Hydrological-Economic Linkages in Water Resource Management

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Doctor of Philosophy

by

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Abstract

The main objective of this thesis is to improve economic analysis of the hydrological functions of a wetland system and to identify the contribution of these functions in terms of net direct and indirect benefits derived from water use within a geographically defined area.

The thesis studies hydrological and economic linkages in the Komadugu-Yobe river basin in Northern Nigeria. The Hadejia-Jama'are floodplain wetlands, lying within this river basin, are under threat by upstream water diversion schemes which could reduce flooding within the wetlands. Using an optimal control framework, trade-offs in terms of benefits lost or gained from changes in water flow are considered in the analysis of development options within the river basin. The results indicate that by including indirect benefits from wetlands in an analysis of the basin wide economic value of water resources, the optimal path of the rate of diversion of water from downstream to upstream areas would be lower.

To support the assertion that the indirect benefits of the floodplain wetlands are in fact positive, the second focus of the thesis is to develop and apply two methodologies to value an ecosystem function of the Hadejia-Nguru wetlands. Hydrological studies show that, aside from direct benefits obtained from the wetlands, the annual recharge of the underlying aquifer is an important *indirect benefit* of the regular flooding. A partial value of this recharge function is therefore obtained through an analysis of domestic consumption of groundwater resources and dry season agricultural production within the wetlands, based on survey data collected during November 1995-March 1996.

Household water demands are modelled using a modified *household production function approach* and by pooling contingent and observed data to augment information on demand for purchased and/or collected water. The study suggests that the household's choice of a water procurement method is determined by the relative prices of collected and purchased water and by household characteristics. Welfare changes due to hypothetical reductions in groundwater levels are calculated for each household to obtain a value for the groundwater recharge function.

A *change in productivity approach* (alternatively called the *production function approach*) is used to assess the value of the groundwater used in irrigation. Production functions for agricultural crops are estimated using farm-level data collected by the study. Appropriate welfare change measures are developed and the results of the analysis are used to calculate welfare changes due to hypothetical reductions in groundwater levels.

The results of the valuation studies show that the recharge function performed by regular flooding has positive benefits for wetland populations. The failure of the wetlands to provide the present level of recharge would result in a substantial economic loss for wetland populations deriving benefits from indirect uses of the wetlands. This result has important implications for the proposed construction of large-scale dams and diversion schemes in the upstream stretches of the Hadejia and Jama'are rivers. A comparison of welfare loss under various water development scenarios indicates that by reducing the productive potential of direct and indirect floodplain benefits, these upstream developments result in a net loss for society. The maximisation of net direct *and* indirect benefits across the river basin, as is shown by the economic-hydrological model developed in the study, is therefore a more appropriate planning tool for the management of a spatially linked resource such as water within a river basin.

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Author's Declaration

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A former version of Chapter 6 has been presented at the 8th Annual Conference of the European Association of Environmental Economists, August, Tilburg, The Netherlands as a joint paper by Acharya, G. and E. B. Barbier and appears as Acharya, G. and E.B. Barbier, (1997) *Using the Production Function Approach to Value Environmental Functions: Groundwater Recharge in the Hadejia-Nguru Wetlands.* Environment Department, Discussion Paper in Environmental Economics and Environmental Management, University of York.

A paper derived from chapter 6 and chapter 2 is published as Acharya, G. "From Theory to Application: the Production Function Approach" in Acutt, M. and P. Mason (1998) *Environmental Valuation, Environmental Policy and Sustainability : Recent Advances in Environmental Economics.* Edward Elgar Publications.

A paper based on chapters 2,5 and 6 and entitled "Valuing the Hidden Hydrological Services of Wetland Ecosystems" was presented at the 4th Workshop of The Global Wetlands Economics Network (GWEN), 16-17 November 1997, Beijer International Institute of Ecological Economics, The Royal Swedish Academy of Sciences, Stockholm, Sweden.

Chapter 1

Introduction

1.1 Introduction

Over the past two decades there has been an increased emphasis in the literature on integrated approaches to resource management. Particularly when resources are spatially and temporally related, such as the resources within a watershed or river basin, a more cautious and holistic approach to resource exploitation is advocated. This emphasis on multi-disciplinary and multi-faceted approaches to resource management has come at a time when resources are becoming increasingly scarce and more difficult to manage using single-objective management approaches.

