MITIGATION OF FLOOD RISKS: THE ECONOMIC PROBLEM

Thesis submitted for the degree of

Ph.D.

In

Environmental Economics and Environmental Management

By

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May 2005

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Chapter 1

Introduction: Flood Risk Management in the Context of Flood Economics

1.1 Tradeoffs in flood risk management

Mitigation of flood risks is one of the purposes of the European Water Framework Directive. The effects of mitigation may also affect the aquatic ecosystems, sustainable water use, water pollution, and droughts, which are addressed in other parts of the Directive. Catchment Flood Management Plans in the UK concern not only multiple-objective management but efficiency improvement in flood management based on catchment-based strategies. The plans incorporate both flood defences and land use in flood management that will be taken into account in this thesis.

Most studies of flood risk consider the problem as a technical issue that mainly involves hydrology, engineering and geography. Many of these studies outline the temporal and spatial features of flood events and modify flood impacts, but few consider the susceptibility of individuals, the capacity of society to mitigate flood risks, impacts on environmental health or on the economy related to flooding, or the interaction between regions.

Without considering the underlying economic and social factors, flood management may be both ineffective and inefficient. Economic analysis hence serves a need. Economics is a science that analyses human choices. The economists' challenge in this case is to evaluate the economic and environmental capacity of a region and to alleviate the perceived difficulties within given constraints in an efficient strategy. In particular, economic analysis can be applied to address the tradeoff between development and averting behaviour, and that between economic gains and flood risk.

This thesis aims at modelling the anthropogenic drivers and responses to flood risks. Tradeoffs occur both between economic development of floodplains and flood risks, and between environmental change in catchments and flood risks. An integrated approach that covers both hydrology and economics enables us to identify these tradeoffs and their implications for policy.

This chapter first addresses development and averting behaviour on a flood-prone area. It then raises the issue of flood risk externalities and methods for internalising them. Following that it discusses the related problem of the public good nature of averting behaviour. The final sections describe the aims of the thesis and outline its structure and content.

1.2 Development and averting behaviour in a flood-prone area

Flooding, associated with extreme precipitation, brings disturbance to both natural and human systems. Directly, it threatens human lives, and causes damage to industry, transport, buildings and properties. Indirectly, it can be a cause of dislocation, famine, waterborne diseases and structural changes in local industries. According to the world's largest reinsurer, Munich Re, storms and floods dominated the fatalities of natural disasters in the year 2001. Floods accounted for more than 2/3 of the 700 major disasters in that year and caused 91% of all insured natural disaster losses (Munich Re Group, 2002).

In the UK, flooding is not a regular threat. However, some flood events occasionally cause serious damage. For instance, the 2000 (autumn) flood in central and eastern England caused 300 million pounds of property loss (Environment Agency, 2004). Elsewhere, flooding can be more frequent and severe. In Taiwan, for instance, flooding is the most frequent natural disaster. According to the Ministry of Interior, there have been 35 floods recorded (excluding those related to typhoons), an 899 death toll, 468 people missing, 1,021 injuries and 49,626 houses damaged from 1958 to 2000 (http://www.wra.gov.tw/default.asp). Moreover, the frequency of floods has tended to increase over this period (Figure 1.1).

In spite of the damage flood events can cause, development on

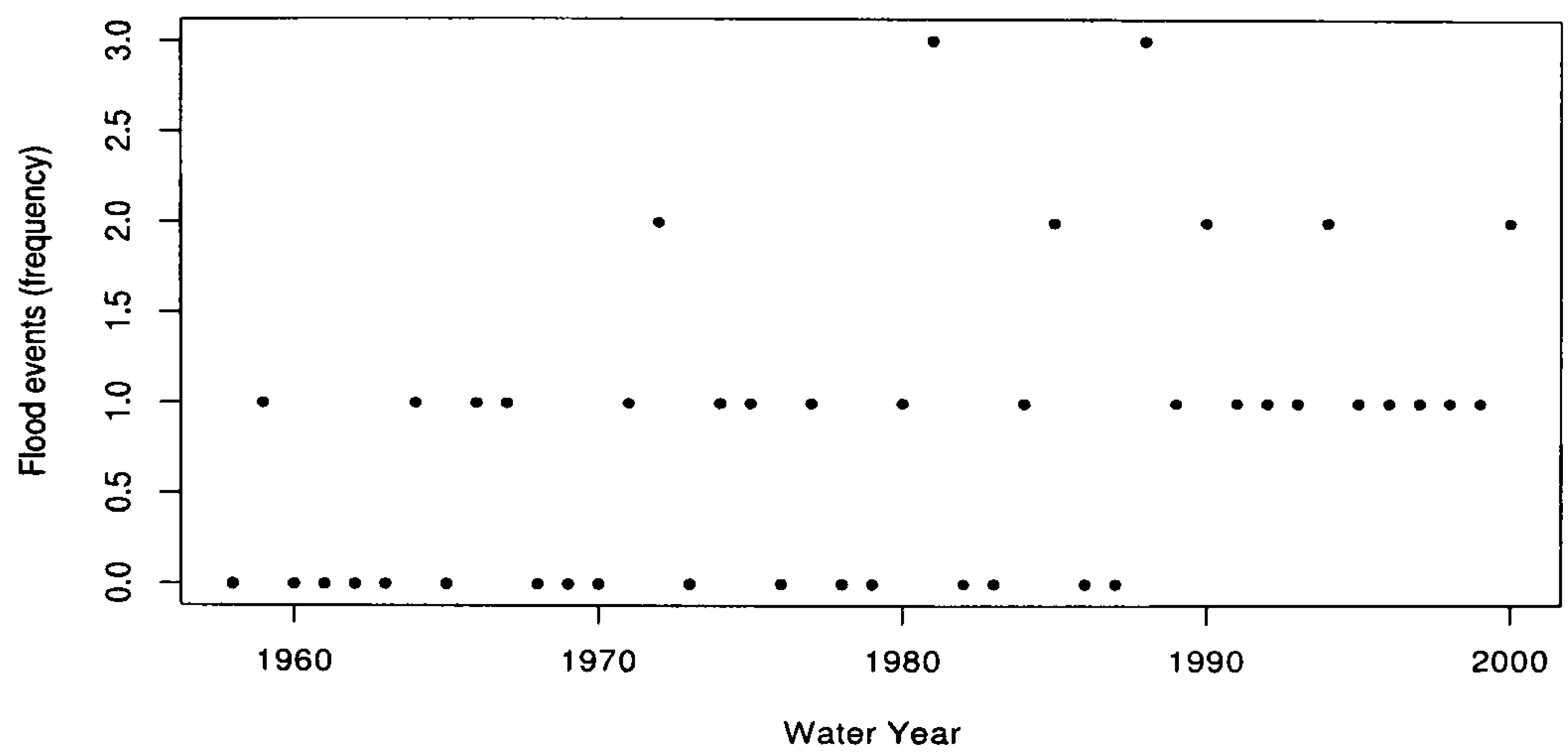


Figure 1.1: Flood events in Taiwan (1958-2000). Data source: Ministry of Interior in Taiwan. http://www.nfa.gov.tw.

floodplains has a long history. In many places around the world, flooding is essential for both economic and ecological performance by replenishing soils and soil nutrients, regenerating plants and aquatic biota, and by recharging aquifers. Floodplains are inclined to contain more fertile soil and to retain more water moisture than other areas. Examples include the granaries along the Yellow River (China), the Nile River (Egypt), the River Ganges (Bangladesh and India), the River Tigris and the River Euphrates (Iraq). Before the introduction of fertilisers, flooding was often essential to soil enrichment. For some areas, flooding is only a disaster if it fails to occur. Floodplain ecosystems are often rich in biodiversity and high in biomass.

Development of floodplains increases both the occurrence and the costs of flooding (Wolman, 1967; Leopold, 1968; Gregory and

Walling, 1973). The occurrence of flooding increases due to the declining infiltration capacity of the land. In this case, flooding becomes an indicator of the impacts of human activities as well as meteorological, topographical and geographical characteristics. Economically, low land prices in flood-prone regions and the increasing demand for land encourage development in flood-prone areas. Up to 2002, 12% of land dedicated to residential use in England is located in flood risk areas. Regionally, residential land located in flood risk areas in East Midlands, East of England, London, respectively are 21%, 18% and 17%. Yorkshire and the Humber is fourth place, at 16%. Figure 1.2 shows that the percentage of land at risk of flooding in each administrative region in England varies widely (Office of the Deputy Prime Minister, 2004).

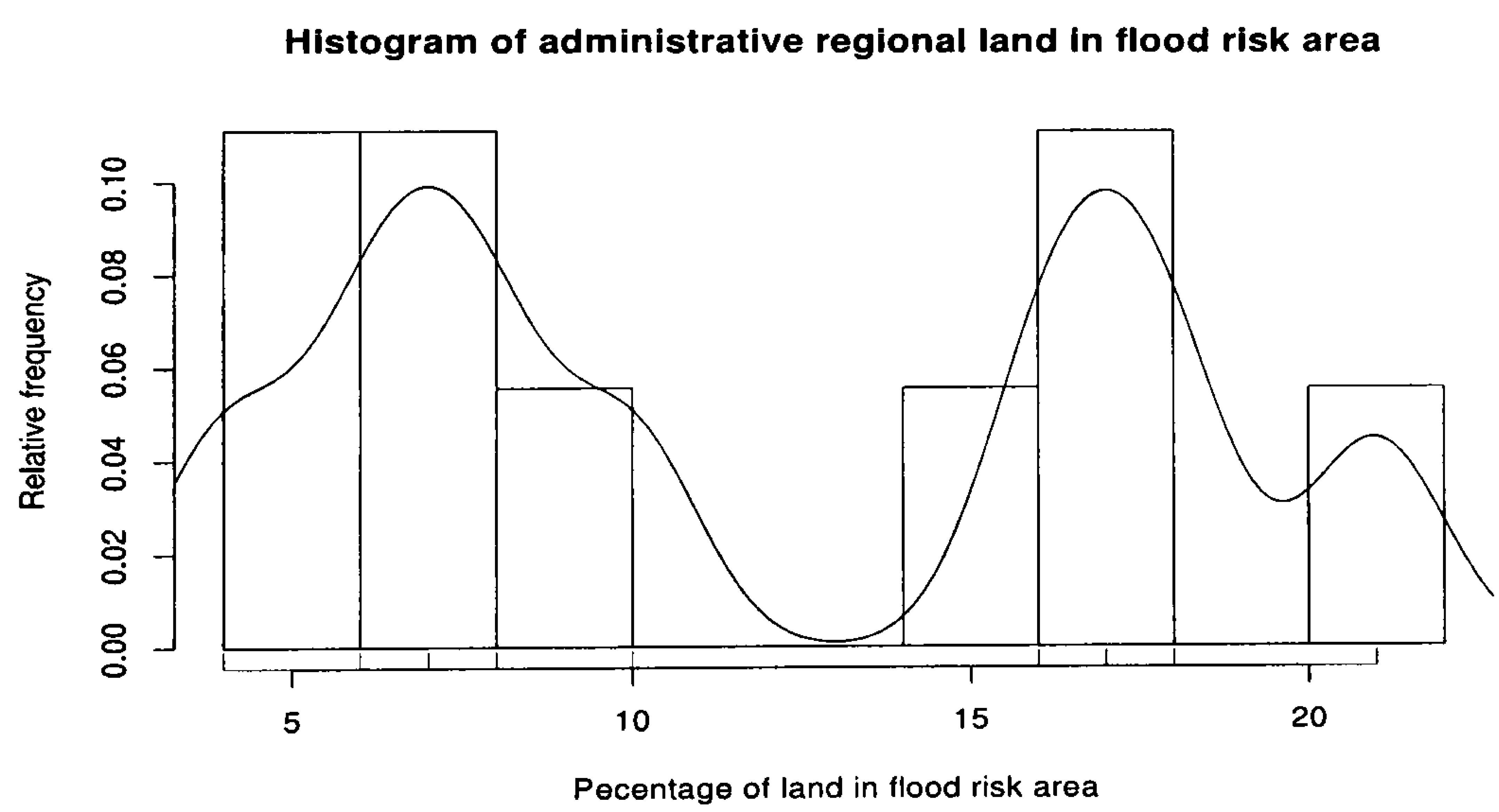


Figure 1.2: Histogram of the percentage of land at risk of flooding by administrative region in England (2002). Data source: Office of the Deputy Prime Minister (2004).

As already indicated, flooding does not necessarily involve damage. Whether it is benign or malign to an area depends on the quantity and the quality of water that runs into and out of a region. Besides, averting behaviour can be undertaken to minimise flood losses and hence the cost of development of floodplains. There are two types of averting behaviour: mitigation for decreasing risks and adaptation for decreasing losses.[1]

Mitigation strategies such as embankments, drainage, washlands, natural buffers and land use management are adopted to reduce flood risks. Adaptation strategies such as purchasing insurance, improving technology for increasing production, and migration are adopted based on experience (*ex post*) and expectation (*ex ante*) to decrease flood losses. Currently around 0.03% of GDP is invested annually in flood defences in UK.[2] Elsewhere, flood defense investments are rapidly increasing. To take the example of Taiwan, already mentioned, Figure 1.3 shows the trend in levees, revetments and spurs/dykes to mitigate flooding. Since averting behaviour involves costs of construction and maintenance, there exists a problem of balancing the development and averting behaviour in flood-prone areas.

In order to manage flood risks, decision rules that evaluate the

[1]They are called mitigation and insurance (or prevention) and cure in Chichilnisky and Heal (1993); self-protection, self-insurance and market-insurance in Ehrlich and Becker (1972).

[2]In the UK, GDP was 994,037 billion sterling at current price in 2001 according to United Nation. Expenditure in England and Wales on flood and coastal defence capital and maintenance works is approximately 335 million sterling per annum (OERA, 2001).

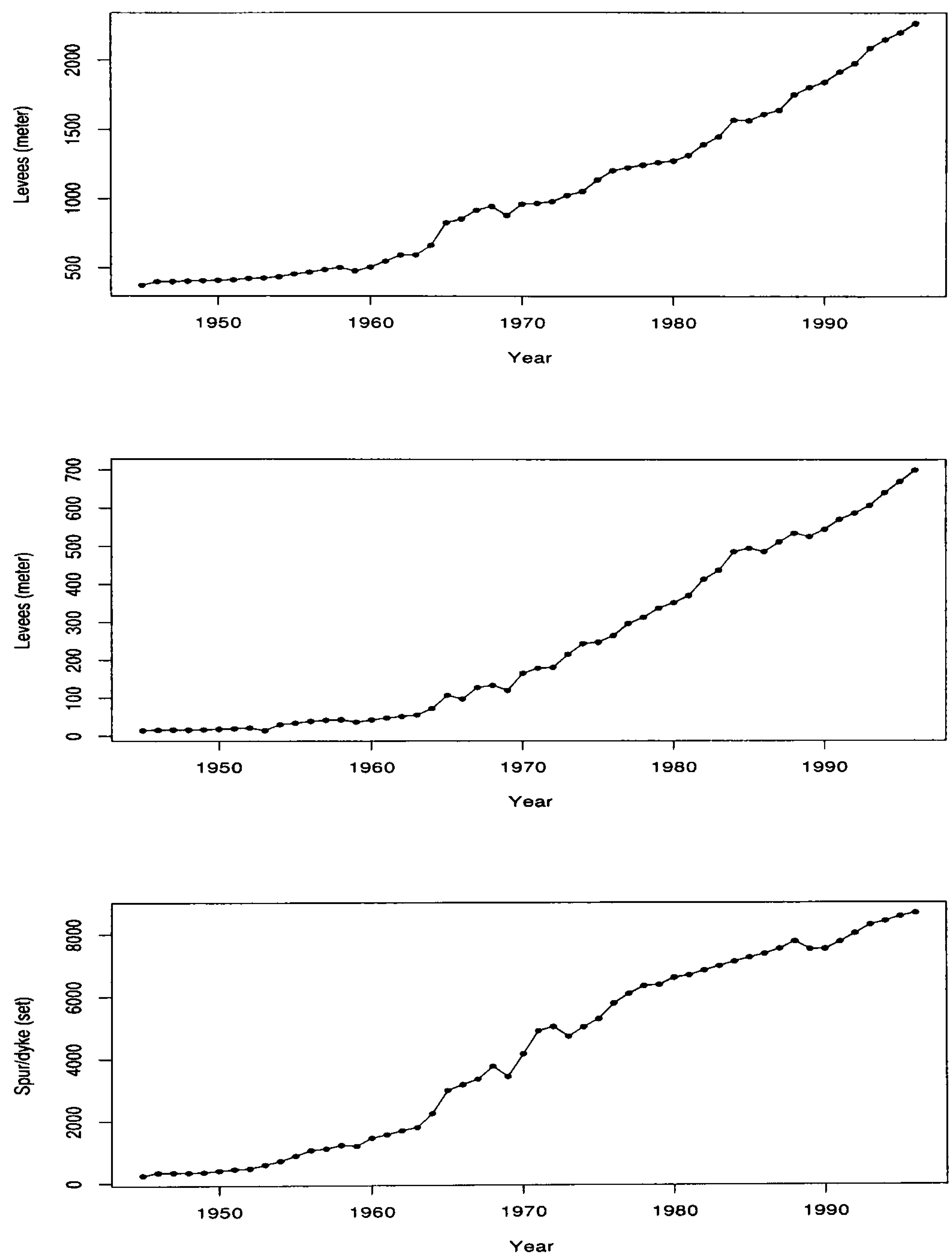


Figure 1.3: Top: Existing levees in Taiwan (1958-2000). Middle: Existing revetments in Taiwan (1958-2000). Bottom: Existing spurs/dykes in Taiwan (1958-2000). Data source: Statistical Reports of the Water Resources Agency at Ministry of Economic Affairs in Taiwan. http://www.wra.gov.tw/default.asp

multiple effects of economic development, averting behaviour and mitigation should be derived. Chapter 2 identifies the key issues in flood management and derive the decision rules. It focuses on the links between economic development and the causes and impacts of flooding. Optimisation theory is applied using models of the tradeoffs in flood risk management in Chapters 3 and 4.

1.3 Flood risk externalities

In the absence of complete markets, development and averting behaviour both involve flood risk externalities. For instance, upstream deforestation or drainage improvement may lead to an increase in downstream flood risk. The externalities in this case are transferable in both temporal and spatial dimensions.

Temporally, current flood losses often trigger future investment in averting behaviour. Moreover, a flood event can also affect future flood events by changing the geomorphological conditions, such as changes in river routes and destruction of vegetation. Besides, in some areas, a stable frequency of flooding brings ecological and agricultural benefits.

Spatially, development and averting behaviour can generate externalities to the neighbouring and downstream areas in the catchment. Adverse externalities are mostly generated by upstream or neighbouring development and hard mitigation (e.g., embankments and drainage) while beneficial externalities are mostly generated by upstream or neighbouring soft mitigation (e.g., washlands and natural land cover).

Therefore, a long-term perspective is required for flood management. Decisions within the long-term perspective are addressed via a dynamic model in Chapter 4 while those related to the strategic interdependence of interest parties are explained in a game theoretical model in Chapter 5. Due to the interdependence among decision-makers located within the same catchment, mechanisms for internalising externalities are essential to improve efficiency.

1.4 Managing public goods

One reason for the failure of markets in flood management is that averting behaviour is a public good. For instance, while the adverse externality generated by hard mitigation often results in an embankments race, the beneficial externality generated by soft mitigation is often compromised due to free-riding. Even though each decision-maker is aware of the problem, insufficient resources will be committed to soft mitigation. Policy instruments to internalise externalities include quantity controls, price controls and a mixture of both. To identify the problem and the potential solutions, we consider three models.

The first is the comprehensive management model. This is a 'rational' device which produces a policy that aims at achieving the desired goal by inputting all relevant data. In the field of environmental management, an interdisciplinary, holistic and long-term perspective is required. This model is helpful for providing the outline of the problem set and the potential solutions. However, comprehensive information about preferences, future and non-market goods are difficult for a decision-maker to access.[3]

The second is the incrementalist management model, in which a decision-maker does not know all the information essential for effective management in advance, but can acquire it over time by trial and error. It is an attempt to bring dispersed knowledge together. However, the decision-maker's scope is still limited by his/her preferences and perceptions. Moreover, updating information is often time-consuming and hence decisions might easily be outdated.

The third is the collaborative management model. A user-oriented design of this sort can be effective in management but can also be costly due to the process of negotiation. Effective communication and information systems are therefore required to ensure its efficiency. By introducing the need for decentralised management, and the fact of insufficiency of information and bounded rationality of policy-makers, this model is used to identify policy options in flood risk management.

The models introduced in Chapters 3 and 4 are based on the comprehensive management model to show how a centralised decision-maker might treat the problem. The problems of commons and policy instruments that solve these problems, such as taxes and subsidies, are discussed in Chapter 5. To address the disadvantages of a centralised management system, stakeholders' committees and tradeable flood permits are introduced for implementing collabora-

[3]The following two models are introduced to avoid the Nirvana fallacy (Demsetz, 1969), the myth of centralised management, which results from the belief in obtaining *complete and perfect information* of resources and human evaluation systems, and in the existence of *altruistic policy makers.*

tive management in Chapters 6 and 7.

1.5 Thesis purposes

The purpose of this thesis is to provide guidelines for a decision-maker to manage flood risks, and to support the sustainable development of catchments (i.e., development strategy undertaken without undermining the ability of the future generations to meet their needs). There are five elements:

- Introducing an indicator incorporating tradeoffs between flood hazards and economic gains, development and protection, costs and benefits of economic development and averting behaviour in flood risk management.

- Developing economic models of flood risks that link causes and impacts of floods, economic development and averting behaviour, from both static and dynamic perspectives.

- Developing a game theoretical model that reveals the problems of externalities in a cross-region catchment.

- Designing the stakeholders' committee and the tradable permit system that solve problems of flood risk externalities within a catchment.

- Investigating the feasibility of the application of the stakeholders' committee and the tradable permit system in the catchment of the Yorkshire Ouse, the Swale, the Ure and the Nidd.

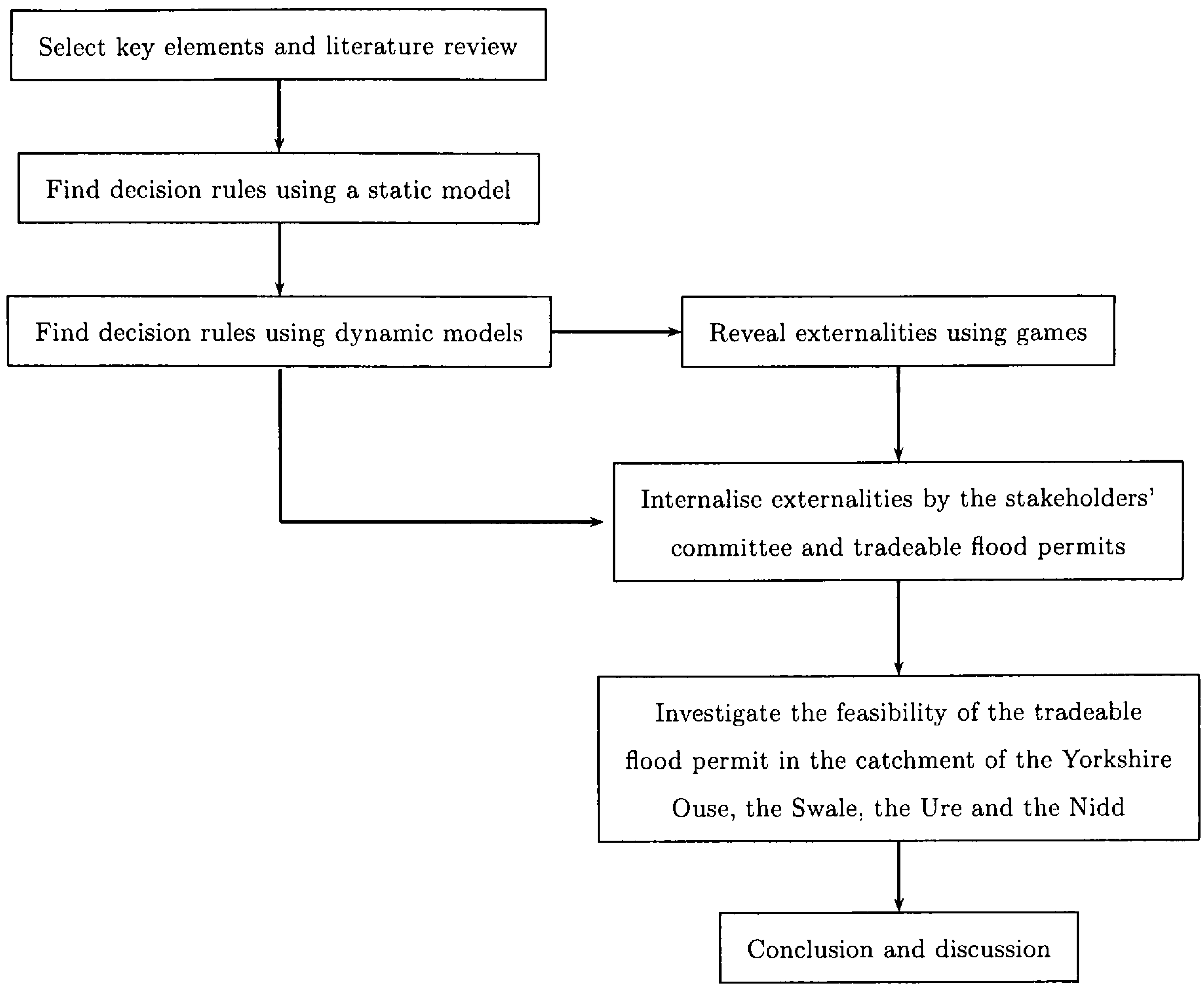


Figure 1.4: Structure of the thesis

1.6 Thesis outline

Figure 1.4 summarises the overall structure of the thesis, and contents of other chapters are as follows.

Chapter 2, entitled 'Flooding, Environmental Health and the Economy: Causes and Impacts of Flooding', identifies the crucial links between flooding, environmental health and the economy. The anthropogenic factors and the impacts of flooding are fundamental in the models that follow. Research gaps and existent models that can be applied are reviewed.

Chapter 3, entitled 'Balancing Development and Protection in Flood Risk Management: A Static Model', derives the decision rules on development and averting behaviour using a static model integrated by infiltration theory and optimisation theory. This prototype conceptualises tradeoffs between economic and environmental value.

Chapter 4, entitled 'Balancing Development and Protection in Flood Risk Management: Dynamic Models', develops two dynamic models following the prototype. Their optimal paths and the characteristics of their equilibria are discussed.

Chapter 5, entitled 'Externalities of Flood Risk Management', is an extended model of the benefits and costs of internalising externalities for improving flood management by homogeneous players in a catchment. A supermodular game is developed to present the 'embankments race' and 'insufficient soft mitigation' due to externalities. Strategies for obtaining Pareto improvement are explored.

Chapter 6, entitled 'Decentralised Flood Risk Management Using the Stakeholders' Committee and Tradeable Flood Permits', develops the stakeholders' committee and the tradeable flood permit system to resolve the economic inefficiency of the embankments race and insufficiency of soft mitigation.

Chapter 7, entitled 'Feasibility of the Tradeable Flood Permit System for the Management of Flood risks in the Yorkshire Ouse Catchment', investigates the institutional requirements of this approach and the feasibility of the tradeable flood permit system in the catchment of the Yorkshire Ouse, the Swale, the Ure and the Nidd.

Chapter 8, entitled 'Conclusion and Policy Recommendations', presents the thesis conclusion and discusses the implications and implementation of the thesis findings and further research.

Chapter 2

Flooding, Environmental Health and the Economy: Causes and Impacts of Flooding

2.1 Introduction

The purpose of this chapter is to describe links between economic development and the causes and impacts of flooding. Section 2.2 describes features of anthropogenic behaviour that may influence the probability and potential extent of flooding. Section 2.3 reviews the methodology for assessing risks involved. Section 2.4 considers the impacts of flooding on the economy and on environmental health. Environmental health in this thesis is mainly about flood risk while the aspects of human health or other environmental impacts are not the focus. Section 2.5 reviews methods for modelling the interaction between flooding and the economy, focusing on the feature of uncertainty. Section 2.6 summarises the chapter.

2.2 Anthropogenic factors in flooding

Generally, the literature categories floods in terms of location, intensity and duration or distribution of rain, and their predictability (Table 2.1). From this descriptive categorisation, we can identify the types of floods corresponding to various geographical and climatological conditions. Such a classification is a valuable precursor to assessing the potential impacts of urban expansion or climate change on flood risk.

Table 2.1: Categories of floods

Location	**Rainfall Intensity**	**Predictability**
coastal flood	flash flood	seasonal flood
river/fluvial flood	broad-scale flood	sporadic flood
urban flood		
flash flood in arroyos[a]		
flash flood in other places[b]		

[a]An arroyo is a winter-carved gully or a normally dry creek in arid or desert regions. When a storm appears, rainwater cuts into the dry and dusty soil and creates a small and fast-moving river. Flooding of this sort may happen suddenly, without warning.

[b]Flash flood may also happen in the valley such as the Boscastle flood in 2004 or low altitude area such the Tynemouth flood of 1952.

Rain, snowfall, sleet and hail are collectively known as *precipitation*. Precipitation can be absorbed by the soil to initially fill small pores and then larger pores. The rate of downward flow of water depends upon the pore size distribution and pore inter-connectivity. This process is called *infiltration*. If the precipitation rate exceeds infiltration rate, surface runoff or local flooding becomes likely. Thus in the hydrological balance (equation (2.1)), apart from precipitation and infiltration, only *runoff*, which directly contributes to flooding, is considered.

$$\begin{aligned}\textbf{Precipitation} = \textbf{infiltration} + \textbf{runoff} + \text{interception} \\ + \text{evaporation} + \text{transpiration}\end{aligned} \tag{2.1}$$

2.2.1 Climate change

Studies in various parts of the world have shown that the frequency of large-scale floods increased substantially during the 20th century and have suggested that the trend will continue (Milly et al., 2002; Palmer and Raisanen, 2002). Trends in coastal flooding are mainly dependent upon sea level rise. Trends in fluvial flooding are explained by changes in rainfall patterns (though they are often difficult to detect) and changes in factors such as land use and flood mitigation. Hence, a regional perspective is more useful in averting risk of fluvial flooding, as well as taking a global view.

From the annual precipitation in England and Wales from year 1766 to 2003, shown in Figure 2.1, 95.8% of all observations are located within two standard errors. Two annual values are above two standard errors in the 19th century while three are above in the 20th century. The average annual precipitation is 915.5 mm. Long-term trends in annual data seem to reveal little about the existence of climate change effects. A time series plot such as Figure 2.1 provides an indication of frequency of typical wet years. However, it does not give direct evidence for increased probability of flooding, since the latter will depend upon the distribution of precipitation and/or snowmelt throughout the year.

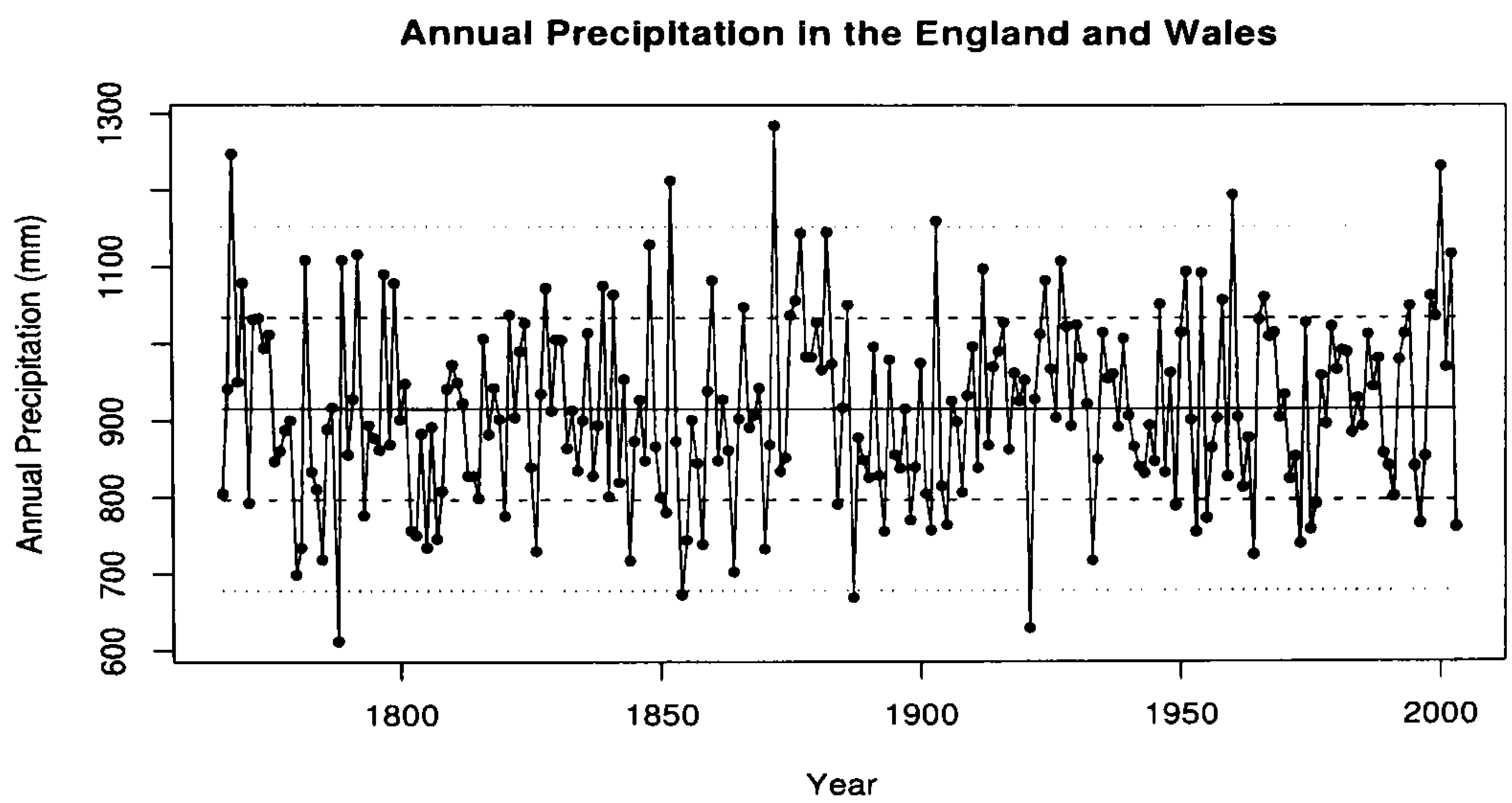


Figure 2.1: Annual precipitation in England and Wales (1766-2003). Solid line: mean; dashed lines: ± one standard error; dotted line: ± two standard errors. Data source: Hadley Centre. Access the link: http://www.met-office.gov.uk/research/hadleycentre/CR_data.

From seasonal data, Robson et al. (1998) found no evidence for climate change from the peak-over-threshold (POT) data and annual maximum flood peaks during 1941-1990.[1] The ratio of winter precipitation (October-March) to annual precipitation from 1766-2003 has an upward trend however (Figure 2.2). The UK Climate Impact Programme in 2002 (UKCIP02) predicted that winter precipitation

[1]POT data comprise a series of flood peaks that are bigger than a selected threshold. Refer to Subsection 2.3.4 for details.

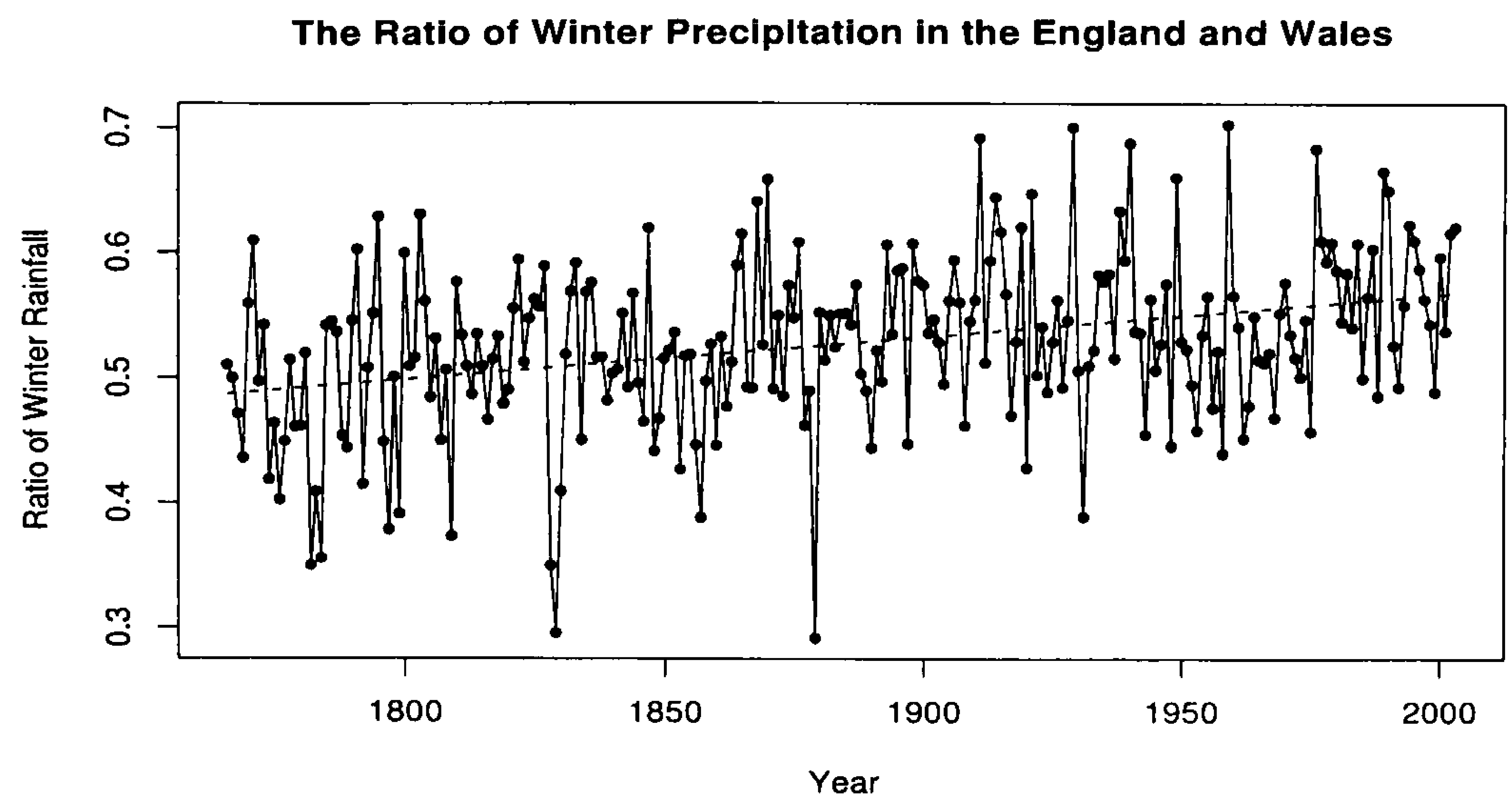


Figure 2.2: Ratio of winter precipitation to annual precipitation in England and Wales (1766-2003). The linear regression coefficient is 0.49 while the slope is 0.34×10^{-3}. Both have p-value ≈ 0. Data source: http://www.met-office.gov.uk/research/hadleycentre/CR_data.

will not increase by more than 15% above the 1961-1990 mean (baseline) before the 2080s in the high emission scenario (Tyndall Centre and Hadley Centre, 2004).[2]

The occurrence of wetter winters and drier summers is a common prediction from most research on climate change in the UK (Mayes, 1996). Palmer and Raisanen (2002) found that the probability of total boreal winter precipitation exceeding two standard errors above normal would increase by a factor of five over parts of the UK in the next 100 years. According to Sefton and Boorman (1997), catchments in northern and western England suffer more floods when most severe reductions in low flows occur in central and

[2]In UKCIP20 Climate Change model, the high emission scenario assumes global temperature increases $3.9°C$ and atmospheric CO_2 concentration becomes 810 ppm.

eastern England.

Asia may also face increased flood events, especially in monsoon regions. Palmer and Raisanen (2002) found increases in the probability of precipitation in many parts of Asian monsoon regions in summer. Milly et al. (2002) concluded that flood frequency in extra-tropical areas would increase, though they also indicated their model's weakness in the simulation of tropical climate.

There is still an on-going debate about climate change and its impacts. Although the detection of anthropogenically forced changes in flooding is difficult because of the substantial natural variability of the environment, precautionary policies are preferred. Most research shows no instant menace of hydrological anomaly as a consequence of predicted climate change in the UK, but preparation for undertaking averting behaviour in the long run is necessary.

2.2.2 Land use

Change of land use may influence flood risks by changing the topographical and hydrological characteristics of an area. This thesis focuses on the elements that affect infiltration.

Infiltration capacity, the maximum rate at which water can enter into soil, depends on factors related to soil texture, soil structure, and the moisture deficit in the upper soil layer. Soil erosion can also impede the infiltration process if, for example, small eroded soil particles clog macropores. Erosion may then accelerate runoff.

Land use patterns of particular interest here include economic plantation, deforestation and urbanisation. Change of land surface is also a factor affecting infiltration capacity. Mulches, cracks and wormholes influence the entrance and passage of infiltration water.

Vegetation influences the hydrological cycle both above and below ground to an extent that depends upon plant types. Plants, especially tree canopies, *intercept* water. Evergreen trees, for example, often intercept more than deciduous trees, especially in winter. Wet woodland can add to the retention of flood water because tree trunks, buttress roots and deadwood on the woodland floor slow down water movement across the flooded ground (Gregory et al., 2003). Tropical afforestation leads to increased transpiration, and roots help stabilise soil structure. According to Cheng et al. (2002), in a monsoon climate, infiltration dominates the water balance equation in areas with forests. The importance of vegetation to flooding can also be found in the high risk of landslides after forest conflagration (Brown, 1972; Lavabre et al., 1992). However, the influence of forest is minimal on landslides or floods caused by large scale storms or rainfall (Lu et al., 2001; Cheng et al., 2002).

One consequence of deforestation is reduced interception of precipitation, so that more water reaches the soil surface. Moreover, the forest canopy may have partly dissipated the energy of falling raindrops. On the other hand, forest may facilitate interception of mist or horizontal precipitation on slopes. Especially in the absence of ground cover vegetation, deforestation may increase the probability of soil erosion. In central and eastern Taiwan, the plantation of shallow-rooted cash crops (such as betel nut and vegetables) or urbanisation in place of forest has been blamed for flooding and landslides (Lu et al., 2001; Cheng et al., 2002).

Cities bring social and economic advantages, ecological losses and environmental risks. The construction of streets, buildings and parking lots seals the ground, and thus lowers the infiltration capacity of the land (Wolman, 1967; Leopold, 1968; Gregory and Walling, 1973). Newson (1992) presented the impermeability of various urban covers (Table 2.2). Not only land use change, but also structural measures such as porous pavement, stormwater management ponds, and constructed wetlands, can improve the infiltration capacity of the land. With the same input of rainfall, the amount of runoff in an urban area is greater than that which occurs on natural terrain due to a decrease in infiltration capacity. The lag time between the occurrence of a rainfall peak and flooding is shorter for urban floods. In other words, the timing and the probability of flooding change due to urbanisation.

There has been a debate about the relationship between soil conservation and flooding. Some attribute forest cover with the ability of attracting rainfall while most suggest that natural forests can prevent floods. Although the interaction between forest cover and landslide activity is a highly complex phenomenon (Haigh et al., 1995), density of vegetation cover and stability of slope usually have a positive relationship. Most studies contend that poor soil conservation leads to more serious flood problems. One reason for that is the effect of development, surface runoff, and the stability of slopes (Gokceoglu and Aksoy, 1996; Jakob, 2000; Dai and Lee, 2002). However, Greenway (1987) found negative relationship between the

Table 2.2: Impermeability of various surfaces (Newson, 1992)

Type of Surface	Impermeability (%)
Watertight roof surfaces	70-95
Asphalt paving in good order	85-90
Stone, brick and wooden block pavements:	
with tightly cemented joints	75-85
with open or uncertain joints	50-70
Inferior block pavements with open joints	40-50
Macadam roads and paths	25-60
Gravel roads and paths	15-30
Unpaved surfaces. railway yards, vacant lots	10-30
Parks, gardens, lawns, meadows - depending on the surface slope and character of the subsoil	5-25

density of vegetation and the stability of slopes.

Little empirical work has been done on impacts of land use change in the UK on the possible trend towards more flooding. The UK landscape has undergone widespread and progressive urbanisation throughout the 20th century. Fuller et al. (1994) stated that the area of urban land increased by about 50% between 1930 and 1990. According to the Ordinance Survey, Forestry Commission and Forest Service in the Department for Environment Food and Rural Affairs, the area of the urban land and land not otherwise specified in the UK is 3,855 thousand hectares,[3] 16% of the total land in the UK in 2002. Robson et al. (1998) emphasised the significance of land use

[3]The land not otherwise specified covers the land other than urban land, crops and bare fallow, grasses and rough grazing, other agricultural land, and forest and woodland.

change and drainage on flood probability but quantitative effects in the UK flood regime were not identifiable in their research.

2.2.3 Mitigation

Mitigation reduces the probability of flooding. There are two types of mitigation: (1) 'hard mitigation', e.g., putting up concrete dykes, leads to more direct and immediate effects; (2) 'soft mitigation', e.g., maintaining (or creating/re-creating) washlands and natural land cover, has longer term ecological, aesthetic and sustainability benefits. Washlands are often associated with hard mitigation, such as flood gates, in order to save storage for higher order flood events. Soft mitigation applies a more natural solution to flooding. Both usually take a long time to prepare and have high opportunity costs. Hence the capacity of the economy is support investment in either option matters.

HARD MITIGATION

Hard mitigation applies traditional engineering concepts to build embankments, dams, flood walls and drainage systems to contain flooding. Its opportunity costs include expenditure on construction and maintenance, engineering failure, deterioration of surrounding ecosystems, diminution of dilution of pollutants by blocking flows, and increasing probability of flooding in neighbouring regions. Furthermore, inadequate building standards, unsafe sites and the bursting of dams may lead to flooding or aggravate flood losses.

To identify the optimal level of mitigation, the classical treatment of the problem was given by Dantzig (1956). He set up a model to minimise the total building cost of the dyke (I) and the current value of the expected flood losses (L) with respect to the height of water that the dyke is capable of retaining (H). The probability of any height of sea level being attained declines exponentially with increasing h. The first order condition for the optimal height of a dyke is

$$dI/dH + dL/dH = 0$$

$p(H)$ denotes the probability of the water level exceeding the height of the dyke. The estimation of flood losses

$$L = p(H)V \sum_{t=0}^{\infty}(1 + 0.01\delta)^{-t} \approx 100p(H)V/\delta = 100p_0 e^{-\alpha X} V/\delta$$

is based upon a threshold equation to estimate the expected value of all future losses associated with coastal floods whilst the sea level is higher than the critical height of the dyke H:

$$S = \begin{cases} 0 & \text{if } h \leq H \\ V & \text{if } h > H \end{cases}$$

where S is the loss, h is the sea level, and H is the critical height of the dyke. Here Dantzig (1956) assumed that a sum L was set aside to cover anticipated losses, and that attracted interest at $\delta\%$. V is the value of goods. This research can also be applied to river flood walls by replacing sea level with river level. As with other research on this problem, economic activities such as development were ignored, or else subsumed in the probability of flooding.

SOFT MITIGATION

Ecological concerns focus attention on soft mitigation. The opportunity costs of soft mitigation mainly involve sacrificing economic gains of land development. Hence there is a need to balance development benefits and potential flood losses. Besides, there is a debate of the effectiveness of soft mitigation against strikes of large amounts of energy from flood water (DEFRA, 2004). Soft mitigation includes constructing parks in cities, restricting land use of environmentally sensitive regions, keeping (or creating/restoring) washlands, and possibly even removing current hard mitigation.

Active erosion and runoff can also be reduced by the application of appropriate soil and land management techniques, such as improved crop rotations, contouring and terracing, gully damming, cover cropping, tree planting, woodland conservation, and so forth (Morgan, 1969). The principle is to absorb and retain more rainfall in the soil. In other words, there must be sufficient moisture storage capacity in the soil, and this is a function of soil depth, structure, porosity and organic matter (Hudson, 1995).

FROM HARD MITIGATION TO SOFT MITIGATION

In spite of its ecological advantages, soft mitigation is not often undertaken under the pressure of development, population growth and the problem of free-riding. There are four disadvantages to hard mitigation that urge us to think of the alternative: draining floodwater to other areas generates externalities; the limitation of technology and the risk of engineering failure confines the effectiveness of hard mitigation; hard mitigation can be expensive; and materials used for hard mitigation may be threatening to the local ecosystems.[4]

Hence, an integrated ecosystem management approach is recognised as a better option for the sustainable development and use of floodplains. Soft mitigation generates multi-functionality and benefits downstream areas and future generations while hard mitigation results in direct effects of flood alleviation in local areas. The ways to convert hard to soft mitigation are considered below.

1. Natural process restoration

Restoring natural processes in a region resumes natural mitigation as in the past. First, a better recognition of functions and values of original natural land covers, such as wetlands and forests, provide opportunities for their rehabilitation or restoration. This may come from the public concern for preserving environmentally friendly or aesthetically or ecologically attractive sites or realising sustainability.

Compared with developed land, deserted land may be politically easier to return to nature. However, it may still be challenging because of soil physical properties, hydrological and climatic conditions, biological activities, and related water and soil pollution. For instance, metal residues in soils may be toxic to plants, exterminating the plants completely or damaging root growth, which results in susceptibility to drought (Bradshaw and Chadwick, 1980).

Bradshaw and Chadwick (1980) discussed the problems of derelict

[4] In the project like 'Moses' at Venice, the anodes protecting the gates from corrosion is estimated to release more than 10 tons of toxic zinc in the lagoon per year (Drake, 2004).

land. For instance, it may be possible to obtain fully developed soil from another site and spread it over the derelict land. Good structure of soil ensures satisfactory water retention. Apart from mitigating flood risks, the restoration of certain derelict land may also prevent a secondary flood hazard, such as decreasing pollution in drainage water. The organic matter and nutrients of the soil constitute a buffer against toxicity.

Though there are techniques for restoring natural processes, the best solution is prevention rather than cure. This should be realised in the process of development, for instance avoiding the unnecessary removal of vegetation, minimising construction of roads, and avoiding decreases in the porosity of land surfaces.

2. Riparian buffer zones

Riparian buffer zones are green zones along streams, rivers, and lakes. They benefit flood risk management by improving bank stability, preventing silt deposition, and removal of sediment and pollutants[5].

Ducros and Watson (2002) conducted research aimed at filling the gap between policy-makers and users by interviewing farmers about their willingness to take up a riparian buffer zone scheme. Economic capacity, concerns about future generations, and attitudes to conservation are key factors to encourage adopting the riparian buffer zone policy. Farmers with less ownership or less land have less to 'sacrifice', hence the policy is less attractive for them. The

[5]The removal of chemicals, such as nitrogen, depends on various factors, i.e., hydrological elements, temperature, slope, biota, and characteristics of the soil.

willingness of farmers with successors or more farms to adopt the scheme appears higher.

However, there are some side effects of mitigation conversion. For instance, the use of heavy earth-moving machinery, especially on soil lacking organic matter, may cause considerable compaction and loss of soil structure. The compaction changes the physical nature of the soil by restricting root penetration, reducing pore space, water holding capacity, aeration, and rates of water movement and gas exchange (Moffat and McNeil, 1994). The higher density remains a barrier to proper root growth and the infiltration of water unless vegetation is established (Bradshaw and Chadwick, 1980). This hinders the recharge of soil's moisture supply in the wet season and hence increases the surface runoff (Moffat and McNeil, 1994).

Overall, hard mitigation rather than soft mitigation is usually more attractive to local authorities because it involves minimum disturbance to landowners (Boardmand, 1995). However, the opportunity costs of hard engineering measures, including risks of engineering failure and impacts on ecosystems, are often high. Furthermore, the disposal of water from dams and drainage can also induce problems of externalities.

2.3 Estimation of the probability of flooding

Having reviewed the anthropogenic factors in flooding, we now need methods to incorporate them into the estimation of the probability of floods. This estimation is mainly based upon hydrological models that discuss the collective risk for a whole region instead of individual risks. Hydrologists express their concern about flood risks in terms of 'exceedance probability', that is the probability of a flood event exceeding a certain amount occurring.

2.3.1 Visualisation of hydrological characteristics

Hydrological datasets are often massive, so visualisation is helpful to condense the information. Flood frequency curves and flow duration curves are valuable in this context. Other descriptive figures such as time series plots for precipitation, river flow, and runoff are not covered in the discussion because of their simplicity.

FLOOD FREQUENCY CURVES

Flood frequency is a statistical measure of the probable occurrence of a flood at a given magnitude (Smith and Ward, 1998). It shows the positive connection between discharge magnitude and the return period, which is the inverse of the probability of flooding.

In reality, there are often too few data available to plot a flood frequency curve precisely. Empirical distribution functions are therefore often not smooth, and not easy to interpolate. Besides, we cannot estimate the frequency of the occurrence of any flood event greater than the maximum recorded.

