, and a destitute population. The central bureaucracy collapses and the central irrigation system is no longer maintained properly. The collapse of the central irrigation system leads to reduced yields and the downward trend becomes greater still.

Since the drought stressed society had greatly expanded its irrigation system during the imposed drought of years 500 to 510, it had greater resources during year 800 and thus was not vulnerable to collapse. The scenario for the collapse of the population in Figure 5.7 beginning at year 1025 differs from that given above for the non-drought case. In this case the population of 960,000 people is at its assumed resource limit. The food reserves were now reduced to less than one year and yields were low because of the inefficiency of the irrigation system at its technological limit. In this case the cause of the collapse is more direct. That is, a drop in the water supply to about 75 per cent of normal causes a decreased yield, starvation, and a collapse of the central bureaucracy. Collapse of the central bureaucracy then leads to a lack of maintenance in the central irrigation system. Salinisation is never a factor since the society is short of water.

Several other runs of IRRIG were made for other assumed climate conditions. For example, a ten-year drought was imposed at year 850 in addition to the fluctuation in the water supply discussed above. As can be seen from Figure 5.6, this drought occurred during a time of population collapse. Since the immediate cause of the collapse was reduced yields due to salinity, the short-term response was a pause in the collapse of the population. That is, less water for irrigation led to reduced salinity. This pause was only temporary and the population then continued its collapse. Other runs were made with a reduced mean water supply. As expected, the initial growth in the population decreased as the mean was reduced until a point was reached at which the population remained constant.

We emphasise that the above scenarios are only qualitative in nature. In all of the runs the model exhibited a high degree of instability, e.g., the rates of growth and collapse were more rapid than might be expected from our discussion in Section 3. This behaviour is in part due to our decision in the analysis to exaggerate the importance of various causal mechanisms. However, the behaviour modes of the model are sufficiently analogous to those observed historically to give some confidence that the model's qualitative relationships are reasonable.

5. DISCUSSION

Two general conclusions emerge from IRRIG. The first insight that the model offers is that, within the constraint of a fixed resource base, climate variability leads to collapse, whereas climate constancy encourages an equilibrium state. A stable equilibrium results when there is a fixed resource base where all other factors are held constant. The constant climatic run contains the same negative feedback loops as do the variable climatic runs. In the constant climatic scenario, positive and negative feedback loops are in balance and population approaches equilibrium with only a light overshoot. However, the system is finely balanced. Once climatic variability is added to the array of existing negative stresses, the achievement of population stability proves an illusory objective. Instead, climatic variability enhances the intensity of negative feedbacks and increases their impact on society. The result is a population oscillation in which time delays retard but cannot remove the impact of negative environmental fluctuations.

A second conclusion that can be drawn from IRRIG is that extreme climatic events can stave off or encourage population collapse. The key variable is the timing of the extreme event in relationship to societal well-being. Beneficial consequences, e.g., enhanced social stability and population growth, result when drought and adequate stored food reserves occur simultaneously. If these conditions also coincide with a period of general population growth and environmental prosperity, then the positive consequences are enhanced. The possession of sufficient surplus stored food reserves enables society to respond to drought by extending the irrigation system. Stressful events and existing coping strategy allow society to attain a population total greater than in other variable climatic runs in which no additional drought was imposed. The reason for this positive effect lies in the stimulus provide to increased infrastructure development. The new irrigation system additions better prepared the society to cope with future reverses by increasing total yields and by enhancing stored food capacity.

Nonetheless, the long-term behaviour of the variable climate system under both drought stressed and non-drought stressed conditions remains the same. A long period of population growth and irrigation system expansion is followed by a subsequent collapse. In a long-time series the disappearance of short-term drought impacts is not surprising; they are simply absorbed into the larger patterns of events. This does not mean that such short-term events are unimportant. On the contrary, they may have a significant impact on society if they happen to occur during times of low food reserves, an over-extension of resources, and bureaucratic decline. Only rarely does the broad outline of these short-term events appear in the historical record, and they are not specifically tested in the present IRRIG runs.