River basins integrate natural systems and social processes and at the same time are highly vulnerable to changes made by human activities and natural processes. Throughout recorded history there is evidence that water resource management and mismanagement has resulted in salinity, waterlogging and other water related environmental problems which, in some cases, have brought about the demise of entire civilizations. Water is a key physical resource limiting or triggering economic development and understanding its role in determining the shape of natural and human environments is therefore an important first step in attempting sustainable use of natural resources. The subsequent interaction between human society and water resources, through the use of various property systems, technologies and other forms of social control, is shaped by the value placed by the society on the role of water resources in the sustenance of natural and human systems.

Watersheds and river basins are increasingly being studied as single ecosystems or as a series of interconnected ecosystems. It has been suggested that riverine ecosystems have longitudinal (upstream-downstream), lateral (floodplain-uplands) and vertical (shallow groundwater-deeper aquifer) dimensions. Some recent studies have looked at the spatial and temporal linkages between resources in watersheds and river basins, particularly in terms of assessing the impacts of resource use in one part of the system, on resources used in another part of the system. For example, an *ex-post* analysis of an irrigation project in Tunisia studies the impact of hydrological changes caused by the project on a neighbouring national park and surrounding areas (Thomas *et al.*, 1990). The study establishes that water diverted from the floodplain which maintains the park has a high opportunity cost in term of forgone fishing and grazing benefits. The net benefits from the irrigation scheme were in fact shown to be negative. Similarly, Hodgson and Dixon (1988) study the ecological linkages between logging and soil erosion and sediment deposition on bay coral reefs, in conjunction with the trade-offs involved with resource use in different sections of the watershed.

While the exact magnitude of linkages between different components of a system requires the empirical study of specific ecosystems, it is possible to broadly state that the use of resources in one part of an interlinked system may affect the availability of resources in another part of that system. Rivers, wetlands and aquifers may be of considerable significance in meeting the water demands of local communities and of communities further away. Changes in the flow of water in a river, which forms the main artery connecting the various components of a watershed or river basin, may therefore affect, and in turn be affected by, changes in the availability of other, interdependent resources. Hence, the hydrological state of a downstream aquifer may be conditioned by the state of the base flow in the river which feeds it and by the hydrological state of wetlands which may act as recharge zones, in addition to rainfall, soil moisture, permeability, and other environmental factors.

Floodplains are often subjected to both natural and anthropogenic shocks, stemming from changes in hydrological regimes. Natural hydrological variability could occur due to the seasonal nature of rains, for example, which cause rivers to overflow their banks during certain months of the year. Anthropogenic changes in hydrological regimes are caused by water utilization in a myriad of ways, ranging from drinking water supplies to hydroelectricity generation and recreational uses.

For centuries, attempts have been made to tame rivers by flood control schemes. River banks have been straightened and cleared of vegetation while wetlands have been drained. Floodplains have subsequently shrunk in size, allowing permanent settlements to develop in previously seasonal areas. This is true for many parts of the industrialized world and is becoming increasingly evident in developing countries where escalating demand for water is resulting in the draining of rivers and reduced flooding. This allows populations to remain permanently on seasonal floodplains, falsely confident that floods will no longer occur.

In recent years, however, there has been a concerted effort to pay attention to the impacts of building large dams on rivers. The development versus environment camps have been pitted against each other and the resulting arguments are often unyielding, firmly *pro* or *anti*, and unwilling to compromise. Yet it is clear that the development needs of clean drinking water and electricity cannot be ignored and neither can the valid arguments that large dams have the potential to cause disruption to communities forced to relocate as a result of changes in hydrological conditions and cause environmental damage. Often development choices are made using flawed institutional frameworks, and without proper quantification of benefits and trade-offs between alternative projects. Brookshire and Whittington (1993) note that water supply projects are justified by alluding to "unquantifiable" benefits rather than by estimating economic and social benefits. This attitude has resulted in the creation of 'monuments' to development (Howe and Dixon, 1993). These unsustainable projects are often double-edged swords, resulting in the disruption or erosion of alternative systems which might have resulted in greater benefits to society. Development choices are therefore best made after comparing the costs and benefits of various alternatives in terms of both financial outlays and the social and environmental impacts of changing the natural hydrological conditions within the river basin.