The strategy is to fit a theoretical frequency distribution to the sample, calculating the parameters from the observed data. Transforming the data to logarithms and using log-normal distribution or

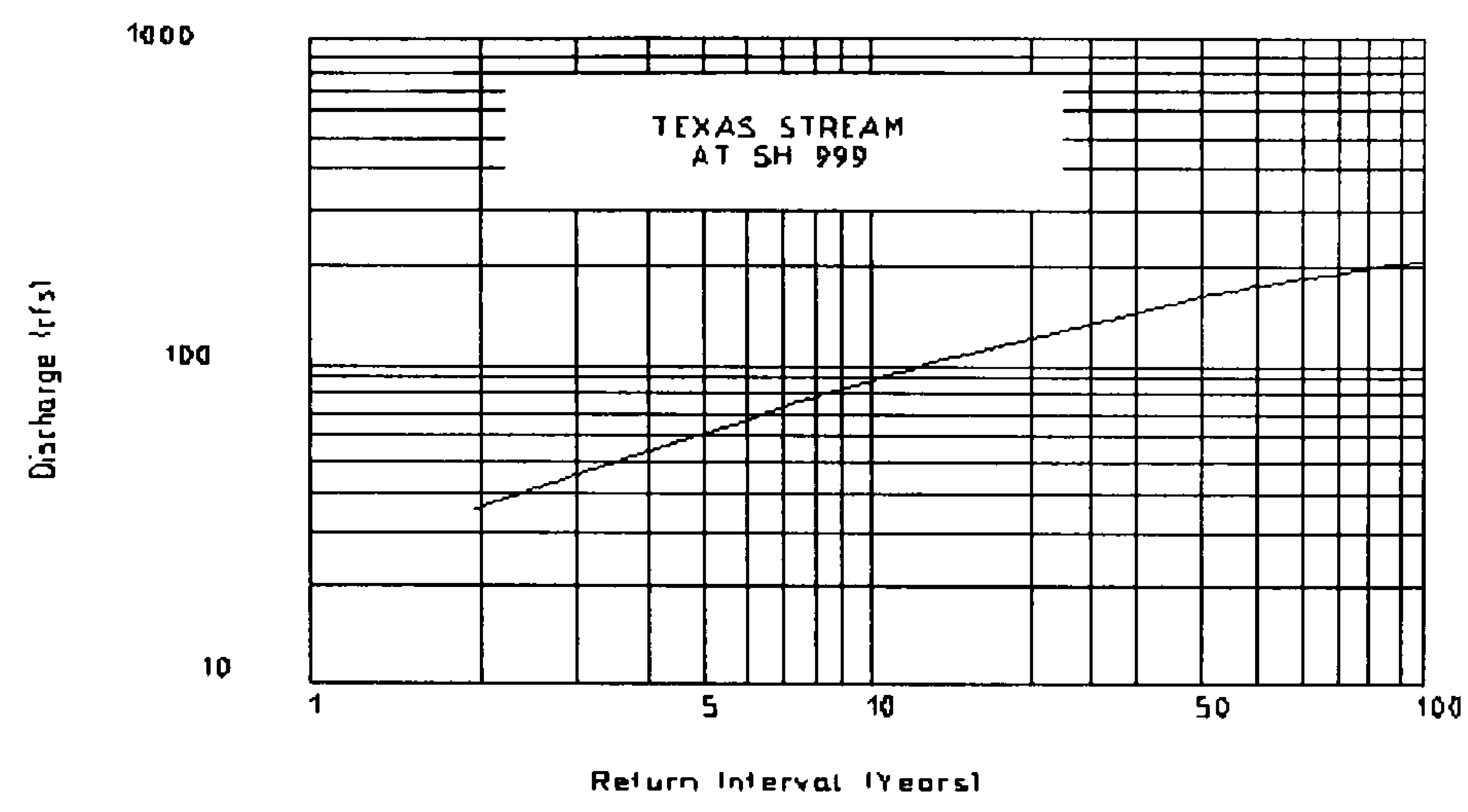


Figure 2.3: Flood frequency curve for the Taxes Stream (the USA). Source: Taxes Department of Transportation (2004).

other skewed distribution, such as general extreme value distribution (Gumbel distribution and Weibull distribution) is more appropriate.

Ideally, flood frequency helps show the probability of the occurrence of different amounts of discharge. However, the flood frequency plot alone is too simple to portray the interaction between various elements in the hydrological cycle, the dynamic variation of the relationship between frequency and magnitude over time, and comparison between catchments. Hence other indicators are necessary for improving the understanding of flow regimes.

FLOW DURATION CURVES

Flow duration curves denote the proportion of time during which a flow is equalled and exceeded (Figure 2.4). A logarithmic scale is usually used for the discharge axis while a normal probability scale is used for the frequency axis. The discharge axes are standardised with respect to the average flow for comparison between catchments. The shape of a flow duration curve provides a slightly simplified overview of the catchment's response to precipitation. A curve with a steep slope indicates variable flow, usually from a catchment with quick flow and little baseflow; a curve with a flat slope usually results from the dampening effects of high infiltration and ground water storage (Burt, 1996).

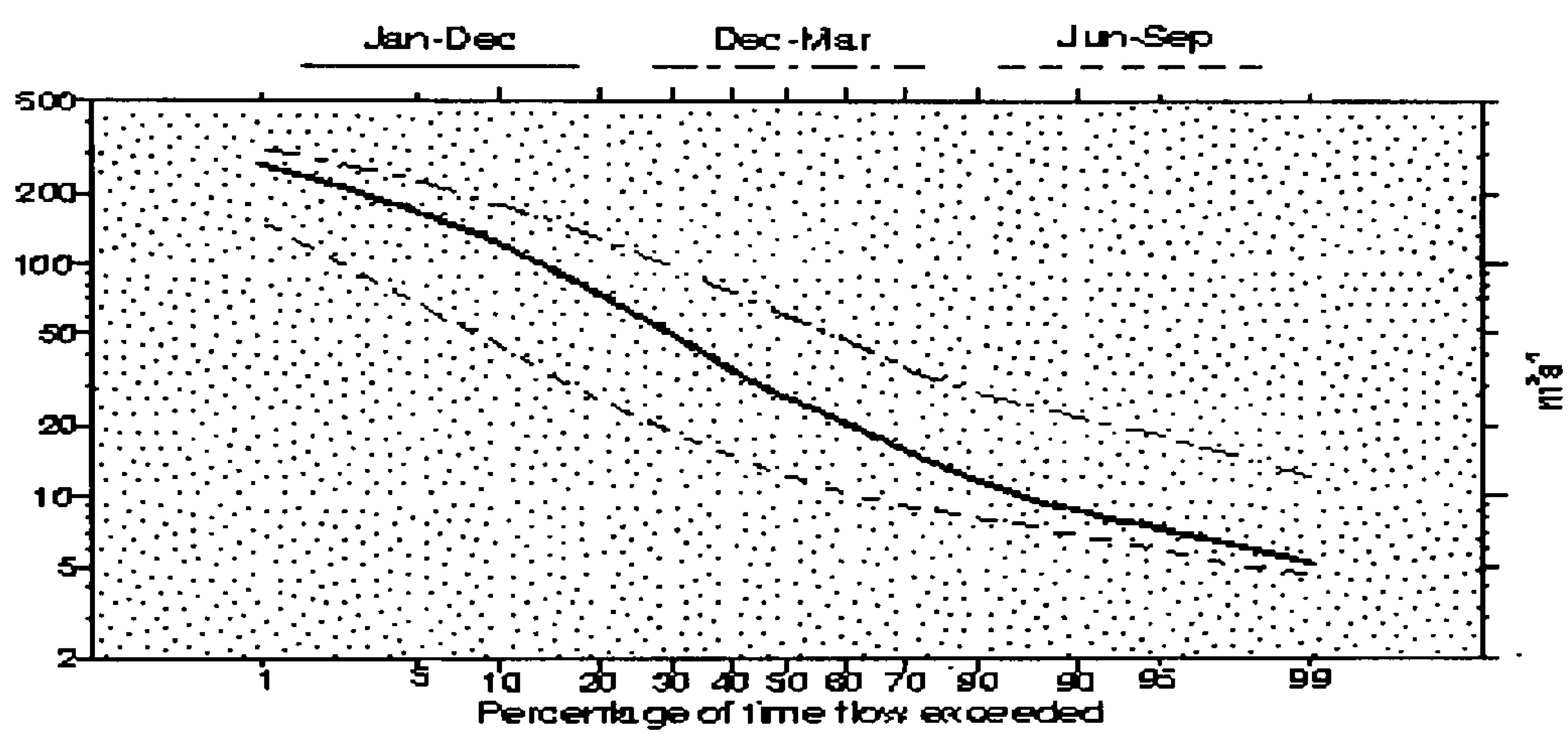


Figure 2.4: Flow duration curve for gauged daily flows of the Yorkshire Ouse at Skelton. Data source: National Water Archive, Centre for Ecology and Hydrology.

2.3.2 General form of river flood estimation

There are many simple empirical flood estimation equations which adopt the general form

$$Q_{max} = CA^n$$

where Q_{max} is the maximum flood discharge, A is the area of the catchment with n as a positive exponent, and C is the coefficient of runoff which represents the geographical characteristics in an area. The maximum flood discharge is assumed to be positively related to the area of the catchment only.

2.3.3 Empirical models

To take more variables into account, hydrological models for estimating the probability of flooding are often applied. For instance, in the UK Flood Estimation Handbook (Robson and Reed, 1999), time to peak flow is estimated by

$$T^p = 4.27 Dpsbar^{-0.35} Propwet^{-0.8} Dplbar^{0.54} (1 + Urbext)^{-5.77}$$

where *Dpsbar* is the mean of all the inter-nodal slopes for the catchment,[6] a measure of channel slope; *Propwet* is the median length of spells when the soil moisture deficit was below 6 mm during 1961-90 (days); *Dplbar* is the mean of distances between each node and the catchment outlet (km), characterising catchment size and configuration; *Urbext* is the fraction of urban and suburban land cover in the catchment in 1990.

Various variables and functional forms can be chosen and tested in a deterministic model of this sort. However, there is seldom substantial explanation of the formulations.

[6] The nodes are on regular 50 m grid.

2.3.4 Peak-over-threshold (POT)

Thresholds play a key role in defining a flood event and hence there are measurements of taking the threshold level of flooding into account. First is peak-over-threshold.

Since runoff within a certain range can benefit the environment and the economy, we need to define a borderline to distinguish benign floods from malign floods. Peak-over-threshold (POT) can be applied to serve this purpose. It is a count of all floods above a specified threshold. POT counts are often used to represent the number of floods in a catchment (Robson et al., 1998; Robson and Reed, 1999; Black and Burns, 2002).

2.3.5 Probable maximum flood and probable maximum precipitation

Probable maximum flood events (PMF, in equation (2.2)) and probable maximum precipitation events (PMP in equation (2.3)) are other measurements associated with threshold. They estimate the largest flood that is possible for a target catchment. They are supposed to be useful in checking how well a mitigation strategy can cope with flood hazards.

There are two methods of estimating PMF. One is deriving PMF indirectly by the conversion of PMP estimates using unit hydrograph procedures and considering physical characteristics (e.g., the spatial variation of rainfall, the direction of storm movement, and the duration and profile of flood-producing precipitation events) of the target catchment (Smith and Ward, 1998).[7]

The other is a statistical method. For instance,

$$PMF = a(A/b)^{1-K} \tag{2.2}$$

where A is catchment area, K is a regional coefficient, and a and b are constants.

There are also two methods of estimating PMP. One is a process-based approach, which generally contains the following three steps (Smith and Ward, 1998):

(1) maximum rainfall for the target catchment and for other comparable areas are identified from rainfall records;

(2) where these rainfall events are for other comparable areas they are transposed to the target catchments;

(3) the transposed values are maximised for the target catchment on the basis of the differences in meteorological conditions between the target catchment and the area over which the rain originated.

The other is a statistical method. For instance, Hershfield (1965) proposed that

$$PMP = P_{bar} + K\sigma \tag{2.3}$$

where P_{bar} is mean precipitation, K is frequency factor, and σ is standard deviation.

According to Newton (1973, cited in Ward (1978)), PMF and PMP, however, occur rarely in reality. Apart from the limitation of

[7] The unit hydrograph model was produced by Sherman in 1932. It was a major advance in rainfall-runoff modelling and the technique had been widely adopted. It assumes that, in a given catchment, a given input of rainfall over a given time period will always produce the same hydrograph response.

extrapolating to a rare event with a long return period from existing data, Kuchment et al. (1993, cited in Smith and Ward (1998)) argued the difficulty in estimating these two values 'correctly' by including 'unusual' factors, such as human activities. Hence they should be combined with other parameters to work out the risk estimation.

2.3.6 Horton's infiltration theory

Horton's infiltration theory considers surface runoff as the amount of precipitation which exceeds the infiltration capacity, in other words, the excess water which is unable to infiltrate into the soil (Horton, 1933).

$$f_t = f_c + (f_o - f_c) \cdot \hat{e}^{-\beta t} \tag{2.4}$$

where f_t is the infiltration rate at time t, f_o and f_c are the maximum and minimum infiltration rates respectively, and β is a parameter which indicates how quickly the infiltration rate decreases from its maximum to its minimum. According to Smith and Ward (1998), it can also be simplified as:

$$(i - f) \cdot t = P_e = Q_o \tag{2.5}$$

where i is rainfall intensity, t is time duration, P_e is precipitation excess, Q_o is surface runoff, and f is infiltration capacity. With the link to infiltration capacity, properties of land such as land use patterns can be incorporated to generate a conceptualised model.

Horton's model (based on a white box approach) provided a physical basis for Sherman's unit hydrograph model (based on a black box approach) (Anderson and Burt, 1990). These two models together dominated catchment hydrology for several decades.

Ward (1978) claims Horton's infiltration theory had subsequently manifested itself in flood prediction methods directly in the form of infiltration indices, and indirectly in the form of antecedent precipitation indices, soil moisture and the proportion of the catchment under different land-use types. These methods are in accord with more recent ideas of runoff formation involving the generation of quick flow from source areas of variable size and location within the catchment. Note that only when baseflow and the difference in soil saturation are not crucial in research can the application of Horton's infiltration theory be appropriate (Betson, 1969; Burt, 1996).

2.4 Impacts of flooding on environmental health and the economy

The health and economic impacts of flooding, summarised in Table 2.3, generally depend on what the flood water brings in and out, how powerful the flood is, the economic activities in the area, and the numbers and types of individuals affected. The impact is neither spatially uniform across the region nor confined to the short term, so heterogeneity and long term effects need to be considered. Adaptation, the actions of eliminating the negative impacts of floods, and the evaluation measurement of flood impacts will also be reviewed.

Table 2.3: Effects of floods on health and the economy

Effect	Health	Economy
Negative	◇ Loss of life ◇ Diseases caused by pathogens or pollutants ◇ Destruction of health systems ◇ Famine ◇ Psychological problems ◇ CO poisoning when using gas-powered pressure washers to clean basements ◇ Electrical hazards ◇ Psychological effects	◇ Damage to properties/ facilities ◇ Losses to animals and crops ◇ Damage to transportation/ communication networks ◇ Harvest is menaced by excessive salinity or alkalinity, or polluted silt ◇ Damage to natural recreational resources ◇ Loss of tourism
Positive	◇ Dilution effects on pathogens ◇ Recharging ground water or pollutants	◇ Regenerating plants/ aquatic biota ◇ Adding fertility to agricultural land from silt

2.4.1 Flooding and health: Dilution v.s. dispersion

Water serves as a pathway for exposure to microbial contagious, and hazardous pollutant-related diseases to an extent that depends upon dilution and dispersion effects. Water can bring in hazardous elements and can also flush away harmful materials. The net result depends on the economic activities, geographical conditions, environmental quality and environmental protection in the region and its neighbouring areas.

Soil is a major recipient of precipitation on land. It is also home to resident and itinerant bacteria and pollutants. The chemical characteristics of a contaminant might change as it percolates through the soil zone to an aquifer (Hu and Kim, 1993). For example, 'if water contaminated by bacteria from sewage enters groundwater system, it may become purified through natural processes. The harmful bacteria may be mechanically filtered out by the sediment through which the water percolates, destroyed by chemical oxidation, or assimilated by other organisms' (Lutgens and Tarbuck, 1986).

However, soil might not be able to purify a huge amount of polluted water from industrial discharges and agricultural runoff which comes all at once such as flood water. Besides, contaminants may migrate from the source into surrounding uncontaminated materials.

For instance, an outbreak of leptospirosis in Thailand after the year 2000 flood caused a death toll of more than 200 and more than 4,000 infection cases. In rural Bangladesh, cholera transmission is seasonal, with a peak after the monsoon (Siddique and Baqui, 1992). Colwell and Spira (1992) considered that the post-monsoon season is associated with a considerable bloom of zooplankton, maximum recreational water contact, and maximum available crustacea in the market place. Several researchers have postulated that there is a permanent environmental reservoir for *Vibrio cholerae* in brackish ponds and canals of rural Bangladesh (Colwell and Spira, 1992).

Not only tropical and subtropical countries but also temperate countries like America have suffered from health problems of this sort. An outbreak of cryptosporidiosis, one of the common drinking water-related diseases, at Milwaukee, Wisconsin in 1993, which resulted in $403,000$ reported cases, coincided with heavy spring rains and runoff from melting snow. It was believed that the spring floods flashed into the reservoir at Milwaukee with *cryptosporidium* from excreta of cattle and then overloaded the filtration function. According to Atherholt et al. (1998), rainfall increases the concentration of *cryptosporidium* through its influence on turbidity, flow volume, and other site-specific environmental factors (e.g., differences in parasite source contributions). In the 2002 flood aftermath in central Europe, dioxin, mercury and bacteria in the sludge carried by flood water triggered health alerts.

Apart from the life threatening injuries, other health problems are usually less severe, including minor injuries, throat infections, skin irritations, gastro-intestinal illness, allergies and psychological health problems such as anxiety and stress after the flood events. The physical impacts result from the characteristics of the flood events, the locations and the averting behaviour undertaken. The psychological impacts result from frustration and anxiety of restoring the normal life and the adjustment of averting behaviour (Flood Hazard Research Centre, 2002), the distress of being threatened or harmed by the hazards (Rotton et al., 1997). As to whether other characteristics such as age and sex influence the susceptibility of physical disabilities or psychological disturbances, different results have been found by different research (Bennet, 1970; Abrahams et al., 1976).

Sometimes, however, flood control appears disadvantageous to health. Emch (2000) found that individuals living in flood-controlled areas were 2.47 times more likely to be hospitalised with cholera. A similar result was found in the case of non-cholera watery diarrhoea. One explanation is that flood control exacerbates cholera boom by some unknown mechanisms (Colwell and Spira, 1992). More clearly, flood control may change the salinity levels or impede the natural flushing out of the cholera-laden water. Thompson (1986) considered that flood-control embankments could often be blamed for cholera outbreaks in rural Bangladesh because seasonal flooding does not flush out the inadequately disposed of sewage after their installation.

2.4.2 Flooding and the economy: Benefit and damage

Though there are both positive and negative impacts of flooding, we are generally interested in situations where damage overwhelms the benefits a flood can bring. Flooding can directly and indirectly destroy inputs and outputs and change consumption patterns. The price and amount of commodities may therefore be affected temporarily, unless the damage is on an enormous scale. Preparation (*ex ante*) and remedy (*ex post*) for flood risks also affects the economic behaviour. Different types of economy suffer different effects. For instance, traffic interruption in York (UK) is very different from widespread morbidity and mortality in Darfur (Sudan). The levels of the impacts also depend on the characteristics of a flood, such as its timing, duration, velocity of water flow and the depth.

In the market, the price of domestic agricultural products usually rises after, or even just before, a flood event because of actual or expected damage to certain products. In extreme cases, the damage to a monopsony (monopolist) directly affects sellers (buyers) of the factor. Some economic impacts are driven by consumption.

Floods may also alter the budget (constraint) of a household, directly through a shock or indirectly by changing the relative price of commodities. People might lose their properties, health, and income. Adjusting to a new budget constraint, households may need to change the consumption patterns either temporarily or permanently. Refurbishment, furniture purchase, and cleaning services might be necessary after floods. However, in some cases, the expenditure on these items might not be affordable for every household, especially for those who lose their properties or jobs.

Population and the socio-economic conditions also affect the scale of flood losses. An area with high density of population or of industries usually suffers more from flood losses because the base a flood can affect is large. Residents with high income can usually afford to invest in mitigation and adaptation whilst people with lower socio-economic status may instead be 'forced' to live in the flood-prone areas.[8]

To further consider the impacts of flooding, agricultural and manufacturing industries are distinguished because of their different levels of dependence on land.[9]

AGRICULTURE

Soil, a crucial input of agricultural production (apart from hydroponics) can benefit from floods due to the fertile silt added by floodwater and groundwater replenishment. However, flooding can be harmful if the silt is too saline, too alkaline, polluted, or if energy of the flood water is too huge. Due to the application of fertiliser and pesticide, non-point source water pollution may be expanded in the wake of a flood. The result can be catastrophic, e.g., exacerbating the forming of oxygen-starved 'dead zones' in the ocean caused by the increasing runoff which contains nitrate-based fertilisers. Hence the location of the farm is crucial. Being located downstream of a factory or a waste water treatment plant poses a higher risk to farms of being contaminated while farms situated on hills may be susceptible to landslides. The characteristics of a flood event also affect its impact on agriculture:

(1) *Timing.* Flooding might have tiny negative impacts or even positive influences when the land is fallow but it might cause a huge

[8]Individuals in the same area may have different flood risks, based on different perception of flooding, location, and different abilities to mitigate or adapt flood hazards.

[9]Other economic activities, e.g., tourism, are excluded in the discussion in this research though they may also be affected by floods.

loss just before harvest or right after planting. In some cases, winter flooding may have damaged old stems and prevented oxygen from reaching the rhizomes (Coops et al., 1994).

(2) *Duration.* Some crops can withstand a short term strike from floods. Most of them might not be able to survive after long-term or even short-term saturation.

(3) *Velocity.* Higher velocity of flood water usually causes more serious damage. Facilities, buildings, crops, livestock and even human beings can be washed away by high speed flood water. Sometimes, damage is caused by the debris travelling from other places.

(4) *Depth.* Agricultural products (including livestock) are mostly located on the ground, where it is locationally susceptible to flooding. Animal carcasses are commonly seen in the countryside in flood aftermath while crops are sensitive within a certain range of flood depth. It makes no difference once the flood depth exceeds a threshold level.

(5) *Water quality.* Flood water which carries fertile elements is beneficial while that brings pollutants is harmful to agricultural production.

MANUFACTURE

Manufacturing industry is generally not as susceptible to floods as agriculture is because of the nature of the industry. However, losses can be devastating once the flood water flushes into a firm either because of the lack of precautionary protection or the tremendous scale of a flood. The location and characteristics of a firm and the effectiveness of averting behaviour influence flood losses. Furthermore, the characteristics of floods also affect the magnitude of flood losses.

(1) *Timing.* Floods without warning might lead to huge damage due to inadequate precautionary protection. If there is enough time for moving to a safe location or protecting facilities and products, the timing of floods will not be crucial. The loss of stock and that of trades can be catastrophic if flooding comes at certain periods of the year such as Christmas or New Year, the peak of many business and sales.

(2) *Duration.* The duration of a flood might prolong the suspension of production and transportation.

(3) *Depth.* Firms situated in accommodation below the surface of flood water are influenced directly whilst those above it are not. In other words, the higher the location, the safer a firm is when faced with flooding. However, even safer firms may suffer from flood losses due to the links to damaged firms.

(4) *Velocity.* Floodwater with high-speed is more likely to destroy facilities and factories.

(5) *Water quality.* Manufacture usually does not benefit from the quality of flood water as agriculture does. On the other hand, industries which rely on clean water supply might suffer from poor water quality.

Overall, to estimate flood losses in a specific region, more details in the categories of production and social capacity are necessary. Besides, adaptation undertaken to decrease flood losses should also be considered.

2.4.3 Adaptation

Adaptation strategies are adopted with a view to reducing flood losses rather than decreasing the probability of flood occurrence in the way that mitigation does. Adaptation strategies include warning system operation, flood memory maintenance, sandbag arrangement, furniture-lifting, rescue programme operation, insurance purchase, migration, facility adjustment, and public health maintenance. Note that different types of floods might result in focus on different patterns of adaptation strategies (Montz and Gruntfest, 2002). An efficient warning system is crucial for adopting adaptive strategies.

WARNING SYSTEM OPERATION

A warning process covers the recognition of the event, recognisation of flood hazards, decisions on alerting others, reaching an official decision, and determination of public protective actions. Timely warning is decisive. A few minutes lost in any part of the process can be devastating. The most effective warning system integrates the subsystems of detection of flooding, management of related information, and timely public response (Sorensen, 2000).

Not only technologies, but the social factors are crucial to the effectiveness of a warning system. For instance, broadcast stations, especially those that can target at specific geographical areas, might be influential and incorporated in the warning system.

Any breakdown in the process can result in an ineffective warning. Sorensen and Mileti (1987) reviewed 39 warning systems in the United States and considered the communication problems, due to equipment and human failure, were the most significant causes of poor warning dissemination. Fundamentally, the recognition gap between emergency managers and the public also needs to be carefully studied.

MAINTAINING FLOOD MEMORY

Maintaining flood memory is for raising the awareness of flood hazards amongst the inhabitants of the area. There are several ways to maintain flood memory: placing 'high water signs' in visible spots commemorating the history of a flood, constructing special posts or obelisks with the flood's highest water level marking, organising permanent exhibits and expositions on local flood history, using the anniversaries of a flood for media to take up the issue (Siudak, 1999), and setting up a landmark such as the King's Arms Pub in York.

SANDBAG ARRANGEMENT AND FURNITURE-LIFTING

Arranging sandbags (or other flexible barriers that are put in place only at times of flood risks) and lifting furniture are the most effective ways to reduce flood losses within a short time, just before or even during flooding. The work in this category can only be done a little time before, or during, floods, hence the opportunity cost can be enormous. For instance, residents were afraid to go on holidays as they knew that they would not be able to relax if rain were forecast (Garvin et al., 2004).

RESCUE PROGRAM OPERATION

Using helicopters to rescue residents trapped by floods is a common scene in a flood disaster. Mobile phones have also become important in the communication link for those who encounter imminent threat and for emergency managers during rescue operations.

INSURANCE PURCHASE

Insurance has a risk-sharing mechanism. Income of the individuals who join the insurance market is redistributed.

Insurers have paid out 5 billion pounds during 1999 – 2003 on weather damage claims in the UK, over twice the amount in the previous five years period (Association of British Insurers, 2004). Though the UK market has been providing 'all risks insurance' including fire, theft, subsidence, property owner's liability, storm, escape of water, and flood, flooding has become very expensive to cover recently, especially after the devastating year 2000 flood.

Some early research found that insurance is more popular in the case of high-probability-low-loss events rather than for low-probability-high-loss events when the expected losses and premiums are equal (Edwards (1962) and Slovic *et al.* (1977), from Quiggin (1993)). This implies that flood insurance is more demanding for an individual who faces higher probability but a lower loss than one who faces lower probability but disastrous damage.

Kunreuther (1984) provided several possible reasons for individuals' failure to purchase flood insurance: differently perceived flood risks and unacceptably high insurance fees. On the demand side, empirical evidence revealed that homeowners had been reluctant to protect themselves against low-probability-high-loss events unless they were required to do so; on the supply side, the insurance industry had also been hesitant about providing this type of cover.

Browne and Hoyt (2000) and Ganderton et al. (2000) presented the results of experiments that indicated the factors of influencing insurance purchase for flood risks and for disaster-type of risks respectively. Browne and Hoyt (2000) set up the following model for the empirical analysis using data from 50 states in America (1983-1993):

$$\begin{aligned} &log(\text{insurance demand}) \\ &\quad = \beta_0 + \beta_i(\text{state i}) + \beta_1(\text{mitigation}) + \beta_2(\text{disaster-relief}) \\ &\quad + \beta_3 log(\text{price}) + \beta_4 log(\text{income}) + \beta_5(\text{FHA-loan}) \\ &\quad + \beta_6 log(\text{recent-flood}) + \epsilon \end{aligned} \tag{2.6}$$

where β_0 is the intercept, β_i is the parameter of a dummy variable (state i) for testing the fixed effects,[10] β_1-β_6 are the parameters of different variables, and ϵ is the error term. The last six variables are federal government expenditures on mitigation, disaster relief expenditure by the federal government, premium per $1,000 of in-

[10] A fixed effect model is a statistical model that stipulates that the units under analysis are the ones of interest, and thus constitute the entire population of units. Only within-study variation is taken to influence the uncertainty of results of a meta-analysis using a fixed effect model.

surance in force, disposable personal income per capita ($\$,000$), the number of the Federal Housing Administration mortgages per $1,000$ population, and total flood damage during the previous year.

The model is used in two ways, using different definitions of the number of flood insurance policies purchased per $1,000$ population in a state during a year, and the face amount of flood insurance in force per capita in a state during a year.[11]

The result supported the hypotheses that 'income' (positively) and 'price' (negatively) were influential factors in the decision to purchase flood insurance. Flood insurance purchase at the state level was found to be highly correlated with the level of 'flood losses in the state during the prior year'. Hence 'time lag' is crucial in the model setup. Concerning price effect, similar results were presented in Ganderton et al. (2000), consistent with the law of demand.

In terms of income effect, the findings of their paper suggested that individuals with higher income are more likely to purchase flood insurance and purchase a greater amount of insurance than low income individuals. This differed from the results in Ganderton et al. (2000) where wealth variable had a negative coefficient. The negative estimated effect implied that as wealth increased, subjects were more likely to self-insure.

Since the demand for insurance against low-probability-high-loss events is not well understood, the idea of catastrophe bond finds its niche. For instance, transactions of 'catastrophe futures' occur in

[11]Face amount is the amount stated on an insurance policy, to be paid upon death or maturity, the date on which a debt becomes due for payment.

Chicago Board of Trade.

When it comes to the responsibility for mitigating flood risks, ideally, governments, insurers, and reinsurers are encouraged to set up a 'risk partnership' for covering risks over a broad scale. Though it is ethically controversial, some research such as Browne and Hoyt (2000) suggested increasing the sales of flood insurance by modifying individuals' perceptions of potential losses.

MIGRATION

Migration occurs *ex ante* when people have to leave the area to secure their safety and wealth. It might happen *ex post* when a flood itself or its damage forces people to leave.[12]

One of the principles of building sustainable communities is ensuring that housing is built in the 'right' place (Edward and Turrent, 2000). Being careful about site selection, choosing a non-flood-prone area for instance, is fundamental to avoid flood hazards.

FACILITIES ADJUSTMENT FOR PROPERTIES

There are ways to make properties less vulnerable to flood damage. One is to raise floor levels directly. The other is to minimise potential damage, e.g., raising electric sockets above flood height, replacing chipboard or medium-density fiberboard floors and fittings with more resilient materials, using door-boards and window guards

[12]On the other hand, migration towards flood-prone areas occurs when driven by economic incentives. In the past few decades, most cases are about human activities' expanding into more flood-prone areas *ex facto*.

to keep out sediments and contaminants. Another is to strengthen the material of construction to provide better shelters.

To reduce runoff, the design and application of permeable surfaces on the ground is crucial. Besides, the capture of rainfall for certain water usage such as watering vegetables and flushing toilets can also reduce the amount of rainwater falling on the ground. Making the best use of the rainwater can not only decrease flood risks but decrease demand from public water supplies.

PUBLIC HEALTH MAINTENANCE

Public health should be considered before, during and after floods to avoid sequential calamities. Based on the observation of flood events, the following principles are crucial for public health management associated with flooding:

(1) Facilities such as hazardous waste landfills and nuclear power stations should be located outside flood-prone areas and well-protected from flooding. This is often listed in the principles of siting.

(2) Risks associated with potential sources of contamination such as sewage systems, chemical plants, and waste water treatment facilities should be scrutinised.

(3) Ironically, a deluge might result in an interruption of water supply because of the deterioration of water quality. Drinking water supply, in particular, should be protected from being polluted by bacteria such as *Salmonella.* The outbreak of Cryptosporidiosis in Milwaukee (USA) in 1993, already referred to, coincided with usually heavy spring rains and runoff from melting snow that pol-

luted drinking water. The concern that inhabitants in the affected area might need to be vaccinated against hepatitis A, which can be spread by faeces leaking into drinking water supplies, was raised in the 2002 flood of the Rhine.

(4) Disinfectant is often sprayed right after flood events to prevent the spread of disease from decomposing bodies. However, the side effects of using chemicals to control outbreaks of biological diseases need attention because such chemicals might trigger pollution in the next inundation.

(5) The dilution effects of flooding should not be impeded by flood control facilities. This is one of the controversial issues of flood mitigation in Bangledesh and the Venice lagoon. Otherwise, a compensatory mechanism should be established.

(6) The destruction or dysfunction of large facilities might also bring secondary flood hazards, such as the overtopping of dams. For example, the menace of overtopping the dam in Calderdale (England) triggered the evacuation of residents in the summer of 2004.

2.4.4 Welfare estimation of environmental goods

The welfare effects of flooding can be quantified in hydrological and economic terms. From the perspective of hydrology, a depth-damage curve is often applied. It aims at providing the reference losses for each category of the flooded area or buildings for prediction by compressing the information on flood losses into one function. In economic analysis, damage function estimation and production function approach are reviewed.

DEPTH-DAMAGE CURVES

There are two ways of obtaining depth-damage curves. One is using the relationship between actual damage from a past flood event and its depth; the other is producing 'synthetic depth-damage curves', as suggested by White (1964) (cited in Perry (1981)). For example, Penning-Rowsell and Chatterton (1977) and Parker et al. (1987) (cited in Perry (1981)) published synthetic depth-damage curves in the UK, and the Ministry of Construction (1996) (cited in Dutta et al. (2003)) published depth-damage curves in Japan. Usually, damage rises dramatically from a certain depth which can be viewed as a threshold. On the other hand, damage is often constrained to a limited amount whilst water depth reaches a higher level.

It is usually not easy to access enough data to plot a depth-damage curve, so a synthetic depth-damage curve appears to be more practical. A synthetic depth-damage curve is estimated by interpolating from existing data.

Ideally, data are categorised into groups, e.g., sectors, characteristics of buildings, or crops and then the damage are monetarised. For convenience, a specific percentage is often employed for each group to calculate flood losses. According to Smith (1994) (cited in Smith and Ward (1998)), flood damage surveys often assume that the average remaining value is 50% of that of a comparable new item. Relevant data, such as warning time, structural damage which results from extreme floods, clean-up and repairing services, are therefore necessary when interpreting the curves.

Smith (1994) (cited in Smith and Ward (1998)) pointed out that although plotting depth-damage curves was internationally accepted as a standard approach to urban flood damage assessment, there had been relatively few published accounts that gave details of the methodology for their construction or application. In reality, damage is not only associated with depth but also related to flood water velocity, effluent content, and flood duration (Perry, 1981). To incorporate more dimensions into the estimation of flood damage, a damage function is hence introduced.

DAMAGE FUNCTION

The damage function approach has, particularly in the past, been popular in analysing environmental impacts. It involves estimation of a damage function, an inventory of materials at risk, and multiplication of them by appropriate unit values (Farber, 1987; Gau and Liu, 2002). Development presents an economic decision while flood risks represent damage.

However, development is not the only type of human activity that affects flood risks. The damage function approach is criticised for ignoring people's averting behaviour. Therefore, a production function approach (and a cost function approach) incorporating averting behaviour have been proposed (Freeman, 1993).

PRODUCTION FUNCTION (AND COST FUNCTION)

This methodology was introduced by Just and Hueth (1979) and developed by Freeman (1993). It explains the welfare change in a society using a production function and measurements of consumer surplus.

In the production function approach, social welfare W comprises welfare of n individuals, m types of inputs, and environmental quality (q). It is a net social welfare, the monetary value of all the products less total factor costs.

$$W(v_{11}, \ldots, v_{nm}, q) = \int_0^y p(u)du - \sum_i \mathbf{F} \cdot \mathbf{V}_\mathrm{i}$$

where v is input, u is output, $p(\cdot)$ is the price of the output. For each individual i, the total cost of input is $[f_1, f_2, \ldots, f_m]^{-1} \cdot [v_1, v_2, \ldots, v_m]$. For convenience, vector $\mathbf{F}$ is the cost of input vector $\mathbf{V}$. Environmental quality, q, is shown as a factor in the production function to influence social welfare using envelope theorem. The 'envelope', by definition, is a curve or surface that is tangent to every one of a family of curves or surfaces. The envelope here is composed of the maximum welfare under all the possible combinations of inputs. Before applying the envelope theorem, the F.O.C.s for choosing input v_{ij} to maximise social welfare are:

$$\partial W / \partial v_{ij} = (\partial y / \partial v_{ij}) \cdot p(y) - f_j = 0 \quad \text{for all } i, j$$

In other words, the value of the marginal product

$$(\partial y / \partial v_{ij}) \cdot p(y)$$

should equal marginal cost f_j.

Using the envelope theorem, net social welfare can be expressed by the sum of both indirect impacts and direct impacts from the change of environmental quality. It also equals the value of the marginal product of q in the production function. This methodology is useful for incorporating the environmental impacts into production decisions.

$$\frac{\partial W}{\partial q} = \frac{\partial y}{\partial v^*(q)}\frac{\partial v^*(q)}{\partial q} + \frac{\partial y(v^*(q), q)}{\partial q} = p(y^*) \cdot \frac{\partial y(v^*(q), q)}{\partial q}$$

The advantages of adopting the production function approach are the following. First, it endogenises environmental quality into the production decision and incorporates averting behaviour. Second, the data of a production function may be easier to access than that of a consumption-based welfare function. When information about the cost function is easier to access, the cost function approach may be applied instead (Freeman, 1993).

OTHER METHODS

The 'shadow value' of risks can also be estimated using other methods such as willingness to pay (WTP), hedonic price and option price. These estimates can also support decision-makers in gathering information about flood risks.

1. Willingness-to-pay (WTP)

The WTP for decreasing the level of flood risks from x_1^0 to x_1^1 can be estimated in either a direct utility function or an indirect utility function. The direct utility function may take the form:

$$U(x_1^1, M - CV) = U(x_1^0, M)$$

where M is the units of a numéraire good and CV is the compensating variation measure of this change. The indirect utility function is:

$$V(p, x_1^1, y - CV) = V(p, x_1^0, y)$$

where y is the wealth level and p is the price of goods. Note that the estimation of WTP is invalid while the decision maker faces a non-linear constraint (Driscoll et al., 1994).

2. Hedonic price

Tobin and Montz (1990) and the Montz (1992, 1993) investigated the effects of floods on property values in communities in the United States and New Zealand. They found the housing price usually decreased temporarily after a flood event and then increased back to, or even exceeded, its previous level. However, if another flood struck this area, the price might not be able to return to the previous level.

In severely flooded areas, a decrease in house price might result from the visual reminders such as unrepaired or abandoned structures, damaged vegetation or high water marks. An increase in value in an area of frequent flooding might occur due to repairs and flood protection work, but the increase is lower than would be the case without flood hazards. The price of houses that have not been flooded, but are located in the affected area, usually decreases. Montz (1992) also testified that the greater the time interval between floods, the less the housing price differential (before/after flooding) would be.

House characteristics, not the hazardous locations of being flooded, are primarily responsible for differences in housing price in the long-run after all. Flood hazards generally only cause temporary disturbance.

3. Option price

Option price theory tries to indicate the value of 'non-used' assets. In this case, a decision-maker facing uncertainty intends to preserve the option to use the resource. Since Weisbrod (1964) proposed this theory for application to environmental evaluation, and it has been ubiquitously used in financial studies. Capozza and Li (1994) provided a general formulation for estimating the value of a development project, including the timing of investment and the intensity of development, in an expectation conditional on the cash-flow process over a period of time. Uncertainty over land prices is reflected by the assumption the prices exhibit using Brownian motion.

2.5 Decision-making under uncertainty

Unlike many other pollution issues, flooding often involves a high level of uncertainty. Averting behaviour has similar effects to insurance, lowering possible damage or costs of flood events. Expected utility (EU) theory, the general principle applied to insurance, is therefore employed.

Uncertainty implies insufficiency of information or knowledge and the limitation of the cognitive ability. EU function developed by von Neumann and Morgenstern (1953)[13] and a plethora of follow-up revisions are the most typical methods in economics for dealing with uncertainty.

[13] The idea can be traced back to Pascal-Fermat's expected value in 17th century and Daniel Bernoulli's solution (1738) to St. Petersburg Paradox.

2.5.1 Definition of the expected utility theory

Note that it is the expected *utility* rather than the *return* in a gamble that is used to avoid St. Petersburg paradox (or St. Petersburg-Menger paradox).[14] The difference is that utility follows the law of diminishing marginal utility whilst the return does not have the property of diminishing value. Utility must also be bounded to resolve the paradox of this sort (Menger, 1934).

von Neumann and Morgenstern (1953) used the summation of various possible utility values multiplied by their own probabilities of occurrence to denote the maximum value to a decision-maker. It can be expressed as follows:

$$EU(L) = \sum_{i=1}^{n} p_i u_i$$

where EU is expected utility, $L = (p_1, \ldots, p_n)$ is a lottery, p_i is the probability of the possible event i ($\sum_{i=1}^{n} p_i = 1$), and u_i is the utility from the event i. In other words, applying EU, uncertainty is described in terms of a range of possible consequences and the probability distribution across the consequences.

According to EU theory, utility is linear in probability as shown in the equations above. It reflects preferences for the utility of expected outcomes instead of dealing with outcome comparison after

[14]St. Petersburg Paradox shows the expected payoff of the following lottery is infinite, but in reality individuals are not willing to pay this amount of money to play the game. Consider tossing a coin repeatedly until the tail comes up. If this happens in the m^{th} toss, the lottery gives a monetary payoff of 2^m. Since the probability of this outcome is 2^{-m}, the expected payoff of this lottery is $\sum_{m=1}^{\infty} 2^m \cdot 2^{-m} = \infty$. It means an individual should be willing to give up all her/his wealth for the opportunity to play this lottery, which is not true.

the fact. The insight of von Neumann and Morgenstern (1953) is to *avoid* defining preferences over outcomes and capturing *everything* in terms of preferences over lotteries shown in the form of a utility function.[15]

Utility differs in different states. EU is the *ex ante* utility of current decisions. For technical convenience, EU captures both probabilities and utilities of different possible states and links each utility to its probability.

The central behavioural concept in EU is risk aversion which helps us compare different options. Formally, from Mas-Colell et al. (1995):

$$(x_1, \ldots, x_s) \succeq (x_1^{'}, \ldots, x_s^{'}) \quad \text{iff} \quad \sum_s u_s(x_s) \geq \sum_s u_s(x_s^{'})$$

where x_i and x_i' are different outcomes. This theory is based on the three axioms that characterise an individual's rationality (Laffort, 1989; Mas-Colell et al., 1995).

1. Pre-ordering preference The individual has a complete pre-ordering on the space, M, of lotteries defined over the consequences. It reflects an individual's appraisal of the likelihood of the various events, and their attitude toward risks.

2. Continuity axiom For all L, $L^{'}$, $L^{''} \in M$ such that $L \succeq L^{'} \succeq L^{''}$. There exists $L^{'} \sim \alpha L + (1-\alpha)L^{''}$ where $\alpha \in [0,1]$. Any small change of probabilities does not change the nature of the ordering between two lotteries. This axiom insures that preferences can be represented by a utility function.

[15]This comment is based upon 'http://cepa.newschool.edu/het/essays/uncert/vnmaxioms.htm'.

3. Independence axiom

The preference relation $\succeq$ on space of simple lotteries M satisfies the independence axiom if for all values of $L, L^{'}, L^{''} \in M$ and $\alpha \in [0,\ 1]$, we have

$$L \succeq L^{'} \text{ iff } \alpha L + (1-\alpha)L^{''} \succeq \alpha L^{'} + (1-\alpha)L^{''} \qquad (2.7)$$

2.5.2 Limitations of the expected utility theory

EU theory lays a rational foundation for decision-making under risk. However, it usually only explains what an individual 'should' do instead of how s/he 'really' behaves, a normative guideline instead of a positive explanation (Mas-Colell et al., 1995). In theory, the independence axiom, though absent in the original von-Neumann-Morgenstern (v.N-M) theory, is problematic. In practice, some of the experimental settings and observations in market are found inconsistent with EU theory (Quiggin, 1993).

1. Extreme values in probability, consequence, and wealth

(1) Low-probability-high-loss hazards

The interpretation of averting behaviour undertaken in response to low-probability-high-loss hazards is debatable. Lees and Rice (1965) considered people would be more likely to insure against larger rather than smaller losses. However, other research show that people 'misjudge' the risks if we compare the probabilities *ex ante* and *ex post.* Kunreuther (1984) contended some people are considered as 'underinsured' based on the common lament from uninsured victims after a disaster. Ganderton et al. (2000) considered EU suitable for explaining some purchase of insurance only for those risks with low probabilities. Furthermore, there is an issue of equity because the money to be spent on assistance is from taxpayers who are mostly not victims.

For most flood-prone areas, this is not a problem because flooding comes regularly. Non-flood prone areas, however, might encounter floods unexpectedly, with low probability. In this case, the application of EU needs adjustment. Kunreuther et al. (2001) pointed out the necessity of giving individuals enough context to draw on their own experience and well-developed risk perception if we ask them to evaluate an unfamiliar risk which has a small likelihood of occurrence. Hence, adjustment estimation is needed in modelling, e.g., applying weighted utility function.

(2) Over-estimation of the risk

Risk perception can be 'biased' in an utterly opposite way. According to Lichtenstein et al. (1978), the overall pattern observed is that people over-estimate the likelihood of low-probability events, but under-estimate that of high-probability events. The reason behind this over- or under-estimation is the difference of the accessibility of 'appropriate' information. If information about the occurrence of an uncertain event is repeated sufficiently frequently, particularly if it is provided to a degree far in excess of its overall relative value, flawed risk perceptions are likely to occur (Viscusi, 1991).

The reasons for misjudgement include: regret, lack of experience, and insufficient information. The first issue is left to psychology. Experience is the history a decision-maker encounters. So it cannot be influenced ethically. The only aspect we can work on is information supply. Though accessing 'sufficient' information may avoid such misjudgement, for low probability events, sufficiently correct information might simply not exist.

(3) Low income individuals

The coefficient of *relative* risk aversion measures risk aversion related to income levels, and is denoted by:

$$r(x) = -x \cdot U^{''}(x)/U^{'}(x)$$

where x is wealth (supposed to be a positive value), r is a measure of the degree of risk aversion, and U is utility with positive marginal utility (U') and negative value of the second order derivative (U'') (Pratt, 1964).

Further, Zeckhauser and Keeler (1970) introduced the concept of the coefficient of partial risk aversion:

$$r(x) = -(x - x_0) \cdot U^{''}(x)/U^{'}(x)$$

where x_0 is a base level that ensures wealth is above the 'minimum surviving level', omitting the consideration of individuals with lower wealth. This coefficient also expands the application of the coefficient of relative risk aversion that needs x to be positive.

A similar idea is provided by the 'first-safety model' (Dasgupta, 1993), in which households with a low amount of income might not be averse to risks. Figure 2.5 describes a utility function $V(Y)$, which is flat at low levels of income and rises sharply near the threshold income Y^*.

These models describe that people with extremely low or high wealth might become risk lovers.

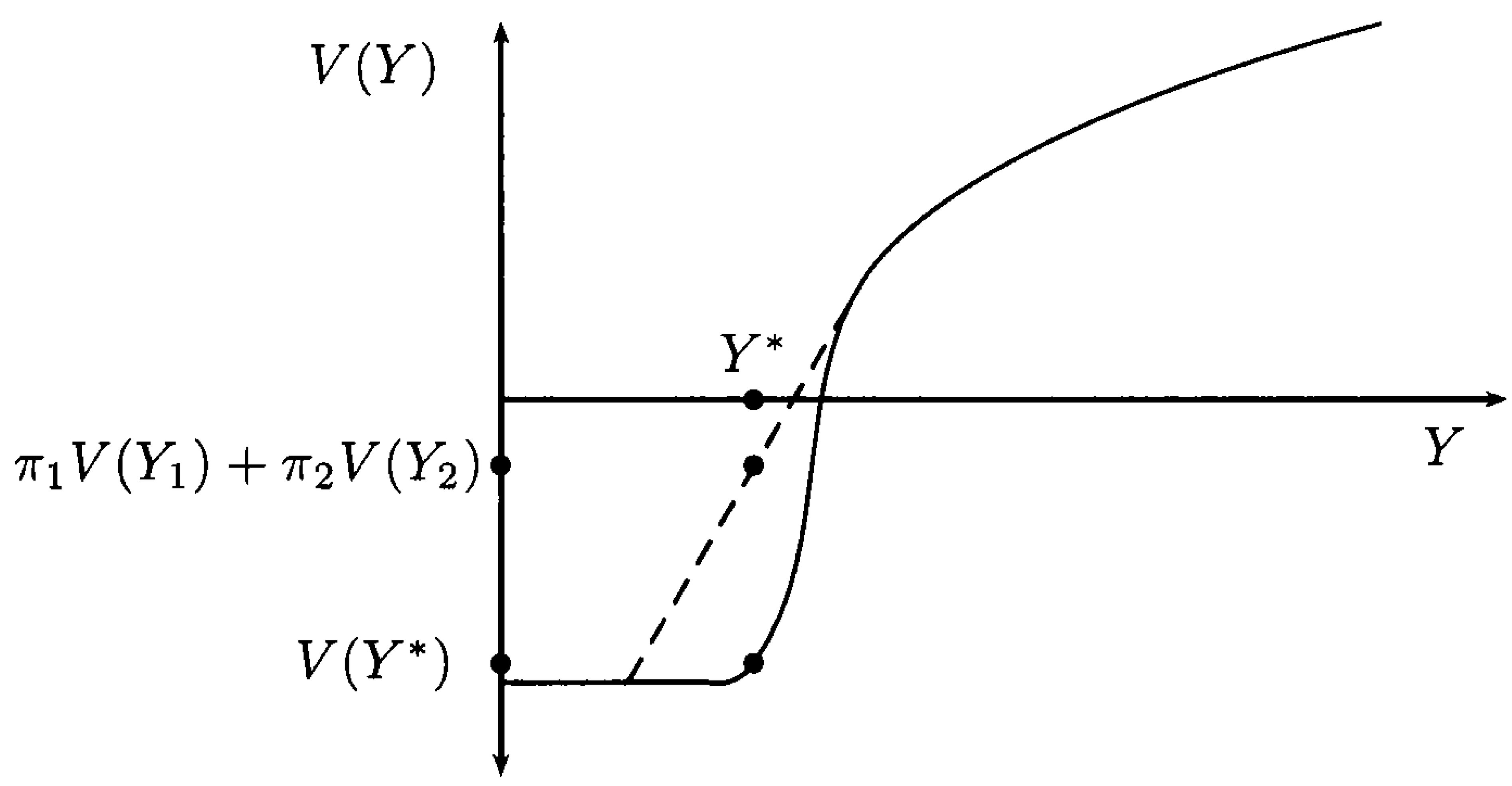


Figure 2.5: von Neumann-Morgenstern utility function at low income (Dasgupta, 1993). $V(Y)$: Utility function; Y^*: Threshold income; Y_1, Y_2: Income under the two states, 1 and 2; π_1, π_2: Probability of the two states, 1 and 2.

2. Violation of the independence axiom

The independence axiom is crucial to EU, but it is also a potential cause for argument. There have been experimental results that violate the independence axiom, such as the Allais paradox (Allais, 1979), common ratio effect, and reverse preference (Quiggin, 1993). Adjustment of the definition of a utility function might help avoid the violation of the independence axiom.

These results of experiments and surveys have revealed the limits of applying EU theory. Nevertheless, the development and revision of EU in ways that diminish the aberration of the original theory can still be suitable for decision-making to condense all the possible circumstances into one value under uncertainty.

2.5.3 Revisions of the expected utility theory

To conquer the challenge in the axioms of EU theory, revisions have been provided. In the weighted EU theory, Chew and MacCrimmon (1979) and Fishburn (1988) considered that people weight the underlying probability distribution based on either the value of outcomes or on their trust in the data. In the rank-dependent utility theory, Quiggin (1993) proposed an introduction of critical thresholds for key model parameters which can serve as a basis for changing from one option to another in the decision-making process. Lichtenstein and Slovic (1971) advocated the possibility of 'preference reversal' and allowed regret in decision-making. Ramsey (1926) asserted that individual assessment of probability relates to the knowledge possessed by a particular individual, which is subjective EU. However, the probability discussed in von Neumann-Morgenstern EU is understood to be 'objective' instead of 'subjective'.

Savage (1972) proposed both qualitative and quantitative methods to calculate subjective probabilities. Qualitative probability defines the preference relation '$\leq$' as 'not more probable than'; quantitative probability assumes a set of outcomes for which a probability is to be measured can be partitioned into an arbitrarily large number of equivalent subsets. Anscombe and Aumann (1963) showed it can have the same practical expression as that in objective EU.

The discussion of subjective probability reminds us to be careful when we apply and explain probabilities, and to avoid unreasonable assumptions. The probability of flooding of each region, contributed to by its climatological and geographical conditions and the averting behaviour undertaken, can be expressed as an objective value. Hence only collective action can be analysed in terms of an objective probability. This will be the case in the following chapters.

The revision for EU theory has challenged the original EU using different functional forms, arranging different types of preference order or revising its axioms. In common with the original EU theory, the follow-up development of EU captures preference in 'utility' with 'probability'.

Though there are limitations of EU theory, it still provides a succinct formula for analysing human behaviour under uncertainty in a normative perspective. Applying hydrology, the probability of flooding is the frequency of flood occurrence that incorporates economic activities and averting behaviour. The utility of outcomes of decisions to invest in hard or soft mitigation is the expected social welfare of those decisions.