The positive short-term response to drought described above occurs in part because of the explicit assumption in IRRIG that a goal of society is to maintain stored food reserves at some fixed level. Such a goal is desirable whenever there is a past history of food supply shortfalls. That is, the incentive for the establishment of an appropriate level of stored food reserve also depends on the presumptive demands of the privileged segment of society (the secondary producers). These demands give secondary producers preferential access to the food reserves that they help to create and that they largely control. Thus, the inclusion of a fixed rather than a variable goal for desired stored-food reserves omits an important dynamical aspect of society. The assumption of a fixed goal is made in order to simplify the analysis and should be modified in future work.

IRRIG does not include the option of incorporating resources from outside its geographical area. These resources often were very important to floodplain society. Deficient in timber, stone, minerals and precious metals, the riverine states produced both finished goods (tools, jewellery, cloth, etc.) and agriculture commodities (dates, rice, etc.) that were unattainable in the cooler and moister neighbouring uplands. Patterns of trade, raid and tribute emerged to provide access to these desired commodities. The investment of resources obtained (often by forced tribute or taxation) from outside the floodplain was an important feature of lowland political economy that is not included in the structure of the IRRIG model. This restriction on the resource base in IRRIG also sets an upper limit to the total amount of water that is available to the irrigation system from the floodplain rivers. The irrigation technology is also assumed to be constant, and this limits the percentage of available water that can actually be extracted by the irrigation system. The introduction of technological innovations, such as lift devices, would increase the water-use efficiency of the irrigation system and improve its ability to cope with fluctuations in available moisture. However, the absence of a provision for technological innovation is reasonable for the first cycle of population growth and decline that is represented by the IRRIG model.

Restrictions on the resource base and the irrigation technology imply that there is a finite amount of water and hence an upper limit to the size of the population that can be supported by the irrigation system. These limits increase the vulnerability of the society at a point when these limits are reached. Historically, irrigation civilisations in the Tigris and Euphrates lowland were able to reduce their vulnerability to environmental risk by gaining access to outside resources by trading activities or by military conquest. The result of this integration was that many floodplain societies reduced their vulnerability by the buffering effect of stored reserves accumulated from outside the territorial limits of the irrigation system itself. In this sense, the increased security of lowland society was purchased by the export of that risk onto surrounding populations. The absence of these options in IRRIG detracts from its realism; increased agricultural intensification on existing arable land is the only mechanism which the model employs.

At a scale of centuries and millenia, it is not possible to discern specific incremental changes in vulnerability to disruptive, recurrent climatic events, like drought. Only broad relationships, as they become evident over long periods of time, can be established. However, we can assume that particular mechanisms for lessening societal vulnerability have been adopted, as, for example, through increased food reserves, expansion of the irrigation system, centralisation of irrigation system control, and innovations in water management and distribution technology.

In IRRIG, two adaptive mechanisms are incorporated. First, we assume that there is a fixed goal of accumulation of stored food or surplus to provide the community with protection against frequent seasonal or annual shortfalls. In particular, we assume that food storage is the major societal buffer against recurrent drought and flood events and depends on the past experience of the society. The second adaptive mechanism is the establishment of a centrally organized irrigation system. Although total destruction of all of the small local irrigation systems along the river would be unlikely, any one local irrigation system would be vulnerable to total collapse. Linking together small irrigation units has short-term adaptive value and leads to a more regular water supply and better yields. The result is a positive feedback loop in which the greater surplus generated by the irrigation system provides additional resources. These resources are invested in further irrigation system expansion by supporting the central bureaucracy and the labour costs of maintenance and construction. This expansion of the local resource base, and its integration into a larger, more hierarchical organisation, is supported by the available archaeological and historical record. As discussed in Section 4, the model runs do indeed demonstrate the adaptive value of this mechanism: the expansion of the irrigation system provides the resources with which to support continued population growth over a sustained time in spite of a variable food supply.