The aim of this thesis is to examine a potential impact of upstream water development projects that is usually ignored in such analysis. Wetlands play an important role in supplying water, in the form of surface water as well as by being recharge areas for groundwater resources. Hence, hydrological changes in surface water supplies can affect groundwater regimes as well and together these changes can have impacts on human welfare. Barbier (1994) notes that development projects in the upstream reaches of rivers may result in losses to floodplain agriculture and other primary production activities, but may also have significant environmental impacts such as losses in groundwater recharge. Net reductions in these production activities as well as net reductions in indirect environmental benefits must therefore be included in policy analysis when development options are being considered. However, hydrological and economic data on these indirect benefits is more often than not, lacking and cannot therefore be included in any quantifiable manner in the analysis of development projects.

This thesis argues that the forgone net benefits of changes in the indirect benefits of the floodplain, in providing groundwater recharge, must be included as part of the opportunity costs associated with upstream development projects. The main objective of this thesis is therefore to value the groundwater recharge function of a specific floodplain, arguing that changes in flood extent will impact groundwater levels and hence human welfare.

Since most groundwater models are restricted to modelling the optimal use of isolated and/or confined aquifers, and river basin planning often omits the inclusion of downstream impacts in project analysis, this thesis also presents an alternative approach to analysing the impacts of upstream diversions and groundwater abstraction, within the context of benefits derived from water use across the entire river basin. In order to maximize the net present value of water resource use in a river basin or watershed, upstream and downstream development options, and surface water-groundwater interactions must be considered. The thesis studies trade-offs in terms of benefits lost or gained from changes in water flow and includes these in the analysis of development options within a selected river basin.

1.2 Outline of the thesis

Chapter two of this thesis introduces the Komadugu-Yobe River Basin in Northern Nigeria. This river basin maintains the floodplain wetlands known as the Hadejia-Nguru wetlands. Dams and diversion schemes along the two main rivers which feed the Komadugu-Yobe and hence the wetlands, have reduced water flow and changed flooding patterns within the wetlands. Diverted water and flood water have values as do other resources such as groundwater which is used extensively in the downstream portions of the river basin. This chapter sets the scene for the remaining portion of the thesis which focuses on water use within this river basin.

Chapter three develops two simple optimal control models with the objective of maximizing net benefits from water use within the river basin. The first model analyses net benefits from upstream diversions and floodplain benefits, without including groundwater use. This model develops optimal decision rules for water allocation between upstream and downstream portions of the river basin. The second model is developed to include the indirect benefits from flooding and includes the net benefits derived from the groundwater recharge provided by the wetlands. This chapter analysis the effect of increasing diversions upstream on floodplain and groundwater use benefits. Data availability is also examined in this chapter and it is noted that an essential piece of the puzzle - the value of groundwater recharge - is missing and would need to be studied in order for the social planner to have a more complete knowledge of benefits derived from the present hydrological conditions in the floodplain.

In order to establish that indirect benefits have a positive and significant value, we turn our attention to the measurement of environmental values and examine the various methodologies available to us for the purpose of measuring the value of groundwater recharge within the Hadejia-Nguru wetlands.

Chapter four introduces certain aspects of the existing literature on valuation techniques, arguing that the use of techniques such as the household production function approach (HPFA) and the production function approach (PFA), is possible in developing countries and relevant to valuing indirect benefits of environmental functions. The valuation literature is weak in applications of these approaches and is particularly lacking in developing country applications, where it is argued data availability problems are likely to be significant. The chapter argues however that such limitations can be overcome and that the success of implementing these approaches depends largely on the identification of physical (ecological) and economic linkages between productive activities and environmental functions or services. Once these linkages are made clear, the PFA and HPFA can be applied with relative ease.

Chapter five and six are applications of the HPFA and PFA valuation techniques discussed in chapter four. Although there are a number of environmental benefits from the floodplain, including groundwater recharge and habitat maintenance for migratory waterfowl, valuing the role of the wetlands in protecting migratory waterfowl is difficult since this would involve taking into account the damage caused by the birds to agricultural crops within the wetlands, the value of the birds to European countries where the birds return to in the spring/summer and the value of the birds in terms of trade and a wild food source. We therefore restrict our analysis to measuring the value of the groundwater recharge function performed by the regular inundation of the floodplain. Groundwater recharge is considered by hydrologists to be an important environmental function performed by the wetlands and is therefore included as an essential component of floodplain benefits.