2.6 Summary

To improve efficiency and to avoid fatal mistakes in decision-making, e.g., whether to discharge 600,000 tonnes of sewage-laden storm water into the Thames or not when flood occurrence is critical, well-structured information and decision-making systems are essential. Hence the guidelines of policies associated with land practice to river management should be focused. Land use, mitigation and adaptation activities, are factors influencing the probability of flooding. Both economic and health impacts are considered in estimating flood losses.

Due to the characteristics of flood events and the focus on economic tradeoffs, a flood economics model is developed. Infiltration theory in hydrology is applied to link land use and hard mitigation to the probability of flood occurrence while expected utility theory and the production function approach in economics are applied in modelling collective behaviour.

Chapter 3

Balancing Development and Protection in Flood Risk Management: A Static Model

3.1 Introduction

This chapter aims at identifying the decision rules facing flood hazards. Both economic and environmental concerns are crucial to social welfare analysis on flood risk management. However, the dual relationship between development and protection for welfare improvement, complementarity and substitution, complicate the problem. An economy can either increase development and provide financial support for flood mitigation, or decrease development and reduce flood risks. The optimal choice depends on the conditions in both economic and hydrological environments. Therefore, integrating hydrological characteristics and economic behaviour is essential for flood risk management.

Information about the magnitude and frequency of floods is required for engineering design of mitigation works, development planning, flood insurance, and decisions on land use. Information on the demand side, including financial capacity, should also be included in the decision-making process. Most research (Pattanayak and Kramer, 2001; Jepsen, 2003) including hydrological and economic analyses, apply the empirical results of hydrological studies to welfare analysis. This chapter, instead, develops a theoretical model incorporating both hydrological and economic theories in order to generate the principles of flood risk management.

In environmental economics, the impacts of environmental hazards have often been estimated by dose/damage functions. This methodology is widely applied to evaluate the impacts of pollution or the effects of pollution control on public health (Alberini et al., 1997; Machado and Mourato, 2002). Freeman and Harrington (1990) proposed the production function approach in order to endogenise environmental quality and averting behaviour in welfare analysis. However, these approaches are implicitly based upon the assumption of perfect foresight whereas uncertainty is a significant feature of flood events. Apart from this, the magnitude of damage is often related to the scale of economic performance. An equivalent magnitude of flood, for instance, can induce more damage in a developed area than in a non-developed area unless the former undertakes a higher level of averting behaviour.

To incorporate uncertainty and the scale of economic development in welfare analysis, this chapter develops a model based on an expected welfare function using a production function approach. It integrates Horton's infiltration theory to include the impacts of land use and averting behaviour on hydrological flows.

Section 3.2 discusses assumptions for the model setup in Section 3.3. Section 3.3 builds up a prototype and derives analytical results from it. Section 3.4 presents the chapter conclusion.

3.2 Assumptions

In the expected utility approach, hydrology and economics are linked by the probability of flooding (a physical dimension) and by the utility of flood events (a welfare dimension). Collective choices on land use and on averting behaviour arise because of the public good nature of mitigation actions. A social decision-maker aims at optimising expected social utility (for estimating welfare) under uncertainty.[1] This chapter develops a flood economics model of the decision process, built upon the following assumptions.

3.2.1 Economic model

To observe the tradeoffs among increasing economic gains, decreasing flood risks, decreasing flood losses and to merge the multiple targets, an indicator '***expected welfare***' is proposed. Expected welfare is the welfare net of floods multiplied by a scaling factor that incorporates the expected flood risks and magnitude of losses. It can be applied to estimate the value of welfare that is scaled down by environmental risk, including flood risks and flood losses.

[1]This thesis follows the modern practice of making no distinction between risk and uncertainty.

Conventionally, a damage function is applied to evaluate the impacts of environmental quality. However, people often undertake averting behaviour whilst facing flood risk. Since Freeman and Harrington (1990), the literature on environmental evaluation has drawn attention to the incorporation of averting behaviour and have presented the social welfare using the production function approach.

$$W(y_{11}, \ldots, y_{nm}, q) = \int_0^y p(y)\mathrm{d}y - \sum_i \mathbf{F} \cdot \mathbf{V}_i \tag{3.1}$$

where $\mathbf{V}$ is a vector of input, y is a vector of outputs, $p(\cdot)$ is the price of output, and $\mathbf{F}$ is the cost of input vector $\mathbf{V}$. Environmental quality, q, is shown as a factor in the production function to influence social welfare using the envelope theorem:

$$\partial W/\partial q = p(y^*) \cdot \partial y \left(V^*(q), q\right)/\partial q$$

Inputs in production can be placed in the first term while the costs of averting behaviour can be kept in the second term on the right hand side of equation (3.1). This methodology assumes that demand functions are compensated so that social welfare function associated with producing u is the area under the demand curve for u, deducted by the cost of inputs. It simplifies the application of welfare analysis because only information on production is required.

According to the Bergson-Samuelson social welfare function, we have social welfare as a function of the utility of a representative individual:

$$\max W = \max W(U)$$

Welfare may be proxied by profit as in Ehui et al. (1990). Their model is to maximise the serially continuous utility index of aggregate benefit from agriculture and forestry. Welfare is measured through the utility of profit ('benefit' in Ehui et al. (1990)).

$$W = \int_0^\infty e^{-\delta t} \cdot W\left(U\left(\pi(\cdot)\right)\right) \mathrm{d}t$$

This function can appropriately deal with problems of pollution. However, it cannot encompass uncertainty. Furthermore, problems like pollution are often taken as by-products of production (Keeler et al., 1971; Freeman, 1993). Averting behaviour that affects either the probability of or the loss due to flooding should be linked to capital instead of production. However, averting behaviour does not affect the probability of the event in existing models. For instance (Freeman, 1993),

$$E(u) = \pi \cdot v\left(M - R, A(R,G)\right) + (1-\pi) \cdot v\left(M - R, 0\right)$$

where M is wealth, R is private spending on averting behaviour, G is government protective spending, A is the magnitude of the event.

They are suitable in evaluating the cases in which only adaptation can be undertaken (in other words, only the consequences can be affected). However, this is not the case in flood management. Ehrlich and Becker (1972) incorporated 'self-protection' (called 'mitigation' in this thesis) to influence the probability of an event and employed 'self-insurance' and 'market insurance' (called 'adaptation' in this research) to affect the loss of an event. For instance, when market insurance and self-protection are jointly available, utility can be presented by

$$U = (1 - p(p^e, r)) \cdot U\left(I_1^e - r - s\pi(r)\right) + p\left(p^e, r\right) \cdot U\left(I_0^e - r + s\right)$$

where p is the probability of the event, p^e is the endowed probability of the event, r is the expenditure on self-protection, I_i represents the states, s is the price of insurance, π is the insurance amount.

Three other features are emphasised. First, most models of this sort capture individual's choices instead of social decisions. Hence, they are useful to find the optimal individual choices rather than collective decisions. Secondly, these models condense all choices into one term, often a monetary term. This is suitable for deciding insurance or entrance fees but not for decisions with multiple purposes. Thirdly, sacrificing economic development to decrease the probability of flooding should be taken into account in the analysis of environmental protection.

Suppose there are two sectors, non-manufacturing and manufacturing. Suppose that manufacturing occurs on developed land while non-manufacturing occurs on non-developed land (including agricultural land and open space).[2] A social planner has to decide the following:

(1) *Economic development*: This increases social welfare by converting non-developed land to developed land at the cost of increasing the probability of flooding. Non-developed land often depreciates due to production (e.g., land degradation) while developed land depreciates on a relatively small scale.

(2) *Mitigation*: This reduces the probability of flooding at the cost of economic gains, including hard mitigation (e.g., embank-

[2]Though there has been a debate on the impacts of agricultural land on flood risk, natural land cover generally has higher infiltration capacity than developed land that is dedicated to industrial purposes or urbanisation.

ments) and soft mitigation (e.g., afforestation and maintaining washlands).

(3)*Adaptation*: This decreases flood losses by purchasing insurance or improving warning systems.

An expected welfare function is employed to evaluate the trade-offs between these three actions in the decision-making process. Moreover, it aggregates individuals' utility into social utility that suits the centralised management of land use and averting behaviour for flooding. It also helps measure social welfare under uncertainty (Crew and Kleindorfer, 1976; Drazen and Grilli, 1993).

Based on von Neumann-Morgenstern's expected utility function,

$$U(L) = y_1 p_1 + \cdots y_N p_N$$

where $L = (p_1, \cdots, p_N)$ is a lottery with an assignment of numbers $(y_1, \cdots, y_N)$ to the N outcomes, the expected welfare function offers an *ex ante* analysis that shows a way to make choices before uncertainty is resolved. A social planner aims at selecting the bundle of decisions which gives the highest expected welfare (EW).

$$\max EW = \max \sum_{i=1}^{N} \rho_i \cdot W_i$$

W_i is the social welfare of the outcome i while ρ_i is the probability of its occurrence. N is the total number of outcomes. $EW_{\mathbf{A}} > EW_{\mathbf{B}}$ is equivalent to $\mathbf{A} > \mathbf{B}$. In other words, $\mathbf{A}$ is more desirable than $\mathbf{B}$ when the expected welfare of $\mathbf{A}$ is larger than that of $\mathbf{B}$. In this case, $N = 2$ (with floods and without floods) and the probability and the corresponding welfare value are presented in Table 3.1. The dichotomy of 'with' and 'without' floods here is for expository convenience. We can also divide the probability of flooding and its corresponding flood losses into n scales, i.e. the value of '$r \cdot v$' can be replaced by $\sum_{i=1}^{n}(r_i \cdot v_i)$, without affecting the analytical results.

Table 3.1: Probability and welfare with/without flooding

i	ρ_i	W_i
with flooding	r	$(1-v)\cdot W$
without flooding	$1-r$	W

EW can then be represented as the product of the probability of being flood damage free (θ) and the maximum social welfare net of floods (W).

$$\begin{aligned} EW &= \sum \rho_i \cdot W_i \\ &= r \cdot ((1-v)\cdot W) + (1-r)\cdot W \\ &= \theta \cdot W \end{aligned} \tag{3.2}$$

where $\theta = 1 - r \cdot v$. Equation (3.2) shows that a society expects to have a 'discounted' welfare taking the probability and losses of flooding into account. θ, where $0 < \theta < 1$, is a scaling factor for scaling down the value of the maximum welfare net of floods by incorporating flood risk.

3.2.2 Hydrological model

A hydrological model is essential for estimating the probability of flooding. Though there are a plethora of models of flood risks and flood losses, most are 'black-box' empirical rather than theoretical models.

Horton's infiltration theory (Horton, 1933; Smith and Ward, 1998) succinctly constructs the interaction between infiltration capacity (ς), precipitation intensity (n),[3] precipitation duration (t) and the amount of runoff (Q) using the concept of water budget. It also allows us to endogenise the threshold level below which the region can cope with ($\bar{Q}$), above which a flood hazard occurs. Symbolically,

$$(n - \varsigma) \cdot t = Q \geq \bar{Q} \tag{3.3}$$

Equation (3.3) can incorporate the economic activities - land use and mitigation - that affect the probability of flooding. Anthropogenic climate change is not considered here. Only factors that influence water on/below the ground are introduced.

Developed land (M) decreases the infiltration capacity of land ($\varsigma'_M \leq 0$) due to paving watertight surfaces in the name of convenience while hard mitigation (K) raises the threshold of flood occurrence ($\bar{Q}'_K \geq 0$). The probability of flooding ($0 < r < 1$) is the exceedance probability of the threshold level:

$$\begin{aligned} r &= r(Q \geq \bar{Q}) \\ &= r\left((n - \varsigma(M))\, t \geq \bar{Q}(K)\right) \\ &= r(M, K) \end{aligned} \tag{3.4}$$

where t is assumed as given and n follows a stochastic process. This conditional probability varies with hard mitigation, economic development and also with the rainfall pattern. By definition, the return period of flooding is the inverse of the exceedance probability. In

[3]This discussion focuses on the role of rainfall.

other words, the T-year flood has a probability of $1/T$ of being equalled or exceeded in any single period of time.

$$P(X > X^*) = (T(X^*))^{-1}$$

or

$$T(X^*) = (1 - P(X < X^*))^{-1}$$

where $T(X^*)$ is the (mean) return period of flood level X^* and X is the magnitude of a flood.

Though Horton's infiltration theory has been criticised for ignoring subsurface flow and the difference in soil saturation (Betson, 1969; Burt, 1996), it is still appropriate for this research. The reason is that infiltration capacity is valid for distinguishing flows between developed land and non-developed land.

3.2.3 The integrated model

The aforementioned hydrological model and economic model provide the foundation to establish an integrated model. The assumptions are based on the discussion in earlier chapters (Chapter 2 mainly), Ehui et al. (1990), Ehrlich and Becker (1972) and economic axioms.

(1) Social welfare net of floods: $W = W(M_+, K_-, D_-)$

Here I assume that social welfare net of floods, W, comprises profits from industries (manufacturing on developed land and non-manufacturing on non-developed land) and costs of averting behaviour. W is assumed to be twice differentiable.

$$W'_M \geq 0, \ W''_{MM} < 0$$

Developed land generally brings a higher profit compared with non-developed land. Following Ehui et al. (1990)'s research about the impact of deforestation on agricultural yield, the input of developed land follows the law of diminishing marginal product.

$$W'_K < 0,\ W''_{KK} < 0$$

It is straightforward that expenditure on hard mitigation reduces welfare and investment in hard mitigation also follows the law of increasing marginal cost. The cost of hard mitigation includes labour, capital, disturbance of ecosystem, risks of engineering failure, and costs of maintenance and repairs.

$$W'_D < 0,\ W''_{DD} < 0$$

Similarly, expenditure on adaptation reduces welfare and investment in adaptation also follows the law of increasing marginal cost.

(2) Probability of being flood damage free:
$\theta = \theta(M_-, K_+, D_+)$, **where** $0 < \theta < 1$

The probability of being flood damage free is formed by the probability of flooding and the proportion of flood losses. The former is affected by development and hard mitigation while the latter is influenced by adaptation. If θ is twice differentiable,

$$\theta'_M \leq 0,\ \ \theta''_{MM} < 0$$

This states that development of land reduces the probability of being flood damage free via the probability of flood as it decreases infiltration capacity. It is based on the discussion about the impact of development on flood risk in the Subsection 2.2.2 and assumption about damage function in conventional environmental economics (Perman et al., 1999). The rate of decrease in the probability of being flood damage free accelerates with the increase in developed land. It is caused by the movement onto more flood-prone areas as economic development proceeds. On the other hand, soft mitigation increases the probability of being flood damage free. Its effect on the probability of being flood damage free diminishes because the flood-prone areas are supposed to be released to efficiently store flood water at an early stage in a rational decision.

Secondly, we have that

$$\theta'_K \geq 0, \quad \theta''_{KK} < 0$$

It follows Ehrlich and Becker (1972)'s discussion about the relationship between expenditure on self-protection (mitigation in this case) and probability of hazard (the probability of flood in this case). The probability of being flood damage free increases with hard mitigation via the probability of flood. The increase in the rate of hard mitigation slows down the increase in the probability of being flood damage free due to technological limitations.

Thirdly, '$1-v$' scales down the welfare due to flood losses. Adaptation decreases flood losses.

$$\theta'_D \geq 0, \quad \theta''_{DD} < 0$$

postulates that the probability of being flood damage free increases with adaptation via the proportion of flood losses. It follows Ehrlich and Becker (1972)'s discussion about the relationship between expenditure on self-insurance (adaptation in this case) and loss (loss due to flooding in this case). The increase in the rate of adaptation slows down the increase in the probability of being flood damage free due to technological limitation. The remaining second-order derivative of either W or θ function are assumed to be equal to zero. The rationale behind the model is plotted in Figure 3.1 and the options of flood risk management are presented in Table 3.2.

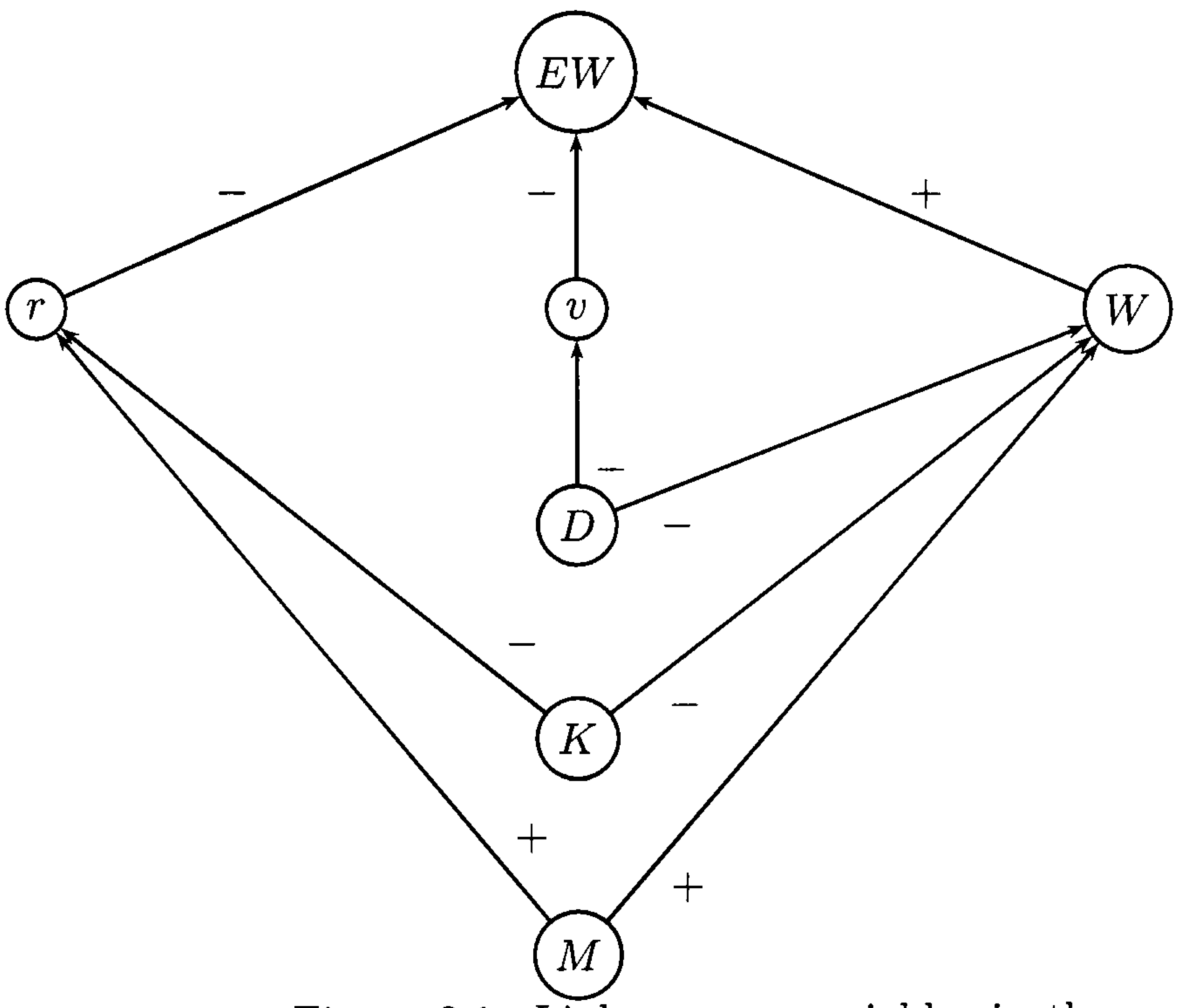


Figure 3.1: Links among variables in the model. $EW = W(M, K, D) \cdot (1 - r(M, K) \cdot v(D))$.

(3) Objective and constraints

In light of these definitions, the objective function and the constraints are as follows:

$$\begin{aligned} &\max\ \theta(M, K, D) \cdot W(M, K, D) \\ &\text{s.t. } 0 \leq M \leq \bar{A},\ 0 \leq K, D \end{aligned} \tag{3.5}$$

Table 3.2: Strategies for dealing with flood hazards and their cost and benefit

	Averting Behaviour			Doing
	Mitigation		Adaptation	Nothing
Benefit	$\downarrow r$	$\downarrow r$	$\downarrow v$	$\uparrow W$
Choice	hard mitigation	soft mitigation	warning, insurance	economic development
Cost	expenditure on hard mitigation	opportunity cost of non-development	expenditure on adaptation	$\uparrow r$

Note: W is the welfare net of floods; r is the probability of flooding; v is the proportion of flood losses to the welfare net of floods.

where $\bar{A}$ is the total amount of land and

$$W'_M \geq 0,\ W''_{MM} < 0,\ \theta'_M \leq 0,\ \theta''_{MM} < 0$$
$$W'_K \leq 0,\ \ W''_{KK} < 0,\ \theta'_K \geq 0,\ \ \theta''_{KK} < 0$$
$$W'_D \leq 0,\ \ W''_{DD} < 0,\ \theta'_D \geq 0,\ \ \theta''_{DD} < 0.$$

In summary, employing EW function brings three advantages in the flood risk management. First, it integrates all possible outcomes into one function. Secondly, the costs and benefits of economic development and averting behaviour can be clearly distinguished in one functional form. Thirdly, the conflicting relationship between economic gains and flood risks, as well as their complementarity, can be observed in the tradeoff between θ and W.

3.3 Model setup and the analytical results

Consider the case which has a stable equilibrium. Time is netted out and so is the distinction between flow and stock.

θ is a monotonically increasing function of K and D but monotonically decreasing with respect to M. On the other hand, W is a monotonically decreasing function of K and D but monotonically increasing with respect to M.

3.3.1 Conditions for the equilibrium

When the economic system is at equilibrium with optimal decisions, the first partial derivatives of the objective function (equation (3.5)) with respect to all the choice variables (M, K and D) are equal to zero.

$$EW'_{\mathbf{X}} = \theta'_{\mathbf{X}}W + W'_{\mathbf{X}}\theta = 0 \tag{3.6}$$

where

$$\mathbf{X} \equiv (M, K, D)^T$$

with the constraint

$$M \leqslant \bar{A}$$

From equation (3.6), we have

$$\theta'_{\mathbf{X}} \cdot W = -W'_{\mathbf{X}} \cdot \theta \Rightarrow \theta'_{\mathbf{X}}/W'_{\mathbf{X}} = -\theta/W \tag{3.7}$$

The economy is statically fully efficient if condition (3.7) is satisfied for all M, K and D. In other words, the ratio of the marginal impact of each control variable on the probability of being flood damage free to that on the maximum welfare should equal the ratio of the probability of being flood damage free to the welfare net of floods.

Rearranging equation (3.7), we have

$$\frac{\theta'_{\mathbf{X}}(\mathbf{X}/\theta)}{W'_{\mathbf{X}}(\mathbf{X}/W)} = -1$$

or

$$\epsilon_{\theta\mathbf{X}} = -\epsilon_{W\mathbf{X}} \tag{3.8}$$

where ϵ represents the partial elasticity of θ (or W) with respect to $\mathbf{X}$.[4]

Equation (3.8) asserts that the sensitivity of changes in the probability of being flood damage free in response to each variable should balance that in the maximum social welfare net of floods with respect to the same variable. Two propositions are derived from the model:

PROPOSITION 3.1: If $\epsilon_{\theta\mathbf{X}} + \epsilon_{W\mathbf{X}} > 0$, the amount of $\mathbf{X}$ should increase until $\epsilon_{\theta\mathbf{X}} + \epsilon_{W\mathbf{X}} = 0$. If $\epsilon_{\theta\mathbf{X}} + \epsilon_{W\mathbf{X}} < 0$, the amount of $\mathbf{X}$ should decrease until $\epsilon_{\theta\mathbf{X}} + \epsilon_{W\mathbf{X}} = 0$.

Proof: When

$$\theta'_{\mathbf{X}} \cdot \frac{\mathbf{X}}{\theta} > -W'_{\mathbf{X}} \cdot \frac{\mathbf{X}}{W}$$

we have

$$W \cdot \theta'_{\mathbf{X}} + \theta \cdot W'_{\mathbf{X}} = EW'_{\mathbf{X}} > 0$$

The decision-maker in this case has incentives to increase the level of $\mathbf{X}$ until the marginal impact of $\mathbf{X}$ on EW becomes zero. On the other hand, when

$$\theta'_{\mathbf{X}} \cdot \frac{\mathbf{X}}{\theta} < -W'_{\mathbf{X}} \cdot \frac{\mathbf{X}}{W}$$

we have

$$EW'_{\mathbf{X}} < 0$$

[4] According to the assumptions, there is not interaction among the decision on M and that on K or D. $W'_{M,K} = 0$, $W'_{M,D} = 0$, $W'_{K,D} = 0$, $\theta'_{M,K} = 0$, $\theta'_{M,D} = 0$, $\theta'_{K,D} = 0$. Therefore, equation 3.8 is the equilibrium solved simultaneously for the three variables (M, K, D).

where $\mathbf{X}$ should decrease to bring up the value of $EW'_{\mathbf{X}}$. Furthermore, when

$$\theta'_{\mathbf{X}} \cdot \frac{\mathbf{X}}{\theta} = -W'_{\mathbf{X}} \cdot \frac{\mathbf{X}}{W}$$

we have

$$EW'_{\mathbf{X}} = 0$$

at which the equilibrium occurs. These three conditions can be reconsolidated into the following statement:

$$\begin{cases} (\epsilon_{\theta\mathbf{X}} + \epsilon_{W\mathbf{X}}) \cdot EW'_{\mathbf{X}} > 0, & \text{when } \epsilon_{\theta\mathbf{X}} \neq -\epsilon_{W\mathbf{X}} \\ EW'_{\mathbf{X}} = 0, & \text{when } \epsilon_{\theta\mathbf{X}} = -\epsilon_{W\mathbf{X}} \end{cases} \tag{3.9}$$

The policy implications of this are straight forward. Since the unit of measurement is not concerned in the elasticity, and hence equation (3.9), is convenient to apply in empirical studies. Each strategy will increase (decrease) when its expected marginal benefit is larger (smaller) than its expected marginal cost and cease when these two marginal values are equal.

For instance, a catchment with lower probability of flooding has a lower $\epsilon_{\theta K}$ and hence the catchment employs a smaller quantity of hard mitigation (K) to keep a lower value of $|\epsilon_{WK}|$. Similar logic can be applied to adaptation (D) and soft mitigation (decreasing M). A catchment with higher probability of flooding has higher $\epsilon_{\theta K}$ and $\epsilon_{\theta D}$. Hence, the catchment can reach its optimal status by investing in hard mitigation and adaptation to bring up ϵ_{WK} and ϵ_{WD}.

PROPOSITION 3.2: When θ is high, a rational decision-maker should increase W and vice versa.

Proof:

Equation (3.7) shows that when W increases, the absolute value of $\theta'_{\mathbf{X}}/W'_{\mathbf{X}}$ should be decreased. With $\theta''_{\mathbf{XX}} < 0$ and $W''_{\mathbf{XX}} < 0$, K and D should be increased while M should be decreased. θ is then enhanced.

On the other hand, when θ increases, the absolute value of $\theta'_{\mathbf{X}}/W'_{\mathbf{X}}$ should be increased. With the assumptions $\theta''_{\mathbf{XX}} < 0$ and $W''_{\mathbf{XX}} < 0$, K and D should be decreased while M should be increased. W is then increased.

Resources are applied to boost the weaker part in the product of the expected welfare. It makes the marginal gain higher because of the larger base.

θ/W is often high at the beginning of the economic development due to little increment of flood risks induced by development and also the low value of welfare net of floods. Equation (3.7) showed that hard mitigation and adaptation should be low and development should be high to obtain a high level of $|\theta'_K/W'_K|$, $|\theta'_D/W'_D|$ and $|\theta'_M/W'_M|$. In other words, when a fast developing economy faces a low environmental risk, the priority is to increase welfare.

Gradually, θ/W decreases accompanied with an increase in economic development. Hard mitigation and adaptation should be high and development should be low to obtain small values of $|\theta'_K/W'_K|$, $|\theta'_D/W'_D|$ and $|\theta'_M/W'_M|$. When an economy develops at the cost of environmental risks, averting behaviour should be undertaken.

3.3.2 Income and substitution effects

Following the assumptions above, we have

$$EW = \theta(M, K, D) \cdot W(M, K, D)$$

$$\begin{aligned} &W'_M \geq 0, \ W''_{MM} < 0, \ \theta'_M \leq 0, \ \theta''_{MM} < 0 \\ &W'_K \leq 0, \ W''_{KK} < 0, \ \theta'_K \geq 0, \ \theta''_{KK} < 0 \\ &W'_D \leq 0, \ W''_{DD} < 0, \ \theta'_D \geq 0, \ \theta''_{DD} < 0. \end{aligned}$$

INCOME EFFECT

The income effect is the impact of a change of the endowments on the income in each decision. When endowment increases, i.e., W increases, M will decrease and K and D will increase following equation (3.7). On the other hand, if an economy suffers huge flood losses and hence incurs a huge decrease in the endowments, M should be increased and K and D should be decreased.

SUBSTITUTION EFFECT

The substitution effect is the impact of an exogenous increase in the price of each averting behaviour or development on its equilibrium. According to equation (3.7), an increase in the marginal benefit of developed land (W'_m) results in an increase in hard mitigation and adaptation. It represents the increased financial support for these two types of averting behaviour. It also shows the increased opportunity cost of undertaking soft mitigation. Hence, the economy will be better off by adopting hard mitigation and adaption instead. An increase in the marginal cost of hard mitigation (-W'_k) results in an increase adoption in its substitutes, adaptation and soft mitigation.

3.4 Discussion and conclusion

I conclude this chapter by recapitulating the results and discussing the prototype model. First, expected welfare is a way to estimate welfare when a decision-maker faces uncertainty and multiple purposes in flood risk management. It links the causes and impacts of flooding. Welfare is scaled down by the related environmental risk. The product of the probability of being flood damage free and the welfare net of floods involves both substitution and complementarity between environmental and economic realms in welfare analysis.

Secondly, an economy reaches its optimal level when the impact of the probability of being flood damage free with respect to each decision equals that of the welfare net of floods (Proposition 3.1). Development will keep increasing (decreasing) while it has positive (negative) marginal impact on the expected welfare; the level of a choice variable will be maintained while its marginal impact on expected welfare is zero. The same logic applies to averting behaviour.

Thirdly, the property of maximising the product of probability of being flood damage free and the welfare net of floods suggests that an economy should increase the former as the latter is high or the other way around within resources constraints (Proposition 3.2).

Fourthly, when the opportunity cost of hard mitigation is high, the option of soft mitigation or adaptation will be preferable. When the costs of both hard mitigation and adaptation are high accompanied with high level of development, soft mitigation is favoured.

The parameters for the probability of being flood damage free and the measure of welfare net of floods should be estimated based on individual cases. In other words, the tradeoffs between economic development and environmental risks should reflect the interests and concerns of residents and related groups.

The application of this prototype can be possibly extended to other environmental issues. The losses and probability of contracting a serious illness following exposure to a chemical can be decreased by undertaking averting behaviour. Incorporating the causes and impacts of climate change on flood risk management can extend the current model to a long-term perspective.

The following constraints of this model should be noticed. First, the landscape is assumed homogeneous in this model while it is usually heterogeneous in reality. This concern will be considered in the later chapters.

Second, the impact of climate change can be evaluated using the current model by adjusting the stochastic process of rainfall amount in the probability of flooding. This requires information about the interaction between the variation of rainfall and industries on a global scale. This concern will be left for further study.

Third, the elasticity value might change due to learning or environmental constraints. In other words, the optimal decision at each period of time does not necessarily equal the optimal decision in the long run. Though the envelope theory can be helpful for incorporation of the optimal decisions in the long run based on this model, the optimal paths of different variables should be derived in a dynamic framework.

Chapter 4

Balancing Development and Protection in Flood Risk Management: Dynamic Models

4.1 Introduction

Sustainable development requires a long term perspective. A dynamic model, providing decision paths over time, serves the need. This chapter develops two dynamic models based on the prototype introduced in Chapter 2 using optimal control theory.

The setting of the two dynamic models differs in accommodating different foci of optimisation. The first model has one control variable and one state variable associated with development (1×1 dimension). The second model includes one more state variable, the stock of mitigation (1×2 dimension).

A theoretical model with one control variable and one state variable is typical in optimal control theory. In reality, however, we often face multiple control variables and multiple state variables which complicates the mathematics. Dorfman (1969) suggested considering the control variables, state variables, and their derivatives as vectors to make the problem appear identical to the one-state-one-control case. There are two types of variables which can be compiled into one vector.

- Identical behaviour. For instance, hard mitigation and adaptation can be merged into one vector in the dynamic system because they behave consistently in affecting the maximum welfare net of floods (W) and the probability of being flood damage free (θ), apart from the impacts of their relative price change.
- Applying difference and ratio to screen out one of the variables. For instance, we can use the difference or the ratio as a control variable when two variables, measured by the same unit, have a fixed sum. Setting the land area covered by forest as a control variable like Ehui et al. (1990) brings no need to set another variable to indicate deforestation when no other economic activities involved.

Introducing the environmental perspective makes the model possess the following additional features:

- The accumulation of land stock, comparing with the accumulation of capital in capital theory, has positive effects on future production and negative impacts on flood risks.
- The tradeoff is not a question about consumption in the present or increasing production in the future. It aims at balancing the welfare effects of production and environmental damage.

Undertaking averting behaviour can also avoid damage to a certain extent.

In this chapter, investment in development, or averting behaviour, is set as a control variable while the stock of development assets is a state variable. Maximising expected welfare remains as the objective. Section 4.2 shows that the optimal growth rate of development should be decreasing before reaching the optimal level of development. Section 4.3 shows development and averting behaviour are complements up to the optimal level of development. After that, soft mitigation should dominate. Section 4.4 concludes this chapter.

4.2 Model (1)

The task of the first model is to find the optimal path of economic development in the face of environmental hazards. Averting behaviour is viewed as sacrificing economic benefit from development. This involves a strong assumption that the marginal cost of averting behaviour undertaken equals the marginal benefit of development. To maximise expected welfare, a decision-maker balances the sum of current and future welfare net of floods against the value of the future probability of being flood damage free.

The control variable, designated by m_t, is current investment in development. This is a closed loop control problem in which the optimal trajectory is not only a function of time but incorporates new information that arises from current state of the system.

The state variable M_t is total extent of developed land at time t. M_0 is the initial state. A large M_0 indicates a highly developed level while a small M_0 denotes a less-developed region. The 'depreciation' of developed land, at the rate of δ_m, includes wearing of hard surfaces over time and growth of vegetation that improve the infiltration rate. The costate variable μ_{mt} denotes the marginal shadow value of the developed land at time t.

4.2.1 Model structure

The aim of this problem is to plan the development rate to maximise expected welfare at the initial date ($t = 1$).

$$
\begin{aligned}
&\max_{m_t} PV = \int_{t=1}^{T} \theta(M_t) \cdot W(M_t, m_t) \cdot e^{-\sigma t} dt \\
&st. \;\; \dot{M} = m_t - \delta_m \cdot M_t \\
&\qquad 0 \leq M_t \leq \bar{A}, \; m_t \leq \bar{A} - M_t, \; M_{t=0} = M_0
\end{aligned}
\tag{4.1}
$$

The objective is to maximise discounted expected welfare over the time horizon, T. σ is the social rate of time preference. The choice is constrained by the motion of the developed land and boundary conditions.

The current value Hamiltonian for the problem describes expected welfare at time t from the perspective of time t.

$$
H = \underbrace{\theta(M_t) \cdot W(M_t, m_t)}_{\text{current expected welfare}} + \underbrace{\mu_{mt} \cdot (m_t - \delta_m \cdot M_t)}_{\text{future expected welfare}} \tag{4.2}
$$

The first term on the right hand side of the current value Hamiltonian represents the *current* expected welfare induced by the current decision. The second term denotes the *future* expected welfare, the monetary value of the changes of the total developed land at time t measured by its shadow value. Note that the dual role of M_t on affecting W_t and on θ_t makes the sign of this term ambiguous. It is no more guaranteed to be positive as that in the capital theory.

The first order conditions (F.O.C.s) are derived by maximising the current value Hamiltonian (equation (4.2)) with respect to m_t.

$$\frac{\partial H}{\partial m_t} = \theta \cdot W'_{mt} + \mu_{mt} = 0 \tag{4.3a}$$

$$\frac{\partial H}{\partial M_t} = \sigma \cdot \mu_{mt} - \dot{\mu_m} = \theta'_{M_t} \cdot W_t + \theta_t \cdot W'_{Mt} - \mu_{mt} \cdot \delta_m \tag{4.3b}$$

$$\frac{\partial H}{\partial \mu_{mt}} = \dot{M_t} = m_t - \delta_m \cdot M_t \tag{4.3c}$$

Condition (4.3a) indicates that along the optimal path of the investment in development at any period of time the marginal expected welfare of investment must just counterbalance its effect on decreasing the probability of being flood damage free an instant later.

Condition (4.3b) shows along the optimal path of developed land, the contribution of one unit of developed land to the expected welfare should just cover its impact on current expected welfare and the discounted and depreciated impact of investment on expected welfare ($-\dot{\mu_m} = EW'_M + (\sigma + \delta_m) \cdot EW'_m$).

Condition (4.3c) states that change in the extent of developed land is the difference between investment and depreciation or between conversion and reversion of land.

4.2.2 Equilibrium analysis

To solve the system of equations, we start by taking the time derivative of equation (4.3a), substituting it into equation (4.3b) to obtain

$$-\dot{\mu}_m = \theta'_M \cdot \dot{M} \cdot W'_m + \theta \cdot \left(W''_{mm} \cdot \dot{m} + W''_{mM} \cdot \dot{M}\right)$$
$$= \theta'_M \cdot W + \theta \cdot W'_M + (\sigma + \delta_m) \cdot \theta \cdot W'_m$$

The rate of investment in developed land then can be expressed as:

$$\dot{m} = \frac{\theta'_M W + \theta \cdot W'_M + (\sigma + \delta_m) \cdot \theta \cdot W'_m - (\theta'_M \cdot W'_m + \theta \cdot W''_{mM}) \dot{M}}{\theta \cdot W''_{mm}}$$
$$= \left(EW''_{mm}\right)^{-1} \cdot \left(EW'_M + (\sigma + \delta_m) \cdot EW'_m - EW''_{mM} \cdot m\right)$$
$$\dot{m} \gtreqless 0 \text{ when } EW'_M + (\sigma + \delta_m) \cdot EW'_m \gtreqless EW''_{mM} \cdot m \tag{4.4}$$

The sign of EW'_m is positive. EW''_{Mm}, the cross partial derivative, measuring the rate of change in EW'_M with respect to m, is assumed to be negative because of the compensatory property between M and m and the law of diminishing marginal product. The split point of the signs of EW'_M can only be obtained when the information about the functional forms of θ and W are given. The growth rate of development ($\dot{m}$) therefore decrease until the stock level comes lower than the maximum point. This growth rate is positive unless the negative marginal impacts of development are stronger than the aggregate impacts of investment on marginal expected welfare with respect to its stock and on the expected welfare discounted and depreciated.

At the steady state, $(\hat{m}, \hat{M})$, $\dot{M} = \dot{m} = 0$. In this case,

$$\hat{m} = \delta_m \cdot \hat{M} \tag{4.5}$$

From equation (4.4), we can obtain the condition

$$EW'_{\hat{M}} = EW''_{\hat{m}\hat{M}} \cdot \hat{m} - (\sigma + \delta_m) \cdot EW'_{\hat{m}} \tag{4.6}$$

$(\hat{m}, \hat{M})$ can be derived from equations (4.5) and (4.6). Equation (4.5) asserts that investment should equal the amount of depreciation at the steady state. The smaller the depreciation is, the less the investment should be. Equation (4.6) indicates the steady state value of investment in development. It shows that the marginal loss of expected welfare caused by the effect of development on flood risk should equal the marginal gain in terms of expected welfare.

4.2.3 Example

Suppose the probability of being flood damage free is positively related to the proportion of the land with protection (either without development or with averting behaviour). Welfare net of floods is a function of profits from developed land and developing land. The expected welfare function is denoted by a Cobb-Douglas function in which the relative share of total expected welfare accruing to the probability of being flood damage free is $a/(a + b)$ while that accruing to the welfare net of floods is $b/(a+b)$. Once land is transformed into developed land, it loses infiltration capacity and hence increases flood risks. For development, keeping up investment in averting behaviour is a way to avoid flood losses. Symbolically,

$$\begin{aligned}
\theta_t &= \left(1 - \left(M_t/\bar{A}\right)\right)^a \\
W_t &= \left(P(t)(M_t + m_t)\right)^b \\
EW_t &= \left(1 - \left(M_t/\bar{A}\right)\right)^a \left(P(t)(M_t + m_t)\right)^b \\
& 0 < a, b < 1, \; M_{t=0} = M_0
\end{aligned}$$

where $P(t)$ is the marginal profit of each unit of developed land. Hence we have

$$\begin{aligned}
EW &= \left(1 - \frac{M}{\bar{A}}\right)^a P(t)^b (M + m)^b \\
EW'_m &= \left(1 - \frac{M}{\bar{A}}\right)^a bP(t)^b (M + m)^{b-1} > 0 \\
EW'_M &= \left(1 - \frac{M}{\bar{A}}\right)^a P(t)^b (M + m)^b \left(\frac{-a}{\bar{A} - M} + \frac{b}{M + m}\right) \\
EW''_{Mm} &= bP(t)^b \left(1 - \frac{M}{\bar{A}}\right)^a (M + m)^{b-1} \left(\frac{-a}{\bar{A} - M} + \frac{b - 1}{M + m}\right) < 0
\end{aligned}$$

Substituting these expressions into equation (4.6) and applying (4.5) yields

$$\hat{M} = \left(\frac{B}{D + B}\right) \bar{A} \tag{4.7a}$$

$$\hat{m} = \delta_m \left(\frac{B}{D + B}\right) \bar{A} \tag{4.7b}$$

where

$$\begin{aligned}
B &= b\left((1 + \sigma + \delta_m)(1 + \delta_m) + (1 - b)\delta_m\right) > b \\
D &= a(1 + \delta_m)(1 + \delta_m(1 - b)) > a
\end{aligned}$$

The boundary constraints in equation (4.1) should also be satisfied. First, because $B, D > 0$,[1] the optimal stock of developed land is an interior solution, below the total amount of land. In other words,

[1] Since $B > b$, $D > a$, and $a, b > 0$, we have $B, D > 0$.

the economy will not develop all the land while incorporating both environmental and economic concerns into optimisation.[2] According to equation (4.6), $EW'_M < 0$ when the equilibrium occurs. It implies $-a/(\bar{A}-M)+b/(M+m) < 0$ because the investment in development can increase current welfare and bring only damage afterwards.

Convergence to equilibrium can be shown in a phase diagram (Appendix A) obtained from equations (4.3c) and (4.4). Figure 4.1 shows the two saddle paths leading the system towards equilibrium, the singular point $E(\hat{M}, \hat{m})$. The arrows indicate the directions of the movement of decisions over time. For instance, when $a = b = 0.5$, $\bar{A} = 100$, $\sigma = 0.02$, and $\delta_m = 0.001$, the steady state $(\hat{m}, \hat{M})$ is $(0.05, 50.52)$.

The initial value also affects decisions. When $M_0 > \hat{M}$, we have $EW'_{M_0} < EW'_{\hat{M}}$. From equation (4.6), we can deduct either small or even negative value of m_t. When $M_0 > \hat{M}$, the initial value of developed land exceeds its optimal level, the community should decrease the investment in development. In some cases, converting developed land back to its natural status might be necessary. In any case, the level of investment in development should be lower than that in the case of $M_0 \leq \hat{M}$.

4.2.4 Policy implications

The following discussion considered the effect of changes in policy parameters, primarily using the example in Subsection 4.2.3. The relevant parameters are the rate of time preference and measures of

[2] Unless averting behaviour has no effects ($a = 0$), which is not the case here.

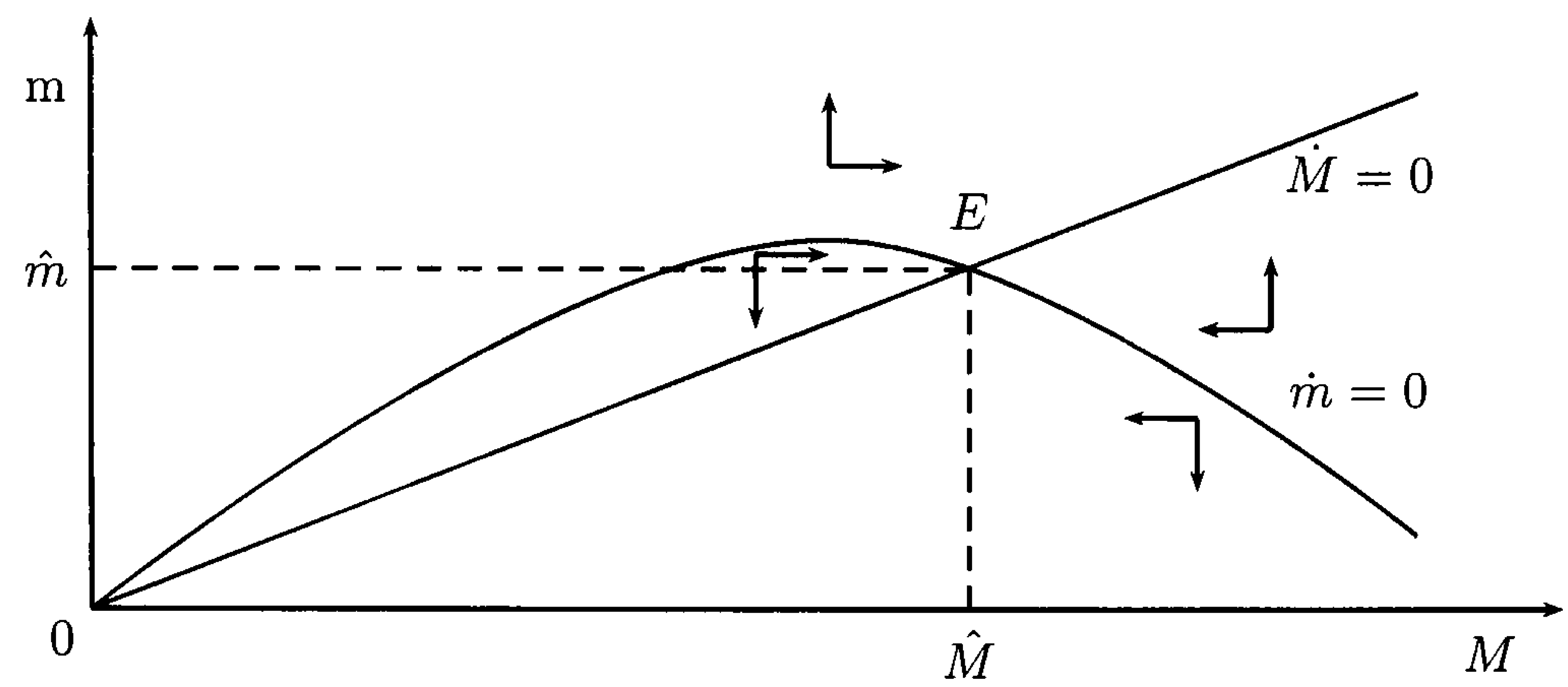


Figure 4.1: Phase diagram solution. E: the equilibrium; M: total developed land; m: investment in land development.

economic and environmental values.

(1) Discount rate: σ

$$\begin{aligned}
\frac{\partial M}{\partial \sigma} =& \bar{A}\left(\frac{b(1+\delta_m)}{D+B} - \frac{Bb(1+\delta_m)}{(D+B)^2}\right) \\
=& \frac{\bar{A}b(1+\delta_m)D}{(D+B)^2} > 0 \\
\frac{\partial m}{\partial \sigma} =& \frac{\delta_m \bar{A}b(1+\delta_m)D}{(D+B)^2} > 0
\end{aligned}$$

A decrease (an increase) in the discount rate implies an increase (a decrease) in the value of future income or damage. When the discount rate decreases, rate at which floodplains are developed will decrease. In other words, the higher the value of future income, the lower the optimal developed land should be. The adjustment path is illustrated in Figure 4.2.

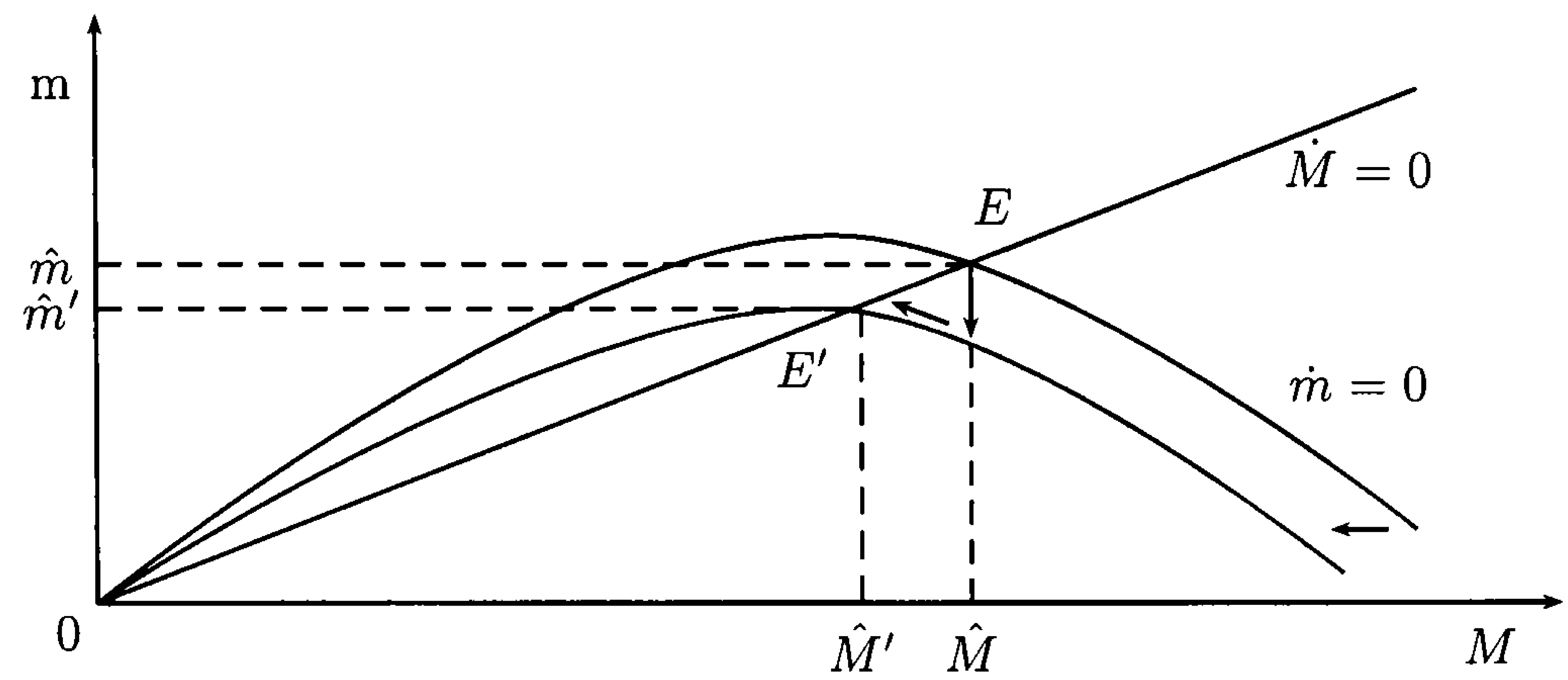


Figure 4.2: Effects of a fall in the discount rate in the phase diagram. Equilibrium moves from $E(\hat{M}, \hat{m})$ down to $E'(\hat{M}', \hat{m}')$. M: total developed land; m: investment in land development.

(2) Expected welfare and the probability of being flood damage free: $a/(a+b)$

The value of being flood damage free increases with the concern for environmental health. The influence of the probability of being flood damage free on the expected welfare can be derived by the differentiation of equations (4.7a) and (4.7b) with respect to a.

$$\frac{\partial M}{\partial a} = -\frac{B(1+\delta_m)(1+\delta_m(1-b))}{(D+B)^2} < 0$$

$$\frac{\partial m}{\partial a} = -\frac{\delta_m B(1+\delta_m)(1+\delta_m(1-b))}{(D+B)^2} < 0$$

The higher the value of the probability of being flood damage free, the lower the area of developed land should be.

(3) Expected welfare and welfare net of floods: $b/(a+b)$

The impact of welfare net of floods on expected welfare can be derived by the differentiation of equations 4.7a and 4.7b with respect to b.

$$
\begin{aligned}
\frac{\partial M}{\partial b} &= \frac{\bar{A}\left((D+B)(B-\delta_m b) - B(-a(1+\delta_m)\delta_m + B - \delta_m b)\right)}{(D+B)^2} \\
&= \frac{\bar{A}\left(D(B-b\delta_m) + aB\delta_m(1+\delta_m)\right)}{(D+B)^2} > 0 \\
\frac{\partial m}{\partial b} &= \frac{\delta_m \bar{A}\left(D(B-b\delta_m) + aB\delta_m(1+\delta_m)\right)}{(D+B)^2} > 0
\end{aligned}
$$

The higher the welfare of development net of floods, the greater the area of developed land should be. An increase in parameter value b might result from the efficiency improvement of production, an increase in compensatory inputs, or emphasising the philosophy about consumption.