These relationships raise the issue of whether or not the increased integration and organisation required by the adaptive mechanisms lead to greater societal vulnerability to large magnitude, infrequent events. For example, once the irrigation-based society develops an integrated water management system, changes in the upstream areas have enhanced impacts on downstream groups. Thus, severe climatic-related impacts in one area might produce serious adverse consequences elsewhere in the region. Do mechanisms which insulate the society from relatively frequent climatic, political, or economic disturbances imply a greater potential for catastrophe from rare, extreme events in the future?

Once stress in the form of a variable climate is introduced in IRRIG, society responds to mitigate its effects. Better and more integrated water management produces higher yields and food surpluses which support a larger population. This larger population in turn provides the labour to enhance system productivity and efficiency. For nearly one thousand years the overall population trend is progressively increasing. These adaptive strategies prove to be counter-productive, for under variable climate conditions collapse ultimately occurs. However, further work needs to be done to identify which adaptive strategies are most likely to contribute to catastrophic collapse. For instance, the relative impact of a ten-year drought on a centralised as opposed to a decentralised society could be determined. The relative merits of a large or a small food reserve could be assessed under conditions of extreme drought. By working out such scenarios one-by-one, both the mechanisms which lessen vulnerability, and their relationships to the potential for catastrophe, could be explored.

Climatic variation by itself is not the sole cause of catastrophe, since in the model runs the imposition of an earlier, intense ten-year drought had no effect on the population. But an external forcing variable such as climate can have a catastrophic impact on society during a period of internal stress. A cascade of misfortune (Post, 1977) then sets in. A scenario of the process might be as follows. The system created to cope with the anticipatable shortfall in available moisture, proves incapable of dealing with a new constellation of events. A rapid shift to a new system with smaller population, localised administration, less stored food, and greater vulnerability to recurrent environmental impacts emerges. This decentralised system is able to survive extreme events at the cost of the heightened vulnerability of individual components to more frequent occurrences. This benefit is insufficient to prevent future generations from attempting once again to pursue the remembered golden epoch of increased security from everyday hazards that the integrated, centrally managed irrigation system represents.

Additional questions are also generated by the development of the IRRIG model. A question that merits further consideration concerns the primary motivations for the development of the irrigation system. Far more theories have been offered to explain collapse than have been developed to elucidate the initial growth of an integrated irrigation system. Present explanations (Redman, 1978) stress multiple feedback processes associated with the rise of urbanisation, the beginnings of the state, and the inception of social stratification, but specific causal mechanisms remain obscure.

What is the role of non-irrigation based resources in buffering the floodplain irrigation system? To a certain extent this question is a consequence of assuming that the lowland floodplain was a closed system. The taxes generated from peripheral provinces, the products essential to the floodplain economy derived by trade, and the booty brought home by conquering warriors were not accounted for in IRRIG. Neither the role of animals as food storage buffers in the sedentary community, nor the complex exchanges of people and animals between nomadic pastoralists and irrigation farmers are explicitly acknowledged by IRRIG. It is possible that the resistance of the integrated irrigation system to catastrophic shock would be greatly enhanced by the inclusion of such factors.

Finally, is there a relationship between climatic variability and the size of a society's stored food reserves? Does greater variability encourage provision for greater stored food supplies, either in central granaries or on the hoof? When does such storage become counterproductive, placing excessive stress on the production system and the environment that sustains it? The answers are unclear.

It is evident from the above discussion that the mechanisms for collapse in complex systems are not unicausal and differ depending on various factors. Hence it is not surprising that there are a number of differing theories for collapse. All may be correct in the sense that they may be relevant at one time or another. The problem is to determine which theory, or combination of theories, is correct for which society at what time.

Note: This chapter was completed without the benefits of new insights into the patterns of human settlement and land use in Mesopotamia recently published in *Heartland of Cities* by Robert McC. Adams, (1981) University of Chicago Press, Chicago.

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Author Index

Subject Index

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