Chapter five therefore examines the use of groundwater for domestic water consumption and measures the indirect use value of the wetlands in providing groundwater recharge, in terms of impacts on domestic water demand. This chapter provides an interesting adaptation of the household production function approach to understand demand for groundwater and uses a contingent behaviour survey to augment information obtained from revealed preference approaches. The data was collected from selected villages in the wetlands, during the months of November-December 1995 and during March-April 1996. In particular, this chapter shows the possibility of carrying out analysis based on the HPFA in a developing country context, where data availability may be poor.

Chapter six identifies dry season agriculture within the floodplain as a second major user of groundwater resources and therefore applies the production function approach to measuring the indirect use value of the groundwater recharge function performed by the overlying wetlands. The analysis is based on production data collected during the months of November-December 1995 and during March-April 1996. The resulting production relationships for produced crops are used to derive the indirect use value of the wetlands in providing groundwater recharge.

Chapter seven concludes the thesis and provides a brief description of future research possibilities, both in the context of the specific findings of the thesis and in the more general context of valuing environmental functions.

Chapter 2

The Komadugu-Yobe River Basin: Background and Problem Definition

2.1 Introduction

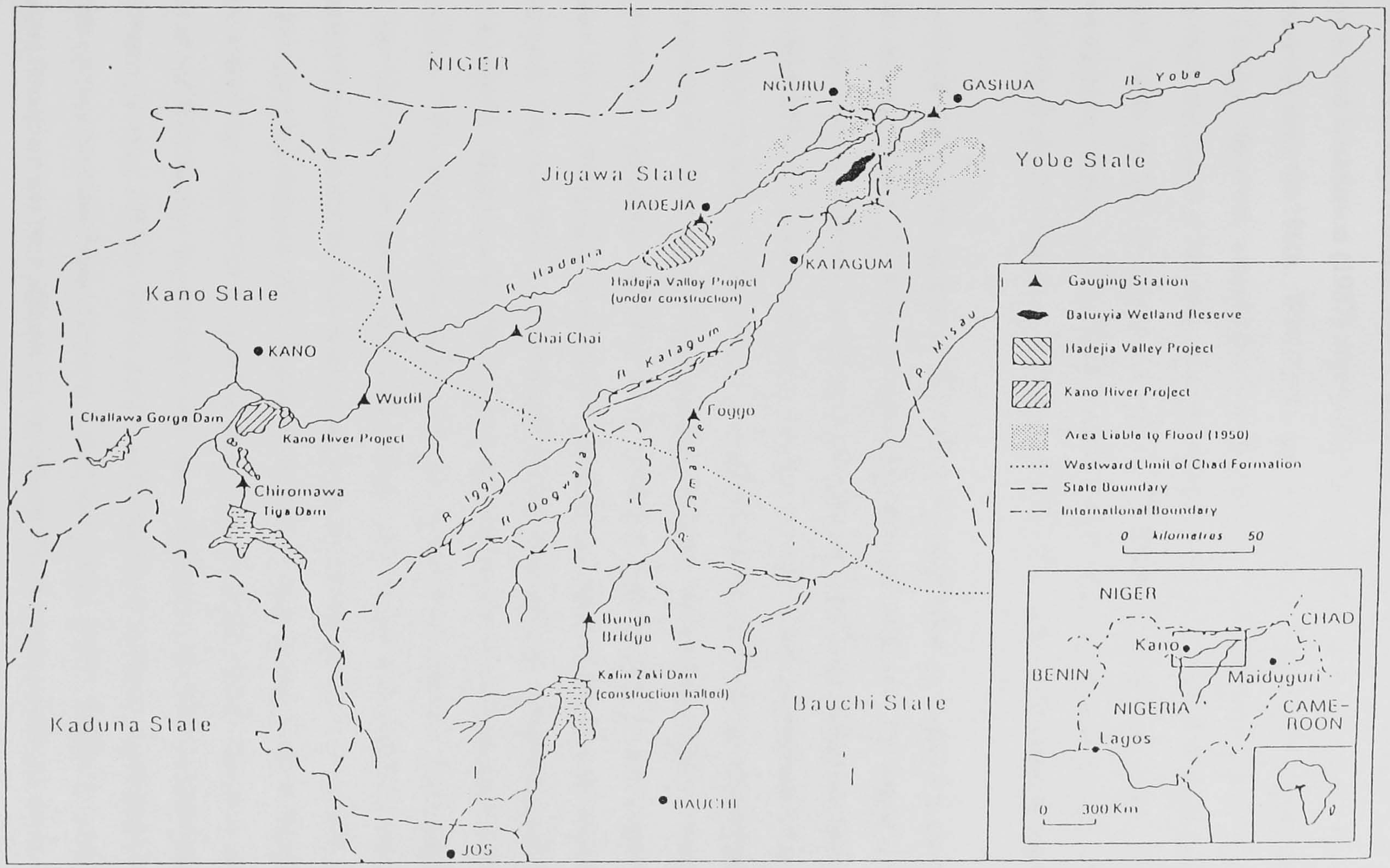
Managing water resources in semi-arid regions of the world is a subject that has interested a number of disciplines, evidence of the immense complexity and importance of this subject area. Particularly in light of the drought conditions presently prevailing across much of Sub-Saharan Africa, managing a scarce and vital resource such as water is a daunting and difficult task of some urgency. This study focuses on a river basin comprising a vast and productive floodplain, located in the semi-arid north-eastern region of Nigeria. The characteristics of the Komadugu-Yobe river basin in Northern Nigeria, including the Hadejia-Nguru floodplain, and the nature of benefits derived from the water resources and from the floodplain will be discussed in this chapter. This chapter will therefore provide a context for the remaining portion of the study which develops an optimal control model for water use within the basin and carries out a partial valuation of the groundwater recharge function of the Hadejia-Nguru wetlands.