In summary, this model shows that investment in development should be restrained and averting behaviour should be undertaken if there are concerns for future generations or for long-term environmental health. However, there are two restrictions in this model. First, examining economic development alone cannot help an economy to decide when to increase its development to financially support averting behaviour and when to sacrifice its development directly. Secondly, the accumulation of mitigation and adaptation in fact does not influence welfare in the same way that developed land does. The next model will distinguish these two types of capital stocks and derive the policy implications for both development and averting behaviour undertaken.

4.3 Model (2)

In the second model, it is assumed that a ratio α of every unit of land is compulsorily committed to hard mitigation. m_t, investment in developed land, remains as the control variable at time t. Apart from M_t and μ_{mt}, a new pair of state and costate variables, K_t and μ_{kt}, is introduced. The land on which mitigation (and adaptation) are undertaken at time t is K_t. K_t, and their depreciates (or returns to a natural state) at a positive rate δ_k.

α of every unit of developed land is protected by mitigation. Depreciation of hard mitigation infrastructure is assumed to be higher than that of developed land, $\delta_k > \delta_m$. μ_{kt} is the shadow value of averting behaviour at time t.

4.3.1 Model structure

Suppose the objective function and the constraints are

$$\begin{aligned}
&\max_{m_t} PV = \int_{t=1}^{T} \theta(M_t, K_t) \cdot W(M_t, m_t) \cdot e^{-\sigma t} dt \\
&st.\ \dot{M} = m_t - \delta_m \cdot M_t,\ M_{t=0} = M_0 \\
&\quad\ \ \dot{K} = \alpha \cdot m_t - \delta_k \cdot K_t,\ K_{t=0} = K_0 \\
&\quad\ \ 0 \leq M_t \leq \bar{A},\ m_t \leq \bar{A} - M_t
\end{aligned} \tag{4.8}$$

We can then obtain the current value Hamiltonian

$$\begin{aligned}
\tilde{H} =& \underbrace{\theta(M_t, K_t) \cdot W(M_t, m_t)}_{\text{current expected welfare}} \\
& \underbrace{+\mu_{mt} \cdot (m_t - \delta_m \cdot M_t) + \mu_{kt} \cdot (\alpha \cdot m_t - \delta_k \cdot K_t)}_{\text{future expected welfare}}
\end{aligned} \tag{4.9}$$

The F.O.C.s are:

$$\frac{\partial H}{\partial m_t} = \theta \cdot W'_{mt} + \mu_{mt} + \alpha\mu_{kt} = 0 \tag{4.10a}$$

$$\frac{\partial H}{\partial M_t} = (\sigma + \delta_m) \cdot \mu_{mt} - \dot{\mu_m} = \theta'_{Mt} \cdot W_t + \theta_t \cdot W'_{Mt} \tag{4.10b}$$

$$\frac{\partial H}{\partial K_t} = (\sigma + \delta_k) \cdot \mu_{kt} - \dot{\mu_k} = \theta'_{Kt} \cdot W_t \tag{4.10c}$$

$$\frac{\partial H}{\partial \mu_{mt}} = \dot{M_t} = m_t - \delta_m \cdot M_t \tag{4.10d}$$

$$\frac{\partial H}{\partial \mu_{kt}} = \dot{K_t} = \alpha \cdot m_t - \delta_k \cdot K_t \tag{4.10e}$$

Condition (4.10a) indicates the marginal expected welfare of the developed land should equal its value of decreasing the probability of being flood damage free less the effect of required amount of averting behaviour. $\alpha\mu_k$, with a positive value, is new here compared with the corresponding condition in model (1). Hence the optimal m should be higher for bringing down the value $\theta \cdot W'_{mt}$.

Condition (4.10b), same as the corresponding condition in model (1), indicates that along the optimal path of the investment in development at any period of time the marginal expected welfare of investment must just counterbalance its effect of decreasing the probability of being flood damage free an instant later. Similar interpretation can be applied to condition (4.10c).

Condition (4.10d), same as the corresponding condition in model (1), states the change in the extent of developed land equals the investment in developed land less depreciation on reversion. A similar interpretation is applied to condition (4.10e).

4.3.2 Equilibrium analysis

To solve the system, we can take the time derivative of equation (4.10a):

$$\dot{\mu_m} + \alpha \cdot \dot{\mu_k} = -\theta\left(W''_{mm}\dot{m} + W''_{mM}\dot{M}\right) - \left(\theta'_K\dot{K} + \theta'_M\dot{M}\right) \cdot W'_m$$

Compare this with the sum of equation (4.10b) and equation (4.10c) multiplied by α. Combining equation (4.10a) and $\mu_m = -\theta W'_m - \alpha\mu_k$ produces

$$\begin{aligned}
\dot{\mu_m} + \alpha \cdot \dot{\mu_k} &= -\theta\left(W''_{mm}\dot{m} + W''_{mM}\dot{M}\right) - \left(\theta'_K\dot{K} + \theta'_M\dot{M}\right) \cdot W'_m \\
&= (\sigma + \delta_m)\mu_m - \theta'_M \cdot W - \theta \cdot W'_M \\
&\quad + \alpha(\sigma + \delta_k)\mu_k - \alpha\theta'_K W \\
&= -(\sigma + \delta_m)\theta W'_m + \alpha(\delta_k - \delta_m)\mu_k - \theta'_M \cdot W \\
&\quad - \theta \cdot W'_M - \alpha\theta'_K W \\
&= (\sigma + \delta_m)\mu_{mt} - \theta'_M \cdot W - \theta \cdot W'_M \\
&\quad - (\sigma + \delta_k)(\theta \cdot W'_m + \mu_{mt}) - \alpha\theta'_K W
\end{aligned}$$

Hence we obtain

$$\begin{aligned}
\mu_{kt} &= \frac{(\sigma + \delta_m)\theta W'_m + \Phi + \alpha\theta'_K W - \Upsilon - \theta'_K\dot{K} - \theta'_M W'_m}{\alpha(\delta_k - \delta_m)} \\
\mu_{mt} &= \frac{\Upsilon + (\theta'_K\dot{K} + \theta'_M\dot{M})W'_m - \Phi - (\sigma + \delta_k)\theta W'_m - \alpha\theta'_K W}{\delta_k - \delta_m}
\end{aligned}$$

where $\Upsilon = \theta \cdot \left(W''_{mm}\dot{m} + W''_{mM}\dot{M}\right)$, $\Phi = \theta'_M W + \theta W'_M$

Applying equations (4.10b) and (4.10c) yields

$$\dot{\mu_k} = -\theta'_K W + (\sigma + \delta_k) / \left(\alpha(\delta_k - \delta_m)\right)$$
$$\cdot \left((\sigma + \delta_m)\theta W'_m + \Phi + \alpha\theta'_K W - \Upsilon - (\theta'_K \dot{K} + \theta'_M \dot{M}) W'_m\right)$$
$$\dot{\mu_m} = -\theta'_M W - \theta W'_M + (\sigma + \delta_m)/(\delta_k - \delta_m)$$
$$\cdot \left(\Upsilon + (\theta'_K \dot{K} + \theta'_M \dot{M}) W'_m - \Phi - (\sigma + \delta_k)\theta W'_m - \alpha\theta'_K W\right)$$

where $\Upsilon = \theta \cdot \left(W''_{mm}\dot{m} + W''_{mM}\dot{M}\right)$, $\Phi = \theta'_M W + \theta W'_M$

At the steady state, $\dot{\mu_m} = \dot{\mu_k} = \dot{M} = \dot{K} = 0$. Hence we have the conditions at equilibrium:

$$(\sigma + \delta_m) EW'_{mt} = -EW'_{Mt} - \left(\alpha(\sigma + \delta_m) EW'_{Kt}\right) / (\sigma + \delta_k) \quad (4.11a)$$

$$m_t - \delta_m \cdot M_t = 0 \quad (4.11b)$$

$$\alpha \cdot m_t - \delta_k \cdot K_t = 0 \quad (4.11c)$$

The value of EW'_{mt} and EW'_{Kt} are positive and EW'_{Mt} should therefore be negative. Two propositions follow.

PROPOSITION 4.1: If σ decreases, a decision-maker should increase the value of EW'_{mt} by decreasing investment in land development.

This follows directly from the condition that

$$\partial EW'_{mt} / \partial \sigma < 0$$

PROPOSITION 4.2: If α increases, a decision-maker should decrease the value of EW'_{mt} by increasing investment in land development.

This follows directly from the condition that

$$\partial EW'_{mt} / \partial \alpha < 0$$

4.3.3 The stability of equilibria

The study of stability includes identification of 'plausible' conditions that ensure stability but usually focuses on sufficient conditions. There are three types of equilibria: stable, unstable and neutral (Gandolfo, 1997). A system is stable if all subsequent motions remain in a correspondingly small neighbourhood of the equilibrium with slight perturbation from its equilibrium state. An unstable equilibrium may be an important feature in some cases, such as a saddle point. A neutral equilibrium occurs when a disturbance leads to a new situation which does not change unless there is a further disturbance.

In a case with one state variable, stability can be shown using a phase diagram as in model (1). In a case with more than one state variable, stability is often examined by calculating the characteristic roots (eigenvalues) of the linearised dynamical system evaluated at the steady state.

The nonlinear systems of equations we have are

$$\begin{aligned} \dot{M} &= F(M_t, m_t, K_t) \\ \dot{m} &= G(M_t, m_t, K_t) \\ \dot{K} &= J(M_t, m_t, K_t) \end{aligned} \tag{4.12}$$

where F, G, and J are continuous and differentiable. To investigate the properties of stability in the neighbourhood of the steady state, we can approximate this system in a Taylor expansion about the steady state $(\hat{M}, \hat{m}, \hat{K})$.

$$\begin{aligned}\dot{M} =& \frac{\partial F}{\partial M_t}\left(M_t - \hat{M}\right) + \frac{\partial F}{\partial m_t}\left(m_t - \hat{m}\right) + \frac{\partial F}{\partial K_t}\left(K_t - \hat{K}\right)\\ \dot{m} =& \frac{\partial G}{\partial M_t}\left(M_t - \hat{M}\right) + \frac{\partial G}{\partial m_t}\left(m_t - \hat{m}\right) + \frac{\partial G}{\partial K_t}\left(K_t - \hat{K}\right)\\ \dot{K} =& \frac{\partial J}{\partial M_t}\left(M_t - \hat{M}\right) + \frac{\partial J}{\partial m_t}\left(m_t - \hat{m}\right) + \frac{\partial J}{\partial K_t}\left(K_t - \hat{K}\right)\end{aligned} \tag{4.13}$$

According to the proof in Birkhoff and Rota (1969), when the linear system as shown in equation (4.13) is structurally stable, the nonlinear system in equation (4.12) will have the same behaviour in the neighbourhood of $(\hat{M}, \hat{m}, \hat{K})$.

Following the example in subsection 4.2.3, we can obtain

$$\begin{cases} F = \dot{M} = m_t - \delta_m M_t = 0 \\ G = \dot{m} = (\sigma + \delta_m)\left(P(t) - \alpha C(t)\right) \\ \qquad\qquad + \left(bP(t) - \dfrac{a\left(P(t)(M+m) - C(t)\alpha m\right)}{\bar{A} - M + K}\right) \\ \qquad\qquad + \dfrac{\alpha(\sigma + \delta_m)}{\sigma + \delta_k}\left(\dfrac{a}{\bar{A} - M + K}\left(P(t)(M+m) - C(t)\alpha m\right)\right) \\ \qquad = 0 \\ K = \dot{k} = \alpha m_t - \delta_k K_t = 0 \end{cases}$$

Let

$$\begin{aligned} a_{11} =& \partial F/\partial M_t, a_{12} = \partial F/\partial m_t, a_{13} = \partial F/\partial K_t, \\ a_{21} =& \partial G/\partial M_t, a_{22} = \partial G/\partial m_t, a_{23} = \partial G/\partial K_t, \\ a_{31} =& \partial J/\partial M_t, a_{32} = \partial J/\partial m_t, a_{33} = \partial J/\partial K_t \end{aligned}$$

The eigenvalues (λ's) of the Jacobian matrix

$$\mathbf{X} = \begin{pmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{pmatrix}$$

are given by the characteristic equation

$$
\begin{aligned}
det[\mathbf{X} - \lambda I] &= \begin{pmatrix} a_{11} - \lambda & a_{12} & a_{13} \\ a_{21} & a_{22} - \lambda & a_{23} \\ a_{31} & a_{32} & a_{33} - \lambda \end{pmatrix} \\
&= \begin{pmatrix} -\delta_m - \lambda & 0 & \mathbf{A} \\ 1 & \alpha - \lambda & \mathbf{BC} \\ 0 & -\delta_k & -\mathbf{AC} - \lambda \end{pmatrix} \\
&= \lambda^3 + (\delta_m - (1-\alpha)\mathbf{AC})\,\lambda^2 \\
&\quad - \mathbf{C}\,(\alpha\mathbf{AC} - (1-\alpha)\delta_m\mathbf{AC} + \delta_k\mathbf{BC})\,\lambda \\
&\quad + \mathbf{C}\delta_m\,(\alpha\mathbf{A} - \delta_k\mathbf{B}) \\
&= 0
\end{aligned}
$$

where

$$
\begin{aligned}
\mathbf{A} &= \frac{a\,(P(t)(M+m) - C(t)\alpha m)}{\left(\bar{A} - M + K\right)^2} > 0 \\
\mathbf{B} &= \frac{a\,(P(t) - C(t)\alpha)}{\bar{A} - M + K} > 0 \\
\mathbf{C} &= \frac{\alpha(\sigma + \delta_m)}{\sigma + \delta_k} - 1 < 0
\end{aligned}
$$

By trial and error, we can factor the cubic function as

$$
(\lambda + \delta_m)\left(\lambda^2 - (1-\alpha)\mathbf{AC}\lambda + \mathbf{C}\,(\alpha\mathbf{A} - \delta_k\mathbf{B})\right)
$$

whose characteristic roots are

$$
\begin{aligned}
\lambda_1 &= -\delta_m \\
\lambda_{2,3} &= 2^{-1}\left((1-\alpha)\mathbf{AC} \pm \left((1-\alpha)^2\mathbf{A^2C^2} - 4\mathbf{C}(\alpha\mathbf{A} - \delta_k\mathbf{B})\right)^{1/2}\right)
\end{aligned}
$$

When $\alpha\mathbf{A} - \delta_k\mathbf{B} < 0$, we have two negative eigenvalues (stable roots) and one positive eigenvalues (unstable root); when $\alpha\mathbf{A} - \delta_k\mathbf{B} >$

0, we have one negative eigenvalue (stable root) and two positive eigenvalues (unstable roots).

4.3.4 Policy implications

Consider the implications of changing the discount rate and the compulsory hard mitigation rate.

THE ROLE OF DISCOUNT RATE

Proposition 4.1 suggests that a decrease in the discount rate σ increases the value of EW'_m. In this case, investment in developed land should fall.

THE ROLE OF COMPULSORY HARD MITIGATION ON DEVELOPED LAND (α)

Proposition 4.2 suggests when the compulsory ratio of hard mitigation increases, the value of EW'_m should decrease. Developed land therefore increases. That is, the optimal extent of developed land increases with the compulsory ratio of hard mitigation. One implication of this is that soft mitigation is encouraged/discouraged by decreasing/increasing the compulsory ratio of hard mitigation.

ENSURING THE STABILITY OF THE SYSTEM

We can always make the system stable provided that we are free to choose as many initial conditions as there are unstable roots (Gandolfo, 1997). When $\alpha\mathbf{A} - \delta_k\mathbf{B} < 0$, the system can reach stability by choosing the initial level of the investment in developed land. In the case of $\alpha\mathbf{A} - \delta_k\mathbf{B} > 0$, the stability can only be obtained by affecting the initial developed land. Hence it may not be easy to obtain.

4.4 Conclusion

The dynamic models indicate the conditions under which the development of floodplains, and the adoption of hard or soft mitigation is optimal.

As in other problems in environmental economics, a decrease in the discount rate implies a fall in current development. An increase in the concern for environmental health encourages investment in soft mitigation, including deterring development. The second model also suggests that an increase in the compulsory rate of hard mitigation leads to higher levels of development. In other words, undertaking soft mitigation might be ignored when investment in hard mitigation is the focus.

However, within a catchment, different regions may attach different values to the probability of being flood damage free. Externalities may also occur. For instance, the increase in drainage in uplands was suspect to be associated with the increase in flood occurrence in York in the 1980s. Hence, research on the interactions between regions is required to clarify the externalities caused by regional economic activities and averting behaviour.

Chapter 5

Externalities of Flood Risk Management

5.1 Introduction

The decision models in Chapter 3 and Chapter 4 are based on central planning from both static and dynamic perspectives. In reality, decisions are often the results of interactions among related individuals, institutional agents in this case, within a catchment. Moreover, individual decisions often involve strong externalities. This raises the issues of how to take account of both the strategic interactions among these individuals, and the potential benefits of cooperation.

The occurrence of externalities,[1] adverse externalities in particular, is common in flood risk management. For example, upstream drainage and over-grazing in the Yorkshire Dales increase the probability of flooding in the Rivers Swale and Ouse. The extent of

[1]The externality is defined as the action of one decision maker that affects the welfare of another, and that is not captured by market transactions. By definition, adaptation is beyond the scope of discussion.

flood externalities has long been recognised. For example, the Code of Hammurabi (eighteen century B.C.) states the punishment for generating externalities of flood risk.[2]

Flood risk externalities comprise a change in the likelihood of floods resulting from the regime of others. A reciprocal externality implies a common pool resource (e.g., regions located on both sides of a river). A unidirectional externality implies a one way or upstream-downstream effect.

Policy instruments of internalising externalities for catchment management include restrictions, water fees, and increasing public participation, etc.. A few theoretical models have been recently explored (Marino and Kemper, 1999; Saleth and Dinar, 1999; Ostrom, 1999). Economic research on risk management primarily involves the financial market and the insurance market. The methodology is often based on expected utility theory, the approximation of the probability function, and the instruments of hedging.

To model the interplay among decision-makers, game theory is applied. There are two reasons of this. First, a game is able to explain which allocations can be sustained and which cannot in the strategic interaction among decision-makers. Secondly, a game the-

[2]It included the duty of maintaining the mitigation facilities and also the responsibility for causing floods. Section 53: If anyone is too lazy to keep his dam in a proper condition, and does not so keep it; if then the dam breaks and all the fields are flooded, then shall he in whose dam the break occurred be sold for money, and the money shall replace the corn ruined by him. Section 55: If anyone opens his ditches to water his crop carelessly, and the water floods his neighbour's field, then he shall pay his neighbour corn for his loss. Section 56: If a man let in the water, and the water overflow the plantation of his neighbour, he shall pay ten gur of corn for every ten gan of land (revised from http://www.wsu.edu/~dee/MESO/CODE.HTM).

oretical model describes the operation of a decentralised system.

Game theory addresses the interaction among institutional agents, such as local authorities, environmental authorities, and NGOs, etc. in both conflicting and cooperative relationships and provides a framework for understanding private decisions. Conflicts among players in this case mainly result from the downstream flood risks associated with upstream hard mitigation and economic development. Benefits can come from soft mitigation due to efficiency improvement of water storage and from avoiding efficiency losses in hard mitigation.

Environmental games which combine externality analysis and game theory have been widely used, especially in modelling transboundary agreements such as those for managing acid rain impacts (Maler, 1989) and greenhouse gases reduction. In flood management, research by Alber et al. (1972) applied a game with single-dimensional strategy space to show different payoffs for either consolidation or split-up when farmers face flood hazards.

However, the strategy space is often more than one dimension. There are usually several sub-strategies (e.g., soft mitigation, hard mitigation, and development) corresponding to several specific sub-objectives for one major objective (e.g., containing flood risk and maximising the welfare net of floods are merged into one major objective, maximising expected welfare). Thus, tradeoffs between sub-objectives and between sub-strategies should be taken into account. The principle of sub-objective dominance (deleting the choice which might violate the purpose of undertaking it) and supermodularity are applied to interpret the decisions involving strategic complementarity of (sub)strategies in a multi-dimensional strategy space within a catchment.[3]

Apart from externalities, threshold effects related to development or mitigation are also crucial for indicating the critical point of abrupt change of efficiency in aggregating decisions within a catchment. Threshold effects occur in many ecological processes and environmental hazards. For instance, Hartwick and Olewiler (1998) presented a situation in which the total damage function contains two linear segments, with discontinuity at the threshold emission level. Beyond the threshold level, there is a step change in both marginal damage and marginal abatement cost.

The impacts of threshold effects differ in the cases with and without externalities. Threshold effects are not crucial in the cases without externality because a rational decision-maker already perceives the losses from surpassing thresholds. However, they may be triggered by aggregate decisions of players in the cases related to externalities. Figure 5.1 illustrates the case where the probability of flooding in a catchment increases sharply once developed land exceeds $\hat{M}$. Increasing hard mitigation $\hat{K}$ becomes a source of efficiency loss once hard mitigation reaches a certain level. Further investment in hard mitigation generates no effect on decreasing the probability of flooding in the catchment after passing the threshold level.

[3]Strategic complementarity of strategies means that when others increase their effort levels, you wish to increase yours as well; strategic complementarity of sub-strategies means that when one of the substrategies increases, you wish to increase other sub-strategies accordingly.

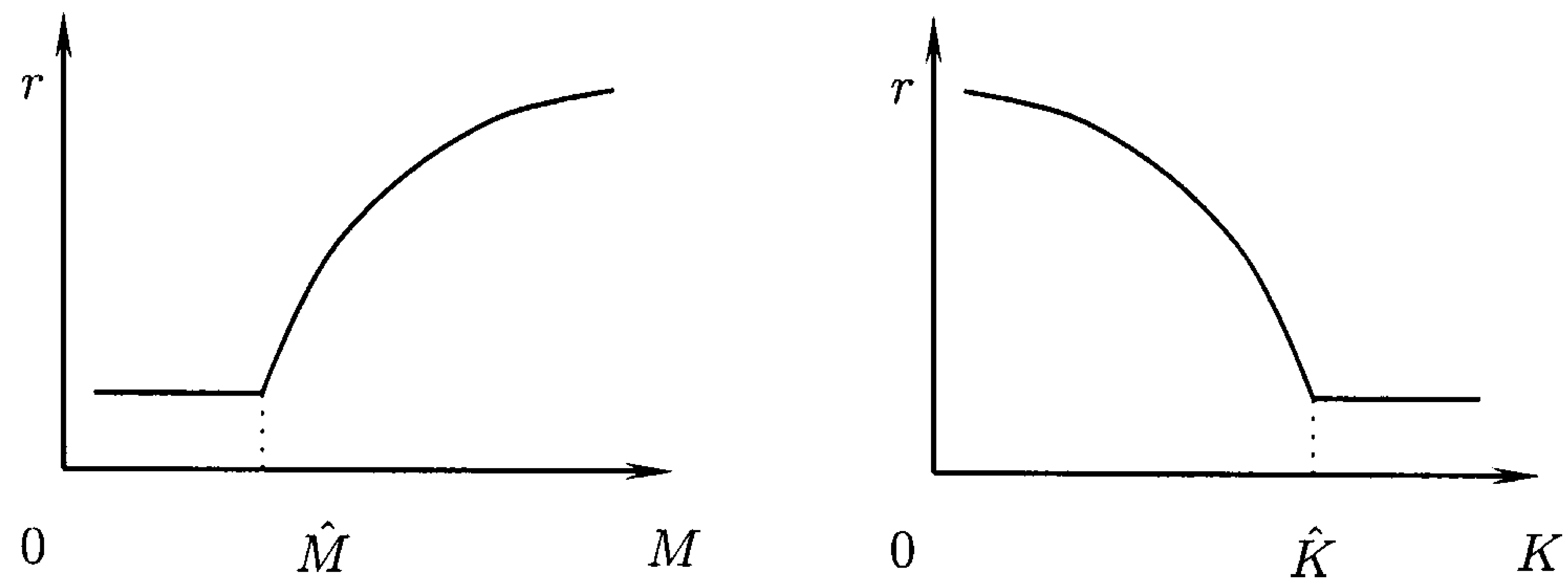


Figure 5.1: Left: The threshold effect of development/soft mitigation; right: The threshold effect of hard mitigation.

Section 5.2 reviews the theoretical background to set up the game theoretical model. Section 5.3 presents externalities associated with flood risk management in a common pool, while Section 5.4 presents externalities in the upstream-downstream case. Section 5.5 discusses the policy implications of the results related to the game of common pool and upstream-downstream externalities. Section 5.6 presents my conclusions.

5.2 Theoretical background

First, the concept of equilibrium in game theory is reviewed, and then the types of games associated with this research will be introduced.

5.2.1 Equilibrium

There are various types of equilibrium in a game: Nash equilibrium, undominated equilibrium, and Pareto-dominant equilibrium being the most frequent. The first two are normative while the third is often a reference point. The Nash equilibrium and the Pareto-dominant equilibrium can be applied to justify the necessity of co-operation.

A Nash equilibrium (s_i^* for player i, referring to equation (5.1)) occurs when everyone plays his/her optimal strategy simultaneously. It is the best state that a player can reach in the absence of cooperation. Hence, it can be used as a 'threat point' when there is an opportunity for Pareto improvement. If cooperation cannot be agreed upon, a Nash equilibrium will occur.

A strategy profile $s = (s_1, \ldots, s_I)$ constitutes a Nash equilibrium s^* for every individual $i = 1, \ldots,\ I$, when the payoff

$$u(s_i^*, s_j^*) \geq u(s_i, s_j^*), \quad s_i^* \neq s_i \tag{5.1}$$

where s_j is the counterparts' strategy.

A strategy is strictly dominated if another strategy always improves payoffs whatever the other players do. Ruling out the irrational strategies (those generate less payoffs) obtains the undominated equilibrium.

A Pareto-dominant equilibrium is often a cooperative equilibrium. Cooperation will not be obtained unless agreements are well bound and enforceable, free-riding is trivial or fixed, and no player is worse off. It can be shown as

$$u(s_i^c, s_j^c) \geq u(s_i^{-c}, s_j^{-c}) \tag{5.2}$$

where c represents cooperation and $-c$ indicates non-cooperation.

5.2.2 Non-cooperative game and cooperative game

Welfare comparison between a non-cooperative game and a cooperative game is helpful to justify cooperation. Cooperation only occurs when Pareto improvement is obtained by a win-win solution. Hence, it only happens in a non-zero-sum game that can be defined by a positive sum of payoffs:

$$\sum_{i=1}^{N} u_i(s_i) > 0$$

where u_i and s_i are the payoff and strategy set of individual i, and N is the number of players. The equilibrium of a zero-sum game (with pure conflict) is not taken into account because of the focus on efficiency improvement. The occurrence of threshold effects and the economic and geographical differences among players and/or among regions provide the foundation of a non-zero-sum game.

For efficiency improvement, players can agree on the choice with the most efficient combination of location, mitigation technique, hard mitigation, and economic activities for the whole catchment, and then allocate the gains to each player. Hence, the incentives to conclude an agreement and the mechanisms for allocating the extra value from cooperation characterise a cooperative game. Flood tax, subsidy for hard mitigation and for soft mitigation, restrictions on land use and on hard mitigation, and compulsory insurance are the options for re-structuring the rules of the game.

5.2.3 Supermodular game

A supermodular game considers strategic complementarity and multi-dimensional strategy. Multiple equilibria, resulting from strategic complementarity, provide a possible coordination failure (or success) which is inefficient (or efficient) to the economy.[4] The supermodular game was introduced by Topkis (1979) and first applied in economics by Cooper and John (1988), and then Milgrom and Roberts (1990) and Vives (1990). In a supermodular game, the order of choices in the strategy space should be clear and the reaction curves should be upward sloping under the assumption of strategic complementarity. A supermodular game can be applied among players and/or among strategies.

- When the strategy sets of all players are partially ordered, the marginal return to increasing one's strategy will rise with an increase in the counterparts' strategies (strategic complementarity). It implies an increase in player j's action encourages an increase in player i's action. The increasing payoff accordingly suggests the occurrence of strategic complementarity.

$$\partial^2 u_i / \left(\partial s_i \partial s_j\right) \geq 0$$

[4]Coordination failure in macroeconomics often implies the economy can get fixed, for example, in an unemployment equilibrium (Romer, 1996). The coordination failure in this thesis implies inefficient use of resources.

- In multi-dimensional strategy sets, the marginal return to one sub-strategy rises with an increase in other sub-strategies (Milgrom and Roberts, 1990). u_i is supermodular in strategy s_i, if and only if, for any two components $s_{i,b}$ and $s_{i,-b}$ of s_i,

$$\partial^2 u_i / \left(\partial s_{i,b} \partial s_{i,-b}\right) \geq 0.$$

In applications, a way to obtain the ordering of sub-strategies is required. In the dynamic version, stocks instead of flows should be ordered (Milgrom and Roberts, 1990).

Supermodular games are frequently applied to externalities in macroeconomics, such as the search model in Diamond (1982), the rational expectations model in Bryant (1983), some of the Bertrand oligopoly with differentiated products quality, new technology adoption in Katz and Shapiro (1985), the arms race game in Milgrom and Roberts (1990), and the explanation of multiplier effects (Romer, 1996).

In summary, using the typical single-dimensional strategy space to solve multi-dimensional strategy by stablising other dimensions is a way to the answer, but the enlarged payoff matrix generates difficulties in deriving an analytical solution. By recognising the knowledge gap, the principle of dominant sub-objective, a revision of the principle of dominance in multi-dimensional decision space, and supermodularity are introduced to solve a game with multi-dimensional strategy.

5.3 Reciprocal externalities in a catchment: Common pool

In common pool, externalities of flood risk are reciprocal among homogeneous players. It hence shapes a symmetric game.

Decision-makers increase the welfare net of floods (W) instead of the probability of being flood damage free (θ) in a non-cooperative game because of the awareness of strategic interdependence on the probability of flooding (r).[5] Increasing the welfare net of floods is at the cost of decreasing probability of being flood damage free. On the other hand, increasing the probability of being flood damage free is at the cost of decreasing the welfare net of floods.

5.3.1 Assumptions

For simplicity, we assume there are only two identical regions, i and j, in a catchment (e.g., symmetrically facing a river in common pool). They have equal bargaining skills and aim at maximising their own welfare

$$EW_\iota = \theta_\iota \cdot W_\iota, \qquad \iota = i, j$$

The payoff functions are continuously differentiable. There are three options: hard mitigation (increasing K), development (increasing M), and soft mitigation (decreasing M).

Suppose economic markets are open and competitive. Only economic development, soft mitigation, and hard mitigation can cause

[5]Recall that $EW = r \cdot (1 - v) \cdot W + (1 - r) \cdot W = (1 - r \cdot v) \cdot W = \theta \cdot W$ in Chapter 3.

externalities, presented in the change of the probability of flooding. An increase in i's development or hard mitigation generates adverse externalities to j's probability of flooding. On the other hand, an increase in i's soft mitigation generates beneficial externalities to j's probability of flooding. In the static version, suppose the objective function is

$$\max_{M_i,K_i} EW_i = \max \theta_i((M_i + M_j), (K_i - K_j)) \cdot W_i(M_i, K_i) \qquad (5.3)$$

where

$$\begin{cases} M & \leq \bar{A} \\ W'_{M_i} & \geq 0,\ W''_{M_i} < 0,\ W'_{K_i} < 0,\ W''_{K_i} < 0,\ W''_{K_i,M_i} \geq 0 \\ \theta'_{K_i} & > 0,\ \ \theta''_{K_i} < 0,\ \ \theta'_{K_j} < 0,\ \ \theta''_{K_j} < 0,\ \ \theta''_{K_j,M_i} \geq 0 \\ \theta'_{M_i} & < 0,\ \ \theta''_{M_i} < 0,\ \ \theta'_{M_j} < 0,\ \ \theta''_{M_j} < 0. \end{cases}$$

To ensure the existence of an interior solution, we have

$$\lim_{K \to 0} EW_i(K_i, K_j) > 0 \text{ and } \lim_{K \to \tilde{K}} EW_i(K_i, K_j) < 0$$

$$\lim_{M \to 0} EW_i(M_i, M_j) > 0 \text{ and } \lim_{M \to \tilde{M}} EW_i(M_i, M_j) < 0$$

where $\tilde{K}$ and $\tilde{M}$ are the upper bounds of K and M.

5.3.2 Characteristics of the game

Extensive research has been carried out to investigate the efficiency improvement of internalising externalities and welfare comparison among policy instruments. This model instead focuses on the patterns of strategic interdependence for exploring the possibility of concluding an agreement.

Derived from the assumptions in Subsection 5.3.1, the characteristics of this game are the following:

- (C1) **Negative spillovers** occur from j to i when economic growth is adopted $\because \frac{\partial EW_i}{\partial M_j} = \theta'_{iM_j} \cdot W_i \leq 0$ when $\Delta M > 0$.
- (C2) **Positive spillovers** occur from j to i when soft mitigation is adopted $\because \frac{\partial EW_i}{\partial M_j} = \theta'_{iM_j} \cdot W_i \leq 0$ when $\Delta M < 0$.
- (C3) **Negative spillovers** occur from j to i when hard mitigation is adopted $\because \frac{\partial EW_i}{\partial K_j} = \theta'_{iK_j} \cdot W_i \leq 0$.
- (C4) **Strategic substitution** exists in undertaking soft mitigation and development
$$\because \frac{\partial^2 EW_i}{\partial M_i \partial M_j} = \theta''_{iM_iM_j} \cdot W_i + \theta'_{iM_j} \cdot W'_{iM_i} \leq 0.$$
- (C5) **Strategic complementarity** exists in undertaking hard mitigation
$$\because \frac{\partial^2 EW_i}{\partial K_i \partial K_j} = \theta''_{iK_iK_j} \cdot W_i + \theta'_{iK_j} \cdot W'_{iK_i} \geq 0.$$
- (C6) EW is **supermodular** in the strategy set of economic development and hard mitigation
$$\because \frac{\partial^2 EW_i}{\partial M_i \partial K_i} = \theta''_{iM_iK_i} \cdot W_i + \theta'_{iM_i} \cdot W'_{iK_i} + \theta'_{iK_i} \cdot W'_{iM_i} + \theta_i \cdot W'_{iM_iK_i} \geq 0$$

On the one hand, (C1) implies increasing economic development in area i increases its own welfare net of floods at the cost of decreasing the probability of its counterpart being flood damage free. On the other hand, (C2) shows area i sacrifices its own welfare net of floods by undertaking soft mitigation to increase the probability of its counterpart being flood damage free. Similar to other public choice issues, a community may have no incentive to sacrifice self-interest to benefit free-riders unless there is compensation, altruism, or an agreement. (C3) shows an increase in hard mitigation of one area may offset the effects of the hard mitigation in its counterpart area.

Strategic substitution (C4) suggests a negative slope of the reaction function associated with soft mitigation and development. Strategic complementarity (C5), on the other hand, suggests a positive slope of the reaction function associated with hard mitigation. Figure 5.2 presents them in a linear relationship.

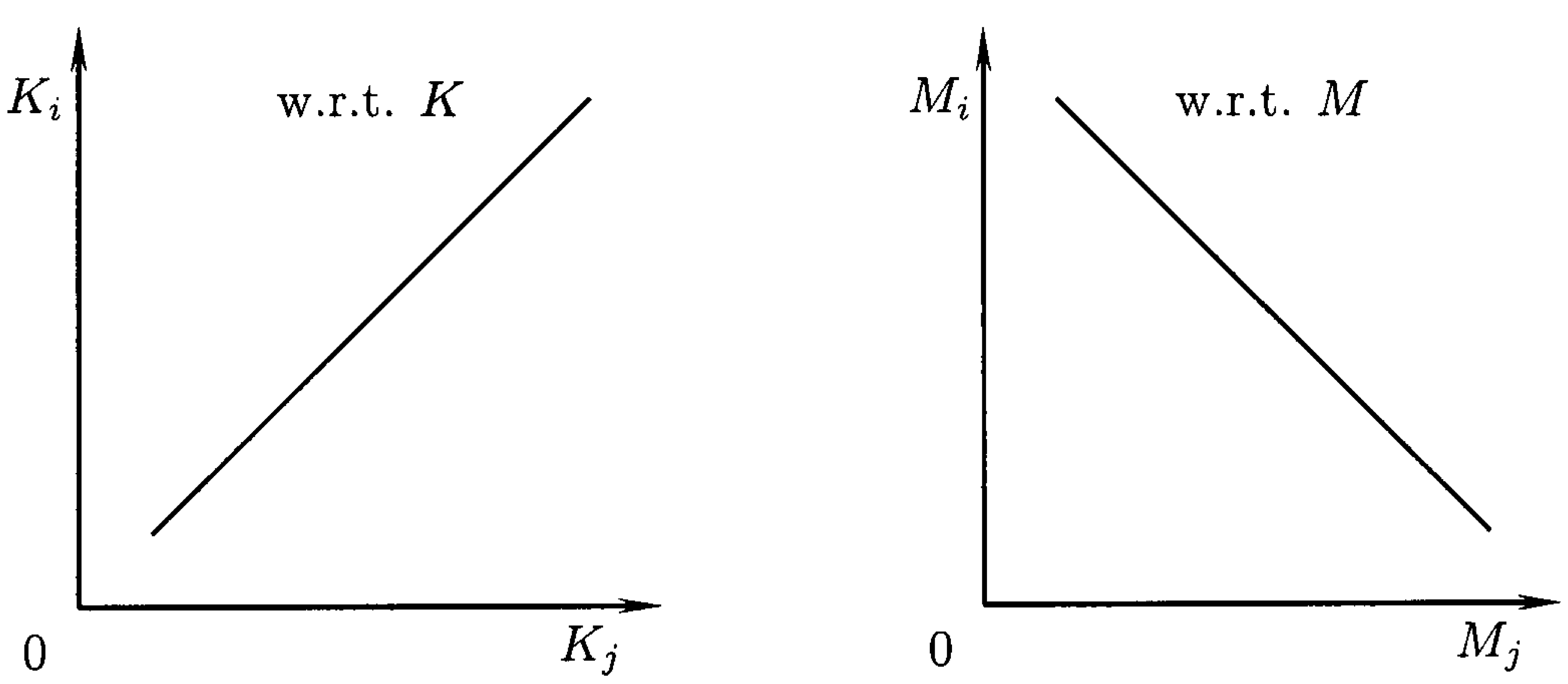


Figure 5.2: Left: The linear reaction curves of hard mitigation; right: The linear reaction curves of development/soft mitigation.

Supermodularity is presented in two forms respectively ((C5) and (C6)). Among players, supermodularity occurs between hard mitigation. Among strategies for each player, supermodularity exists in economic development and hard mitigation. For substitutes, the equilibrium occurs when their marginal welfare values are equal; for complements, multiple equilibria often occur.

Different from the multiplier effect in macroeconomics, this chapter presents the strategic complementarity with negative spillovers. Figure 5.3 illustrates the payoff function (EW) with two equilibria. Negative spillovers imply the function of choosing a higher level of effort (e_h) locates lower than that of choosing a lower level of effort (e_l) because of the efficiency losses in competition.

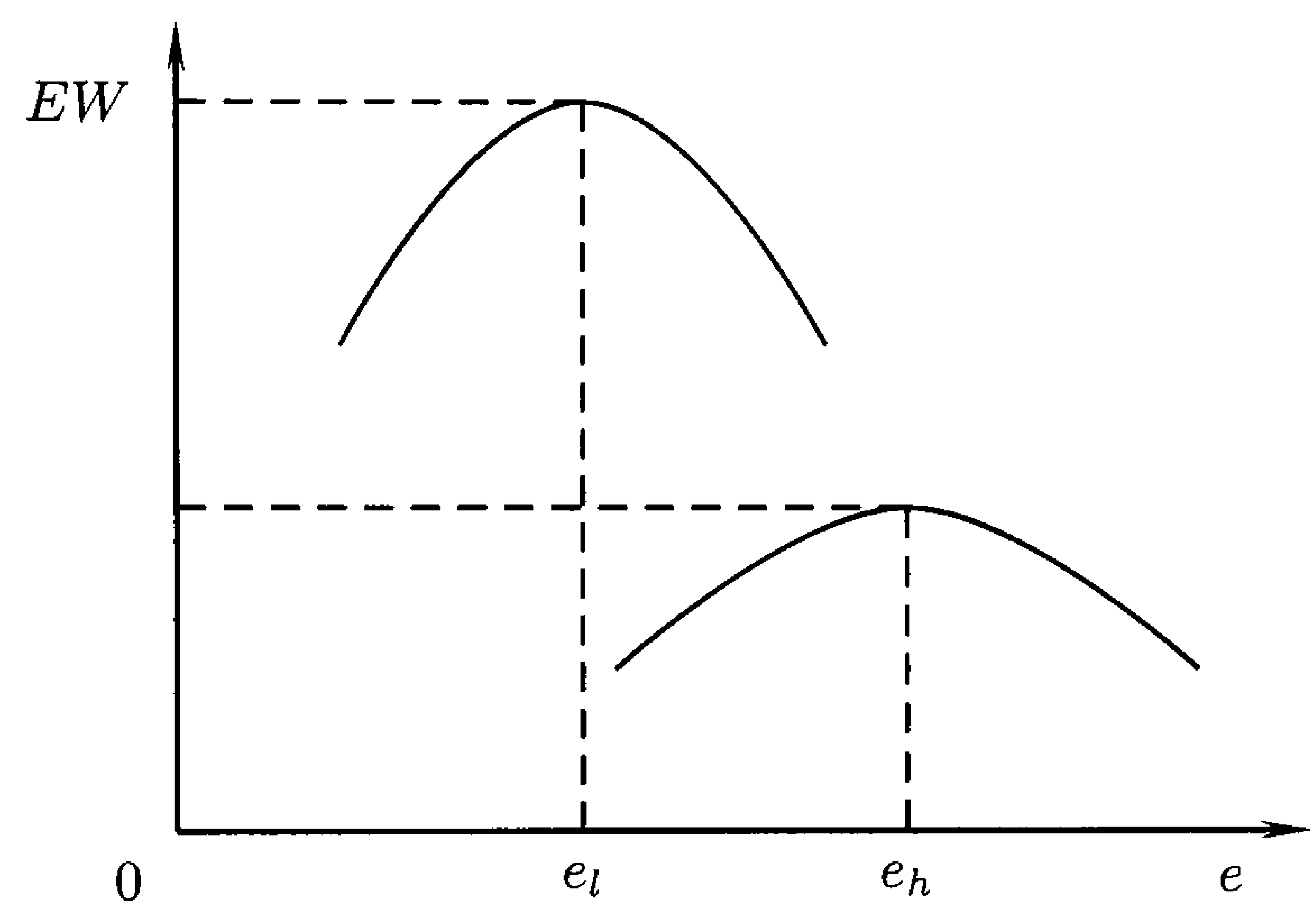


Figure 5.3: Payoff functions of a high/low level of efforts in the case of negative spillovers (after Cooper (1999)). EW: payoff. e: equilibrium.

5.3.3 Equilibrium of the single dimensional strategy

First how the single dimensional game works with respect to soft mitigation and hard mitigation is considered. In a game that consists of sub-objectives and sub-strategies, the equilibrium may not be obtained using traditional techniques without knowing numerical values. Hence, the *principle of sub-objective dominance* for ruling out choices which violate the sub-objective of a sub-strategy is applied to derive the equilibrium. The result shows that players tend to increase development and hard mitigation, and decrease soft mitigation accordingly.

THE PRINCIPLE OF SUB-OBJECTIVE DOMINANCE

Without the information about the functional form and values of parameters, which is occasionally the case in reality, we cannot make a comparison based on payoffs. In some cases, neither dominant equilibria nor Nash equilibria can be obtained. However, an equilibrium can be derived using the principle of sub-objective dominance. It rules out the decisions which may violate their own sub-objectives. The axiomatical approach is shown as follows.

- AXIOM 1. For each game, there is a unique solution.
- AXIOM 2. Each sub-strategy aims at improving only one sub-objective.
- AXIOM 3. Each sub-strategy has dual impacts on the payoff through costs and benefits.
- AXIOM 4. When the multi-dimensional strategies are well-ordered, choices depend on the rank of payoffs; when the strategies are not well-ordered, one deletes any strategy that violates its own sub-objective.
- AXIOM 5. The solution is a symmetric function, with no distinction between player i and player j.

SOFT MITIGATION

A single dimensional payoff matrix with respect to soft mitigation is presented in Table 5.1. Player i's payoff, in terms of the change of the maximum welfare net of floods (W) and the probability of being flood damage free (θ), is given on the top while player j's is at the bottom of each cell. Denote the payoff combination in the bottom-right cell as a reference point, for instance, the optimal value without concerning externalities. Since the two players are identical and move simultaneously, the equilibrium is expected to occur along the diagonal.

Table 5.1: Payoff matrix with respect to soft mitigation and development.

$i \setminus j$	$\downarrow M_j$ ($for\ \uparrow \theta_j$)	$\uparrow M_j$ ($for\ \uparrow W_j$)	$\rightarrow M_j$ ($\rightarrow \theta_j, W_j$)
$\downarrow M_i$ ($for\ \uparrow \theta_i$)	$(\theta_i \uparrow W_i \downarrow \sharp$ $\theta_j \uparrow W_j \downarrow)$	$(\theta_i \rightarrow W_i \downarrow$ $\theta_j \rightarrow W_j \uparrow)$	$(\theta_i \uparrow W_i \downarrow$ $\theta_j \uparrow W_j \rightarrow)$
$\uparrow M_i$ ($for\ \uparrow W_i$)	$(\theta_i \rightarrow W_i \uparrow$ $\theta_j \rightarrow W_j \downarrow)$	$(\theta_i \downarrow W_i \uparrow *$ $\theta_j \downarrow W_j \uparrow)$	$(\theta_i \downarrow W_i \uparrow$ $\theta_j \downarrow W_j \rightarrow)$
$\rightarrow M_i$ ($\rightarrow \theta_i, W_i$)	$(\theta_i \uparrow W_i \rightarrow$ $\theta_j \uparrow W_j \downarrow)$	$(\theta_i \downarrow W_i \rightarrow$ $\theta_j \downarrow W_j \uparrow)$	$(\theta_i \rightarrow W_i \rightarrow \sharp$ $\theta_j \rightarrow W_j \rightarrow)$

Note: '$*$' non-cooperative equilibrium; '$\sharp$' cooperative equilibrium

Different types of land use satisfy different sub-objectives. The payoff matrix in Table 5.1 contains three sub-objectives, increasing the probability of being flood damage free ($\uparrow \theta$) by converting developed land to natural land, increasing the welfare net of floods ($\uparrow W$) by converting natural land to developed land, or doing nothing. The matrix hence reveals the nature of conflicts between economic development and environmental protection. A player can either increase ($\uparrow$), decrease ($\downarrow$) or maintain ($\rightarrow$) the level of soft mitigation in this single dimensional game. The result will not violate a player's sub-objective no matter whether the counterpart increases or maintains the amount of soft mitigation. However, if the counterpart increases development, keeping up development will be the only choice that will not violate one's sub-objective. The catchment will then end up with increasing development if no cooperation occurs. What is the impact of this trend of increasing development?

Suppose there are ℓ regions in the catchment. Each of them possesses $\bar{A}$ amount of land. Let M_i be the private good (development) and A_i (soft mitigation) be the public good invested by area i. P_m is the rate of profit per unit of developed land. Suppose region j (all $j \neq i$) provides A^* units of soft mitigation. Given a specific function form that $EW = (\Sigma A)^a \cdot (P_m \cdot M_i)^b$. The probability of being flood damage free, θ, is $((\ell - 1) \cdot A^* + A_i)^a$. The welfare net of floods, W, is $(P_m \cdot M_i)^b$. Region i's problem can be presented by

$$\max_{M_i, A_i} \; EW_i = \max \left(a \cdot log\left((\ell - 1) \cdot A^* + A_i\right) + b \cdot log\left(P_m \cdot M_i\right)\right)$$
$$s.t. \; A_i + M_i \leq \bar{A} \tag{5.4}$$

From a Lagrangian function:

$$L = a \cdot log\left((\ell - 1) \cdot A^* + A_i\right) + b \cdot log\left(P_m \cdot M_i\right) + \lambda \cdot \left(\bar{A} - A_i - M_i\right)$$

and deriving solutions from the first order conditions:

$$\partial L / \partial A_i = 0 \tag{5.5a}$$

$$\partial L/\partial M_i = 0 \tag{5.5b}$$

At the symmetric Nash equilibrium, the solution of A_i must equal A^*. We may now solve the equations to conclude that region i's choice at this equilibrium is

$$\begin{aligned} M^* &= (b\ell\bar{A})/(aP_m + b\ell) \\ A^* &= (aP_m\bar{A})/(aP_m + b\ell) \end{aligned} \tag{5.6}$$

A whole catchment faces the problem of

$$\begin{aligned} &\max_{M_w, A_w} \ EW = \max\left(a \cdot logA_w + b \cdot log\left(P_m \cdot M_w\right)\right) \\ &s.t. \ A_w + M_w \leq \ell\bar{A} \end{aligned} \tag{5.7}$$

and the equilibrium at which

$$\begin{aligned} M_w^* &= (b\ell\bar{A})/(a+b) < \bar{A} \\ A_w^* &= (a\ell\bar{A})/(a+b) < \bar{A} \end{aligned} \tag{5.8}$$

Compare the equilibrium in equation (5.8) with the aggregate results from ℓ regions using equation (5.6). The undersupply of public goods and the oversupply of private goods are notable when the number of regions is large. The difference between the two equilibria is the following:

$$\frac{b\ell^2\bar{A}}{aP_m + b\ell} - \frac{b\ell\bar{A}}{a+b} = b\ell\bar{A}\left(\frac{\ell}{aP_m + b\ell} - \frac{1}{a+b}\right) \tag{5.9a}$$

$$\frac{a\ell\bar{A}}{a+b} - \frac{a\ell\bar{A}}{a+b} = a\ell\bar{A}\left(\frac{P_m}{aP_m + b\ell} - \frac{1}{a+b}\right) \tag{5.9b}$$

When $\ell \gtreqless P_m$, equation (5.9a) $\gtreqless 0$ and equation (5.9b) $\lesseqgtr 0$.

This result suggests that the aggregate decisions of individuals already generate the problem of over-development and insufficiency of soft mitigation. The increasing investment in development is supposed to make the problem worse.

HARD MITIGATION

Table 5.2: Payoff matrix with respect to hard mitigation

$i \backslash j$	$\uparrow K_j$	$\rightarrow K_j$
$\uparrow K_i$	$(\theta_i \rightarrow W_i \downarrow *$ $\theta_j \rightarrow W_j \downarrow)$	$(\theta_i \uparrow W_i \downarrow$ $\theta_j \downarrow W_j \rightarrow)$
$\rightarrow K_i$	$(\theta_i \downarrow W_i \rightarrow$ $\theta_j \uparrow W_j \downarrow)$	$(\theta_i \rightarrow W_i \rightarrow \sharp$ $\theta_j \rightarrow W_j \rightarrow)$

Note: '$*$' non-cooperative equilibrium;
'$\sharp$' cooperative equilibrium

Table 5.2 contains only one sub-objective, increasing the probability of being flood damage free ($\uparrow \theta$). Hence we can derive the Nash equilibrium using the conventional dominance elimination process. Since hard mitigation is often located in flood-prone areas, decreasing hard mitigation implies the area will be flooded as a buffer zone (considered as '$\downarrow M$' in Table 5.1).

Whichever strategy the counterpart chooses, a player will increase hard mitigation to prevent the probability of flood damage free from decreasing. A non-cooperative solution hence involves an increase in hard mitigation. Increasing hard mitigation is the only way to cope with a higher river level in this single dimensional game and hence an *embankments race* follows. For instance, pumping flood water between areas keeps some areas flooded in water after a flood event.

5.3.4 Multi-dimensional strategy in a supermodular game

In reality, a strategy often covers multi-dimensions in flood risk management. In the case of flood management, a decision-maker takes economic development, soft mitigation, and hard mitigation into account. Hence a supermodular game that covers multi-dimensional strategies is applied.

THE SETUP OF A SUPERMODULAR GAME

There are three requirements for setting up a supermodular game. First, the strategy set shall be a complete lattice. Second, the payoff function shall be supermodular in strategy. Third, the payoff function of a player exhibits increasing first differences in his/her strategy and the counterpart's strategy, i.e., the marginal utility of each player's strategy is monotonic in the counterpart's strategies (Cooper, 1999). The ordering of sub-strategies shall be obtained. Stock instead of flow is considered in the dynamic model though policy implications need to be decoded in terms of flow.

First, suppose a strategy set L is partially ordered and composed of S_i and S_i'. In this strategy set, we have all the combinations of (S_i, S_i') from the infimum $(0, 0)$ to the supremum $(\tilde{S}_i, \tilde{S}_i')$.[6] Therefore, L is a complete lattice. It is the same in each sub-lattice divided by the threshold levels of developed land and hard mitigation including all the possible choices. Once the complete sublattices are defined, the upper bound and the lower bound of a strategy set can be clearly identified. A single equilibrium is expected to be either the

[6] Infimum is the greatest lower bound while supremum is the least upper bound in a set.

upper ($S_i \vee S_i'$, $max(S_i, S_i')$) or the lower bound ($S_i \wedge S_i'$, $min(S_i, S_i')$).

Secondly, we know that EW_i is supermodular in S_i (given S_j) because M_i (developed land) and K_i (hard mitigation) are strategic complementarity (Subsection 5.3.2 (C6)). An increase in M_i with K_i implies the awareness of environmental health and financial capacity for a growing economy to manage flood risk by hard mitigation. A decrease in M_i with K_i suggests i's replacing hard mitigation by soft mitigation without considering economic recession.