2.2 The Komadugu-Yobe river basin

The basin of the Komadugu-Yobe river covers an area of 84,138 km^2 in Northeastern Nigeria. The rivers Hadejia and Kano, arising in Kano state, and the Jama'are river arising in Plateau and Bauchi states, drain into the Yobe, which flows into Lake Chad. The portion of the floodplain where the Hadejia and Jama'are rivers meet is known as the Hadejia-Jama'are wetlands. The area of floodplain lying between the towns of Hadejia and Gashua and South of Nguru, are widely referred to as the Hadejia-Nguru wetlands (figure 2.1).

The semi-arid zone of West Africa is subject to strongly seasonal patterns of rainfall and river flow. Most of the annual rainfall in Northern Nigeria occurs in just 3-4 months, between June and September. During this season, the rivers flood, providing support for a large number of varied activities, dependent on the floodplain and admirably adapted to the seasonal fluctuations within the area. The rivers that maintain this floodplain are affected by a number of dam and reservoir projects, some built and some proposed.

Figure 2.1 The Komadugu-Yobe river basin and the Hadejia-Nguru wetlands



Source: Hollis et al., 1993

In addition to the marked seasonal distribution, rainfall in Africa is also highly variable, both spatially and temporally. This is especially the case in arid and semi-arid regions of Africa (Adams, 1992; Agnew and Anderson, 1992) where a tendency for the clustering of dry and wet years is evident (Grove and Adams, 1988) and droughts are a persistent threat affecting Africa's floodplains (Glantz, 1987). Rainfall in the region is punctuated by wet and dry periods and Rasmusson (1987) argues that the magnitude of dry episodes has increased consistently since the 1960s. West Africa has experienced three major droughts during the 20th Century. However, a recent study by Holmes *et al.*, (1996), based on the examination of a high resolution 5,500 year paleolimnological record from the Kajemarum Oasis (a closed basin in the Manga grasslands of Northern Nigeria), provides evidence of environmental change in Sub-Saharan Africa, indicating that droughts have affected the Sahel episodically over the last 1,500 years and are not solely a 20th Century phenomenon.

These harsh and variable natural conditions can be exacerbated by inappropriate changes in water regimes induced by water resource development schemes. The impact of naturally occurring drought conditions are therefore more extreme and downstream environments are particularly affected. Dams retain water through the wet season and release it for irrigation or electricity generation fairly evenly throughout the year (Drijver and Marchand, 1985). These reservoirs are subjected to high evaporation rates, further reducing the water available for downstream environments. Other development projects such as by-pass canals have the explicit aim of minimising the perceived water losses within floodplains by retaining water in channels. The reduction of downstream flooding following the construction of dams such as Akosombo, Kainji and Kariba has had significant effects on downstream floodplains (Scudder, 1991). For example, Kariba Dam has reduced downstream flood magnitudes in the Zambezi River by about 24% (Masundire, 1997) while Adams (1985) notes that the Bakalori Dam in northwest Nigeria reduced flood extent and depth by over 50% in parts of the downstream floodplain of the Sokoto River. As a result, in areas below Bakalori Dam, cultivators have shifted from growing rice to lower value millet. The size and species diversity of fish catches has declined and many fishermen have left the floodplain to fish elsewhere (Adams, 1985b). Downstream of Kainji Dam, in Niger, significant reductions in fish catches have also been recorded (Lelek and Zarka, 1973). Similarly, grazing in the Logone floodplain has been affected by the reduced flood extent which has caused pastures to be replaced by less productive dry vegetation (Drijver and Marchand, 1985).

This is not to say that the retention of water upstream has no benefits. Water resource development projects are often designed to meet increasing demands for drinking water, electricity, and other urban requirements. The relative benefits of water used upstream and downstream areas of the Komadugu-Yobe river basin will be described in the next few sections.

2.3 Utilization of water within the upper river basin

The logic of river basin planning is simply to coordinate the different uses of water in each river basin so that upstream and downstream uses can be coordinated. The Tennessee Valley Authority (TVA) from the 1930s is often cited as one of the first integrated river basin planning authorities. Development of the river basin was planned and carried out by a centralized authority - the TVA. River basin planning has been adopted in Africa on a wide scale and since the 1960s in Nigeria with the establishment of the Niger Delta Development Board and the Niger Dams Authority (Adams, 1992). This includes the Lake Chad Basin Commission which is supposed to provide an international forum for planning development of all the rivers draining into Lake Chad, involving Chad, Cameroon, Nigeria and Niger. The first two River Basin Development Authorities (RBDAs) were set up in Sokoto-Rima and Lake Chad in 1973, followed by seven others in 1976. Since then, with boundary changes and the creation of numerous new states, a number of new RBDAs were created and are now known as River Basin and Rural Development Authorities. As has been noted by a number of people with first-hand experience of these RBDAs (e.g., Adams, 1992), the boundaries of these authorities are not related to actual river basin boundaries and are subject to political whims and fancies.

As a result, project development within the river basin is not directed by a single coherent plan (Hollis and Thompson, 1993) and schemes have been proposed and developed by a number of agencies at both federal and state level. Tables 2.1 and 2.2 show the number and location of the main dam and irrigation schemes (Thompson, 1995). These projects have been implemented by individual state ministries as well as by the River Basin Development Authorities (RBDAs). The most important of the schemes in the Hadejia Valley are Tiga Dam and the Kano River Irrigation Project, Challawa Gorge Dam and the Hadejia Valley

Project. Kafin Zaki Dam is the largest proposed scheme for the Jama'are Valley.

Most irrigation in Nigeria is classified as small-scale or indigenous (Adams, 1992) and the water development schemes on the Hadejia and Jama'are rivers have been directed towards increasing the area under large-scale, formal irrigation. In the early 1970s the Federal Military Government (FMG) initiated a number of large-scale irrigation projects, including the South Chad Irrigation Project in Borno State, the Sokoto-Rima Project in Sokoto State, and the Kano River Irrigation Project at the upstream end of the Hadejia River system in Kano State (Wallace, 1980).

2.3.1 Large-scale irrigation schemes

The largest of these schemes is the Kano River Irrigation Project (KRIP), designed in two stages. Phase I (KRIP-I), had as its target a total irrigated area of 27,000 hectares while Phase II (KRIP-II) was expected to add 40,000 hectares. Construction of Phase I began in 1977 and to date around 14,000 hectares receive irrigation from the project. Water supplies for this project are provided by Tiga Dam, the biggest dam in the river basin, constructed between 1971-74. Water from the Tiga is also released into the Kano River for abstraction downstream by the Kano City Waterworks. The major crops grown in the wet season are rice, maize, cowpeas and millet and tomatoes and wheat are grown in the dry season. Barbier *et al.* (1993) calculated that the present economic value of the scheme was between 153 and 233 Naira per hectare[1]. These figures include the project operating costs, which have ranged from 7.5% to 37% of total value of crop production, but neglect the substantial sunk capital costs which in 1988 amounted to 180 million Naira (Adams and Hollis, 1988). Although feasibility studies for Phase II of the KRIP (40,000 hectares) have been undertaken and outline designs completed, construction has yet to begin (Thompson, 1995).