Thirdly, the payoff function EW_i exhibits increasing first differences in S_i and S_i'. In other words, when the counterpart increases hard mitigation and developed land, a player shall catch up to avoid losses (i.e., $EW_i(S_i, S_j) - EW_i(S_i', S_j)$ is increasing in S_j when $S_i \geq S_i'$). When the counterpart chooses a higher level of hard mitigation and developed land, keeping up is the best choice for a player without cooperation. $EW_i(S_i, S_j)$ is supermodular in S_i if for each S_j satisfies equation (5.10). In other words, efficiency is higher in strategies prone to complementarity.

$$EW_i(S_i, S_j) + EW_i(S_i', S_j) \leq EW(S_i \wedge S_i', S_j) + EW(S_i \vee S_i', S_j) \tag{5.10}$$

Consider a simple case in a two dimensional Euclidean space $\mathbb{R}^2$. $(0,0)$, $(0,1)$, $(1,0)$, $(1,1)$ are the combinations of developed land and hard mitigation for two homogeneous players. $(0,0)$ represents the baseline of developed land and hard mitigation; $(0,1)$ denotes no change of developed land but an increase in hard mitigation; $(1,0)$ indicates an increase in developed land but no change of hard mitigation; $(1,1)$ shows an increase in both developed land and hard mitigation. Either $(0,0)$ or $(1,1)$, the minimal or the maximal element, is the fixed point according to the definition of supermodularity.

RESULTS: REACTION FUNCTIONS AND NASH EQUILIBRIA

To prove the existence of a Nash Equilibrium in a supermodular game, Topkis (1979) suggested the application of Tarski's fixed point theory and the property of monotonicity. Tarski's fixed point theory, unlike the conventional Kakutani's fixed point theory, need not impose restrictions on payoffs and on strategy space to ensure the convexity and upper semi-continuity of the best reply correspondence. From the feature of monotonicity, the least $(S_i \wedge S_i')$ and the greatest $(S_i \vee S_i')$ elements are monotonically related to the strategy profile of the other player (S_j).

In this case, the best response to $(0,0)$ is $\{(0,0),(1,1)\}$ while the best response to $(1,1)$ is $(1,1)$. For both $(0,0)$ and $(1,1)$, the best response of a player is $(1,1)$, increasing both developed land and hard mitigation. The result is consistent with that in the analysis of single dimensional strategy. A geometric exposition of this result is given in Figure 5.4. It illustrates the reaction function in this supermodular game and the points which cross the 45° line are the equilibria.

A symmetric game does help players to understand and accommodate the movements to each other's. However, mathematical symmetry does not exist frequently in reality (Schelling, 1960). For instance, upstream-downstream, which generates asymmetric externalities, is often the case in flood management within a catchment.

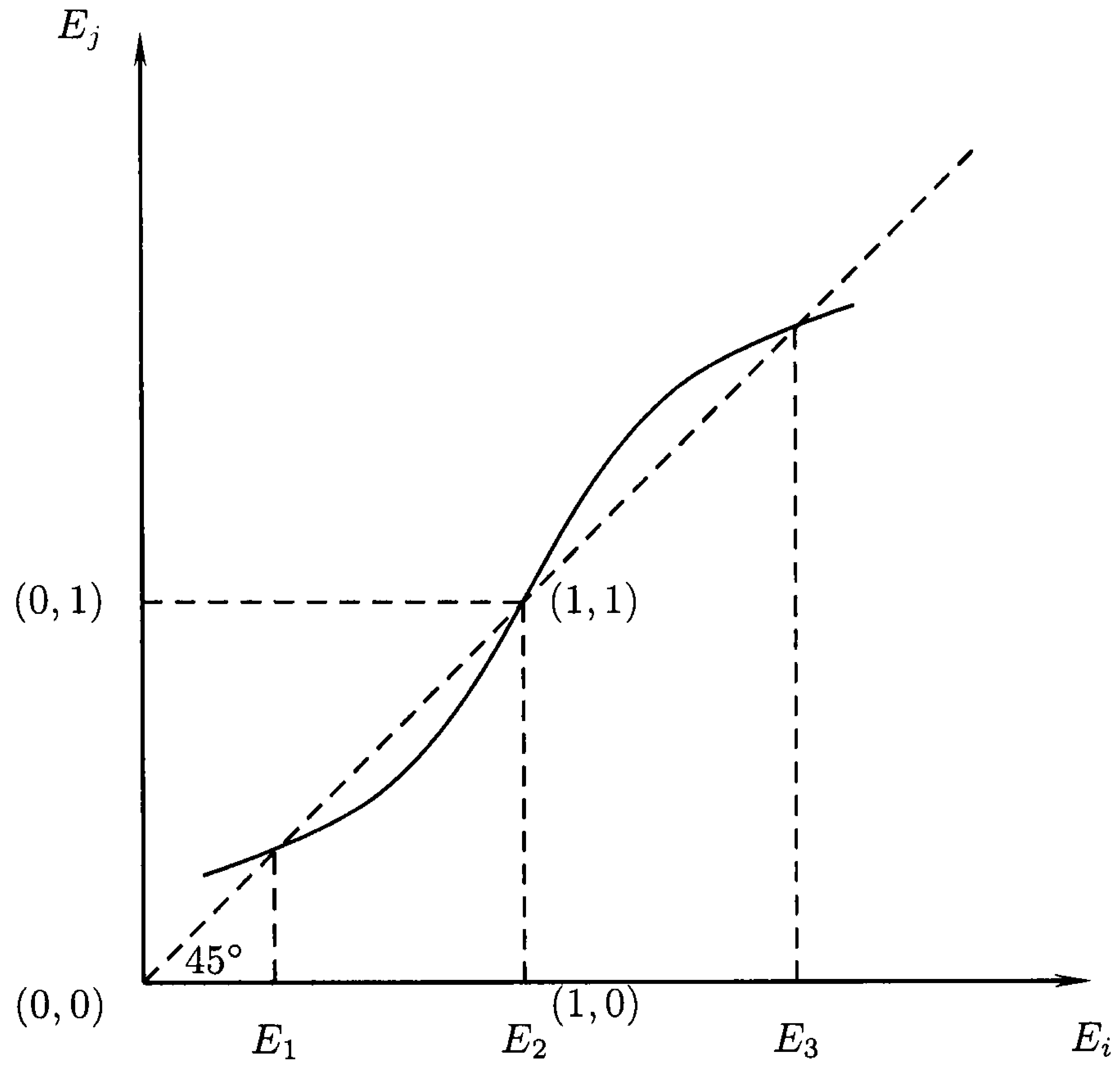


Figure 5.4: Reaction function of the supermodular game (after Cooper and John (1988))

5.4 Unidirectional externalities in a catchment: Upstream-downstream

The unidirectional externality is concerned with the case of upstream-downstream effects. The equilibrium of the unidirectional externality in a catchment is simply without strategic dependence unless cooperation is involved.

5.4.1 Assumptions

Apart from the probability of being flood damage free in the upstream area, the assumptions are identical to those in the common pool. Suppose the objective function of the upstream area (denoted by the lower case u) and the objective function of the downstream area (denoted by the lower case d) are:

$$\begin{aligned}
&\max_{M_u,K_u} EW_u = \max\left(\theta_u(M_u,K_u)\cdot W_u(M_u,K_u)\right)\\
&\max_{M_d,K_d} EW_d = \max\left(\theta_d((M_d+M_u),(K_d-K_u))\cdot W_d(M_d,K_d)\right)
\end{aligned} \tag{5.11}$$

where

$$\begin{cases}
M_i & \leq \bar{A}\\
W'_{M_i} & \geq 0,\ W''_{M_i}<0,\ W'_{K_i}<0,\ W''_{K_i}<0,\ W''_{K_i,M_i}\geq 0\\
\theta'_{K_i} & >0,\quad \theta''_{K_i}<0,\ \ \theta'_{K_j}<0,\ \ \theta''_{K_j}<0,\quad \theta''_{K_j,M_i}\geq 0\\
\theta'_{M_i} & <0,\quad \theta''_{M_i}<0,\ \ \theta'_{M_j}<0,\ \ \theta''_{M_j}<0\\
i & =u,\ d\\
j & =u \text{ when } i=d
\end{cases}$$

Similarly, to ensure the existence of an interior solution, we have

$$\begin{aligned}
&\lim_{e\to 0} EW_i(K_i,K_j)>0 \text{ and } \lim_{K\to\tilde{K}} EW_i(K_i,K_j)<0\\
&\lim_{e\to 0} EW_i(M_i,M_j)>0 \text{ and } \lim_{M\to\tilde{M}} EW_i(M_i,M_j)<0
\end{aligned}$$

where $\tilde{K}$ and $\tilde{M}$ are upper bounds of K and M.

5.4.2 Equilibrium

The case associated with unidirectional externality is basically without interactive strategy. The equilibrium occurs when the upstream area optimises its own decision and the downstream area optimises its decision given the upstream decision.

5.4.3 Opportunities for cooperation

Even though the downstream area cannot influence upstream flood risks, there are still chances for cooperation by influencing upstream welfare net of floods. The opportunities lie in the capacity of the downstream area to compensate upstream.

Table 5.3 presents the impacts of various upstream actions upstream and on the downstream area. The downstream area apparently prefers upstream to retain water and suffers from draining water upstream. It hence sheds the light of the cooperation between downstream and upstream areas.

Cooperation can only occur when

$$B_u \geq C_u + C_d$$

where B_u is benefit for changing upstream action, C_u is upstream cost of changing action, and C_d is downstream cost of making the upstream area change action. Issues associated with the hydrological cycle such as droughts, navigation, water supply, and water quality control can stimulate the cooperation.

In practice, Axelrod (1984) proposed principles of promoting cooperation, enlarging the shadow of future by making the interaction

Table 5.3: Impacts of upstream actions

Action	Impact on downstream	Impact on upstream
Hard mitigation - retain water	Decreased flood risks; (increased water supply;)[a] risk of engineering failure	Cost of dam construction; risk of engineering failure
Hard mitigation - drain water	Increased flood risks	Cost of flood walls
Soft mitigation - retain water	Decreased flood risks; (increased water supply)	Sacrificing development

[a] Items in parenthesis depend on the geological and hydrological characteristics of the area.

more durable and more frequent, teaching people to care about each other, teaching reciprocity (common belief, in other words), improving recognition abilities, and changing payoffs. They help to reshape the characteristics of the interaction so it is possible to have a stable cooperative equilibrium in the long run.

5.5 Discussion

Development and mitigation of floodplains are frequently public goods, and also involve the management of common property resource. Game theory shows that strategic complementarity exacerbates the problem by encouraging both development and hard mitigation. Surpassing flood risk thresholds can increase the negative effect of developed land and reduce the effectiveness of hard mitigation. However, game theory has its limitations. In reality, the payoff matrix, the rules for reaching an equilibrium, welfare and constraints are often implicit. They are often revealed through political procedures instead.

5.5.1 Policy implications of the game theoretical models

Strategic complementarity is efficient below the threshold level. Once the threshold is surpassed, strategic complementarity can prevent free-riding but not increase efficiency. Efficiency loss in an embankments race occurs when a player's investment in hard mitigation is only to offset the incremental flood risk produced by the counterpart's investment in hard mitigation. Strategic complementarity speeds up the flood risk once the threshold of developed land is exceeded.

However, in a non-cooperative game, soft mitigation is often ignored due to the incentive to free-ride. The tit-for-tat principle is often applied in a dynamic game so cheating may not occur all the time. Nevertheless, a catchment will end up with an increasing share of floodplain being developed, increasing hard mitigation, and a reluctance to undertake soft mitigation. Hence, mechanisms are needed to induce cooperation.

The difference between the supermodular game described in this chapter and supermodular games described elsewhere in the literature lies in the type of externality. Strategic complementarity here aims at keeping the payoff from falling, and should stop before triggering the threshold effects. To avoid reaching a threshold for efficiency improvement, cooperation is an option.

Cooperation can lead to efficiency improvement in the long term.

Repetitive interactions between players can constrain opportunism and reinforce the information received by players. The whole catchment should be able to obtain a higher payoff by concluding an agreement, in which no one suffers a welfare loss.

The incentives to cooperate include the extra cost on penalty for violating the agreement, and the distribution of the benefits due to cooperation. The allocation of the benefits is usually discussed in terms of core theory, von Neumann-Morgenstern solutions (or stable sets), Shapley value, nucleolus, minimising the maximum complaint that any coalition could have against it. The principle of equity is applied where players are homogeneous while the stakeholders' principle applied where players are heterogeneous. Apart from economic incentives, cooperation can also be induced by traditional methods including the stability of institutions and leadership itself (Schelling, 1960).

Incentives such as flood taxes, subsidies, punishments for breaching a contract, and the distribution of the benefits of cooperation change the structure of the game. The design of economic incentives can also be classified into different levels according to the impacts. For instance, developers responsible for different flood risks should face different flood tax rates.

Players may use historical knowledge to guess other players' behaviour. When a game has been played repeatedly, players have more opportunities to learn to coordinate their actions to achieve Pareto improvement. Cheating, which easily occurs in a static game, but may be deterred by punishments such as 'tit-for-tat' in a dynamic game.

5.5.2 Limitations of the game theoretical models

Flood risk management in a catchment often involves far more individuals with far more heterogeneous characteristics than have been discussed in this chapter. The related information is also more complicated. In other words, the information required for constructing the payoff matrix, rules of obtaining the equilibrium, welfare, and constraints becomes too complicated to be clearly expressed in a game theoretical model. Hence, mechanisms for integrating different interests and producing efficient solutions should be introduced.

Moreover, the game theoretical models in this chapter are not tactical because the information on the geographical and economic conditions of players is often explicit. Bargaining tactics involve delicate strategies such as bluffing, cheating, making concession, threatening, deterrence, the timing of actions and personal relationships among players (trust). However, only the actions that can be related to rationality are discussed.

5.6 Conclusion

This chapter explores the interplay among decision-makers, and shows how flood risk externalities open the way to decentralised management, on a catchment-scale in particular. The assumption of centralised decision-making is relaxed to investigate optimal resource allocation in a catchment that covers multiple decision-makers from multiple regions. The game theoretic models show that efficiency losses in terms of an embankments race and insufficient soft mitigation are a consequence of decentralised decision-making.

Increasing upstream hard mitigation forces downstream areas into higher levels of hard mitigation. Once an upstream embankment or drainage system is built, downstream mitigation follows. Upstream soft mitigation, on the other hand attenuates downstream flood risks.

Since the social optimum level or the threshold, whichever is smaller, is the split point between cooperation and non-cooperation, information about the social optimum is important for designing cooperation mechanisms and for solving the embankments race and the undersupply of soft mitigation.

Other methods for internalising flood risk externalities, such as the establishment of developer's responsibility for mitigating flood risks are considered in later chapters. However, whether there is an efficiency improvement or not depends on a welfare comparison of the outcomes under different institutions. Most methods for internalising the externalities, such as tax, fees, and compensation, are consistent with a centralised management system.

The next chapter will explore the options in a decentralised system taking the insufficiency of information and biased decision-makers into account. The stakeholders' committee, for integrating diverse interests to obtain the social target, will be introduced along with the tradeable permit system, for obtaining the target effectively and efficiently.

Chapter 6

Decentralised Flood Risk Management Using the Stakeholders' Committee and Tradeable Flood Permits

6.1 Introduction

Chapter 3 and Chapter 4 considered mitigation and development in the context of optimal flood risk management from a social planner's viewpoint. However, this assumes that there exists a policy-maker[1] who is omnipotent and altruistic, that information is complete and perfect, and that individual decision-makers have freedom to choose. In many cases, these conditions are not satisfied. Very often the larger the scale of an issue, the more serious the problem is.

Nevertheless, relaxing the assumption of centralisation of flood

[1]The decision-maker of public affairs is called the policy-maker from now on.

management in Chapter 5 presents problems. The adverse externality from hard mitigation and the beneficial externality from soft mitigation may not be internalised. The former generates an embankments race while the latter causes insufficient soft mitigation. In fact, the very factors that produce market failure also make it difficult for government to obtain a satisfactory solution (Friedman and Friedman, 1979).

This chapter addresses market failures within a decentralised decision framework, rather than resorting to centralised control. Many decisions on mitigation are in the hands of government while others are in the hands of local management groups (see Table 6.1). All decisions on development are constrained by regulations.[2] The problem addressed in this chapter is how to coordinate decisions among regions within a decentralised framework in order to achieve an efficient and equitable outcome.

Even though improving efficiency is the supreme principle in economics, individuals in fact evaluate efficiency differently. In many cases, the outcome reflects a political consensus. In such cases, establishing market mechanisms within a framework of collaborative management might be a practical option. An 'efficient' public choice can be made by allowing a representative group to set the social objective, and then using market mechanisms to improve efficiency.

For collaborative management, a two-tier decision-making process is introduced. First, the social objective is identified through a collective consensus-building mechanism. Then, a market mecha-

[2]Development in the UK is mainly constrained by the Town and County Planning Act.

Table 6.1: Statistics on hard mitigation in the catchment of the Yorkshire Ouse, the Swale, the Ure, and the Nidd. Data source: Environment Agency, courtesy to Ms. Diana Orr of the Environmental Agency at York in 2004. R: river; T: total number of mitigation works; U: unknown organisation; R: riparian owner; EA: Environment Agency; IDB: Internal Drainage Broad; LA: local authority; YW: Yorkshire Water; B: British Waterways; N: Newby Hall Estates; D: Danby Estates; NA: no available information.

R	T	Maintainer								Owner									
		U	R	EA	IDB	LA	YW	B	NA	U	R	EA	IDB	LA	YW	B	NA	N	D
Ouse	134	43	3	71	7	0	2	1	7	6	3	73	36	1	2	1	12	0	0
Ure	44	13	3	11	0	0	1	0	16	1	5	16	8	2	3	0	1	6	2
Swale	65	48	3	3	9	0	0	0	2	10	3	0	50	2	0	0	0	0	0
Nidd	24	21	0	3	0	0	0	0	0	6	0	3	14	0	0	0	1	0	0

nism is created to assure an efficient resource allocation for achieving this target. This involves two institutions: a stakeholders' committee (SC) and a tradeable flood permit (TFP) system (Table 6.2).

Table 6.2: Characteristics of the two-tier decentralised management

	Stakeholders' committee	Tradeable flood permit
Mechanism	Negotiation	Market
Function	Defining the social target, setting up rules, solving the embankments race	Obtaining the target, improving efficiency, avoiding free-riding

The SC can more comprehensively cover topics while the tradeable permit system often focuses on one specific aspect in management. The SC obtains objectives through negotiation while the TFP system improves efficiency by allowing agents to optimise their use of resources within a quantitative restriction. In conflict resolution, issues that do not threaten life can resort to the market while those that are life-threatening rely on negotiation based on equity.

This chapter focuses on multiple heterogeneous players operating in a landscape involving geographical differences. The potential effectiveness of the policy regime is examined using the catchment of the Yorkshire Ouse, the Swale, the Ure, and the Nidd.

Section 6.2 considers the problems of commons and their solutions. Section 6.3 discusses the organisation of an SC in flood management. Section 6.4 gives the theoretical background and develops three types of TFPs. Section 6.5 presents the chapter conclusions.

6.2 Solving the problems of commons

The problem of commons is addressed in Chapter 5. Decentralised decisions on flood management produce the problems of commons in terms of insufficient soft mitigation and an embankments race. Quantity control, price control, and redefining property rights provide the solutions. However, insufficient information and the bounded rationality of a policy-maker lead the choice to redefining property rights through an SC and a TFP system.

6.2.1 Problems of commons

There are a bundle of rights within land. First, development of an area (area i) is a public bad for its neighbouring and downstream areas (area j, where $i \neq j$) by increasing their flood risks. Equation (5.11) suggests $\partial EW_j/\partial m_i \leq 0$ where W_j is the welfare function of area j.

Secondly, land used for soft mitigation is a public good for the whole catchment excluding upstream areas. An analogous reasoning is applied due to the fixed sum of developed land and non-developed land that includes undertaking soft mitigation. That is, a decrease in m_i can benefit area j.

Thirdly, the right to develop brings income to the land owner. $\partial W_i/\partial m_i \geq 0$ shows development is a private good for increasing area i's welfare.

Hard mitigation (k) is a public bad because it generates adverse externalities to its neighbouring and downstream areas, $\partial W_j/\partial k_i \leq 0$. However, it is a private good to the area it protects, $\partial W_i/\partial k_i \geq 0$.

Undersupply of soft mitigation, a result of free-riding, was shown by a game theoretical model in Subsection 5.3.3. Comparing the equilibria between equation (5.6) and equation (5.8), we find the insufficiency of '$a\ell\bar{A}\left(P_m/\left(a+b\right)-1/\left(aP_m+b\ell\right)\right)$' units of soft mitigation when $\ell > P_m$. Knowing whether ℓ is larger than P_m is often an easy task. The definite efficiency loss of undersupply of soft mitigation is, for example, the triangular area $ee'e''$ in Figure 6.1.

Oversupply of hard mitigation, an embankments race, is derived by the supermodular game in Chapter 5. In an asymmetric embankments race, downstream mitigation needs to be increased according to any increase in upstream mitigation; in a symmetric embankments race, enhancing flood walls (or drainage) to mitigate the increased flood risk induced by neighbouring embankments (or drainage) generates constant conflicts in a common pool. Chapter 5 shows the efficiency loss of the latter based on the assumption of identical players. The former needs to be discussed under the assumption of heterogeneous players.

6.2.2 Solutions to the problems of commons

A policy-maker needs to justify interfering with private decisions to obtain a social optimum. Once the need is confirmed, s/he should find the social objective and constraints, and select an efficient policy to meet the target . Three solutions are suggested:

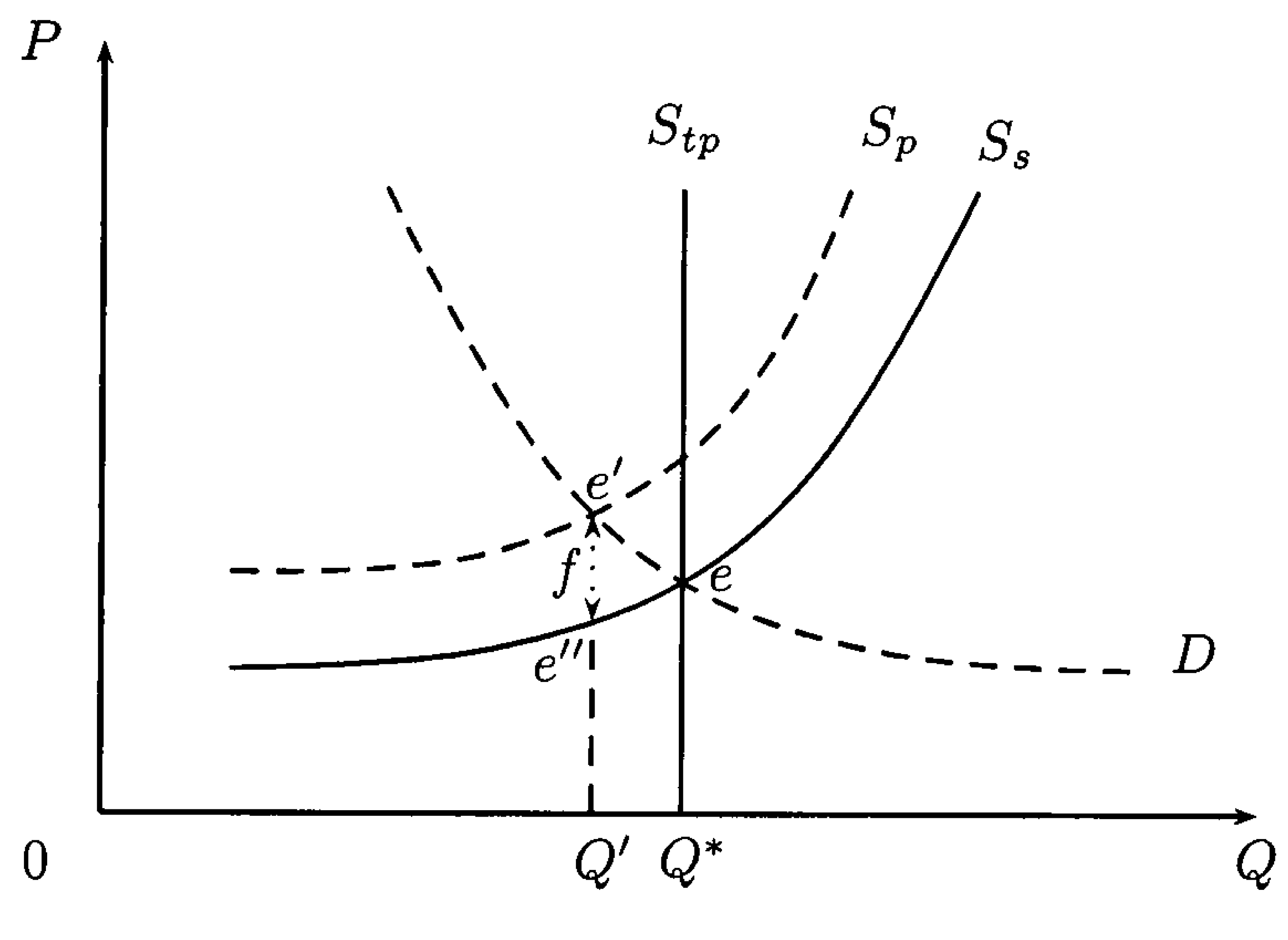


Figure 6.1: Undersupply of soft mitigation and its solutions. Q^* is the optimal level; $Q^{'}$ is the current level; S_s is the social supply curve; S_p is the aggregate private supply curve; S_{tp} is the supply under a TFP system; D is the demand curve; e is the equilibrium under a tradeable permits system; e' is the equilibrium without policy intervention; e'' is the initial equilibrium after policy intervention on $Q^{'}$; f is the subsidy per unit of soft mitigation.

QUANTITY CONTROL

Quantity control, a type of centralised management, secures the optimal quantity of soft and/or hard mitigation. It demands an authority to determine and to allocate the social optimal mitigation Q^* to each area. In theory, the optimal quantity of soft and/or hard mitigation can be guaranteed by distributing this optimal quantity to individual areas. However, it is often too costly for an authority to issue a quota according to the spatial distribution of geographical characteristics and economic capacity among regions. Moreover, there is no incentive for any area to sacrifice its potential benefits from using the land in other ways. Hence, the enforcement of quota allocation is at the cost of efficiency.

PRICE CONTROL

Price control can internalise externalities through the market mechanism. If the property right of flood risk reduction belongs to the bearers of flood risk, a policy-maker shall impose a tax on the under-supply of soft mitigation or over-development. On the other hand, if it belongs to those who are capable of undertaking soft mitigation, (f in Figure 6.1) suppliers of soft mitigation shall receive a subsidy. However, this implies that the authority has full information on supply and demand of development and mitigation like S_s, S_p, and D . Practically, though the rates of tax/subsidy are adjustable over time, the environmental quality (Q^*) is often uncertain due to the imperfect and incomplete information which is available to policy-makers.

REDEFINING PROPERTY RIGHTS

Redefining property rights can also drive the rearrangement of development and mitigation in flood management. Command-and-control (disregarded due to its nature of centralisation), negotiation, and transaction are the three ways to redefine property rights.

Hard and soft mitigation, with their own pros and cons, can substitute for each other to a certain point. Moreover, the beneficial externality generated by soft mitigation and the adverse externality generated by hard mitigation are both transferable. Negotiation and transaction both have potential for covering the transfer efficiently.

Quantity control in isolation is highly centralised while price control might face uncertainty of environmental quality. A tradeable permit system that mixes quantity control with price control is hence introduced to secure a certain level of environmental quality in an efficient way. Consistent with its nature of compromise, its rule of allocating the initial permits and that of operating the system is basically a public decision. The authority can either auction or allocate Q^* the optimal amount of permits to individuals and then let the market reallocate resources. Restrictions on the embankments race can be life-threatening, hence negotiation through a mechanism like the SC should be introduced. Given the diversity of technical, economic, and social contexts in which flood management occurs, the need for introducing an SC to reach an agreement on a social target and related rules is immediately apparent.

6.3 Stakeholders' committee

Setting the optimal flood risk and related rules is not only a technical problem but a political issue. Being a committee composed of related stakeholders, an SC chiefly aims at solving two problems: determining the optimal setting for management and resolving conflicts which cannot be tackled within the market. Investigating each stakeholder's costs and benefits of participating in the committee and proposing plans for conflict resolution accordingly are crucial. Based on the nature of collaborative management, the SC can also enhance the political acceptability of the TFP system. It has been widely applied in water management in the Netherlands, Germany, and France (Andersen, 1999; OECD, 1996; Uniterkamp et al., 1995) and in natural resources and environmental management in the UK, Denmark, Hungary, Luxembourg, the USA, Australia, New Zealand, Fiji, Papua New Guinea, and Taiwan (Selman, 2004; Shaw et al., 2003).[3] According to Selman (2004), most of these works are on a small scale, e.g., community-based resources management. Cases on a large scale require more expert involvement.

6.3.1 Aims of a stakeholders' committee

An SC first needs to set the target before defining a social welfare function for the catchment. By agreeing on the acceptable set of tradeoffs between flood risk and development benefits, an SC defines the indifference curves between the acceptable flood risk and the

[3]The current land use management system in the UK is supposed to be consultative, but it often fails to engage communities notwithstanding (Corkindale, 2004).

social welfare net of floods as indicated in Figure 6.2. Given the physical and financial constraints, this makes it possible to identify an optimal solution (e). What is left is to find an efficient and feasible way to reach the optimum.

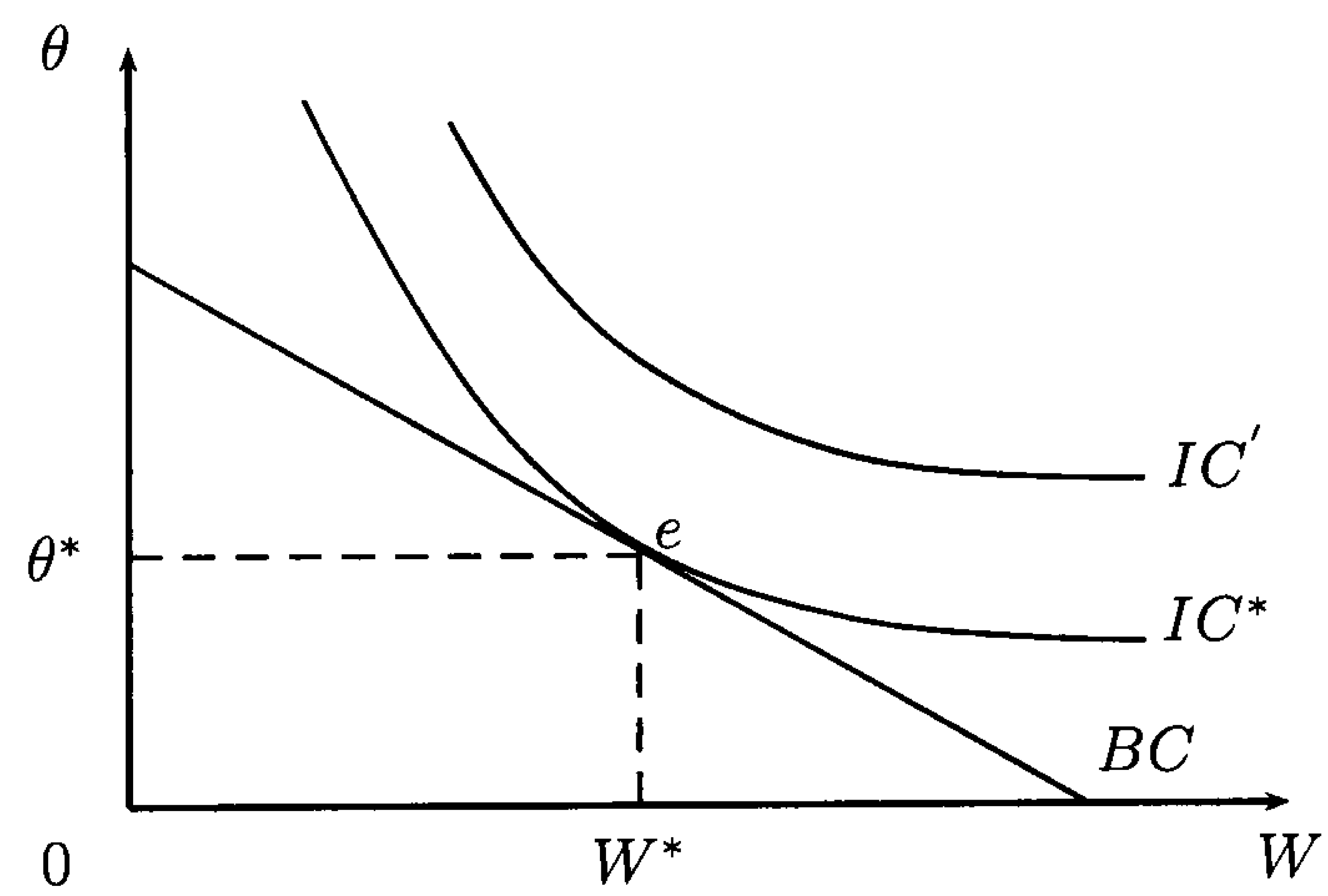


Figure 6.2: Indifference curves and the optimal solutions in flood risk management. IC: indifference curves. BC: budget constraint. θ^*: the probability of being flood damage free. W^*: the maximum welfare net of floods. e: the combination of (θ^*, W^*), the optimal solution.

Moreover, negotiation is the obvious choice to solve an embankments race using a decentralised measure. An SC constitutes a form within which to negotiate the conflicts that arise.

6.3.2 Principles for designing a stakeholders' committee

The direct involvement of all stakeholders in the decision-making process was recommended by the World Bank (1993). It has informational advantages especially at the design stage of a policy since local conditions, technology, customs, and needs can hence be engaged for decision-making. Basically, involving all stakeholders implies dealing with a huge number of participants. Hence, the transaction costs of decision-making may be high and agreements may not be easy to reach.

Jonoski (2004) tried to scale down the participation of stakeholders by assigning representatives. This does risk losing all the relevant interests, but the size of a group also affects the efficiency of decision-making and the effectiveness of meeting a target for the group. Olson (1965) found that it is easier for a small group to meet its target than for a large group because of economic incentives and social pressure. Members of a small group often know each other and this creates pressure for them to make an effort to achive the goal. Contrarily, a large group is often unstable, 'latent' or inclined to disappear because of its inability to meet the target. Members in a big group will not act to advance their common objectives unless there is coercion to force them to do so, or if separate incentives, distinct from the achievement of the group interests, are individually offered to the members of the group.

It is easier for a small group to find its way to decentralised management because of its simplicity. When decentralised management evolves into a huge scale of participation, there is a need to strengthen the integrity of the group without losing the spirit of decentralisation. An SC consists of small groups with various interests or abilities in flood management. Provided there are well-structured information and incentive systems, the integrity of a large group might be kept intact through the disaggregation of this kind.

Decisions are made by the majority vote of stakeholders. Votes are the signals which reveal the information of each stakeholder. There are generally two principles to assign votes. One is the principle of equal contribution while the other is the principle of contribution and participation. The contribution includes mitigation abilities and financial capacities. There has been much debate on which principle to choose. Shaw et al. (2003) showed that the problems of commons can be avoided by applying the second principle rather than the first principle. Applications of the second principle are in fact appearing more often. In this case, the distribution of votes proportional to the contribution and participation of each individual drive the management process. It provides incentives for participation in collective action.

6.3.3 Interested parties

The major interested parties involved in flood management are the organisations responsible for flood mitigation, local authorities, water authorities, land owners, and other potential players. To illustrate, consider the catchment of the Yorkshire Ouse in England.

ORGANISATIONS RESPONSIBLE FOR FLOOD MITIGATION

The Department for Environment, Food and Rural Affairs (DEFRA) has policy responsibility for flood risk in England. It provides financial support for research on improving flood management. It funds most of the Environment Agency's (EA) flood management activities in England and other flood defence operating authorities (e.g., local authorities and Internal Drainage Boards (IDBs)). Hence, DEFRA shall also represent opinions of expertise, including suggestions from academia. However, DEFRA does not build defences, nor direct other authorities on what specific projects to do. Policy delivery is the responsibility of the EA, local authorities, and IDBs. Three basic means of funding for flood defence schemes are implemented by these three bodies: local levies (EA), drainage rates (IDBs) and council taxes (local authorities).

The EA maintains and operates vital flood defences, monitors river water levels and flows, and assesses flood risk. It advises local authorities of development and environmental problems. The EA is also responsible for the national flood warning system. It oversees the issue of flood warnings and advises local authorities on emergency responses.

IDBs are responsible for the maintenance of drainage systems, some ordinary watercourses and pumping stations. They are also involved in habitat protection and species conservation. Some members are elected by the payers of drainage rates while some are appointed by local authorities subject to levy funding.

LOCAL AUTHORITIES

Local authorities represent the residential and industrial purposes within specific administrative boundaries. The related local authorities in this catchment are East Riding County Council and North Yorkshire County Council. Local authorities participate in operating flood warning systems managed by the EA. The level of their involvement in flood defence and land drainage depends mainly upon the nature of the area of the local authority.

With respect to flood defences, a local authority assesses the potential effects on socio-economic and environmental aspects, maximises efficiency, raises funds, and abides by conservation rules. It also ensures the maintenance of flood defences on private land while the private land owners are responsible for the maintenance of flood defences. It sometimes operates pumping stations and culverts.

A local authority needs to ensure the optimal operation of some ordinary watercourses within their authorised areas, e.g., clearing the excess silt and aquatic vegetation and keeping screens clear of debris. It also provides an emergency response service, e.g., the distribution of sandbags to vulnerable properties, with the assistance of the police force. The ambulance service, and fire and rescue services also participate in emergency operation. Avoiding pollution caused by public sewers is also the responsibility of local authorities under the Public Health Act, 1936.

A local authority also plays a key role in development that includes discouraging inappropriate development in areas at risk of flooding. Here lies a tradeoff. In carrying out its responsibilities, a local authority should balance economic development against environmental health. With its local knowledge and its influence on policy-making, a local authority should provide a well-balanced plan for economic development and flood mitigation. Some local authorities secure substantial funds from developers for compensation for the hydrological consequences of development, whether within the region or in upstream areas.

REGIONAL FLOOD DEFENCE COMMITTEES (RFDCs)

Regional Flood Defence Committees (RFDCs) are made up of representatives appointed by DEFRA, EA, and local authorities. The RFDCs supervise all matters relating to flood defence within a certain region. This catchment for instance, is mainly administered by the Yorkshire RFDCs.

WATER COMPANIES

The water company (e.g., Yorkshire Water in Yorkshire) is not directly in charge of flood control, though it may favor the mitigation that increases future water collection. Nevertheless, it is responsible for water quality affected by flood-related water pollution, e.g., sewer flood. Involving water authorities in flood management is desirable to avoid problems associated with the aftermath of flooding and the supply of water. Mitigation and development located at upstream or in neighbouring areas to water treatment facilities might be their main concern.

LAND OWNERS

Farmers manage over 3/4 of the land in the UK and hence they are in charge of water management over a large scale. However, farmers accounted for only 1.8% of the workforce in 2003 and agriculture's contribution to the gross domestic product has been declining in the UK (see Figure 6.3). Even though the importance of agriculture in the economy has been weakening, its potential environmental significance, such as mitigating flooding, remains strong. Farmers might bargain by themselves or delegate the bargaining power to the local authority or a farming organisation such as the National Farmers' Union (NFU). The NFU represents about 3/4 of full-time commercial farmers of England and Wales. Although flood control currently is not its major concern, a substantial benefit from regulating water amount on farming land might trigger its interests.

Land owners alongside rivers or roads are responsible for flood defences on private land and most roadside ditches. Land owners of developed land, upstream areas, flood-sensitive areas, or other places with predominant impacts on flood mitigation potentially have interests in transaction and negotiation of flood management. They might participate in the trading or bargaining activities individually or through communities or local authorities.

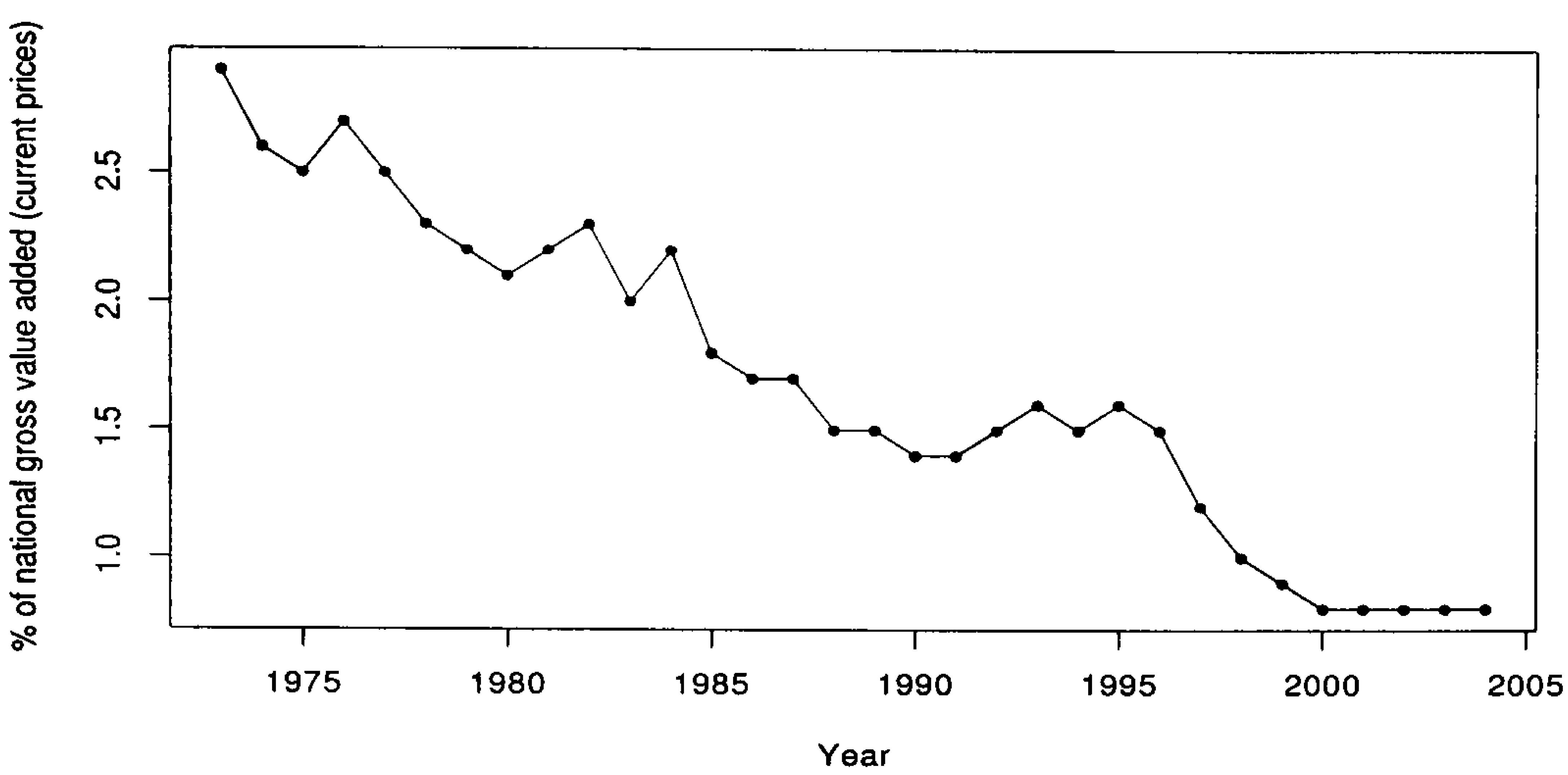


Figure 6.3: Agriculture's contribution to GDP in the UK (1973-2004). Data source: http://farmstats.defra.gov.uk/cs/ farmstats_data/DATA/nuts_data/nuts_query.asp.

OTHER POTENTIAL PLAYERS

Since mitigation often affects ecological functions, flood management induces attention of environmental groups, such as English Nature and the Royal Society for the Protection of Birds. Moreover, some other industries, such as fisheries, might be affected by the change of water quantity or quality due to development or mitigation undertaken within or near their areas.

6.4 Tradeable flood permit

The idea of tradeable permits, proposed by Crocker (1966) and Dales (1968), integrates the advantages of quantitative restriction and economic incentives. It can secure environmental quality and efficiency, reduce conflicts between economy and environment, avoid the complication of economic growth and inflation, distinguish geographical differences, provide financial resources of compensation and a possible increase in tax base. In other words, it is designed as a market-based instrument in order to deliver a cost-effective solution in flood management. The policy feasibility can be increased by grandfathering. However, it is often criticised due to significant transaction costs, possibly no regular income for government and equity violation. The pros and cons of implementing tradeable permits applied in other environmental aspects, such as water resources, air pollution, natural resources, and biodiversity, are listed in Table 6.3.

There are applications of tradeable permits to the fields of air pollution, water pollution, zoning, habitat conservation, fisheries in international waters, and biodiversity. Here I investigate the applications to flood risk trading which has not been explored.

6.4.1 Criteria of a successful tradeable permit system

A successful tradeable permit system should satisfy the following criteria. First, the advantages of applying tradeable permits need to be manifested. Otherwise, the policy-maker loses credibility when using a tradeable permit system instead of other policy instruments.

Secondly, it should overcome the difficulties related to transaction costs. High transaction costs might reduce trading levels and increase mitigation costs. Asymmetric information and unsound incentive structures are often the key factors of high transaction costs.

Asymmetric information can lead to low initial trading volume as

Table 6.3: Pros and cons of implementing tradeable permits (adapted from Baumol and Oates (1988))

Pros
1. Securing environmental quality and efficiency.
2. Reducing conflicts between economy and environment.
3. Avoiding the complication of economic growth and inflation.
4. Distinguishing geographical differences.
5. Increasing policy feasibility by grandfathering.[a]
6. Providing financial resources of compensation.
7. A possible increase in tax base.
Cons
1. Significant transaction costs
2. Equity violation due to grandfathering.
3. Possibly no regular income for government.

[a]Grandfathering is to distribute initial permits according to the historical output. It provides means of alleviating distributional impacts from the introduction of a tradeable permit system.

potential traders postpone transactions while waiting for additional information (Ben-David et al., 1999). To increase the efficiency of communication, application of technology such as the use of the internet is an option (Cason and Gangadharan, 1998). To avoid problems of asymmetric information, a permit bank that serves as a broker can be considered.

However, Hahn (1986) and Stavins (1995) suggests that the incentive structures provided by a tradeable permit market might generate misleading price signals. For instance, a tradeable permit system might lead to a decrease in tax income due to residents' expectation of higher land price in the protected areas and overloaded financial burden for the developed areas due to an increase in development. Therefore, adequate incentives are essential for the successful use of the trading market.

Thirdly, a clearly presented and validly justified policy purpose, a well-designed number of permits, and well-designated protected and developed areas are crucial. These should be based on the knowledge of the geographical and economic properties of the targeted areas.

Lastly, effective public communication eliminates conflicts and difficulties during implementation. This highlights the importance of collaborative management. Education can also be a catalyst to encourage participation in a new management regime.

Overall, revealing the merits, minimising transaction costs, caring about the design of a permit system itself, and effecting public communication are keys to a successful flood permit system. In conjunction with other issues, e.g., flood control, development, and zoning, is also helpful for policy implementation.

6.4.2 Conditions for converting hard to soft mitigation

The TFP system chiefly aims at avoiding the insufficiency of soft mitigation. Proposition 4.1 holds that investment in soft mitigation is more preferred the lower the rate at which future costs and benefits are discounted. It is less costly to adopt soft mitigation than hard mitigation in a less developed economy while it becomes problematic to reclaim the developed land for flood mitigation in a highly developed economy. Undertaking soft mitigation is only appropriate in certain situations. Guidelines for converting hard to soft mitigation are summarised in the following:

- Effectiveness. When the anticipated energy of flooding is too strong for soft mitigation to cope with, options should lie between hard mitigation (Burgess, 2004) and adaptation. Soft mitigation should only be undertaken when it is sufficiently effective. Inappropriate replacement of embankments with saltmarshes might incur devastating floods instead. The adoption and the scale of soft mitigation hence need careful evaluation.

- Sufficient area. The size of the area dedicated to soft mitigation shall be sufficient to mitigate flooding for the targeted area. An insufficient area only offers limited protection against localised flooding (Mauchamp et al., 2002) or may even lose its function.

- Local interests and knowledge. Local interests and knowledge should be taken into account, not only for the tradeoff between economic and environmental values but for choosing a proper way to manage flood risk.

- Integrated approach. To balance the capacity for coping with huge flood energy against ecological concerns, an integrated approach that combines hard mitigation and soft mitigation can be considered. Hard mitigation can be constructed in a way of minimising damage to the ecosystems, such as using environmentally friendly materials and giving aquatic biota proper space and design (e.g., fish entrainment at flood defences). Its impact on the flow regime must also be considered. Soft mitigation can be undertaken with flexible hard mitigation, e.g., movable gates. The optimal ratio of hard mitigation to soft mitigation depends on economic capacity, flood risk, geographical characteristics, and local interests.

- Minimising damage from mitigation conversion. Avoiding side effects of mitigation conversion is essential. For instance, any change of land use can cause massive disturbance in soil characteristics, amenity uses, ecological resources, and water courses. Inadequate understanding of ecosystems is often a main reason for the failure of land restoration (Harris et al., 1996).

- Capacity. The capacity for implementing mitigation conversion shall be sufficient to accomplish the mission (Harris et al., 1996). Failure in carrying through all aspects of the plan causes unsuccessful conversion.

Options for converting hard to soft mitigation considered in Chapter 2 are natural processes restoration, riparian buffer zones creation, and allowing flooding on the land. Restoring natural processes in an area is to resume its natural condition as it was in the past. Riparian buffer zones improve bank stability, reduce silt deposition, and remove sediments and pollutants. Land owners can also retain water or allow water to flood their land, especially during a certain period of time. What they can do is either simply opening water gates to lead water in or increasing the infiltration capacity of the land by improving the vegetation.

In some cases, tradeoffs do not lie between hard mitigation and soft mitigation. When both economic and ecological concerns are high, adaptation such as migration, relocating economic activities to a safe area, is a compromise.

6.4.3 Theoretical models

This subsection considers the reason for introducing a TFP system using theoretical models. Suppose a catchment consists of ℓ areas. Decisions of each area influence the flood risk of itself and its neighbouring and downstream areas.

Assume areas are heterogeneous in terms of geographical characteristics such as infiltration capacity and flow direction. The heterogeneity of areas is presented by $\mathbf{G}$, a geographical coefficient that indicates the influence of spatial characteristics on runoff. g_{ji} indicates that one unit of runoff from source i contributes to the runoff at area j. $g_{ji} \leq 1$ because the runoff from area i towards other areas

(js) at least partially infiltrates into soil or evaporates. The smaller the value of $\sum_{i=1}^{\ell} g_{ji}$, the less runoff generated from i reaches other areas (js). The property of runoff accumulation in the catchment is described by an $\ell \times \ell$ matrix of unit runoff reduction coefficients:

$$\mathbf{G} = \begin{pmatrix} & \vdots & \\ \cdots & g_{ji} & \cdots \\ & \vdots & \end{pmatrix}$$

For a common-pool, each g_{ji}, where $i \neq j$, has an identical positive value. For upstream-downstream flows where areas are coded from 1 at the top to ℓ at the bottom along the stream, each $g_{ji} = 0$ when $j < i$ and $0 < g_{ji} \leq 1$ when $j > i$. This yields a triangular matrix. Here we focus on the case of upstream-downstream flows.

$\bar{A}$ is the total amount of land; m is the amount of developed land; '$\bar{A} - m$' is the amount of non-developed land assumed to be dedicated to soft mitigation; k is the amount of hard mitigation; and r^* is the optimal probability of flooding. Runoff, described by $\mathbf{G}$, links to the probability of flooding. k_j increases the amount of runoff released at j by draining water downwards while '$\bar{A} - m_j$' decreases the amount of runoff from j by improving infiltration capacity.

We can infer that upstream soft mitigation generates beneficial externalities and hard mitigation produces adverse externalities. Knowing $\mathbf{G}$, one can derive the optimal amount of each type of mitigation for every area.

Using a tax or subsidy regime to obtain efficiency in a geographically complicated catchment is costly for the SC. The optimal rates of tax/subsidy should be set up according to different geographical conditions. A TFP system is hence introduced to let market forces tackle geographical and economic differences within a secured level of flood risk.

There are two ways to develop TFPs. The first concerns trade in soft mitigation. This type of tradeable permit aims only at avoiding the undersupply of soft mitigation. The second involves trade in both soft mitigation and hard mitigation, given the optimal probability of flooding. Permits of this sort are aimed at improving the efficiency of the overall flood mitigation.

One might think of encouraging a trade in hard mitigation only, but given the safety concern, it would be improper for the SC to restrict hard mitigation at the cost of risking lives and properties. A policy-maker should be cautious of using this instrument. If there is any trading regime involved, its function should only be efficiency improvement in hard mitigation itself rather than in the overall mitigation. Hard mitigation can only be restricted in specific cases in which soft mitigation takes over the role or adaptation is arranged.

The model proposed in Baumol and Oates (1988) is to minimise the cost given a certain target. If we take this cost as an opportunity cost, the problem can turn out to be targeting at maximising welfare. Social welfare of the catchment is assumed to be scaled down by flood risk. $R(r_i^*)$ shapes the amount of runoff corresponding to the optimal probability of flooding at i. $\mathbf{R}(\mathbf{r}^*) = (R(r_1^*), R(r_2^*), \ldots, R(r_\ell^*))^T$.

TRADE IN SOFT MITIGATION

Suppose $EW(m)' \geq 0$ and $EW(m)'' < 0$. $h(m_i)$ indicates the amount of runoff caused by development at i. $h(m)' \geq 0$ and $h(m)'' > 0$. $\mathbf{H}(\mathbf{m}) = (h(m_1), h(m_2), \ldots, h(m_\ell))^T$.

The SC faces a problem of choosing development (and soft mitigation) to maximise expected social welfare, $\sum_i EW_i$, given the probability of flooding the catchment is prepared to tolerate (r^*):

$$\begin{aligned} max_{m_1,\ldots,m_\ell} \quad & \sum_i EW(m_i) \\ s.t. \quad & \mathbf{G} \cdot \mathbf{H}(\mathbf{m}) \leq \mathbf{R}(\mathbf{r}^*) \end{aligned} \tag{6.1}$$

The necessary conditions for an interior solution are

$$\begin{aligned} & EW(m_i)' = \sum_{j=1}^{\ell} (\lambda_j \cdot g_{ji}) \cdot h(m_i)', \qquad i = 1 \ldots \ell \\ & \mathbf{G} \cdot \mathbf{H}(\mathbf{m}) = \mathbf{R}(\mathbf{r}^*) \end{aligned}$$

which can be re-written as

$$\begin{aligned} & \sum_{j=1}^{\ell} (\lambda_j \cdot g_{ji}) = EW(m_i)'/h(m_i)', \qquad i = 1 \ldots \ell \\ & \mathbf{G} \cdot \mathbf{H}(\mathbf{m}) = \mathbf{R}(\mathbf{r}^*) \end{aligned} \tag{6.2}$$

where λ_j is the shadow value of the targeted probability of flooding at j.

Let $\sum_{j=1}^{\ell}(\lambda_j \cdot g_{ji}) = \Re_i$ which presents the magnitude of the effect on flood risk i can generate. Equation (6.2) presents a positive relationship between $\Re_i$ and soft mitigation '$\bar{A} - m_i$' at i. When the magnitude of the effect on flood risk i can generate is large due to the geographical conditions or the targeted probability of flooding in other places, adopting soft mitigation instead of development benefits the catchment. However, this equilibrium cannot exist under a decentralised system where each area makes decisions on its own.

Without concern for externalities, $\Re_i = \lambda_i \cdot g_{ii}$, the optimal level of soft mitigation is lower for i unless $\sum \lambda_j \cdot g_{ji} = 0$, $j \neq i$. W_i in this case is higher than that in equation (6.2). If the property right of generating runoff to other places belongs to each area itself, a welfare transfer should take place for the beneficiaries to compensate those who undertake soft mitigation. On the other hand, if the property right of generating runoff belongs to the runoff receptors, those who generate runoff should buy the right from the receptors.

This model is only appropriate when hard mitigation is constant or when hard mitigation plays a minor role in flood control. The next model will incorporate the importance of hard mitigation.

TRADE IN MITIGATION

The assumptions of m remain. Suppose $EW(k)' \geq 0$ and $EW(k)'' < 0$. $h(m_i, k_i)$ indicates the amount of runoff caused by development and hard mitigation at i. $h(k)' \leq 0$ and $h(k)'' < 0$. $\mathbf{H}(\mathbf{m}, \mathbf{k}) = (h(m_1, k_1), h(m_2, k_2), \ldots, h(m_\ell, k_\ell))^T$.

The SC faces a problem of choosing development, soft mitigation, and hard mitigation to maximise expected social welfare, $\sum_i EW_i$, given the level of risk the catchment is prepared to tolerate (r^*):

$$\begin{aligned} max_{m_1,\ldots,m_\ell,k_1,\ldots,k_\ell} \quad & \sum_i EW(m_i, k_i) \\ s.t. \quad & \mathbf{G} \cdot \mathbf{H}(\mathbf{m}, \mathbf{k}) \leq \mathbf{R}(\mathbf{r}^*) \end{aligned} \tag{6.3}$$

The necessary conditions for an interior solution are

$$
\begin{aligned}
EW(m_i)' &= \sum_{j=1}^{\ell}(\lambda_j \cdot g_{ji}) \cdot h(m_i)', \qquad i = 1 \ldots \ell \\
EW(k_i)' &= \sum_{j=1}^{\ell}(\lambda_j \cdot g_{ji}) \cdot h(k_i)', \qquad i = 1 \ldots \ell \\
\mathbf{G} \cdot \mathbf{H}(\mathbf{m}, \mathbf{k}) &= \mathbf{R}(\mathbf{r}^*)
\end{aligned}
$$

which can be re-written as

$$
\begin{aligned}
&\sum_{j=1}^{\ell}(\lambda_j \cdot g_{ji}) = EW(m_i)'/h(m_i)' = EW(k_i)'/h(k_i)', \qquad i = 1 \ldots \ell \\
&\mathbf{G} \cdot \mathbf{H}(\mathbf{m}, \mathbf{k}) = \mathbf{R}(\mathbf{r}^*)
\end{aligned}
\tag{6.4}
$$

where λ_j is the shadow value of the targeted probability of flooding at j.

Equation (6.4) shows that i balances the optimal hard mitigation with soft mitigation with respect to $\Re_i$. Similar to that in equation (6.2), it describes a positive relationship between $\Re_i$ and soft mitigation '$\bar{A}-m_i$' at i. However, $\Re_i$ does not have a constant relationship with hard mitigation.

When $\Re_i$ is high, adopting soft mitigation at i can benefit the catchment. However, whether increasing or decreasing hard mitigation at i depends on the marginal impacts, $EW(k_i)'$ and $h(k_i)'$.

The first model suggests that soft mitigation is appropriate for areas that generate severe externalities of flood risk. Whether incentives or penalties should be offered depends on the definition of the property right to runoff. The second model has similar implications for soft mitigation while the choice of hard mitigation relies on its marginal impact on welfare and that on runoff.

6.4.4 Types of tradeable flood permits

A TFP system aims at allocating 'flood risk' efficiently by considering flood mitigation and land use. There are three types of TFPs for implementation, developed from the two models in subsection 6.4.3 (refer to Figure 6.4) . First is the tradeable development permit (the TraD permit, also named the transferable development right). It only relates to land use and has been implemented for management of flood hazards, preservation of historical remains, and conservation of ecological systems. To integrate hard mitigation into flood management, the tradeable flood reduction permit (the TFR permit) and the tradeable risk neutral permit (the TRiNe permit) are developed. They are aimed at restricting choices of land use and/or flood mitigation which increase flood risk and/or cause related externalities. Incentives to sell permits are monetary while those to purchase permits are either environmental or economic.

TRADABLE DEVELOPMENT PERMIT (TraD PERMIT)

The purpose of implementing the TraD permit on a floodplain is to restrict the increase in flood risk in designated areas. Issuing development permits is a common strategy to control flood risk. It originally aims at protecting open space and historic sites, though the areas allowed to develop might end up with high density of development. Making the development permits tradeable was suggested

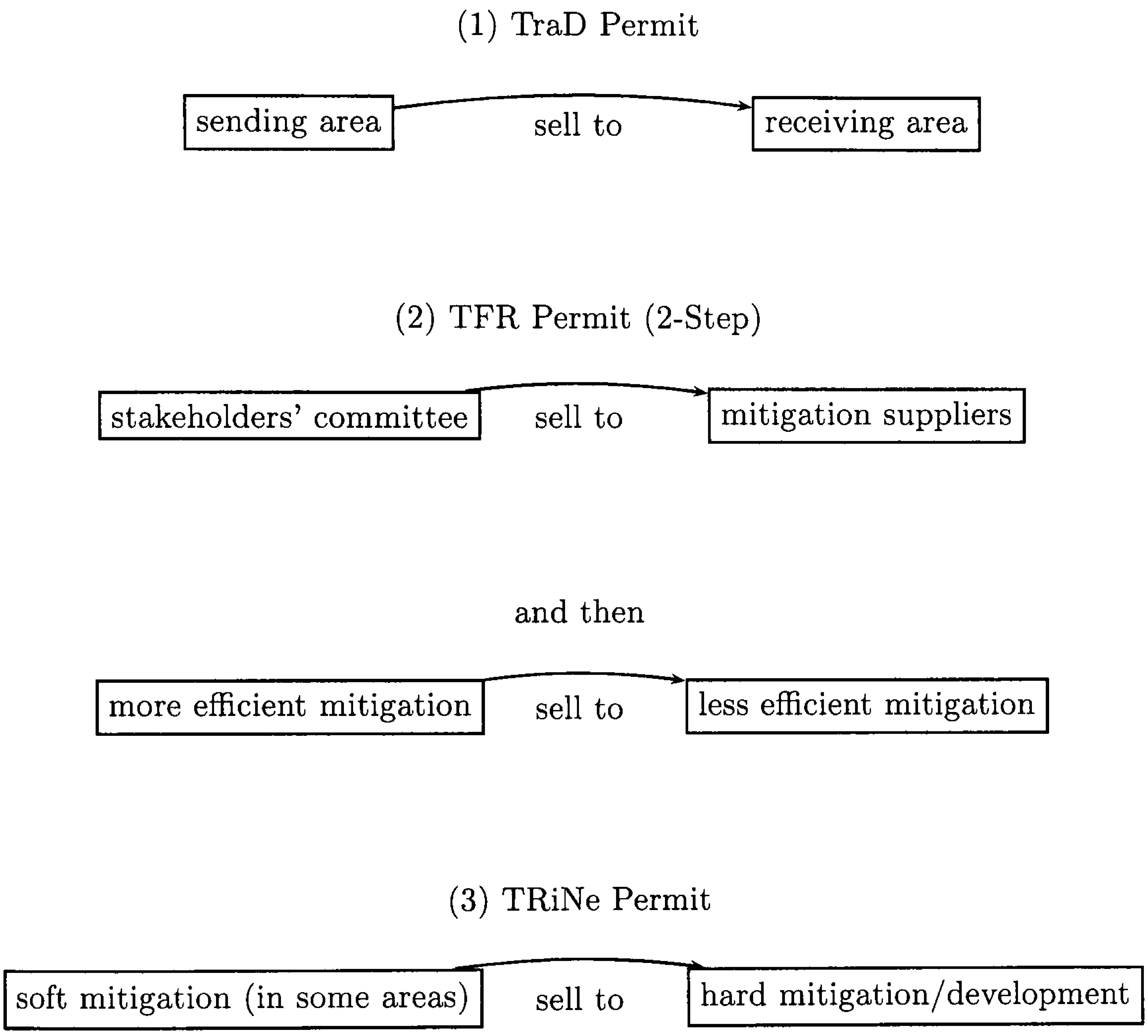


Figure 6.4: Transactions in the three types of TFP systems

in the Town and County Planning Act in the UK and has been implemented in many places, especially in the USA.

A TraD permit system should have well-designated 'sending areas' (where land conservation is sought) and 'receiving areas' (where land development is encouraged) and a well-designed market. A developer should buy enough TraD permits in sending areas to proceed with the development in receiving areas (McConnell et al., 2003; Corkindale, 1999).

There are two ways of using the TraD permit to decrease flood risk. First is to designate sensitive areas and upstream districts as sending areas. More credits can be assigned to land with higher ecological sensitivity (River Basin Center, 1998) and that with better infiltration capacity. Each piece of land is valued according to its environmental importance. Secondly, the SC or other non-developers can purchase permits without exercising the right of development.

Sellers are those land owners [4] in sending areas. Buyers are either those who demand development in receiving areas or those who support a decrease in environmental risk.

With a knowledgeable SC that discerns the mitigation capacity and flood vulnerability of each area, a TraD permit system can avoid undersupplied soft mitigation. However, merely considering land use is insufficient in flood management when hard mitigation is crucial.

[4] Property owners can also be sellers in some cases of Transferable Development Rights. Here only land is under consideration.

TRADEABLE FLOOD REDUCTION PERMIT (TFR PERMIT)

The purpose of implementing the TFR permit is to decrease flood risk using the most efficient mitigation strategy. Different types of mitigation and locations generate diverse effects. Hard mitigation is immediately and locally effective while soft mitigation is sustainably and extensively functional. Soft mitigation benefits the local area and generates beneficial externalities to downstream and neighbouring areas. Adverse externalities of undertaking hard mitigation partially counteract the benefits to the local area it generates.

The SC determines the optimal flood risk, and then auctions or issues the permits to mitigation suppliers. Transactions then follow. Obtaining information of mitigation in each region is no longer necessary. Information is revealed through the market mechanism.

Buyers are those who have responsibilities for flood mitigation, those who benefit from a decrease in flood risk, or less efficient mitigation adopters. Potential sellers are those who can offer mitigation, especially more efficient mitigation. For instance, the downstream area might purchase upstream soft mitigation or compensate the upstream area to abandon hard mitigation. Additionally, the SC need not participate in transactions and is required to only provide relevant information to ease the transactions.

The TFR permit is appropriate to the cases in which adverse externalities of hard mitigation are not severe. Otherwise, either imposing a restriction on hard mitigation or introducing the following type of permit should be considered.

TRADEABLE RISK NEUTRAL PERMIT (TRiNe PERMIT)

In the TRiNe permit system, a region can secure its rights to undertake hard mitigation or to develop only if it can neutralise the incremental flood risk of the externality receptors by purchasing them enough mitigation. Apparently, soft mitigation that generates beneficial externalities is encouraged.

Even though the spirit of decentralisation does not remain strong due to the regulation, the SC is only in charge of establishing and enforcing rules. Transactions of the TRiNe permits take place. Developers and hard mitigation adopters purchase mitigation for the receptors of the externalities generated by them. Hence soft mitigation that does not generate adverse externalities is encouraged. Sellers, the suppliers of soft mitigation, are mostly farmers and other land owners. Free-riding can be avoided while soft mitigation adopters are compensated by market mechanisms.

Furthermore, setting a higher standard for risk reduction instead of neutralisation is a good attempt to modify this type of TFP system. On the other hand, a lower standard for risk reduction can be a compromise.

DISCUSSION

The TraD, TFR, and TRiNe permits differ in trading objectives and the information an SC needs. Hence they are recommended under different institutional conditions.

The TraD permit system focuses on land use. If the SC knows the extent of flood risk externality an area can generate, the marginal welfare/cost with respect to development, and the marginal effect of development on generating runoff of some areas in the catchment, it will be capable to undertake the TraD permit system. Adopting the TraD permit system guarantees the undertaking of soft mitigation. Though this system originates from neutralising or attenuating the adverse externalities, it focuses only on land use. Hence, the management is flawed when hard mitigation is crucial.

The TFR permit system incorporates soft and hard mitigation. The access to information about the extent of flood risk externality an area can generate, the marginal welfare/cost with respect to development, the marginal welfare/cost with respect to hard mitigation, the marginal effect of development on generating runoff, and the marginal effect of hard mitigation on generating runoff are not required for the SC. It increases the efficiency of mitigation but faces problems of adverse externalities.

The TRiNe permit system targets obtaining zero adverse externality. When the problem of externalities is critical, the extent of flood risk externality in most areas is large for instance, an externality-free system of this sort can be brought into play. The conditions for adopting these three types of permit systems are presented in Table 6.4.

Similar to other 'user-pay' based methods of flood management, the financial burden of flood control can be apportioned. When the property rights and the targeted areas of flood risk reduction are obvious, the financial source can also be clear. The difference is money goes directly to those who should be compensated rather than through the SC. Consequently, contrary to taxes, the price of mitigation is determined by the market instead of by a policy-maker.

In the two-tired decentralised management, an SC decides which type(s) of the permits the catchment (or region) is going adopt, sets up the rules, designs and distributes the permits, and monitors the implementation of the permit system. In the UK, an SC may want to ask the current environmental authority in charge of flood mitigation, such as the Environment Agency, to report to the SC.

Table 6.4: Conditions for adopting the three types of tradeable permit systems

Condition	TraD	TFR	TRiNe
Hard mitigation (k) is essential		√	√
Severe ecological externalities of k	√		√
Severe flood risk externalities of k	√		√
Soft mitigation at certain locations is essential	√		
Uncertainty about marginal cost of k		√	√

6.5 Conclusion

This chapter has proposed a way to coordinate decisions among local areas within a decentralised framework to achieve an efficient and effective outcome in flood management given the limitations of information and bounded rationality. This entails the introduction of the two-tier decentralised decision-making process.

Information valuable for management is brought together by incorporating multiple interests of the SC and by introducing the market mechanism of the TFP. An SC is responsible for determining related targets and rules to improve both efficiency and equity. The market mechanism ensures the internalisation of externalities and compensation goes directly to those who suffer from losses. Three types of TFPs, TraD, TFR and TRiNe permits, are suggested based on different institutional conditions composed of different policy foci and the information accessed by the SC.

In application, a change of flood risk can be estimated from the change of hard mitigation capacity and that of infiltration capacity. The capacity of hard mitigation is given by engineering. Infiltration capacity can be measured using a ring infiltrometer or estimated using river flow and catchment area. The application of this two-tier decentralised flood management is particularly promising in the catchment with severe externalities from upstream economic activities such as over-development, deforestation, or hard mitigation.

The development of this decentralised management system is still at an early stage. Bridging knowledge between related disciplines, such as hydrology and economics, as well as systems design, is indispensable to enhancing its practicality and improving the efficiency.

Finally, tasks and knowledge involved differ in cases. This chapter demonstrates the way to form the SC. The next chapter will focus on the feasibility and the institutional setup of implementing the TFP system in the catchment of the Yorkshire Ouse, the Swale, the Ure and the Nidd.

Chapter 7

Feasibility of the Tradeable Flood Permit System

7.1 Introduction

This chapter aims at examining the feasibility of implementing the tradeable flood permit (TFP) system in the catchment of the Yorkshire Ouse, the Swale, the Ure and the Nidd in order to make policy recommendations for flood management. Section 7.2 reviews the incidence and severity of flood events and the hydrological characteristics in this catchment to provide an overview of the problem of flooding and its connection to natural factors. Section 7.3 investigates the anthropogenic factors influencing floods in the catchment and the prerequisites for adopting the TFP system. The heterogeneity in the geographical and economic dimensions, and the externalities in land use and mitigation are reviewed. Section 7.4 compares the effectiveness of the three permit systems with that of the current management system and identifies the prioritisation of the three TFP systems. It also addresses the institutional setup for implementing the new management system. Section 7.5 presents the chapter conclusions.

7.2 The problem of flooding

The purpose of this section is to characterise the problems of flooding and to pinpoint the nature of the problem in the test catchment.

7.2.1 Flood events

There are two types of floods in this catchment – fluvial flood and tidal flood. The tidal waters have a reach of 317 km upstream in the River Swale (Winn et al., 2003). Only fluvial flooding is under consideration in this research.

Table 7.1 and Figure 7.1 show an increasing frequency of flood events over time. This phenomenon may result from an increase in flood occurrence or the improvement in flood recording. The peak-over-threshold (POT) counts at Skelton on the Ouse (Figure 7.2) coincides with this pattern and suggests an increasing flood risk after the late 1950s. The runoff and river flow data will be reviewed in Subsection 7.2.2 to judge which is the case. Table 7.1 also indicates that heavy rainfall, with snowmelt in some cases, is the predominant cause of flooding in this catchment. Additionally, most floods occur in autumn, winter and early spring. However, this pattern has changed recently after the summer floods in the years

Table 7.1: Chronology of significant floods in the study catchment (1947-2005). See Subsection 7.2.3 for discussion. Data source: University of Dundee, Dartmouth Flood Observatory, Halcrow Group Limited (2001), Babtie Brown and Root (2005), and BBC news.

Date	**Area Affected**	**River**	**Major Cause**
2005, Jan	Yorkshire	Ouse	heavy rain
2002, Dec 22 - 2003, Jan 4	North East	Ouse	succession of rainfall events
2002, Aug 10-12	North Yorkshire	Ouse, Ure, Nidd	heavy rain
2002, Feb 12-16	Yorkshire	Ouse	heavy rain
2001, Feb		Ure	
2000, Oct 30-Nov	Yorkshire	Ouse, Swale, Ure, Nidd	heavy rain
2000, Jun		Ure	heavy rain
1998, Easter	Yorkshire	Ouse	heavy rain
1995, Jan 28-Feb 4	Yorkshire	Ouse, Ure, Nidd	
1991, Feb 23-5	Yorkshire	Ouse, Ure, Nidd	
1982, Jan 4	Yorkshire	Ouse, Swale, Ure, Nidd	
1978, Dec	York	Ouse	heavy prolonged rain
1968, Nov	York	Ouse	
1968, Jul 2	Ripon	Ure	storm
1968, Mar 23	York, Ripon, Boroughbridge	Ouse, Ure	rain after snow
1965, Dec	York	Ouse	
1957	Knaresborough, Boroughbridge	Ure	
1951, Nov	York	Ouse	
1947, Mar	York	Ouse, Ure	frost, snow and rain

2000 and 2002.

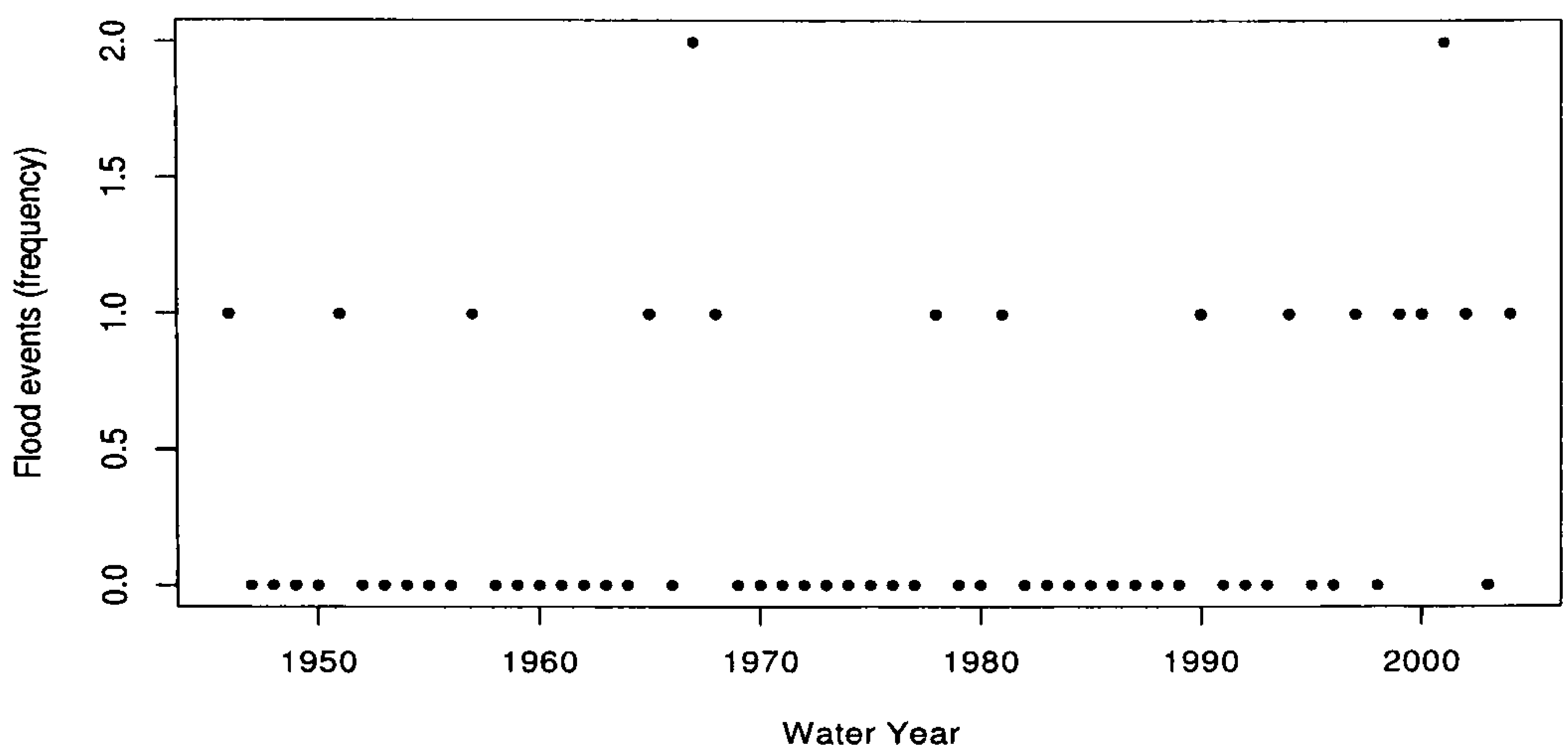


Figure 7.1: Counts of flood occurrence per year in the catchment of the Yorkshire Ouse, the Swale, the Ure, and the Nidd (1947-2005), based on data from Table 7.1.

7.2.2 Hydrological characteristics

This catchment has a temperate maritime climate. The maritime climate is strongly influenced by the oceans, which maintain fairly steady temperatures across the seasons. However, there is no specific feature in terms of precipitation pattern in a climatic zone of this sort. The temporal trends of catchment runoff, of river flow, and of rainfall, and the impacts of snow, are reviewed below.

The time series of hydrological data are calculated over the *water year* from October 1 to September 30 in the following year in the UK.

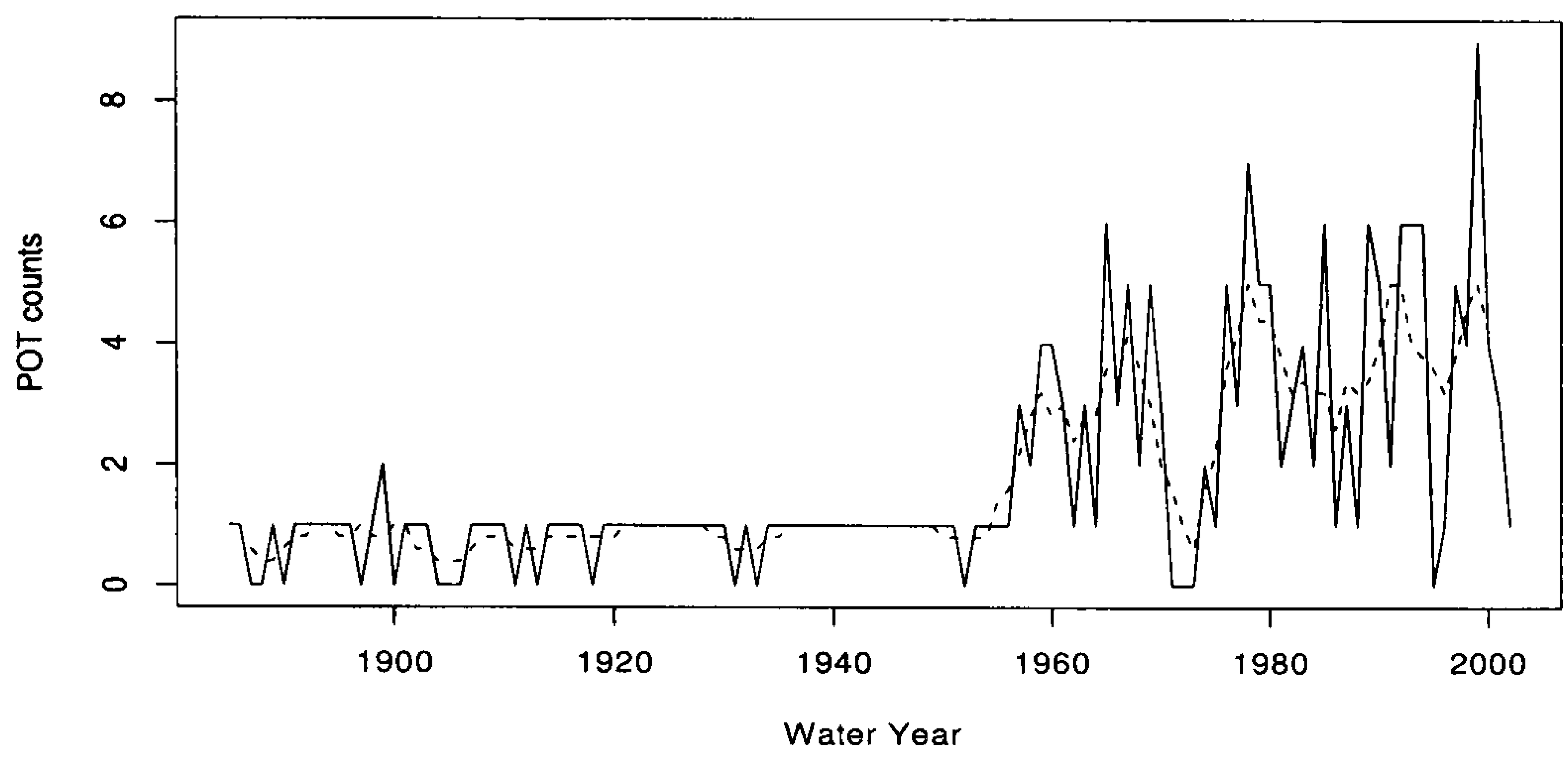


Figure 7.2: Counts of the peak-over-threshold (POT) per year at the Skelton on the Ouse (1885-2002). Solid line: original data; dashed line: smoothing the original data using 5-year moving average. Data source: Environment Agency Hiflows Dataset. POT threshold is 249.38 m^3/sec.

The gauging stations, listed in Table 7.2, were chosen on the basis of availability of long-term data sets and sub-catchment coverage. The catchment is divided into eight sub-catchments (refer to Figure 7.3): the upstream Swale (upstream of Richmond, coded S_u), the downstream Swale (downstream of Richmond, coded S_d), the upstream Ure (upstream of Ripon, coded U_u), the downstream Ure (downstream of Ripon, including Ripon, coded U_d), the upstream Nidd (upstream of Harrogate, coded N_u), the downstream Nidd (downstream of Harrogate, including Harrogate, coded N_d), the upstream Ouse (upstream of York, including York, coded O_u), the downstream Ouse (downstream of York, coded O_d). Hence, there are potentially two layers of transactions in the permit market, within each river and between upstream and downstream rivers.

Table 7.2: Selected gauging stations

River	Runoff	Flow	Rainfall
Ouse	Skelton	Skelton	York
Swale	Richmond	Crakehill	Richmond
	Crakehill		
Ure	Kilgram Bridge	Kilgram Bridge	Leighton Reservoir
			Low Houses
Nidd	Hunsingore Weir	Hunsingore Weir	Birstwith
	Gouthwaite Reservoir		Harlow Hill Reservoir

TEMPORAL TREND OF CATCHMENT RUNOFF

The trend of runoff over time is examined in terms of the annual maximum of monthly runoff at the chosen gauging stations. The original and smoothed data are presented in Figure 7.4.[1] Consider the model for testing the trend in the annual maximum of monthly runoff

$$r_t = a_0 + a_1 \cdot t + \epsilon \tag{7.1}$$

where t is water year, r_t is the annual maximum of monthly runoff at water year t, a_0 is the intercept, a_1 is the slope of the linear line, and ϵ is the error term. The null hypothesis is $a_1 = 0$ while the alternative hypothesis is $a_1 \neq 0$. The regression results are presented

[1]For the purpose of the research, the method employed to deal with the missing values is more than adequate, and the author would not want to introduce other elements that might distract from the main goal. If one introduces methods of imputation, investigation and comparison with other dataset will be required and always problematic to use.

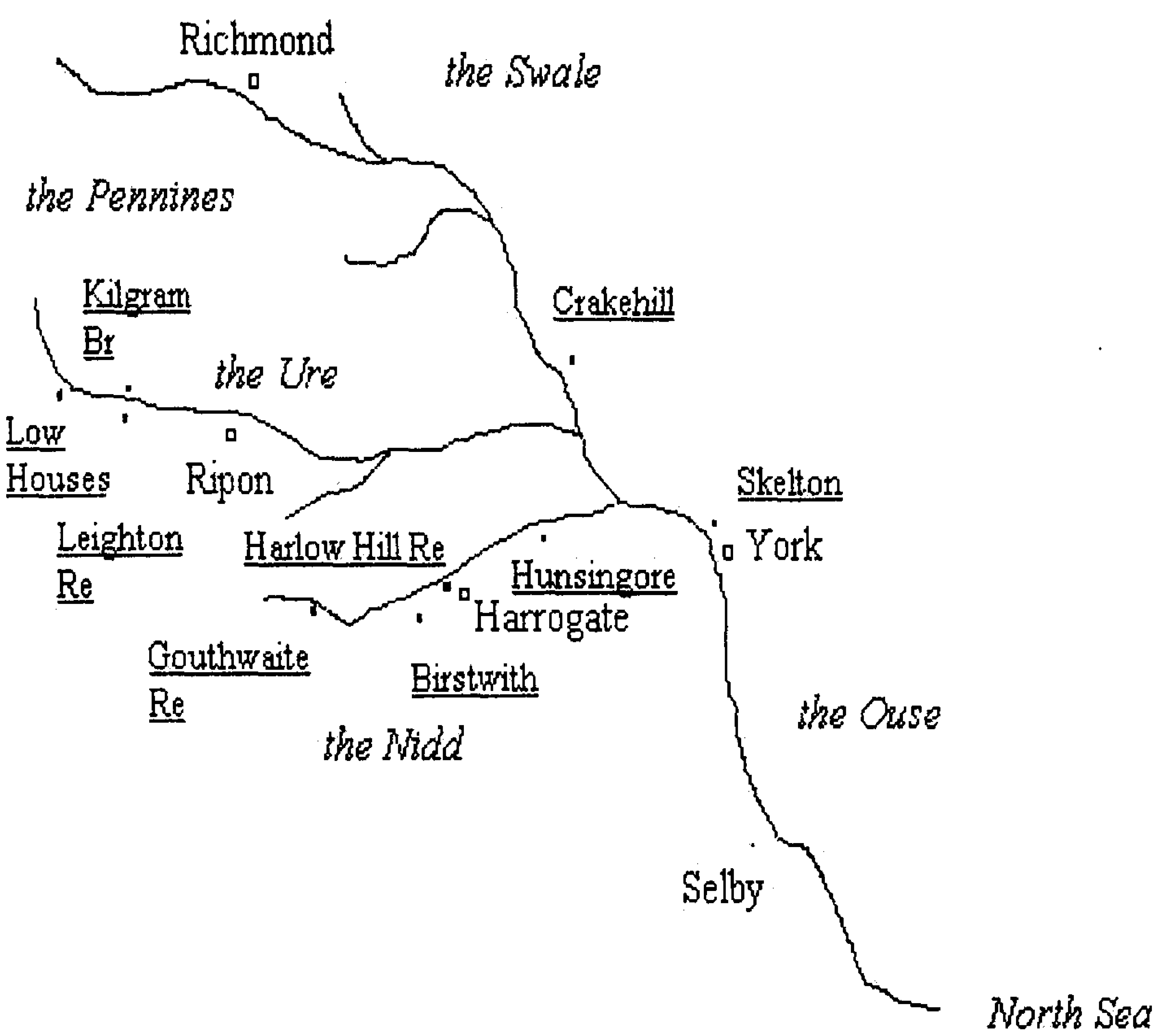


Figure 7.3: The catchment of the Yorkshire Ouse, the Swale, the Ure, and the Nidd.

in Appendix B. The fitted regression lines are shown respectively:[2]

- Kilgram Bridge:

$$\begin{aligned} r_t =& 83.64 + 2.56t \\ & [.03] \quad [.00] \end{aligned} \tag{7.2a}$$

- Skelton:

$$\begin{aligned} r_t =& 80.75 + 1.35t \\ & [.00] \quad [.01] \end{aligned} \tag{7.2b}$$

- Crakehill:

$$\begin{aligned} r_t =& 68.35 + 1.08t \\ & [.00] \quad [.00] \end{aligned} \tag{7.2c}$$

- Richmond:

$$\begin{aligned} r_t =& 194.56 - 2.28t \\ & [.00] \quad [.25] \end{aligned} \tag{7.2d}$$

- Gouthwaite Reservoir:

$$\begin{aligned} r_t =& 136.75 + .84t \\ & [.00] \quad [.04] \end{aligned} \tag{7.2e}$$

- Hunsingore Weir:

$$\begin{aligned} r_t =& 100.63 + .29t \\ & [.00] \quad [.24] \end{aligned} \tag{7.2f}$$

The results suggest that we can reject the null hypothesis that there is no trend over time in the maximum monthly runoff at Skelton (the Ouse), Kilgram Bridge (the Ure), Crakehill (the Swale), and Gouthwaite Reservoir (the Nidd) at the 90% significance level.

[2]The p-values are in the square brackets.

The sign of the paramater indicates an increasing trend in the annual maximum of monthly runoff. On the other hand, we fail to reject the null hypothesis that there is no trend in the maximum of monthly runoff at Richmond (the Swale) and Hunsingore Weir (the Nidd).

TREND OF RIVER FLOW

Figure 7.5 presents the annual maximum values of daily flow at the chosen stations. Consider the model for testing the trend of the annual maximum of daily flow, the maximum value of daily flow in each water year

$$f_t = a_0 + a_1 \cdot t + \epsilon \tag{7.3}$$

where t is water year, f_t is the annual maximum of daily flow at water year t, a_0 is the intercept, a_1 is the slope of the linear line, ϵ is the error term. The null hypothesis is $a_1 = 0$ while the alternative hypothesis is $a_1 \neq 0$. The regression results are presented in Appendix C. The fitted regression lines are shown respectively:

- Kilgram Bridge:

$$\begin{aligned} f_t =& 211.46 + 2.10t \\ & [.00] \quad\quad [.06] \end{aligned} \tag{7.4a}$$

- Skelton:

$$\begin{aligned} f_t =& 213.92 + 10.77t \\ & [.00] \quad\quad [.01] \end{aligned} \tag{7.4b}$$

- Crakehill:

$$\begin{aligned} f_t =& 169.32 + 2.08t \\ & [.00] \quad\quad [.04] \end{aligned} \tag{7.4c}$$

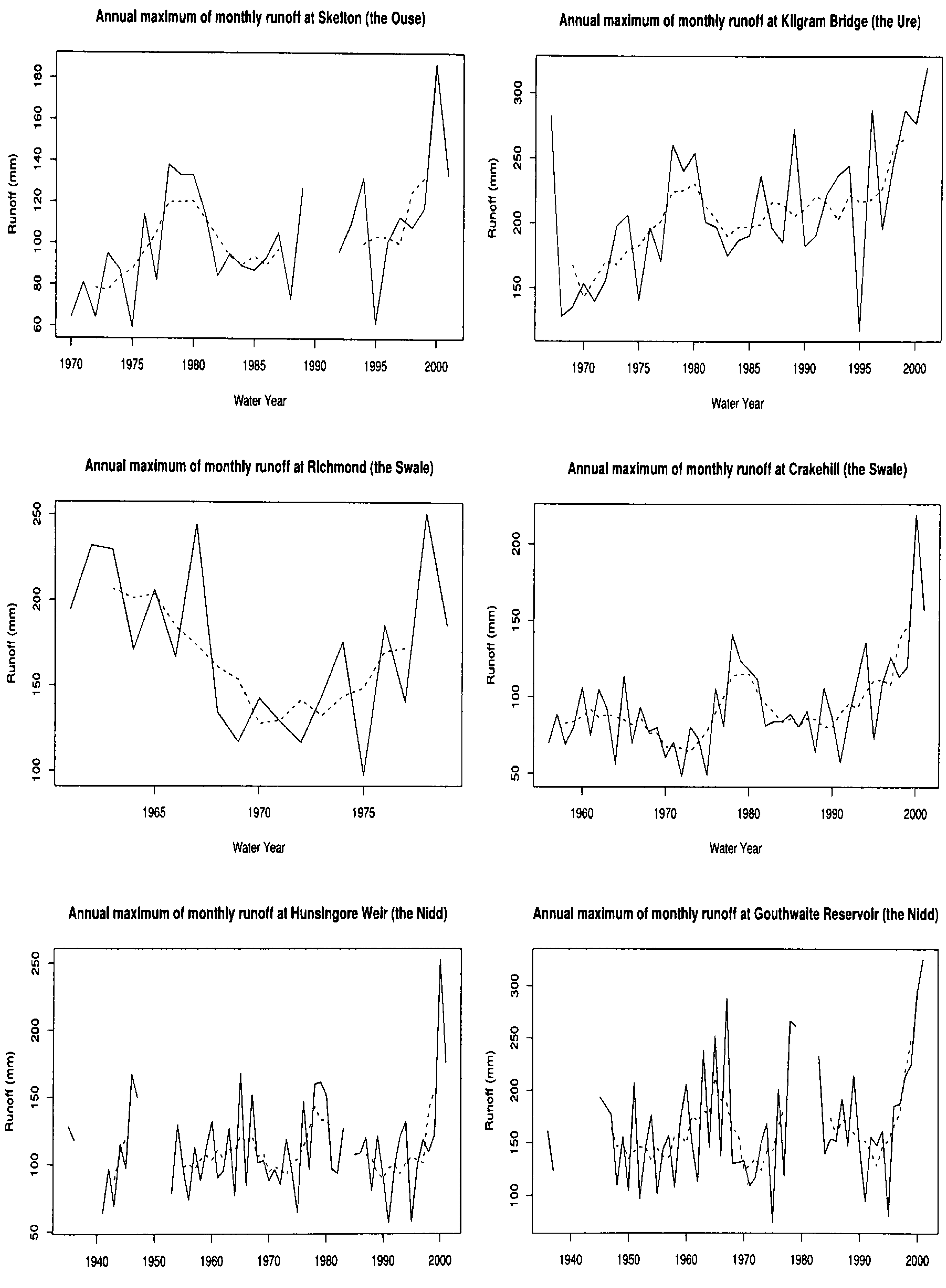


Figure 7.4: Trends over time in the annual maximum of monthly runoff in the catchment of the Ouse, the Swale, the Ure, and the Nidd. Solid line: original data; dashed line: smoothing the original data using 5-year moving average. Courtesy to Ms. Felicity Sanderson of National Water Archive.

- Hunsingore Weir:

$$\begin{aligned} f_t = & 66.89 + .65t \\ & [.00] \quad [.05] \end{aligned} \tag{7.4d}$$

According to the results, we can reject the null hypothesis that there is no trend over time in the maximum values of daily flow at all the gauging stations, Skelton (the Ouse), Kilgram Bridge (the Ure), Crakehill (the Swale), and Hunsingore Weir (the Nidd), at the signicance level of 90%. The sign of the paramater indicates an increasing trend in the annual maximum daily flow, which could be due to progressively more extreme precipitation events, to effects of changes in catchment land use, or scouring effects of upstream river channel. The scouring effect on the river beds is left out in this discussion.

TREND OF RAINFALL

Table 7.1 indicated the major cause of most flood events in this catchment is heavy rainfall. Figure 7.6 and Figure 7.7 summarise the annual rainfall and ratio of winter rainfall (from October to March in the following year) to annual rainfall (from October to September in a water year).

Consider the models for testing the trend of the annual rainfall and that of the ratio of winter rainfall

$$p_t = a_0 + a_1 \cdot t + \epsilon_p \tag{7.5a}$$

$$w_t = b_0 + b_1 \cdot t + \epsilon_w \tag{7.5b}$$

where t is water year, p_t is the annual rainfall at water year t, w_t is the winter rainfall at water year t. a_0, a_1, and ϵ_p are the intercept,

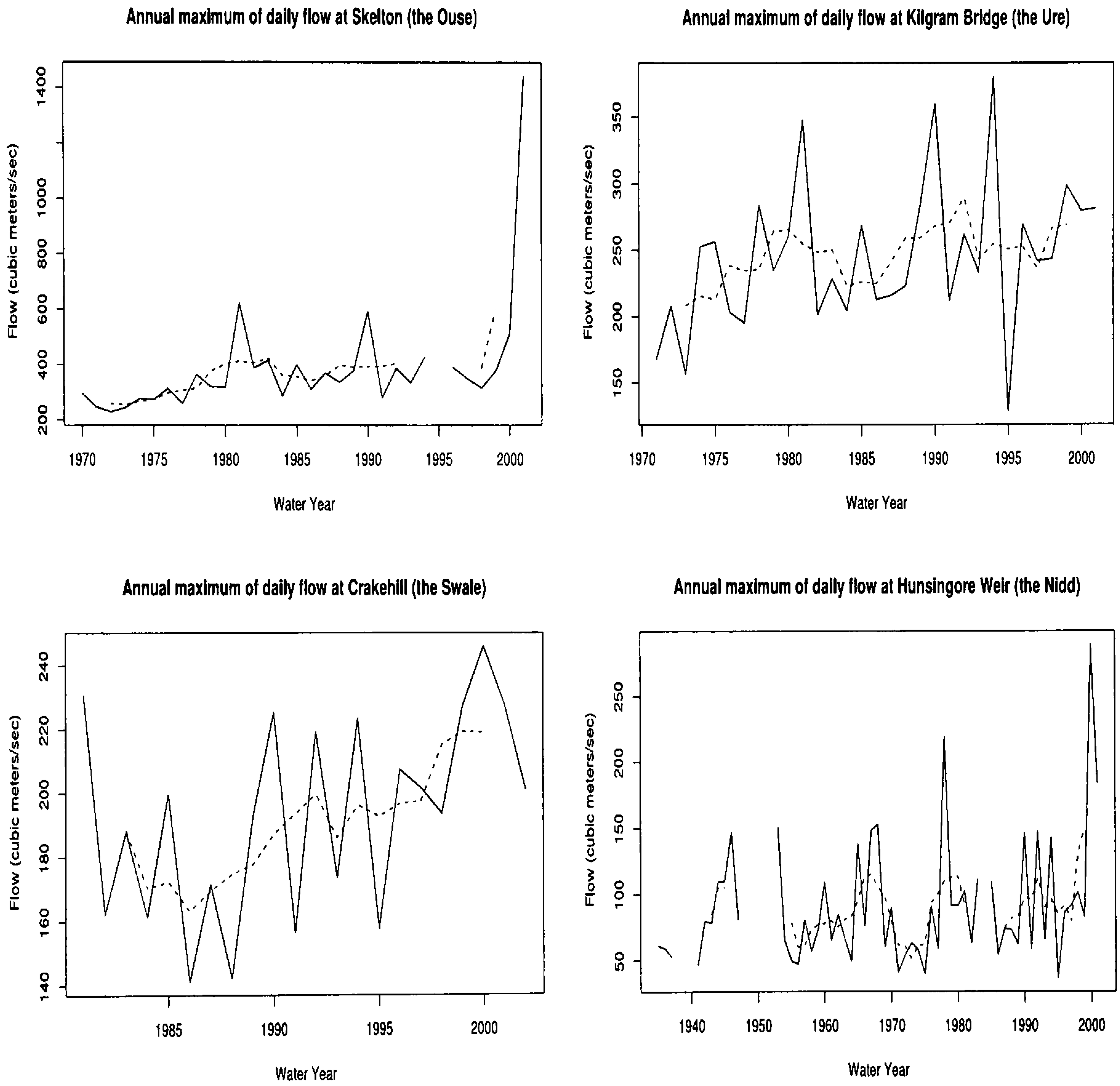


Figure 7.5: Trends over time in the annual maximum of daily flow in the catchment of the Ouse, the Swale, the Ure, and the Nidd. Solid line: original data; dashed line: smoothing the original data using 5-year moving average. Courtesy to Ms. Diana Orr of the Environment Agency at York.

slope, and residual of the model in equation (7.5a); b_0, b_1, and ϵ_w are the intercept, slope, and residual of the model in equation (7.5b). The null and alternative hypotheses for the first model are $a_1 = 0$ and $a_1 \neq 0$ while that for the second model are $b_1 = 0$ and $b_1 \neq 0$. The regression results are presented in Appendix D. The fitted regression lines are shown respectively:

- York:

$$\begin{aligned} p_t =& 640.74 - .51t \\ & [.00] \quad [.27] \\ w_t =& .4707 + .0004t \\ & [.0000] \; [.2809] \end{aligned} \tag{7.6a}$$

- Richmond:

$$\begin{aligned} p_t =& 793.91 - 1.31t \\ & [.00] \quad [.54] \\ w_t =& .4767 + .0028t \\ & [.0000] \; [.0834] \end{aligned} \tag{7.6b}$$

- Low Houses:

$$\begin{aligned} p_t =& 1023.01 - 1.95t \\ & [.00] \quad [.41] \\ r_t =& .5130 + .0029t \\ & [.0000] \; [.0307] \end{aligned} \tag{7.6c}$$

- Leighton Reservoir:

$$\begin{aligned} p_t =& 991.37 - 2.42t \\ & [.00] \quad\ [.3444] \\ w_t =& .5197 + .0034t \\ & [.0000] \ [.0285] \end{aligned} \tag{7.6d}$$

- Birstwith:

$$\begin{aligned} p_t =& 914.09 - 3.51t \\ & [.00] \quad\ [.15] \\ w_t =& .4929 + .0029t \\ & [.0000] \ [.0307] \end{aligned} \tag{7.6e}$$

- Harlow Hill Reservoir:

$$\begin{aligned} p_t =& 814.45 - .48t \\ & [.00] \quad\ [.49] \\ w_t =& .4910 + .0009t \\ & [.0000] \ [.0503] \end{aligned} \tag{7.6f}$$

The results associated with the annual rainfall suggest that there is no strong evidence against the null hypothesis that there is no trend in annual rainfall at each gauging station. However, that related to the ratio of winter rainfall to annual rainfall suggests that we can reject the null hypothesis that there is no trend in the ratio of winter rainfall to annual rainfall at each gauging station apart from York (the Ouse). The sign of the paramater indicates an increasing trend in winter rainfall relative to annual rainfall (i.e., wetter winters and/or drier summers).

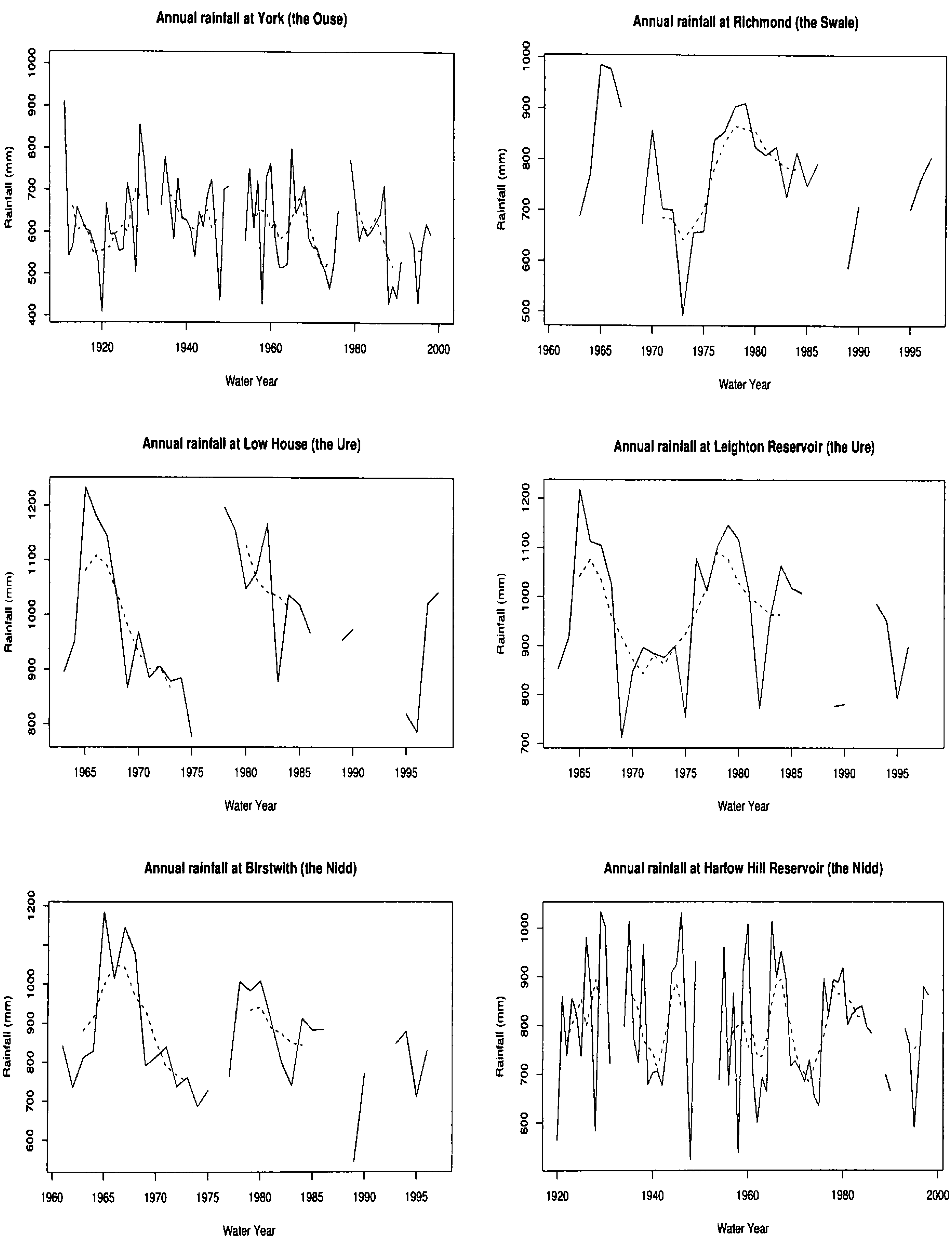


Figure 7.6: Trends over time in the annual rainfall in the catchment of the Ouse, the Swale, the Ure, and the Nidd. Solid line: original data; dashed line: smoothing the original data using 5-year moving average. Data source: MIDAS Land Surface Station Data of the British Atmospheric Data Centre.

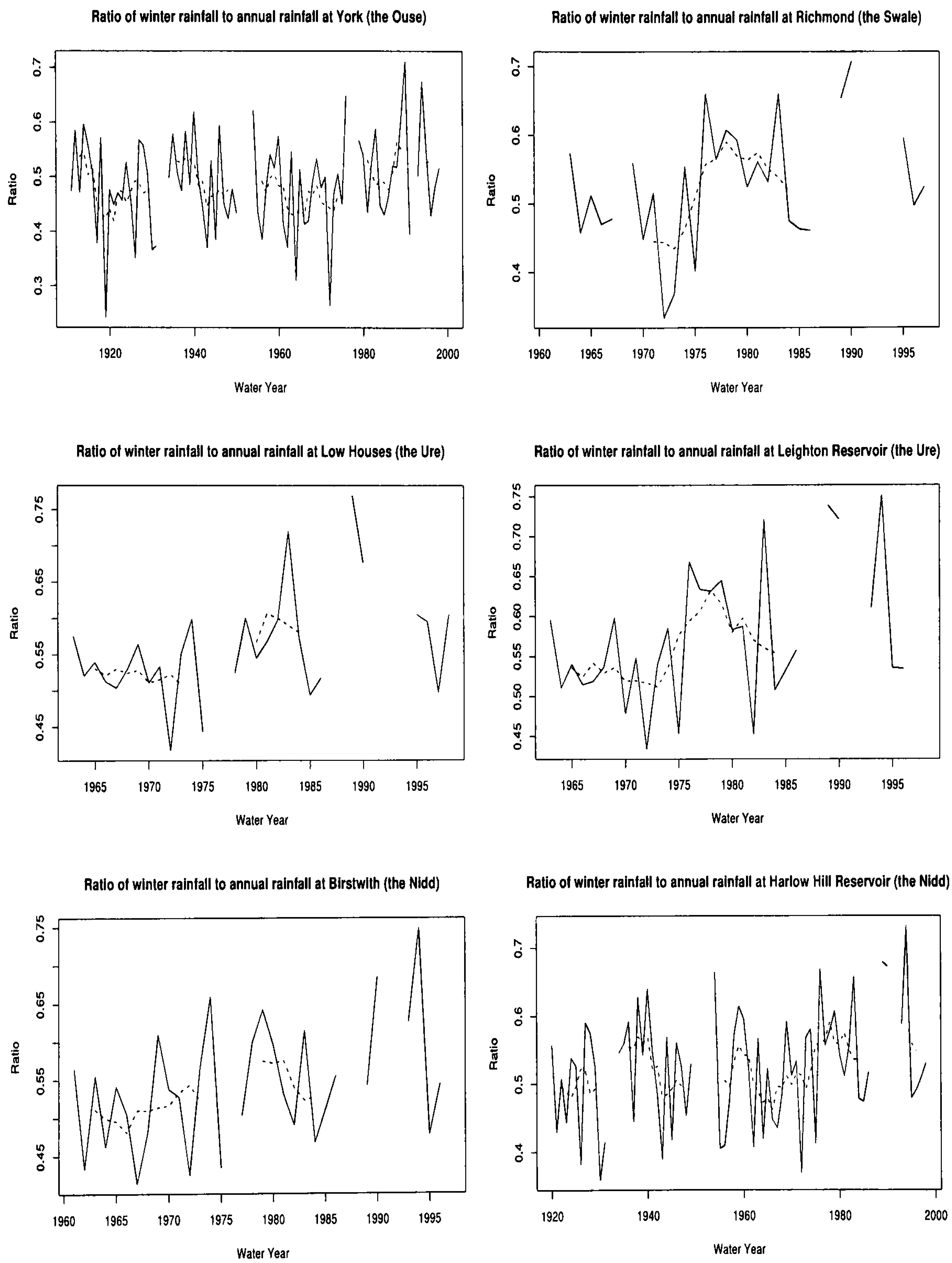


Figure 7.7: Trends over time in the ratio of winter rainfall to annual rainfall in the catchment of the Ouse, the Swale, the Ure, and the Nidd. Solid line: original data; dashed line: smoothing the original data using 5-year moving average. Data source: MIDAS Land Surface Station Data of the British Atmospheric Data Centre.

SNOW AND SNOWMELT

Snow and snowmelt are also factors or catalysts of flooding in this catchment. At higher elevations in the Pennines a significant amount of winter precipitation falls as snow. Snow hence affects the flow of the rivers which drain the area. Flooding in winter might be associated with rain on snow or rapidly thawing snow. Serious floods might come from snowmelt coupled to heavy rainfall.

In Yorkshire, some of the greatest floods have been associated with an extreme rainfall event when there is snow on the ground. As a result, snowmelt is also added to the rainfall for runoff generation in Table 7.1. Snowmelt is a major factor of flooding of the Ure in particular.

7.2.3 Summary

The increasing trends in the maximum value of monthly runoff each year, and in maximum value of daily flow each year suggest an increase over the years in extreme runoff and flow. On the other hand, the annual rainfall in this catchment indicates no increasing trend, even though ratio of winter rainfall to annual rainfall is tending to increase. Flood events in summers of 2000 and 2002 suggest a change of rainfall pattern recently. Since the rainfall pattern does not provide any conclusive evidence of being the driving force of the increasing flood risk in this catchment, the anthropogenic factors associated with economic behaviour (land use) and averting behaviour (hard mitigation and soft mitigation) for flooding need to be investigated. The nature of these anthropogenic factors also affect the feasibility of the TFP system and will be discussed in the following section.

7.3 Checking the prerequisites for implementation of a tradeable flood permit system in the catchment

This section provides a preliminary analysis of the feasibility of applying a TFP system by checking the prerequisites for implementing such as trading system. The check on these prerequisites in the test catchment is conducted through consideration of sub-catchments.

The prerequisites for implementing a TFP system are heterogeneity of geographical and economic characteristics, and the externalities generated by land use and averting behaviour are summarised in Table 7.3. The nature of the externalities and the accessibility of information in the context of prioritising the TraD, the TFR, and the TRiNe permit systems should refer to Table 6.4.

Table 7.3: Prerequisites of adopting a tradeable flood permit system

Prerequisite	**Perspective**
Heterogeneity	geographical and economic characteristics
Externality	land use and averting behaviour

7.3.1 Heterogeneity within the catchment

The heterogeneity of the sub-catchments is examined with respect to their geographical characteristics and their economic characteristics.

GEOGRAPHICAL CHARACTERISTICS

The Ouse, the Swale, the Ure and the Nidd system drains a catchment of approximately $400,000$ hectares. It lies in the eastern part of central England and extends from the high altitude Pennines in the northwest to the lower ground of the Vale of York and the Humber Estuary. Most of the upland area in the Pennines is more than 600 m above sea level while most of the land south of York is less than 20 m above sea level. The Ure and the Swale are principally upstream while the Nidd is a principal tributary of the Ouse which flows south to the Humber Estuary and runs to the North Sea. The difference in height between the upstream areas and the downstream areas results in fast river flow and short lead time for each flood event.

The River Swale rises in the moorlands bordering on Westmoorland. It passes through ravines, valleys, woods and meadows, and finally enters the Vale of York. In its further course it receives the Wiske, Codbeck, and a few smaller streams, and joins the Ure at Myton (GENUKI, 2005). The upstream area of Richmond (S_u) is mainly highland while the downstream area of Richmond (S_d) is mainly residential.

The River Ure has its source in a spring on the summit of a hill (2,186 feet high) on the borders of Westmoorland. It rises in the upland regions of the Pennines and falls through the Yorkshire Dales National Park, the Nidderdale Area of Outstanding Natural Beauty, toward the Vale of York. It joins the Swale to form the Ouse (Halcrow Group Limited, 2001). The upstream area of Ripon

(U_u) is mainly highland while the downstream area of Ripon (U_d) is mainly residential.

The River Nidd starts from the west of Harrogate District and flows through the Nidderdale Area of Outstanding Natural Beauty, and a number of designated Sites of Special Scientific Interest and Conservation Areas. It continues through Nidd Gorge, which separates Harrogate and Knaresborough, and the Green Belt between Harrogate and Knaresborough and a designated Conservation Area located to the south of Knaresborough. The river then continues through agricultural land. In the end it flows into the Vale of York where it meanders east to join the Ouse at Nun Monkton on Harrogate District's boundary (Babtie Brown and Root, 2005). This sub-catchment is relatively small. The steep, narrow profiles of the main and tributary valleys cause the river to rise quickly in response to rainfall. The area upstream of Harrogate (N_u) is mainly highland while the area downstream of Harrogate (N_d) is mainly residential.

The River Ouse has its source to the west of Linton-on-Ouse, at the entry point of the Ure. The Ure and the Swale are the two major tributaries while several other rivers such as the River Derwent and the River Wharfe also flow into the River Ouse to the south of York. The Ouse runs through the Vale of York and becomes tidal below Naburn Weir (Environment Agency, 2004).[3] The area upstream of York (O_u) is mainly residential while the area downstream of York (O_d) is mainly industrial.

[3]Before the construction of Naburn Weir in 1757, the river upstream of Naburn was also affected by tide (Buckham, 1967).

ECONOMIC CHARACTERISTICS

The catchment mainly lies within the administrative areas of North Yorkshire in Yorkshire and Humberside. The economic characteristics mainly relate to land use patterns. Apart from land use, regional GDP is also reviewed to indicate the productivity of this catchment and the potential cost of flood losses.

Problems of catchment management often result from the limitation of administrative boundaries. However, the economic data for analysis mostly needs to be compiled from administrative areas. Hence the interpretation of the data demands caution.

The catchment currently covers seven districts, Craven, Scarborough, Ryedale, Hambleton, Richmondshire, Selby, and Harrogate, and the York City Council area. Prior to 1974, it belonged to the North Riding of Yorkshire. Though it does not exactly match its geographical boundary, the North Riding of Yorkshire (prior to 1974) and (North Yorkshire of) Yorkshire and Humberside (after 1974) represent the administrative boundary of the study area.

GDP contribution

Figure 7.8 shows the contribution to GDP of activities in this study area. There is an increasing trend in GDP per capita over time; GDP contributed by agriculture has fluctuated; it has increased overall at a low rate, but fell in 1997. Manufacturing and service industries contribute significantly more to GDP than agriculture.

Land use change

This catchment supports a variety of land uses from natural land

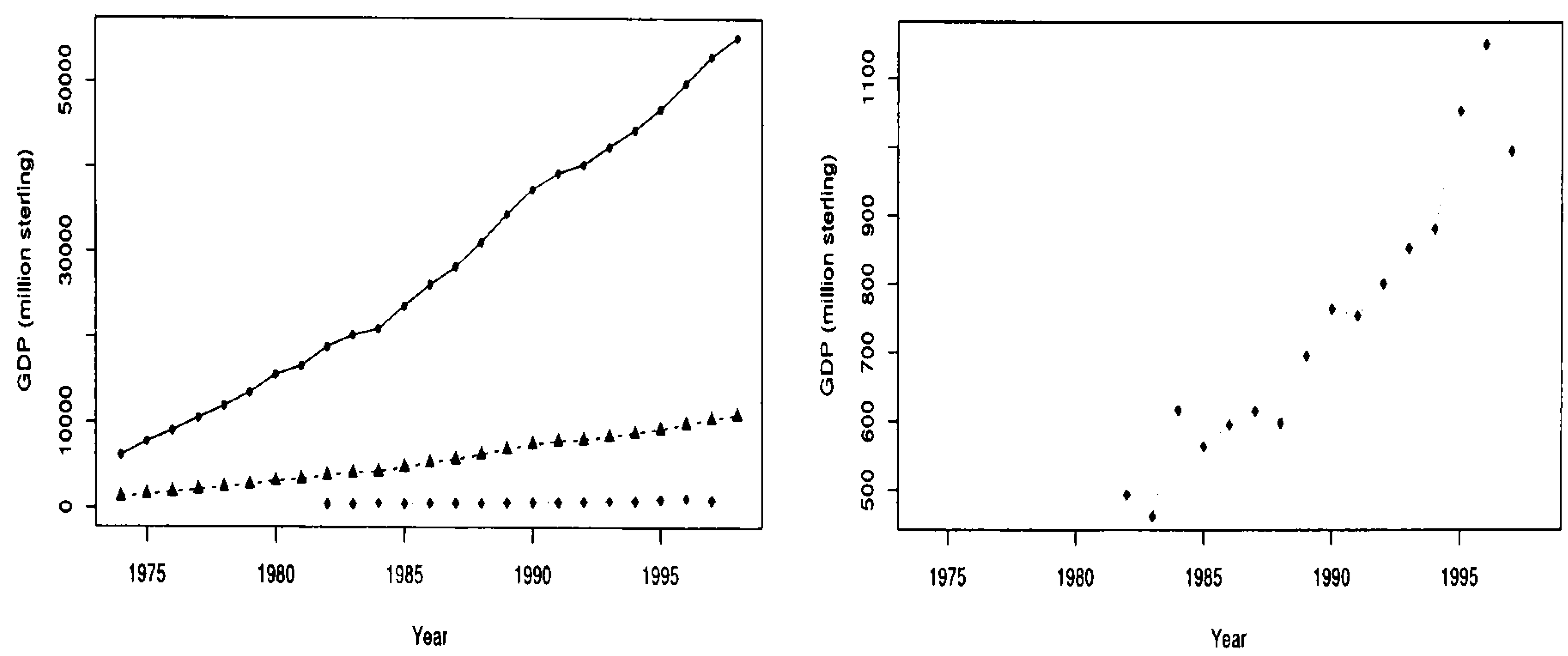


Figure 7.8: Left: GDP, GDP per capita, and GDP contributed by agriculture in the catchment of the Ouse, the Swale, the Ure, and the Nidd; solid line: GDP; dashed line: GDP per capita; dotted line: GDP contributed by agriculture, hunting, forestry and fishing. Right: GDP contributed by agriculture, hunting, forestry and fishing. Data source: Economic and Social Data Service.

(open moorland) through pasture and arable to urban areas. The land use along the Swale, the Ure and the Nidd is mostly rural while that along the Ouse (O_u) is a mixture of intensive agricultural land (such as the Vale of York) and the residential and industrial areas such as York, Selby and satellite settlements like Naburn and Cawood (O_d). Tourism is also an important economic activity in this catchment.

1. Agriculture

In the theoretical model, agricultural land and manufacturing land are represented as 'natural' and 'non-natural' land cover for simplicity. In reality, agricultural land does not guarantee a natural infiltration process. Moreover, the drainage and flood walls which aim at improving agricultural productivity might generate adverse externalities via downstream flood risks.

2. Other industries

Mining has also been an economic feature in this catchment. The Pennines, Yorkshire Dales and Peak District used to have prosperous mining in lead and zinc. Currently, there are three major sand and gravel quarries alongside the Ure at Masham, West Tanfield and Ripon Racecourse. Selby Coalfield on the Ouse has had a long history of prosperous mining.

Industries are mostly located in the downstream areas of York (O_d). Apart from the coalfield, Selby currently has food processing and chemical industries near to the river for both historical transport reasons and because of the ready supply of water. Long Drax Power Station is also located on the Ouse and uses the river for cooling water.

3. Development

The development pressure is generally not great in this catchment. Popular tourist sites such as North Yorkshire Dales and other tourist towns/cities like Ripon and York may have further development that leads to an increase in downstream flood risks. The annual average change from undeveloped land to developed land in Yorkshire and Humberside from 1991 to 2000 is 525 hectares, according to the Office for National Statistics.

7.3.2 Externalities in the catchment

The nature of the externalities is identified below to provide information for the prioritisation of the three permit choices following confirmation of the appropriateness of adopting the permits system.

The reasons for a policy-maker to intervene in flood mitigation and development activities lie in the flood risk externalities between upstream and downstream areas. Flood risk externalities involve flood damage and possible flood-related environmental health problems. The externality of flood damage depends on land use patterns and averting behaviour while that of flood-related environmental health problems depends on water quality.

LAND USE PATTERNS

Over recent decades, a drastic increase in agricultural productivity and the introduction of winter crops in the 1940s to 1950s (after the second world war) led farmers to drain their land, especially for winter crops (refer to Figure 7.9). Flood gates and drainage accordingly were built on a huge scale.

Figure 7.10 illustrates the increasing trend in the arable land and a decreasing trend in fallow land. Permanent grassland, shown in Figure 7.11, has fluctuated over time with a strongly decreasing trend.

Spatially, land use upstream raises three concerns. The first is an increase in drainage. Land-drainage grants given to local land owners in order to encourage them to improve the moors for grouse shooting and sheep grazing by draining the uplands in the 1960s-

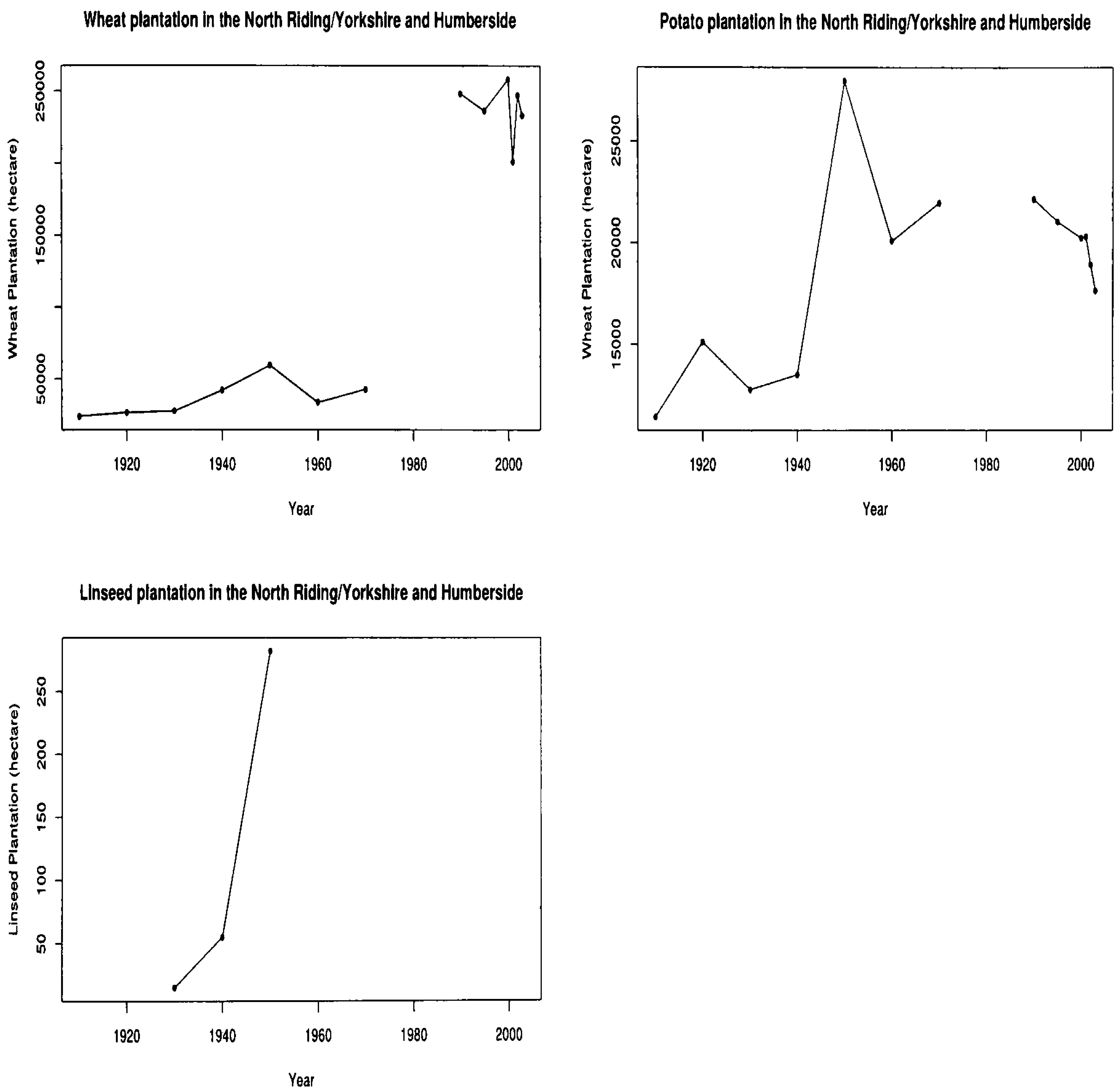
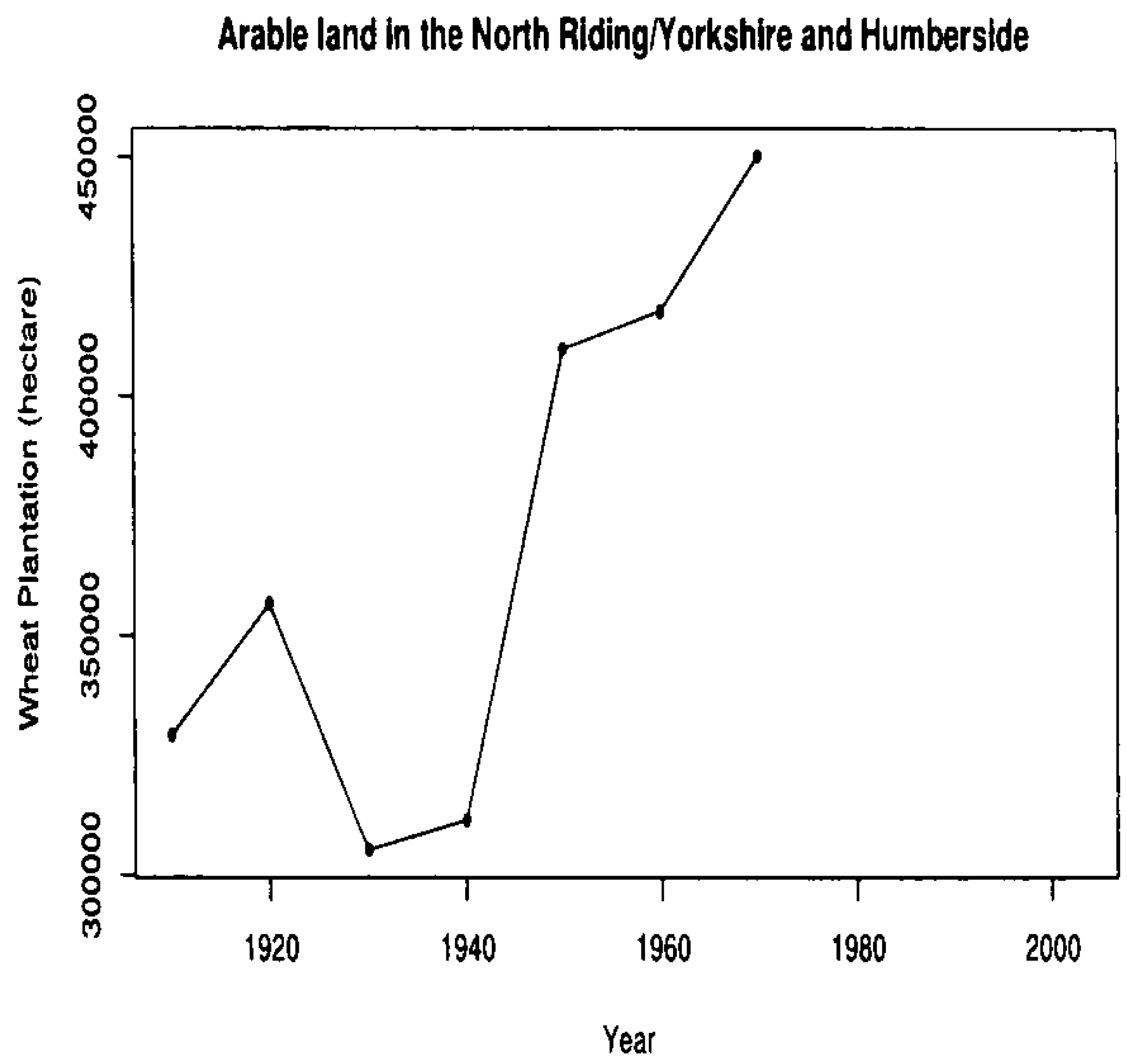


Figure 7.9: Winter crops (wheat, potato, and linseed) in the North Riding of Yorkshire. The data gap is a result of change of administrative boundary in the 1970s. No data is available in the 1980s. Data source: DEFRA Agricultural Census Data.



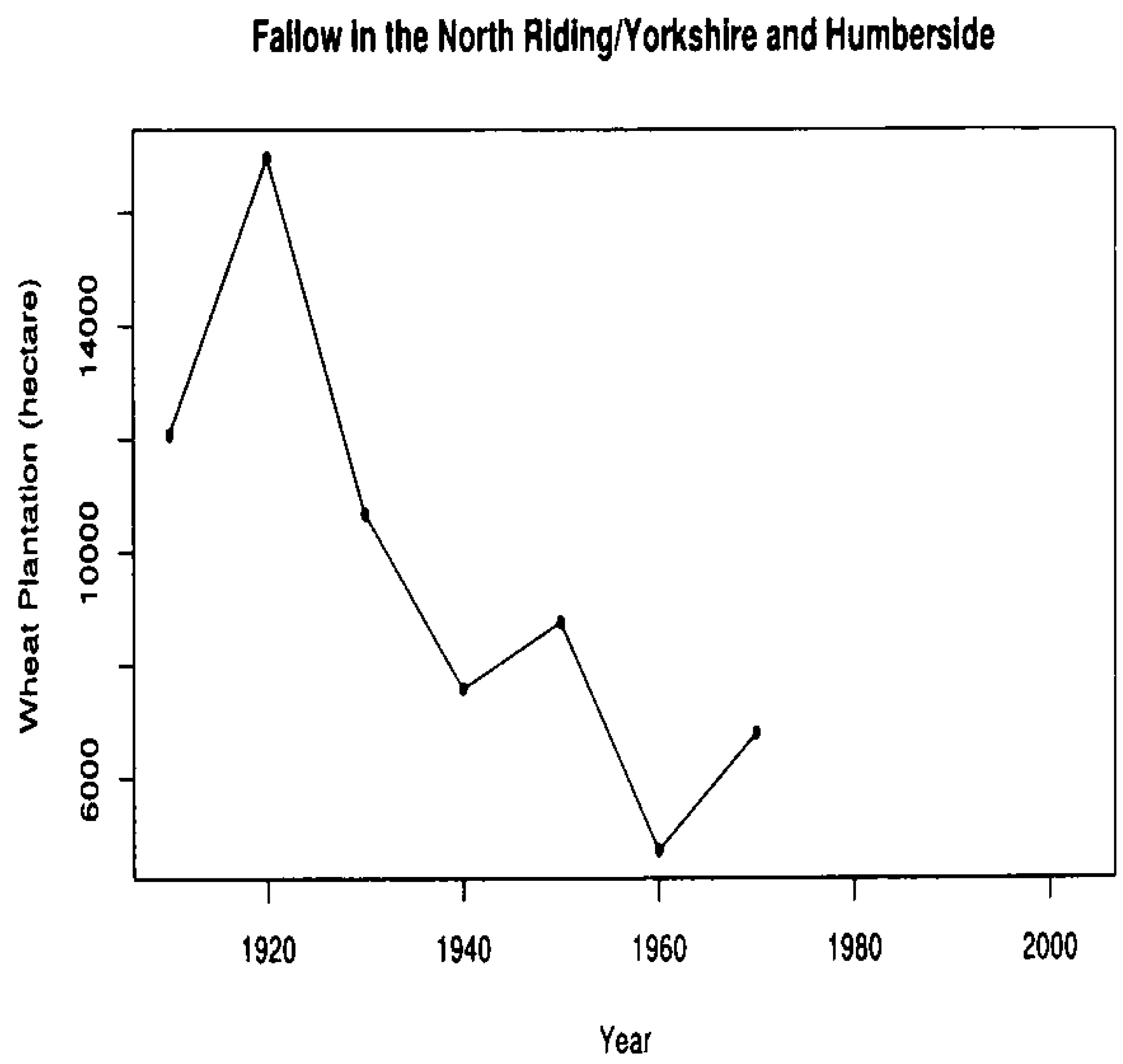


Figure 7.10: Arable land and fallow land in the North Riding of Yorkshire. The data gap was a result of change of administrative boundary in the 1970s. No data is available in the 1980s. Data source: DEFRA Agricultural Census Data.

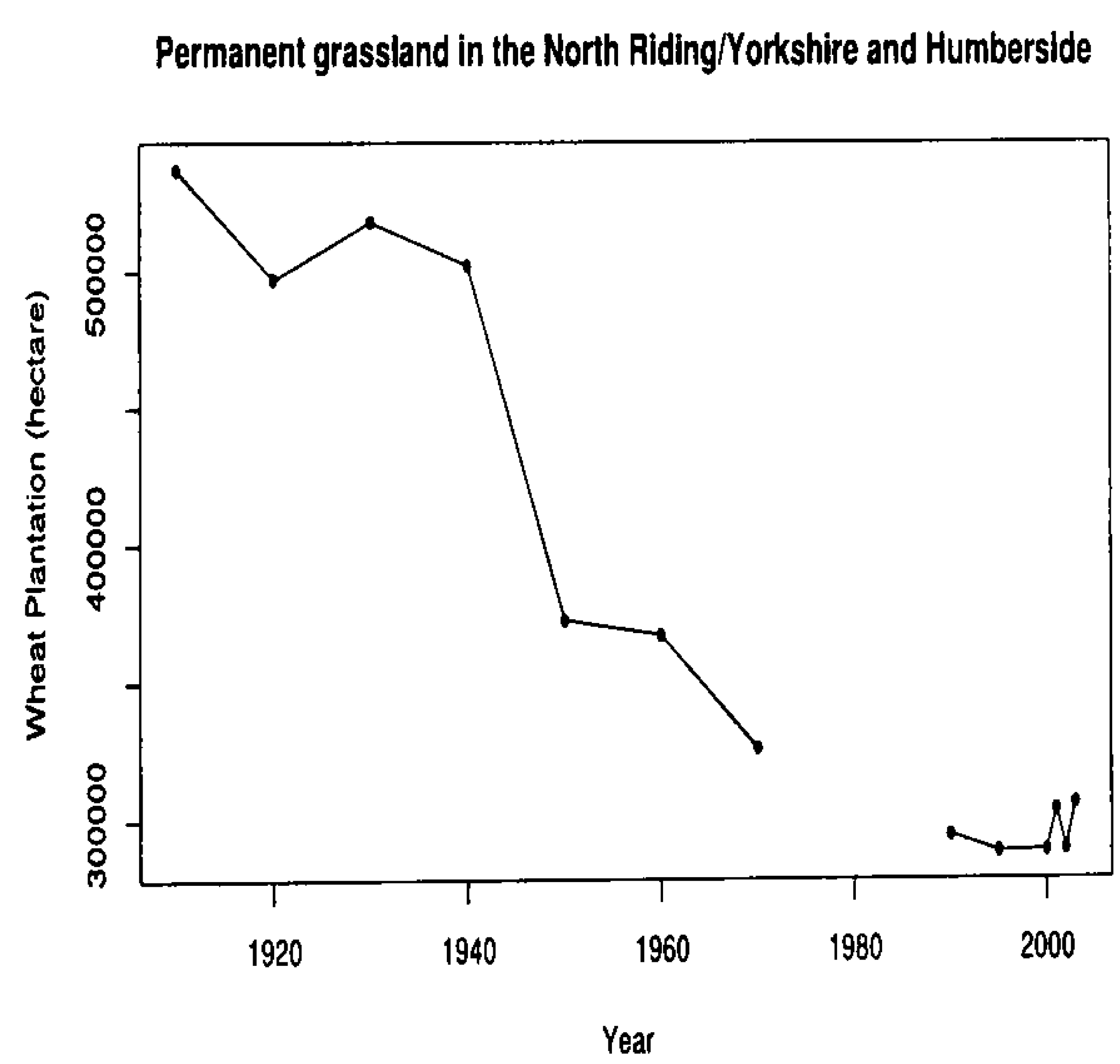


Figure 7.11: Permanent grassland in the North Riding of Yorkshire. The data gap was a result of change of administrative boundary in the 1970s. No data is available in the 1980s. Data source: DEFRA Agricultural Census Data.

1970s played a role in affecting the hydrological characteristics in the catchment. For example, grip drains were dug in the upstream Swale (S_u) and they have allowed rain water to run directly into the Swale. The downstream Swale (S_d) and the Ouse (O_u and O_d) have been affected as a result.

Furthermore, as the moors have dried out, the soil has lost its sponge-like quality so that in terms of high rainfall water poured into the river system raising flood levels way above natural flash flood conditions. Nevertheless, there are few published data to support this proposition. Currently an experiment is being conducted in the catchment of the Wharfe to test this hypothesis (Environment Agency, 2004).

The second problem is overgrazing on the highlands (S_u, U_u and N_u). Overgrazing further reduces the level of vegetation, exacerbating already acute conditions. The number of cattle has been increasing while the number of sheep increased back to its level of the 1930s during the 1960s (refer to Figure 7.12). Both show a decreasing trend after the 1980s. The number of cattle and sheep decreased drastically after the foot and mouth epidemic.

Finally, clear felling of commercial timber plantations in the upstream areas (S_u, U_u and N_u) might also have exacerbated downstream flood risks (S_d, U_d, N_d, O_u, and O_d). Deforestation in this catchment nowadays is not a problem. Instead, forestry plantations have occurred. However, the timing of felling commercial timber can be crucial to the occurrence of a flood event.

Mineral workings in the Ure (U_u and U_d) and the Ouse (O_u and

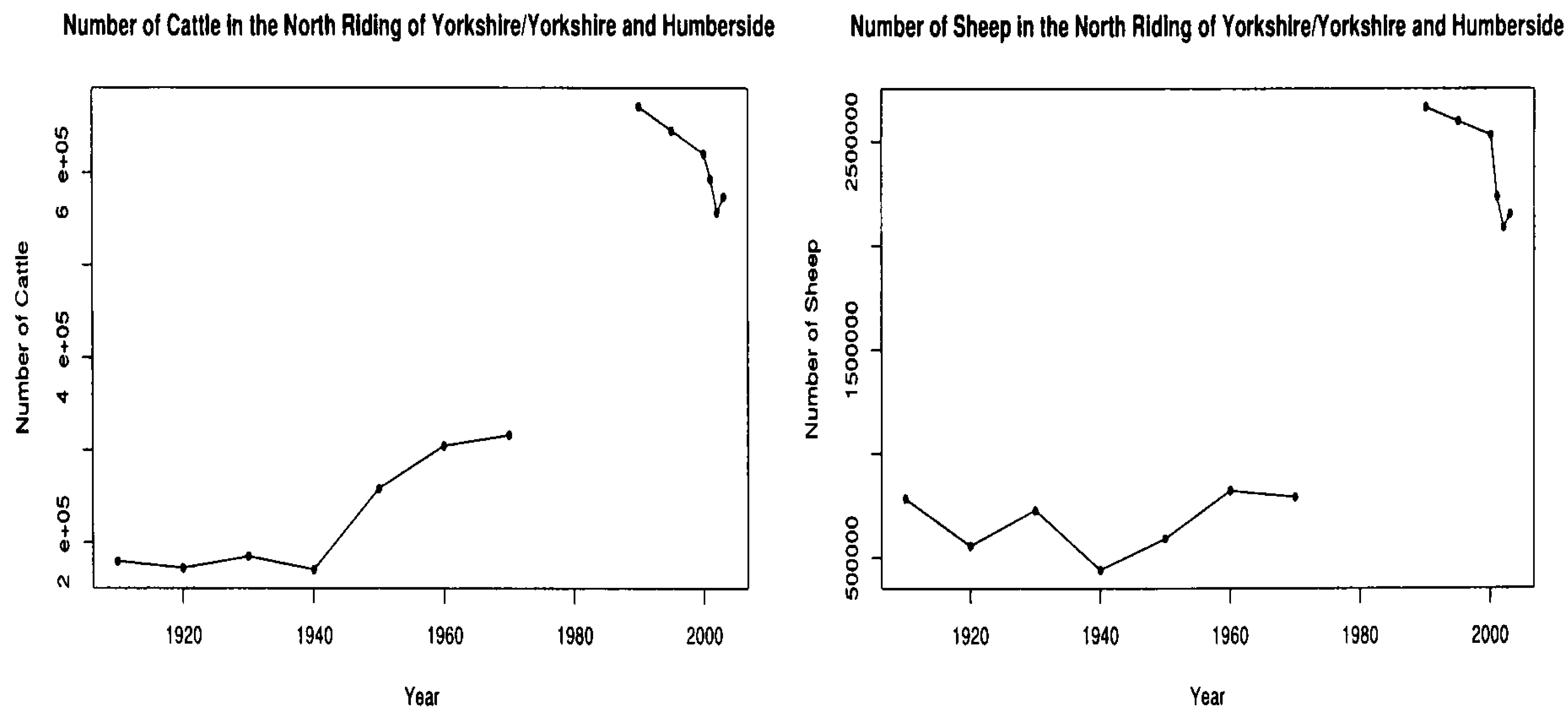


Figure 7.12: Cattle and sheep in the North Riding of Yorkshire. The data gap was a result of change of administrative boundary in the 1970s. No data is available in the 1980s. Data source: DEFRA Agricultural Census Data.

O_d) have four key links to flood events. Firstly, there is potential for sites to be restored to provide off-line flood storage and/or wetland habitat enhancement. Secondly there is the impact of the mine and mining activities on water quality, especially due to flood events. Old mine workings can produce large quantities of acid drainage water containing toxic substances in solution. Heavy rain can give rise to flash floods which cause severe erosion of waste heaps and severe contamination of water courses (Bradshaw and Chadwick, 1980). Thirdly, mining affects the water environment by dewatering or discharges. Fourthly, mining substances can also affect flood defences and their standard of protection, for example, if water is pumped from below ground, or ceases to be used for mineral processing, or streams are dammed to retain water for use when needed.

In summary, an increase in agricultural practice (in terms of grazing, area of winter crops, and drainage) in the 1940s-1950s and its associated effect on flood mitigation in the 1960s-1970s, and an increase in development are probably the causes of a higher likelihood of flooding in this catchment. Changes in other previous and current economic activities such as mining and development also may impose an increasing risk of flooding on the downstream areas.

AVERTING BEHAVIOUR

Averting behaviour undertaken in the study area involves land in both public and private ownership. Local authorities and the Environment Agency in principle are responsible for the flood defences. The Internal Drainage Boards are responsible for general supervision over all aspects of land drainage and for improving aspects of land drainage, including pumping stations, conservation and raising income to support land drainage works.

The record of hard mitigation and soft mitigation is not complete. Not all defence locations are identified, and not all types of flood defence are known (DEFRA, 2001). It is also not easy to date accurately the construction of individual flood mitigation works. There have been two stimuli for the construction of flood defences. One is the occurrence of significant flood events, such as those in 1947, 1982, and 2000 in this catchment (Environment Agency, 2004). The other is the increase in agricultural productivity by introducing winter crops after the second world war.

Hard mitigation

Hard mitigation in this catchment includes drainage, flood defences, reservoirs, and pumping stations. Earth embankments and drainage are prevalent in rural areas while flood walls and pumping stations are common in urban areas.

Reservoirs, often located upstream (U_u and N_u), e.g., Gouthwaite Reservoir on the Nidd, are built for multiple purposes. In spite of regulating water during flooding and drought, they are also used for hydraulic mining (called 'hushing' in the Northern Pennines), ore processing and separating, and to supply the canal network which expanded in the late eighteenth century (Newson, 1992).

Drainage is often installed to 'dry' local land. Each sub-catchment contains drainage works (S_u, S_d, U_u, U_d, N_u, N_d, O_u and O_d). The impact of drainage on soil erosion often results in an increase in downstream flood risks. For instance, moorland gripping (provision of upland drainage channels) was practised extensively in this catchment, and was especially widespread in parts of upper Wensleydale, with the main period of activity in the 1960s to 1970s. It was encouraged by significant grant aid from the Ministry of Agriculture, Fisheries and Food. In some areas the grip channels have become severely eroded and deepened and result in more runoff from rainfall. As these enlarged channels become larger, they are even more efficient at transferring rainfall to a river in the form of runoff. Some residents in Harrogate and York blamed the increase in the upstream drainage of this sort for causing flooding in the 1980s (Rimington, 1982; Robinson, 1990).

Similar adverse externalities occur due to the construction of embankments. Embankments protect arable and urban land from flooding. However, they also delay the use of floodplain storage during events where flood water is passing through houses immediately upstream.

The operation of pumping stations leads water to other places and hence similar adverse externalities might also take place. The dependence on power supply suggests another problem for pumping stations in a flood event. For instance, the efficiency of the Foss Barrier Pumping Station was reduced during the peak of the 2000 flood event because of problems with power supply.

Hard mitigation of this sort is undertaken in each sub-catchment. The conditions of the mitigation works in 2004 in each sub-catchment evaluated by the Environment Agency are summarised in Table 7.4. Those with 'very poor' condition are owned by local Internal Drainage Boards (IDBs). Note that the condition of hard mitigation at the Nidd downstream is relatively poor while that at the Ure downstream is reasonably good. The conditions of hard mitigation for the Ouse upstream and downstream do differ significantly. There is no hard mitigation upstream for the Swale, according to the records.

Soft mitigation

Creation of washlands and control of development are the major strategies of soft mitigation in this catchment. The use of mineral workings for flood storage and agri-environmental schemes for flood alleviation are also options, especially under the consideration of a TFP system.

Washlands are areas of floodplain where water is stored in terms

Table 7.4: Conditions for the mitigation works (hard mitigation) on the upstream and downstream areas of the Ouse, the Swale, the Ure and the Nidd. Courtesy to Ms. Dinan Orr of the Environment Agency at York (2004).

Sub-catchment	**No. of mitigation works**	**Conditions**				
		very good	good	fair	poor	very poor
O_u	36	1	7	23	4	1
O_d	98	1	21	74	2	0
U_u	7	0	1	5	1	0
U_d	37	1	12	21	3	0
S_u	0	0	0	0	0	0
S_d	65	2	10	41	12	0
N_u	8	0	3	4	1	0
N_d	16	0	0	6	8	2

of flood. The principal washlands in this catchment are located at the following places: Myton, Ellenthorpe and Morton on the Swale (S_d); Nunwick (U_u) and Aldborough (U_d) on the Ure; Nun Monkton and Moor Monkton on the Nidd (N_d); Linton (O_u), Clifton (O_u), Middlethorpe (O_d), Kelfield (O_d), Riccall (O_d), Cawood-Wistow Lordship on the Ouse (O_d).

The washlands on the Nidd are in the vicinity of the confluence with the Ouse. They are too far downstream to benefit any significant property or road within the catchment. Instead of benefiting the Nidd, they can have an effect on flood flows in the Ouse.

Development control aims not only to maintain natural ways to mitigate flooding but also to avoid generating new flood risks. For instance, development in an excavated section of the valley side that leads to an increase in flood risks, such as Shaw Mills on the Nidd, should be avoided.

To enforce the developer's responsibility for flooding, Regional Planning Guidance for Yorkshire and the Humber (2001) stressed the need to ensure that new development does not increase the likelihood of flooding, which was stricter than the previous regulation in Policy and Practice for the Protection of Floodplains.

Afforestation is also an option (Environment Agency, 2004) in soft mitigation. Though deforestation on a large scale is not a pressing problem nowadays, restoration of woodlands can aid the retention and delay the release of floodwater, as long as any ploughing at time of planting is not downslope.

Briefly, the recorded downstream hard mitigation was mainly undertaken after the 1947 flood and during the 1980s, while the upstream hard mitigation occurred in the 1940s to 1950s and the 1960s to 1970s. This suggests a possible time lag between the upstream and the downstream averting behaviour. Currently there is intense hard mitigation located in the upstream catchment. Hence, an increase in upstream soft mitigation and a decrease in upstream hard mitigation may be a solution to ameliorate adverse externalities to the downstream catchment.

WATER QUALITY AS AN INDICATOR OF ENVIRONMENTAL HEALTH RISK

There are five primary sources of pollution of concern during flood events. First is sewage or waste water leakage, a point source of pollution. No records of this have been found so far. Sewage treatment works are mostly adjacent to the rivers, and associated with population centres. Hence they should be monitored carefully during flood events. The possible overloading of some works due to influxes of tourists during the peak season needs to be taken into account. Water quality is bad in some places due to the discharge of sewage such as at Oak Beck and Crimple Beck (tributaries of the Nidd), and Masham on the Ure (Halcrow Group Limited, 2001; Babtie Brown and Root, 2005).

Second is another point source of pollution, industrial discharge, including mining. The industrial discharge may be made worse or diluted by flooding. In the Nidd catchment, there are few direct industrial discharges, but those that do exist are generally associated with food processing works. The downstream areas of the River Ouse contain more industries and hence this problem should be cautiously considered.

The third pollution source is non-point source pollution, due to the usage of agricultural chemicals. This is particularly important for catchment areas with primary agricultural land, located in upstream areas.

Fourth, previous mining activities may also affect flood risks, for example via the resurfacing of underground water. The historic lead and zinc mining in the Northern Pennines, Yorkshire Dales and Peak District significantly affect water and sediment quality in downstream areas, and have done for many years (Macklin et al., 1997; Hudson-Edwards et al., 1999).

Fifth, polluted water from landfills is also a concern (Babtie Brown and Root, 2005). Landfills on the catchment of the River Ouse include the industrial waste landfill sites at Drax and British Sugar in York, and smaller household, commercial or industrial waste landfill sites at Barlby, Naburn, Nunthorpe, and York. Hence, concentrations of zinc and cadmium, corresponding to the tributaries associated with mining, should be observed in water quality monitoring.

To further investigate whether these affect the study catchment, the relationship between water quality and river flow is reviewed. The available data on water quality provided by the Environment Agency at York in 2002-3 suggest no critical threat in terms of water chemical quality when river flow is high. The results of correlation tests at each gauging station in Table 7.5 should indicate any potential risk at high flow. All the significant correlations of the concentrations of ammonium, nitrite, and zinc with flow above the 5% significance level are consistently positive while the concentrations of nitrate, magnesium, and calcium consistently negatively corelate with flow. It is well known (Cresser and Edwards, 1987) that calcium and magnesium concentrations fall under high flow conditions in British upland rivers, as water flowing from acidified upper soil horizons makes a greater contribution to river discharge. Both calcium and magnesium are derived largely from mineral weathering, which is more important under base-flow conditions when water drains lower, more mineral-rich soils. This also implies the enhancement effect is dominant for the former three species and the dilution effect is dominant for the later three.

The relationships between ammonium concentraion and discharge, between nitrite concentration and discharge, between nitrate concentration and discharge, and between BOD and discharge are shown in Figures 7.13, 7.14, 7.15, and 7.16.

Table 7.5 shows that the concentration of ammonium is significantly positively correlated to discharge at Topcliffe on the Swale. It also shows that the concentration of nitrite is significantly positively correlated to discharge at Catterick on the Swale, Topcliffe on the Swale, and Middleham/Wensley on the Ure. Both of these species could be associated with sewage works effluent discharge under high flow conditions, possibly when the capacity of treatment works is temporarily exceeded. Main works related to the gauging stations are listed in Table 7.6. BOD (Figure 7.16) also is quite high at high discharge at Topcliffe.

However, there is a significantly negative correlation between the concentration of nitrate and river flow at Catterick on the Swale and Middleham/Wensley on the Ure. This may be for several reasons. When soil is saturated due to high precipitation, the soil conditions may transform from aerobic to anaerobic, leading to denitrification. Secondly, although higher flows occur during autumn and winter periods, when crop uptake of nitrate is much reduced, the dilution effect may be greater, and nitrification rate lower, in winter.

In summary, the heterogeneity of the geographical and economic characteristics, and the occurrence of the externalities in land use and averting behaviour suggest the potential for implementing the

Table 7.5: Correlation between listed variables and flow in the catchment of the Swale, the Ure, the Ouse, and the Nidd. $*$, $**$, and $***$ denote the statical significance at 10% 5% and 1% levels respectively. C(S): Catterick on the Swale. T(S): Topcliffe on the Swale. MW(U): Middleham/Wensley on the Ure. WB(U): Westwick/Borough Bridge on the Ure. SC(O): Skelton/Cawood on the Ouse. SN(O): Skelton/Nether Poppleton on the Ouse. S(N): Skip Bridge on the Nidd. H(N): Hampsthwaite Bridge on the Nidd. Data Source: Environment Agency. Courtesy to Ms. Diana Orr of the Environment Agency at York.

	C(S)	T(S)	MW(U)	WB(U)	SC(O)	SN(O)	S(N)	H(N)
pH	-0.89***	-0.79***	-0.62***	-0.41**	-0.60***	-0.63***	-0.47**	-0.39*
Ammonium	0.23	0.89***	- .01	-0.07	-0.20	-0.11	0.20	0.02
Nitrate	-0.42*	-0.21	-0.59***	-0.17	0.37	-0.06	0.00	-0.14
Nitrite	0.54**	0.85***	0.50**	-0.05	-0.25	-0.20	0.14	-0.15
Magnesium	-0.62**	-0.53***	- 0.59***	-0.38**	-0.70***	-0.90***	-0.44**	-0.67**
Calcium	-0.57**	-0.58***	- 0.65***	-0.42**	-0.71***	-0.92***	-0.43**	-0.66**
Zinc	0.64**	0.68***	0.27	-0.01	-0.23	0.95***	0.76***	0.35*

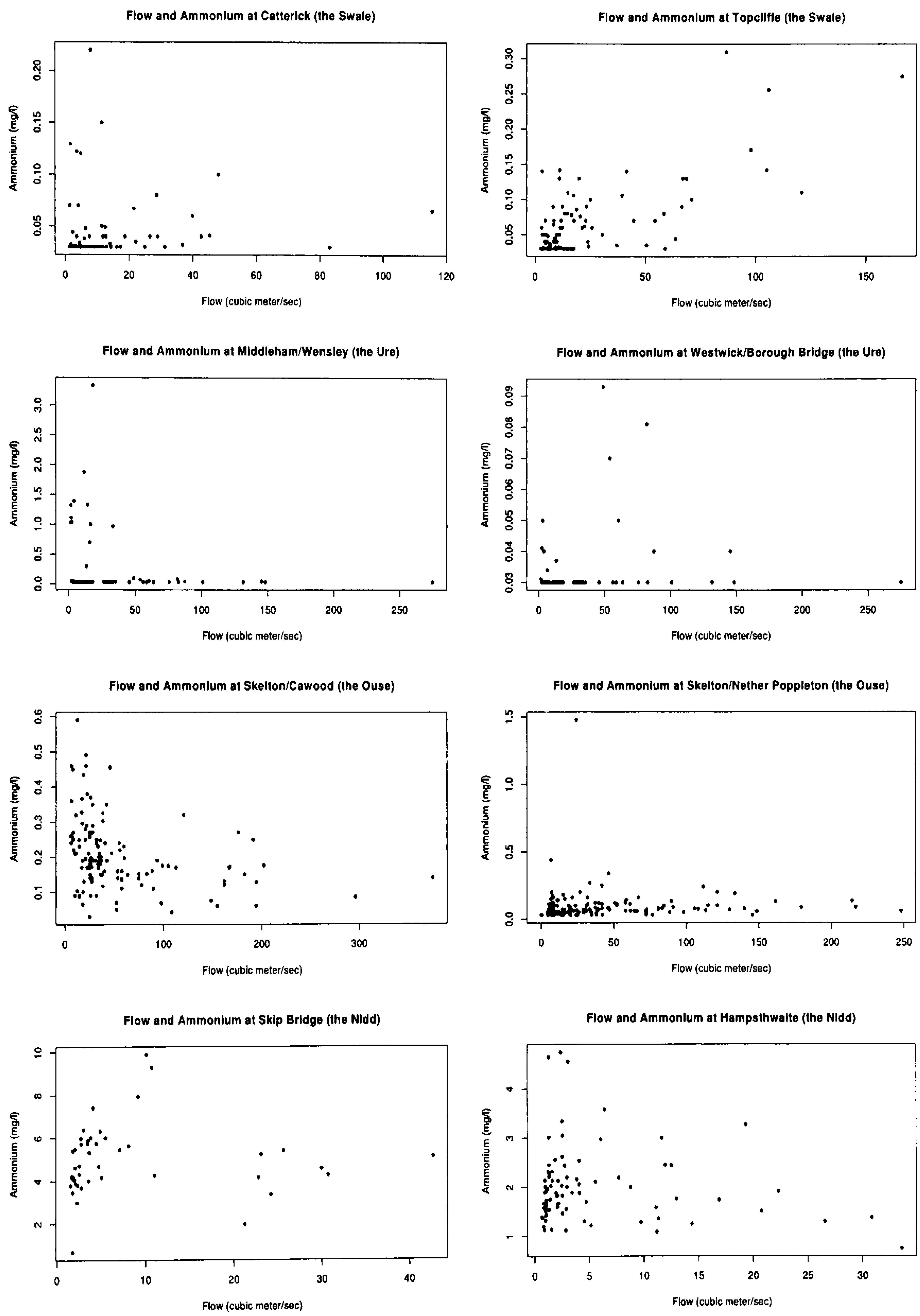


Figure 7.13: Relationships between ammonium concentration and river flow in the catchment of the Ouse, the Swale, the Ure, and the Nidd. Data source: courtesy to Ms. Diana Orr of the Environment Agency at York.

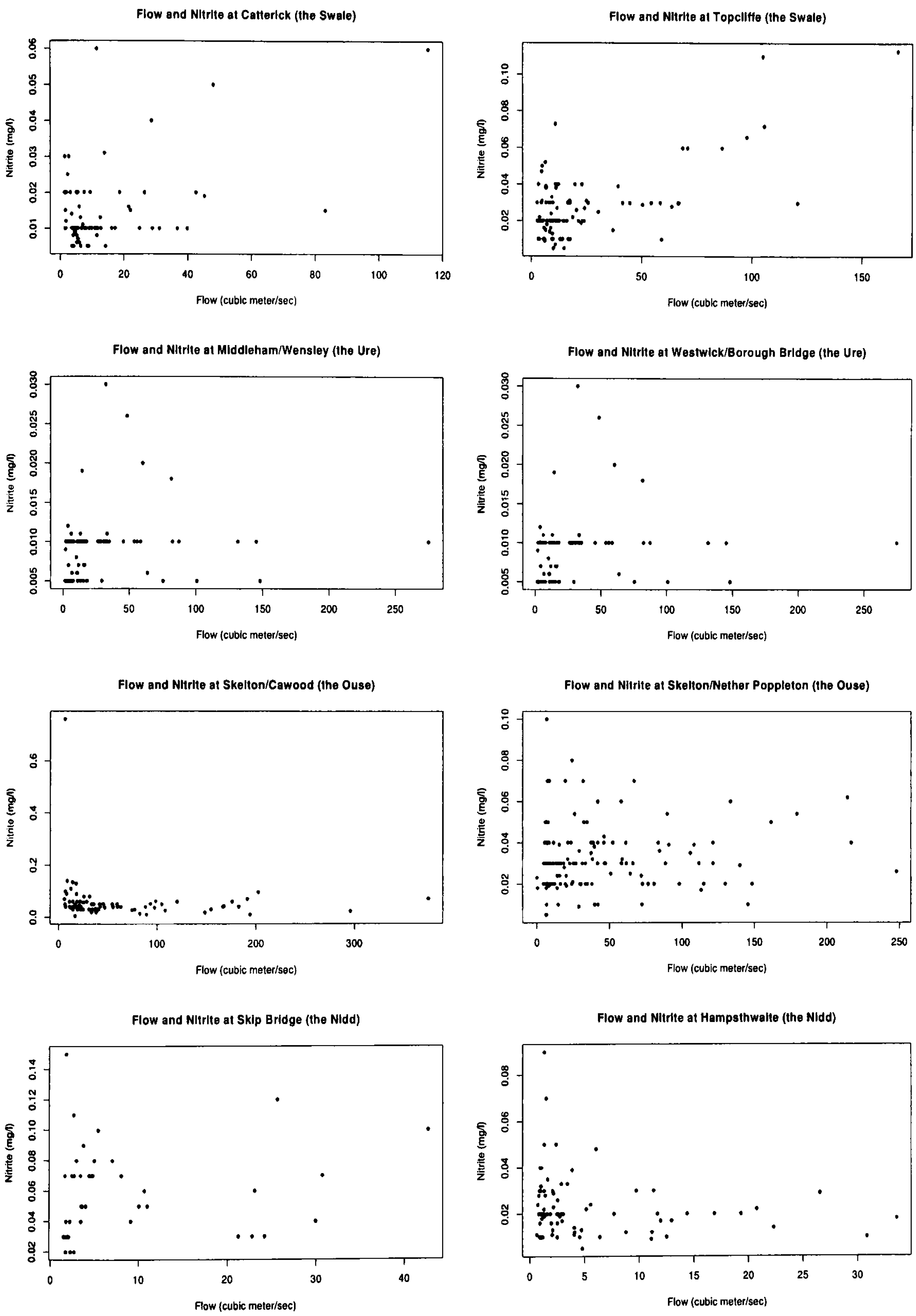


Figure 7.14: Relationships between nitrite concentration and river flow in the catchment of the Ouse, the Swale, the Ure, and the Nidd. Data source: courtesy to Ms. Diana Orr of the Environment Agency at York.

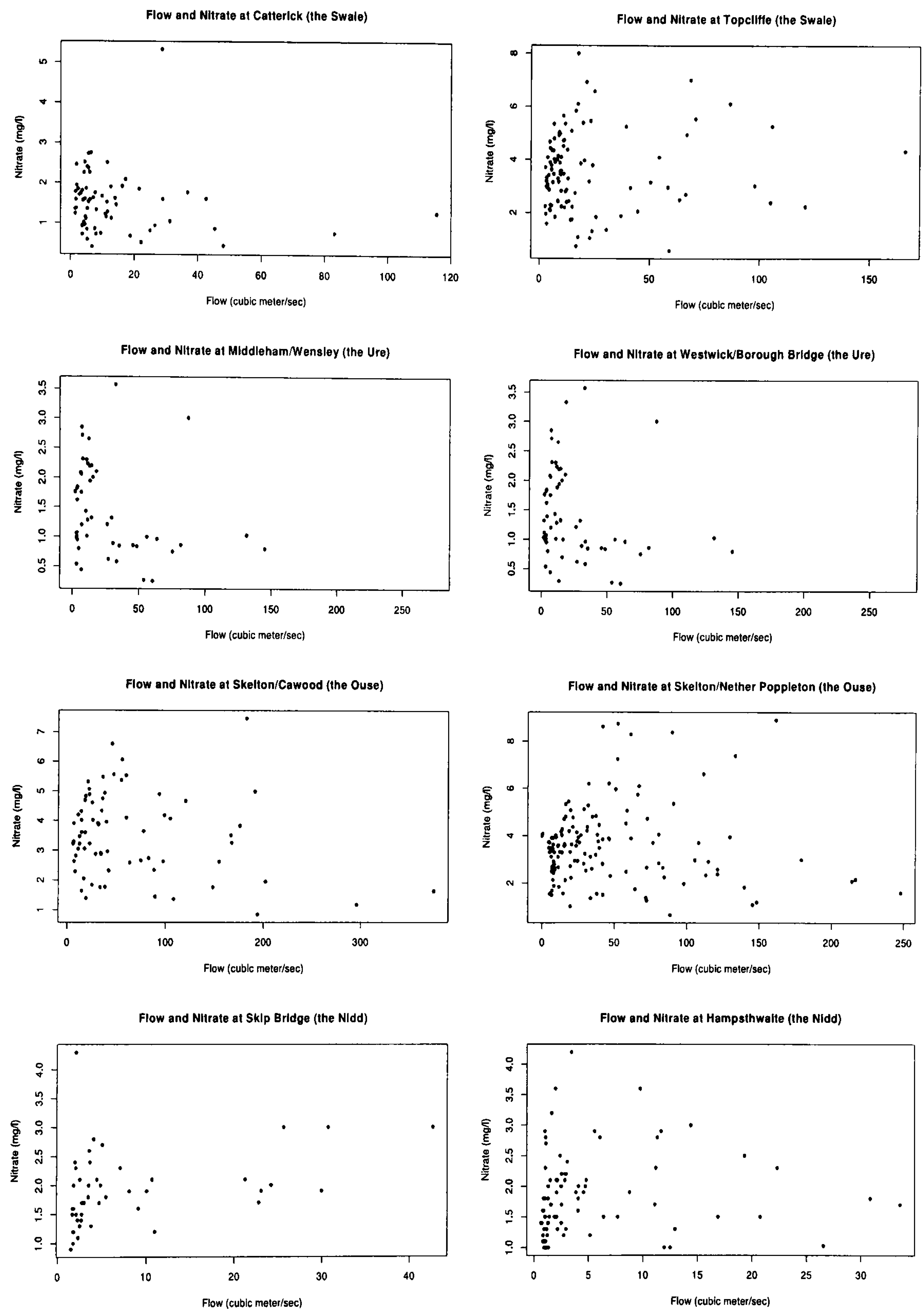


Figure 7.15: Relationships between nitrate concentration and river flow in the catchment of the Ouse, the Swale, the Ure, and the Nidd. Data source: courtesy to Ms. Diana Orr of the Environment Agency at York.

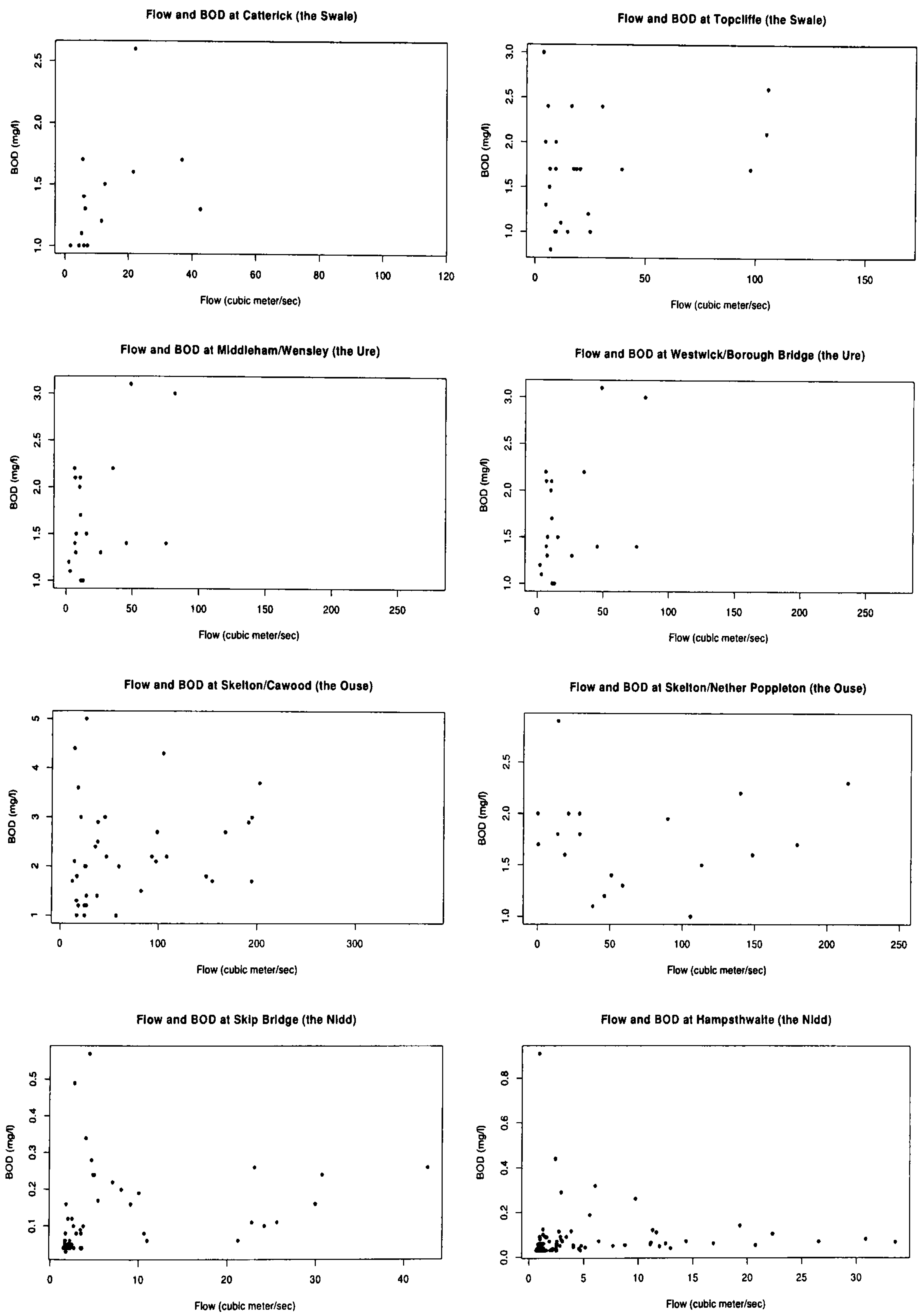


Figure 7.16: Relationships between river flow and BOD in the catchment of the Ouse, the Swale, the Ure, and the Nidd. Courtesy to Ms. Diana Orr of the Environment Agency at York.

Table 7.6: Sewage/waste water treatment works at or at the upstream area of the selected gauging stations

Gauging station	Treatment work	Receiving watercourse
Catterick	Catterick	the Swale
Topcliffe	Skipton	the Swale
Wensley	Wensley	the Wensley Brook
Middleham;Wensley	Witton West	the Ure
Borough Bridge	Borough Bridge	the Ure
Westwick	Skelton-on-Ure	the Ure
Nether Poppleton	Linton-on-Ouse	the Ouse

TFP system (see Table 7.7). The geographical heterogeneity and the externalities provide the physical foundation while the economic heterogeneity gives the financial incentives necessary for the transaction to take place. The nature of the externalities and the accessibility of the related information for each sub-catchment are summarised in Table 7.8, which suggests the choice among three permit systems. Evaluation of water quality at high discharge did not suggest significant sewage overflow contamination in the rivers. The health risk is thus more likely to be associated with backflushing of sewage from local water drains in developed areas themselves.

7.4 Institutional setup for the tradeable flood permit system

Section 7.3 considered whether the conditions that are needed to underpin use of different TFP systems are satisfied. It is argued

Table 7.7: The checklist of adopting the tradeable flood permit system in the Catchment of the Ouse, the Swale, the Ure, and the Nidd

Condition	**The whole catchment**
Heterogeneity in geographical characteristics	√
Heterogeneity in economic characteristics	√
Adverse externality in flood risk	√
Beneficial externality in flood risk	√
Adverse externality in environmental health	√

Table 7.8: The checklist of adopting the TraD, the TFR, and the TRiNe permit systems in the Catchment of the Ouse, the Swale, the Ure, and the Nidd. (H): Hard mitigation is essential; (E): Ecological externalities of hard mitigation are severe; (F): Flood risk externalities of hard mitigation are severe; (S): Soft mitigation is essential; (U): Uncertainty about the marginal cost of hard mitigation.

Condition	$\mathbf{O_u}$	$\mathbf{O_d}$	$\mathbf{S_u}$	$\mathbf{S_d}$	$\mathbf{U_u}$	$\mathbf{U_d}$	$\mathbf{N_u}$	$\mathbf{N_d}$
(H)	√	√		√	√	√	√	√
(E)		√	√		√		√	
(F)	√	√		√		√		√
(S)								
(U)	√	√	√	√	√	√	√	√

that a trading regime is suitable for the Ouse, the Swale, the Ure, and the Nidd, and the sub-catchments of the last three rivers. A trading system may not be effective only in the sub-catchment of the Ouse due to the lower level of heterogeneity between upstream and downstream areas.

This section considers whether the institutional conditions exist and could support a trading system. The economic efficiency of the tradeable permit system depends on participants being able to buy and sell permits relatively easily, with incidental transaction costs at competitive prices. In other words, the number of participants and transactions, the size of transaction costs, and the potential for competitive market are three criteria required to establish a feasible TFP system.

Externalities are generated by soft mitigation, hard mitigation, and development in this catchment, particularly in the upstream areas. Hence transactions that adjust upstream behaviour in exchange for benefits to downstream areas would be expected.

7.4.1 Comparisons among TraD, TFR, and TRiNe permit systems

Table 7.8 indicates that no sub-catchment is ready to adopt the TraD permits system given current conditions. The TRiNe permits system could be applied to the upstream and downstream sub-catchments of each river, especially when flood risk externalities are severe. The TFR permits system suits all upstream and downstream sub-catchments except for the Swale. The economic characteristics of the general catchment indicate that the variety and number of land owners protect against market thinness. Where there are numerous small land owners, either the local authority, the community, or the agricultural/industrial organisation can play a role in negotiation. Moreover, the number of participants, with free entry, can lead to a competitive market. Transaction costs depend predominantly on the design of the trading system.

The TraD system is appropriate only for soft mitigation. Adopting only the TraD system would offer incomplete flood protection unless there were other measures for alleviating externalities generated by hard mitigation.

The TFR system, on the other hand, includes soft and hard mitigation which are both crucial for this catchment. Participants in this system can freely select the ways and locations of mitigation. This property leads to the expansion of the market for permits. Each downstream sub-catchment may purchase soft mitigation from its upstream sub-catchment to reduce the flood risk. Alternatively, it may pay the upstream sub-catchment to decrease the hard mitigation that generates adverse externalities to the downstream sub-catchment. For the Yorkshire Ouse, this applies especially to the Swale, the Ure, and the Nidd, particularly for the first two, larger, sub-catchments.

The TRiNe system is a drastic management method to solve to problems of externalities. It can be considered when the externalities remain problematic.

Overall, there is a potential for land owners (especially farmers) in the upstream sub-catchments to sell soft mitigation to residents and industries in the downstream sub-catchments, especially during winter. Converting upstream hard mitigation to soft mitigation can also be considered by taking the benefits from downstream into account.

7.4.2 Efficiency improvement by the tradeable flood permit system

Current management focuses on the regulation of development combined with subsidies for undertaking soft mitigation and charges for development in some administrative regions. The Environment Agency and local authorities are responsible for flood risk mitigation for the public, while the IDBs are in charge of the mitigation of flood risk in farming regions.

The implementation of a tradeable permit system can save the public investment in hard and soft mitigation, and the subsidies for undertaking soft mitigation. It can also encourage the IDBs to improve the existent mitigation works without the cost of policy enforcement. Current management cost of planned mitigation conversion and that of establishing and maintaining mitigation data can be saved once the trading regime is implemented.

Take the TFR permit for example. Its implementation is expected to bring mitigation conversion from hard mitigation to soft mitigation in the upstream sub-catchments. Research on mitigation conversion in coastal areas often shows improvements. According to Farber and Costanza (1987), a storm defence in the coastal wetlands in Louisiana in the USA is valued between \$1,915 and \$7,549 (American dollars) per acre. The estimated costs of adopting soft mitigation (sum of the benefits from commercial fisheries, fur trapping, and recreation) are relatively low, between \$514 and \$1,428 per acre. King and Lester (1995) estimated that an 80 m wide strip of salt marsh in the UK could result in cost savings of between £300,000 and £600,000 per acre. In this case, there is a bargaining range for the land owner and the authorities responsible for mitigating coastal flood risk.

However, mitigation conversion in riverine areas is more complicated due to the higher land costs. Experience shows that the costs of engineering work are minor compared to land opportunity costs (DEFRA, 2002). Fluvial defence costs £8,400 km/yr (DEFRA/Environment Agency, 2002). To obtain efficiency, soft mitigation can only be undertaken in the places with lower land cost such as agricultural land, rather than residential and industrial areas. Moreover, inclusion of other costs of adopting hard mitigation, e.g., ecological impacts (though there is no common consensus amongst ecologists (DEFRA, 2002)) and sustainability in mitigation is necessary. In this catchment, each upstream sub-catchment is likely to provide soft mitigation to their corresponding downstream sub-catchment. As for which areas can provide soft mitigation to downstream, the information will be revealed once the permit market is established.

Overall, while soft mitigation does indeed involve management at the catchment scale, at the margin a change in the management regime generally involves a single investment/project. In order to consider the temporal and spatial externalities and conduct a complete cost effectiveness analysis of soft and hard mitigation, a broader scope that involves catchment based strategies and long-term perspectives is required.

7.4.3 Institutional setup

The institution for the TFP system needs to be set up. Apart from the current measures to encourage soft mitigation and to restrict development, some other efforts are demanded to launch the TFP system.

First is the information system. Introducing the stakeholders' committee (SC) can enrich the information supplied to the policy-making process. Each individual has the chance to adjust his/her decisions based on the incentives provided. Techniques such as on-line transaction can be applied to organise the huge amount of information and to decrease the transaction costs. The abundant information is also helpful to obtain a competitive equilibrium in the market to gain efficiency.

Second is the incentive system. The incentive system is formed with the permit market. Price can reflect the benefits and costs of the mitigation and development of different locations and actions. Rewards are directly transferred from beneficiaries to those who are adjusting their mitigation or development decisions.

In summary, the TFR permit system is recommended for launching the TFP system in this catchment because of its inclusion of mitigation and development, and the insufficient information on catchment mitigation and the market thickness. Alternatively, the TraD permit system can be adopted with other measures which aim at solving the externalities generated by hard mitigation. However, the administrative cost can be high because there is currently no complete data set which collates all the hard mitigation works in the catchment. Unlike many other places in the world, upstream deforestation is not a crucial problem for this catchment. The externalities are mainly from upstream farming practices and the accordingly hard mitigation. The adoption of the TRiNe permit system is not urgent. It can be adopted when the implementation of the TFR permit system has high effectiveness.

With the consent from the related parties, the SC can facilitate the implementation of the trading system. Additionally, the willingness-to-pay from downstream areas and the willingness-to-accept from upstream areas needs to be researched in order to provide a foundation of establishing the information system.

7.5 Conclusion

The catchment of the Yorkshire Ouse, the Swale, the Ure, and the Nidd provides a promising case of implementing the TFP system because of its geographical and economic heterogeneity and the nature of its externalities. The upstream-downstream externalities lead to the intervention of flood management. Its geographical and hydrological heterogeneity provides the reasons, while its economic heterogeneity indicates the capability and the capacity for implementing the TFP system.

The TFR permit system is recommended for each upstream-downstream sub-catchment except for the Swale. However, the upstream-downstream Swale sub-catchment, as the upstream Ouse, can join the permit market designed for the Ouse. The recommendation is based on the importance of hard mitigation and the insufficient information on mitigation.

Precipitation, though, plays a crucial role in the occurrence and the pattern of flooding, as suggested in other research such as that by Lane (2001). There is no strong evidence of increasing rainfall in this catchment, however. Instead, the increasing frequency of flood events has a strong link to the economic characteristics and averting behaviour. This result provides the foundation for policy intervention.

Tradeable flood permits provide economic incentives to guide the reallocation of mitigation and development under a secured level of the flood risk. Introducing the SC as shown in Chapter 6 can smooth the implementation of the permits system by incorporating related interested parties, bringing together information, and flexibly adjusting rules and objectives. Market initialisation, grandfathering for instance, should also be decided by the SC.

Chapter 8

Conclusion and Policy Recommendations

This thesis considers the problems of flood risk management and lays the groundwork for their solution. The integration of economics and hydrology has been developed for this purpose. The thesis first models the social planner's decisions on flood management, from both static and dynamic perspectives. The related problems of the public good nature of averting behaviour and common property in catchment services were then explored using game theoretical models that incorporate decisions between multiple uses within a catchment. To solve the problem of coordination among local areas, a two-tier decentralised decision-making process that consists of a stakeholders' commitee (SC) and tradeable flood permits (TFP) is introduced. Preliminary analysis of applying this decision-making process was conducted using the Yorkshire Ouse catchment to investigate its feasibility and practicability. The unanswered questions are addressed in the end of this chapter.

8.1 Thesis findings

After pinpointing key issues about flood risk management in Chapter 1, Chapter 2 reviews various measures of averting behaviour and impacts of land use on flood risk. It also formulates the problem of the interaction between flood hazards and economic behaviour. It suggests that land use, mitigation, and adaptation are incorporated as factors in models of the probability of flooding. Both economic and health impacts are considered in estimating flood losses. These reviews address the importance of incorporating both hydrology and economics in flood risk management. Therefore, infiltration theory in hydrology is used to link land use to hard mitigation and the probability of flood occurrence. At the same time, expected utility theory is used to model the collective decision process.

Chapters 3 and 4 present the decision rules for flood risk management in both static and dynamic perspectives, from a social planner's viewpoint. The complementarity between economic development and environmental protection suggests that facilitating the social capacity for coping with flood risks is critical. These results suggest that sufficient wealth and deteriorating environmental health are the driving forces for an economy to undertake averting behaviour.

Chapter 3 uses the expected welfare approach to analyse decisions under uncertainty where there are multiple purposes in flood risk management. Expected welfare links the causes and impacts of flooding and scales welfare by the related environmental risk. The product of the probability of being flood damage free and welfare net of floods involves both substitution and complementarity between environmental and economic functions. Compared with existing studies, this prototype model offers a more comprehensive way for welfare estimation in cases of uncertainty, by including both mitigation and adaptation into decision-making process.

Proposition 3.1 suggests that development will keep increasing (decreasing) while it has positive (negative) marginal impact on the expected welfare. The same logic applies to averting behaviour. Proposition 3.2 holds that by maximising the product of probability of being flood damage free and the welfare net of floods, an economy should increase the former if the latter is high and vice versa. Additionally, when the opportunity cost of hard mitigation is high, the option of soft mitigation or adaptation will be preferable. When the costs of both hard mitigation and adaptation are high, and are accompanied by high levels of development, soft mitigation is favoured.

Chapter 4 stresses the importance of restraining development and increasing investment in averting behaviour due to concerns for the future and for environmental health. Proposition 4.1 suggests that a fall in the discount rate discourages investment in development. Proposition 4.2 suggests when the compulsory ratio of hard mitigation increases, investment in developed land is encouraged. It indicates the complementarity between development and hard mitigation. On the other hand, soft mitigation is encouraged/discouraged by decreasing/increasing the compulsory ratio of hard mitigation.

Because of the spatial interdependence of areas within the catchmetn, such decision rules can mean problems for a whole catchment. These problems are explained, for a decentralised system, in the game theoretical models introduced in Chapter 5. Chapter 5 explores the interplay between multiple institutional decision-makers from multiple regions in a catchment. The theoretic model, based on a supermodular game, shows that externalities take the form of an embankments race and insufficient soft mitigation (over-development). Even though the chapter suggest that incentives for cooperation, such as taxes and subsidies, could improve efficiency, information on the social optimum and the threshold levels is required to design cooperation mechanisms. Hence, Chapter 5 sheds light on scope for integrating the whole catchment into a management scheme.

Instead of centralisation, which involves problems of imperfect information, insufficient incentives, and conflicting interests in flood management, we then consider the development of decentralised measures proposed in Chapter 6. A two-tier decentralised decision-making process that consists of an SC and TFP system is suggested to solve economic inefficiency in flood management. The participatory and multiple-purpose strategies induced accordingly is consistent with the Catchment Flood Management Plans in the UK. Information valuable for management is brought together by incorporating multiple interests within the SC and by introducing the market mechanism of the TFP system. An SC is responsible for determining related targets and rules to improve both efficiency and equity of the management framework. Three types of TFP, the tradeable development permit (TraD), the flood reduction permit (TFR) and the tradeable risk neutral permit (TRiNe), are developed for different institutional conditions, comprising different policy foci and information accessed by the SC.

Chapter 6 illustrates how the SC might work, while Chapter 7 provides a preliminary analysis of the feasibility of applying the TFP system in the catchment of the Yorkshire Ouse. According to Chapter 7, this catchment provides a promising case for the TFP system because of its geographical and economic heterogeneity and nature of its externalities. The research finding suggests that the Environment Agency and Department for Environment, Food and Rural Affairs might consider an SC and the use of the TFP system given the insufficiency of information about mitigation works and the complexity of flood management. For the moment, the TFR system is recommended. Once the problems of externalities become serious, the authority might want to consider the TRiNe system. Further research is therefore worthwhile before reaching detailed policy suggestions.

This thesis shows the problems of centralisation in managing catchment flood risks. To solve the problems, decentralised management, incorporating an SC and TFPs, provides one answer.

8.2 Further Research

In practice, there are quite different hydrological and geographical conditions and residents' preferences in every region. The models and analysis in this thesis provide a basis for policy design in a range of catchments, but detailed research needs to be done before identifying solutions for particular catchments.

For instance, only two sectors were considered in this research for the sake of expository and analytical convenience. In practice, multiple sectors should be incorporated in an empirical model. Moreover, models developed in Chapters 3 to 6 should be estimated for individual cases. The tradeoffs between economic development and environmental risks should reflect the interests and concerns of residents and related groups. However, constrained by the limitations of regional economic data and the insufficiency of data associated with flood mitigation, these tradeoffs were not explained in this thesis.

Besides, to further investigate the feasibility of the SC and TFP system in the Yorkshire Ouse catchment, research aimed at bridging the gap between policy-makers and decision-makers should be conducted. It should be based on surveys of interested parties' willingness to accept the new management systems or farmers' willingness to take up soft mitigation. These would provide more information to facilitate the setup and the operation on the SC and TFP system.

Additionally, the development on the SC and TFP system on flood management is still at an early stage. Bridging knowledge between related natural and social science and system designs, such as applying flood economics, is indispensable to the practicability and the efficiency improvement in application. Furthermore, not only the inclusion of regions, but the integration of different dimensions of natural resources in a catchment using both market-based instruments and the SC might improve the efficiency of environmental management. This is not within the scope of this research however.

Furthermore, applications of the SC and TFP system to other places that have severe flood risk externalities and geographical and economic heterogenity can also be considered. To maintain the efficiency of the collaborative management, regional catchments with previously stated properties are preferred in applying this two-tier decentralised decision-making process in flood management. Applications to large scale catchments, especially transboundary catchments, should be treated with particular caution. The decision process should be able to incorporate representative local interest groups.

Some of the existing guidelines or institutional conditions should also be taken into consideration. The application of TFP system, the role of a catchment in the conservation of biological diversity for instance can be considered. Besides, the legislative background, such as the Town and Country Planning Acts, the European Water Framework Directive, and Catchment Flood Management Plans should also be taken fully into account in the design of related policy.

Finally, the integration of economics and hydrology in the analysis of the hydrological issues such as flood risk management has clear potential but also needs further work. This thesis attempts to blend theory and policy in both disciplines. Furthermore, there is scope for integrated hydrological management that incorporates the hydrological cycle in totality rather than differentiating between floods and droughts.

Appendix A

Deriving the phase diagram in Figure (4.1)

This appendix depicts the process of deriving the phase diagram in Figure (4.1).

M is total extent of developed land while m is the investment in developed land. $\bar{A}$ is the total amount of land. δ_m is the depreciation rate of developed land. The costate variable μ_m denotes the marginal shadow value of the developed land. σ is the social rate of time preference. $EW = \left(1 - \left(M/\bar{A}\right)\right)^a \left(P(M+m)\right)^b$ where $0 < a, b < 1$.

Suppose $F = 0$ and $G = 0$ denote the curves of $\dot{M} = 0$ and $\dot{m} = 0$, the motion of $M = 0$ and that of $m = 0$. Equation 4.3c shows that $\frac{\partial H}{\partial \mu_m} = \dot{M} = m - \delta_m \cdot M$. Equation 4.4 shows that $\dot{m} = 0$ when $EW'_M + (\sigma + \delta_m) \cdot EW'_m = EW''_{mM} \cdot m$, which is $(\sigma + \delta_m) + (M + (1-b)m)\left(\frac{b}{M} - \frac{a}{\bar{A} - M}\right) = 0$.

At the steady state,

$$F = m - \delta_m M = 0$$

$$G = (\sigma + \delta_m) + (M + (1-b)m)\left(\frac{b}{M} - \frac{a}{\bar{A} - M}\right) = 0$$

The slopes of the stationary isoclines are given by:

$$\frac{dm}{dM}|_{\dot{M}=0} = -\frac{\partial F/\partial M}{\partial F/\partial m} = -\frac{F'_M}{F'_m} = -\frac{-\delta_m}{1} = \delta_m > 0 \tag{A.1a}$$

$$\begin{aligned} \frac{dm}{dM}|_{\dot{m}=0} &= -\frac{\partial G/\partial M}{\partial G/\partial m} = -\frac{G'_M}{G'_m} \\ &= -\frac{-\left(\frac{b}{M^2} + \frac{a}{\left(\bar{A}-M\right)^2}\right)m}{\frac{b}{M} - \frac{a}{\left(\bar{A}-M\right)}} \\ &\gtreqless 0 \text{ when } \frac{b}{M} - \frac{a}{\left(\bar{A}-M\right)} \gtreqless 0 \end{aligned} \tag{A.1b}$$

Since there is only one steady state equilibrium in this system, we do not need to be bothered about the complicated shape of curve $\dot{m} = 0$. We know that $EW'_M < 0$ at the steady state, so $\frac{b}{M} - \frac{a}{\left(\bar{A}-M\right)} < 0$. Therefore, the slope of the curve $\dot{m} = 0$ around the steady state is negative.

The slope of the function F, $\frac{dm}{dM}|_{\dot{M}=0}$, is positive and equal the depreciation rate of manufacturing land δ_m. The slope of function G, $\frac{dm}{dM}|_{\dot{m}=0}$ is positive (negative) while $G'_m < 0$. $F'_M < 0$ implies we happen to have $M' > 0$ ($M' < 0$) to the left (right) of the $M' = 0$ curve; hence the plus (minus) signs on the left (right) of that curve. Analogously, $G'_m < 0$, around the steady state, implies as we move continuously from north to south, m' steadily increases. We have $m' < 0$ above the curve $m' = 0$ and $m' > 0$ below the curve $m' = 0$. Therefore, the equilibrium is a saddle point with two saddle paths.

Appendix **B**

Estimation Results of the Trend in the Annual Maximum of Monthly Runoff

This appendix summarises the estimation results of the trend in the annual maximum of monthly runoff at the selected gauging stations.

1. Skelton

Ordinary least squares regression Weighting variable = none

Dep. var. = FS Mean= 102.5000000 , S.D.= 28.11521861

Model size: Observations = 30, Parameters = 2, Deg.Fr.= 28

Residuals: Sum of squares= 18081.16821 , Std.Dev.= 25.41173

Fit: R-squared= .211239, Adjusted R-squared = .18307

Model test: F[1, 28] = 7.50, Prob value = .01061

Diagnostic: Log-L = -138.5896, Restricted(b=0) Log-L = -142.1490

LogAmemiyaPrCrt.= 6.535, Akaike Info. Crt.= 9.373

Autocorrel: Durbin-Watson Statistic = 1.74409, Rho = .12796

Variable	Coefficient	Standard Error	t-ratio	$P[\|T\| > t]$	Mean of X
Constant	80.74527890	9.1999190	8.777	.0000	
T	1.345652851	.49140548	2.738	.0106	16.166667

2. Gouthwaite Reservoir

Ordinary least squares regression Weighting variable = none

Dep. var. = FG Mean= 167.2111250 , S.D.= 55.56434222

Model size: Observations = 56, Parameters = 2, Deg.Fr.= 54

Residuals: Sum of squares= 157299.8508 , Std.Dev.= 53.97185

Fit: R-squared= .073654, Adjusted R-squared = .05650

Model test: F[1, 54] = 4.29, Prob value = .04305

Diagnostic: Log-L = -301.7962, Restricted(b=0) Log-L = -303.9384

LogAmemiyaPrCrt.= 8.012, Akaike Info. Crt.= 10.850

Autocorrel: Durbin-Watson Statistic = 1.69767, Rho = .15116

Variable	Coefficient	Standard Error	t-ratio	$P[\|T\| > t]$	Mean of X
Constant	136.7510502	16.374143	8.352	.0000	
T	.8398641996	.40532266	2.072	.0430	36.267857

3. Crakehill

Ordinary least squares regression Weighting variable = none

Dep. var. = FC Mean= 93.75980435 , S.D.= 30.98440193

Model size: Observations = 46, Parameters = 2, Deg.Fr.= 44

Residuals: Sum of squares= 33720.31513 , Std.Dev.= 27.68340

Fit: R-squared= .219464, Adjusted R-squared = .20172

Model test: F[1, 44] = 12.37, Prob value = .00103

Diagnostic: Log-L = -217.0071, Restricted(b=0) Log-L = -222.7059

LogAmemiyaPrCrt.= 6.684, Akaike Info. Crt.= 9.522

Autocorrel: Durbin-Watson Statistic = 1.41629, Rho = .29185

Variable	Coefficient	Standard Error	t-ratio	$P[\|T\| > t]$	Mean of X
Constant	68.34682899	8.2983314	8.236	.0000	
T	1.081403207	.30745106	3.517	.0010	23.500000

4. Hunsingore Weir

Ordinary least squares regression Weighting variable = none

Dep. var. = FH Mean= 111.6481075 , S.D.= 34.57922345

Model size: Observations = 57, Parameters = 2, Deg.Fr.= 55

Residuals: Sum of squares= 65306.14482 , Std.Dev.= 34.45845

Fit: R-squared= .024706, Adjusted R-squared = .00697

Model test: F[1, 55] = 1.39, Prob value = .24294

Diagnostic: Log-L = -281.6275, Restricted(b=0) Log-L = -282.3405

LogAmemiyaPrCrt.= 7.114, Akaike Info. Crt.= 9.952

Autocorrel: Durbin-Watson Statistic = 1.73986, Rho = .13007

Variable	Coefficient	Standard Error	t-ratio	$P[\|T\| > t]$	Mean of X
Constant	100.6329621	10.388348	9.687	.0000	
T	.2947714967	.24972994	1.180	.2429	37.368421

5. Kilgram Bridge

Ordinary least squares regression Weighting variable = none

Dep. var. = FK Mean= 208.9240544 , S.D.= 51.61349640

Model size: Observations = 35, Parameters = 2, Deg.Fr.= 33

Residuals: Sum of squares= 67234.50377 , Std.Dev.= 45.13767

Fit: R-squared= .257688, Adjusted R-squared = .23519

Model test: F[1, 33] = 11.46, Prob value = .00185

Diagnostic: Log-L = -181.9732, Restricted(b=0) Log-L = -187.1880

LogAmemiyaPrCrt.= 7.675, Akaike Info. Crt.= 10.513

Autocorrel: Durbin-Watson Statistic = 1.90230, Rho = .04885

Variable	Coefficient	Standard Error	t-ratio	$P[\|T\| > t]$	Mean of X
Constant	83.63548381	37.795096	2.213	.0339	
T	2.556909603	.75544878	3.385	.0019	49.000000

6. Richmond

Ordinary least squares regression Weighting variable = none

Dep. var. = FR Mean= 171.7924416 , S.D.= 46.09463165

Model size: Observations = 19, Parameters = 2, Deg.Fr.= 17

Residuals: Sum of squares= 35289.52546 , Std.Dev.= 45.56155

Fit: R-squared= .077274, Adjusted R-squared = .02300

Model test: F[1, 17] = 1.42, Prob value = .24919

Diagnostic: Log-L = -98.4654, Restricted(b=0) Log-L = -99.2294

LogAmemiyaPrCrt.= 7.738, Akaike Info. Crt.= 10.575

Autocorrel: Durbin-Watson Statistic = 1.75283, Rho = .12358

Variable	Coefficient	Standard Error	t-ratio	$P[\lvert T\rvert > t]$	Mean of X
Constant	194.5626351	21.758688	8.942	.0000	
T	-2.277019345	1.9083631	-1.193	.2492	10.000000

Appendix C

Estimation Results of the Trend in the Annual Maximum of Daily Flow

This appendix summarises the estimation results of the trend in the annual maximum of daily flow at the selected gauging stations.

1. Skelton

Ordinary least squares regression Weighting variable = none

Dep. var. = FS Mean= 388.2532258 , S.D.= 215.9826307

Model size: Observations = 31, Parameters = 2, Deg.Fr.= 29

Residuals: Sum of squares= 1094096.758 , Std.Dev.= 194.23562

Fit: R-squared= .218198, Adjusted R-squared = .19124

Model test: F[1, 29] = 8.09, Prob value = .00807

Diagnostic: Log-L = -206.2946, Restricted(b=0) Log-L = -210.1100

LogAmemiyaPrCrt.= 10.601, Akaike Info. Crt.= 13.438

Autocorrel: Durbin-Watson Statistic = 1.14657, Rho = .42671

Variable	Coefficient	Standard Error	t-ratio	$P[\lvert T \rvert > t]$	Mean of X
Constant	213.9241772	70.511158	3.034	.0051	
T	10.76533965	3.7840063	2.845	.0081	16.193548

2. Kilgram Bridge

Ordinary least squares regression Weighting variable = none

Dep. var. = FK Mean= 245.1146129 , S.D.= 55.63666484

Model size: Observations = 31, Parameters = 2, Deg.Fr.= 29

Residuals: Sum of squares= 81892.83359 , Std.Dev.= 53.14029

Fit: R-squared= .118134, Adjusted R-squared = .08773

Model test: F[1, 29] = 3.88, Prob value = .05834

Diagnostic: Log-L = -166.1144, Restricted(b=0) Log-L = -168.0630

LogAmemiyaPrCrt.= 8.008, Akaike Info. Crt.= 10.846

Autocorrel: Durbin-Watson Statistic = 2.54726, Rho = -.27363

Variable	Coefficient	Standard Error	t-ratio	$P[\lvert T \rvert > t]$	Mean of X
Constant	211.4631613	19.559950	10.811	.0000	
T	2.103215726	1.0670828	1.971	.0583	16.000000

3. Hunsingore Weir

Ordinary least squares regression Weighting variable = none

Dep. var. = FH Mean= 90.91932759 , S.D.= 46.77103407

Model size: Observations = 58, Parameters = 2, Deg.Fr.= 56

Residuals: Sum of squares= 116063.4422 , Std.Dev.= 45.52539

Fit: R-squared= .069178, Adjusted R-squared = .05256

Model test: F[1, 56] = 4.16, Prob value = .04607

Diagnostic: Log-L = -302.7405, Restricted(b=0) Log-L = -304.8194

LogAmemiyaPrCrt.= 7.670, Akaike Info. Crt.= 10.508

Autocorrel: Durbin-Watson Statistic = 1.82939, Rho = .08530

Variable	Coefficient	Standard Error	t-ratio	$P[\|T\| > t]$	Mean of X
Constant	66.88762179	13.209800	5.063	.0000	
T	.6534641052	.32031487	2.040	.0461	36.775862

4. Crakehill

Ordinary least squares regression Weighting variable = none

Dep. var. = FC Mean= 193.2318636 , S.D.= 31.15949818

Model size: Observations = 22, Parameters = 2, Deg.Fr.= 20

Residuals: Sum of squares= 16559.51931 , Std.Dev.= 28.77457

Fit: R-squared= .187829, Adjusted R-squared = .14722

Model test: F[1, 20] = 4.63, Prob value = .04391

Diagnostic: Log-L = -104.0771, Restricted(b=0) Log-L = -106.3655

LogAmemiyaPrCrt.= 6.806, Akaike Info. Crt.= 9.643

Autocorrel: Durbin-Watson Statistic = 2.38285, Rho = -.19142

Variable	Coefficient	Standard Error	t-ratio	$P[\|T\| > t]$	Mean of X
Constant	169.3160649	12.700158	13.332	.0000	
T	2.079634670	.96697352	2.151	.0439	11.500000

Appendix D

Estimation Results of the Trend in Rainfall Patterns

This appendix summarises the estimation results of the trend in the annual rainfall and the ratio of winter rainfall to annual rainfall at the selected gauging stations.

1. York

Annual rainfall:

Ordinary least squares regression Weighting variable = none

Dep. var. = RY Mean= 617.8802469 , S.D.= 109.0444524

Model size: Observations = 81, Parameters = 2, Deg.Fr.= 79

Residuals: Sum of squares= 936739.7395 , Std.Dev.= 108.89199

Fit: R-squared= .015259, Adjusted R-squared = .00279

Model test: F[1, 79] = 1.22, Prob value = .27190

Diagnostic: Log-L = -493.8403, Restricted(b=0) Log-L = -494.4631

LogAmemiyaPrCrt.= 9.405, Akaike Info. Crt.= 12.243

Autocorrel: Durbin-Watson Statistic = 1.52848, Rho = .23576

Variable	Coefficient	Standard Error	t-ratio	$P[\|T\| > t]$	Mean of X
Constant	640.7448079	23.946612	26.757	.0000	
T	-.5118931571	.46265443	-1.106	.2719	44.666667

Ratio of winter rainfall to annual rainfall:

Ordinary least squares regression Weighting variable = none

Dep. var. = RRY Mean= .4885554341 , S.D.= .8624481528E-01

Model size: Observations = 80, Parameters = 2, Deg.Fr.= 78

Residuals: Sum of squares= .5788646119 , Std.Dev.= .08615

Fit: R-squared= .014892, Adjusted R-squared = .00226

Model test: F[1, 78] = 1.18, Prob value = .28088

Diagnostic: Log-L = 83.6334, Restricted(b=0) Log-L = 83.0333

LogAmemiyaPrCrt.= -4.879, Akaike Info. Crt.= -2.041

Autocorrel: Durbin-Watson Statistic = 2.10017, Rho = -.05009

Variable	Coefficient	Standard Error	t-ratio	$P[\|T\| > t]$	Mean of X
Constant	.4706891681	.19065136E-01	24.688	.0000	
T	.4051307469E-03	.37309178E-03	1.086	.2809	44.100000

2. Richmond

Annual rainfall:

Ordinary least squares regression Weighting variable = none

Dep. var. = RR Mean= 770.9000000 , S.D.= 112.7488201

Model size: Observations = 29, Parameters = 2, Deg.Fr.= 27

Residuals: Sum of squares= 351000.6729 , Std.Dev.= 114.01765

Fit: R-squared= .013889, Adjusted R-squared = -.02263

Model test: F[1, 27] = .38, Prob value = .54262

Diagnostic: Log-L = -177.4673, Restricted(b=0) Log-L = -177.6701

LogAmemiyaPrCrt.= 9.539, Akaike Info. Crt.= 12.377

Autocorrel: Durbin-Watson Statistic = 1.04907, Rho = .47547

Variable	Coefficient	Standard Error	t-ratio	$P[\|T\| > t]$	Mean of X
Constant	793.9095412	42.901255	18.506	.0000	
T	-1.313536803	2.1300583	-.617	.5426	17.517241

Ratio of winter rainfall to annual rainfall:

Ordinary least squares regression Weighting variable = none

Dep. var. = RRR Mean= .5261827528 , S.D.= .8736123281E-01

Model size: Observations = 29, Parameters = 2, Deg.Fr.= 27

Residuals: Sum of squares= .1908544531 , Std.Dev.= .08408

Fit: R-squared= .106886, Adjusted R-squared = .07381

Model test: F[1, 27] = 3.23, Prob value = .08344

Diagnostic: Log-L = 31.6921, Restricted(b=0) Log-L = 30.0530

LogAmemiyaPrCrt.= -4.885, Akaike Info. Crt.= -2.048

Autocorrel: Durbin-Watson Statistic = 1.76523, Rho = .11738

Variable	Coefficient	Standard Error	t-ratio	$P[\|T\| > t]$	Mean of X
Constant	.4767239192	.31634951E-01	15.070	.0000	
T	.2823437350E-02	.15706834E-02	1.798	.0834	17.517241

3. Low Houses

Annual rainfall:

Ordinary least squares regression Weighting variable = none

Dep. var. = RLH Mean= 990.7035714 , S.D.= 127.3765008

Model size: Observations = 28, Parameters = 2, Deg.Fr.= 26

Residuals: Sum of squares= 426405.4453 , Std.Dev.= 128.06330

Fit: R-squared= .026625, Adjusted R-squared = -.01081

Model test: F[1, 26] = .71, Prob value = .40675

Diagnostic: Log-L = -174.5635, Restricted(b=0) Log-L = -174.9413

LogAmemiyaPrCrt.= 9.774, Akaike Info. Crt.= 12.612

Autocorrel: Durbin-Watson Statistic = 1.28928, Rho = .35536

Variable	Coefficient	Standard Error	t-ratio	$P[\|T\| > t]$	Mean of X
Constant	1023.009680	45.313031	22.577	.0000	
T	-1.949506564	2.3117260	-.843	.4067	16.571429

Ratio of winter rainfall to annual rainfall:

Ordinary least squares regression Weighting variable = none

Dep. var. = RRLH Mean= .5603483003 , S.D.= .7447801794E-01

Model size: Observations = 28, Parameters = 2, Deg.Fr.= 26

Residuals: Sum of squares= .1247053573 , Std.Dev.= .06926

Fit: R-squared= .167345, Adjusted R-squared = .13532

Model test: F[1, 26] = 5.23, Prob value = .03065

Diagnostic: Log-L = 36.0658, Restricted(b=0) Log-L = 33.5019

LogAmemiyaPrCrt.= -5.271, Akaike Info. Crt.= -2.433

Autocorrel: Durbin-Watson Statistic = 1.78698, Rho = .10651

Variable	Coefficient	Standard Error	t-ratio	P[$\|T\| > t$]	Mean of X
Constant	.5129908953	.24504977E-01	20.934	.0000	
T	.2857774438E-02	.12501656E-02	2.286	.0307	16.571429

4. Leighton Reservoir

Annual rainfall:

Ordinary least squares regression Weighting variable = none

Dep. var. = RL Mean= 952.2633333 , S.D.= 132.9610975

Model size: Observations = 30, Parameters = 2, Deg.Fr.= 28

Residuals: Sum of squares= 496288.3729 , Std.Dev.= 133.13371

Fit: R-squared= .031974, Adjusted R-squared = -.00260

Model test: F[1, 28] = .92, Prob value = .34444

Diagnostic: Log-L = -188.2739, Restricted(b=0) Log-L = -188.7613

LogAmemiyaPrCrt.= 9.847, Akaike Info. Crt.= 12.685

Autocorrel: Durbin-Watson Statistic = 1.25616, Rho = .37192

Variable	Coefficient	Standard Error	t-ratio	P[$\|T\| > t$]	Mean of X
Constant	991.3651662	47.370990	20.928	.0000	
T	-2.418670077	2.5150177	-.962	.3444	16.166667

Ratio of winter rainfall to annual rainfall:

Ordinary least squares regression Weighting variable = none

Dep. var. = RRL Mean= .5754383179 , S.D.= .8467757560E-01

Model size: Observations = 30, Parameters = 2, Deg.Fr.= 28

Residuals: Sum of squares= .1746635040 , Std.Dev.= .07898

Fit: R-squared= .160023, Adjusted R-squared = .13002

Model test: F[1, 28] = 5.33, Prob value = .02850

Diagnostic: Log-L = 34.6232, Restricted(b=0) Log-L = 32.0075

LogAmemiyaPrCrt.= -5.013, Akaike Info. Crt.= -2.175

Autocorrel: Durbin-Watson Statistic = 2.15434, Rho = -.07717

Variable	Coefficient	Standard Error	t-ratio	$P[\|T\| > t]$	Mean of X
Constant	.5197284327	.28102599E-01	18.494	.0000	
T	.3445972279E-02	.14920215E-02	2.310	.0285	16.166667

5. Birstwith:

Annual rainfall:

Ordinary least squares regression Weighting variable = none

Dep. var. = RB Mean= 853.9354839 , S.D.= 138.5683070

Model size: Observations = 31, Parameters = 2, Deg.Fr.= 29

Residuals: Sum of squares= 535217.9110 , Std.Dev.= 135.85209

Fit: R-squared= .070859, Adjusted R-squared = .03882

Model test: F[1, 29] = 2.21, Prob value = .14777

Diagnostic: Log-L = -195.2119, Restricted(b=0) Log-L = -196.3511

LogAmemiyaPrCrt.= 9.886, Akaike Info. Crt.= 12.723

Autocorrel: Durbin-Watson Statistic = 1.16424, Rho = .41788

Variable	Coefficient	Standard Error	t-ratio	$P[\|T\| > t]$	Mean of X
Constant	914.0888492	47.238116	19.351	.0000	
T	-3.505177302	2.3569689	-1.487	.1478	17.161290

Ratio of winter rainfall to annual rainfall:

Ordinary least squares regression Weighting variable = none

Dep. var. = RRB Mean= .5435509222 , S.D.= .7984811493E-01

Model size: Observations = 31, Parameters = 2, Deg.Fr.= 29

Residuals: Sum of squares= .1623682138 , Std.Dev.= .07483

Fit: R-squared= .151112, Adjusted R-squared = .12184

Model test: F[1, 29] = 5.16, Prob value = .03068

Diagnostic: Log-L = 37.4170, Restricted(b=0) Log-L = 34.8776

LogAmemiyaPrCrt.= -5.123, Akaike Info. Crt.= -2.285

Autocorrel: Durbin-Watson Statistic = 2.18148, Rho = -.09074

Variable	Coefficient	Standard Error	t-ratio	$P[\|T\| > t]$	Mean of X
Constant	.4929320849	.26018230E-01	18.946	.0000	
T	.2949593899E-02	.12981923E-02	2.272	.0307	17.161290

6. Harlow Hill Reservoir

Annual rainfall:

Ordinary least squares regression Weighting variable = none

Dep. var. = RH Mean= 795.6594203 , S.D.= 128.9291111

Model size: Observations = 69, Parameters = 2, Deg.Fr.= 67

Residuals: Sum of squares= 1122239.171 , Std.Dev.= 129.42117

Fit: R-squared= .007171, Adjusted R-squared = -.00765

Model test: F[1, 67] = .48, Prob value = .48906

Diagnostic: Log-L = -432.4439, Restricted(b=0) Log-L = -432.6922

LogAmemiyaPrCrt.= 9.755, Akaike Info. Crt.= 12.593

Autocorrel: Durbin-Watson Statistic = 1.91891, Rho = .04055

Ratio of winter rainfall to annual rainfall:

Variable	Coefficient	Standard Error	t-ratio	$P[\|T\| > t]$	Mean of X
Constant	814.4537419	31.187923	26.114	.0000	
T	-.4765924991	.68511381	-.696	.4891	39.434783

Ordinary least squares regression Weighting variable = none

Dep. var. = RRH Mean= .5247575372 , S.D.= .8290618525E-01

Model size: Observations = 69, Parameters = 2, Deg.Fr.= 67

Residuals: Sum of squares= .4412333805 , Std.Dev.= .08115

Fit: R-squared= .055970, Adjusted R-squared = .04188

Model test: F[1, 67] = 3.97, Prob value = .05033

Diagnostic: Log-L = 76.3972, Restricted(b=0) Log-L = 74.4100

LogAmemiyaPrCrt.= -4.994, Akaike Info. Crt.= -2.156

Autocorrel: Durbin-Watson Statistic = 2.00167, Rho = -.00084

Variable	Coefficient	Standard Error	t-ratio	$P[\|T\| > t]$	Mean of X
Constant	.4909932409	.19555905E-01	25.107	.0000	
T	.8562059707E-03	.42959003E-03	1.993	.0503	39.434783

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