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[1] 1989/90 prices; 1 US$ = 7 Naira

Table 2.1 Existing and Proposed Reservoirs in the Komadugu-Yobe Basin

Site	River	Status	Basin area (km^2)	Annual inflow (10^6m^3)	Live storage (10^6m^3)	Annual abs. (10^6m^3)	Annual evap. (10^6m^3)	Total abs. (10^6m^3)
Tudun Wada	Kano	Existing	85	14	18	5.0	?	5.0+
Marashi	Challawa	Existing	43	8	6	0.6	1.9	2.0
L. Marashi	Challawa	Planned	No data					
Pada	Challawa	Existing	62	11	10	1.2	3.6	4.8
Tiga	Kano	Existing	6,641	914	1,283	732	164	896
Challawa	Challawa	Existing	3,859	465	948	348	98	446
Bagauda	Kano	Failed	207	39	21->0	1.8	3.3	5.1
R. Kanya	Kano	Existing	No data					
Kunza	Kano	Planned	No data					
Shimar	Kano	Planned	No data					
Garanga	Kano	Planned	No data					
Karaye	Challawa	Existing	80	14	16	9.3	1.7	11.0
Magaga	Challawa	Existing	119	21	17	8.4	3.3	11.7
Kango	Challawa	Planned	41	8	8	-	-	-
Guzuguzu	Challawa	Existing	106	19	22	5.0	8.0	13.0
Watari	Challawa	Existing	653	89	93	35.0	17.0	52.0
Kiwia		Planned	No data					
Kafin Zaki	Jama'are	Halted	5,151	1,404	2,579	940	294	1,234
Marra	Jama'are	Planned	1,541	347	323	226	45	271
Kawali	Jama'are	Halted	9,053	2,470	-	-	-	-
Galala	Jama'are	Planned	462	97	20	-	-	-
Birnin Kudu	Jama'are	Existing	40	1	1	2.5	0.5	3.0
Kafin Gana	Jama'are	Planned	-	-	0.8	0.13	0.74	0.9
Iggi	Iggi	Planned	No data					
Dogwala	Dogwala	Planned	No data					
Iyakako		Planned	No data					

Source: Diyam (1986); cited in Thompson, 1995

Table 2.2 Existing and Proposed Formal Irrigation on the Hadejia and the Jama'are

River	Scheme	Net area (000 ha)	Irrigation % rice / sugar cane	Intensity of irrigation % other crops	Seasonal pattern of irrigation	Water demand (10^6m^3)
Kano	KRIP-I	27	13	107	Wet and dry	370
Kano	KRIP-II	40.2	0	200	Wet and dry	442
Hadejia	HVP	11.3	100	100	Wet and dry	170
Hadejia	Wudil - Dabi	13.5	47	126	Wet and dry	170
Hadejia	Dabi - Ringim	4.5	20	149	Wet and dry	51
Hadejia & D. Gaya	Harbo - Gilima	3.5	76	96	Wet and dry	57
Burum Gana	Burum Gana	12.4	0	110	Extended wet	169
Total Hadejia		107.5				1673
Jama'are	Kawali-Badayeso	9.7	33	140	Wet and dry	121
Jama'are	Kila-Disnia	38.5	26	144	Wet and dry	520
Jama'are	Lafia-Wali	7.8	43	129	Wet and dry	101
Jama'are	Sakva-Sandigalou	19.1	106	69	Wet and dry	317
Jama'are	Katagum	6.6	100	75	Wet and dry	74
Jama'are	Abonabo	2.5	-	-		43
Total Jama'are		84.1				1176

Source: Diyam (1986); cited in Thompson, 1995

The second major irrigation scheme within the river basin is the Hadejia Valley Project (HVP) which is still under construction. A barrage built across the Hadejia River has created a storage pond capable of holding a week's irrigation water requirements for 12,500 hectares of land and the scheme has so far completed the laying out of 7,000-8,000 hectares of land (Thompson, 1996). A third dam, the Challawa Gorge Dam, on the Challawa River, one of the tributaries of the Hadejia River (Figure 2.1) was completed in 1992.

At present only one dam has been completed in the Jama'are Basin. This dam at Birnin Kudu has a capacity of $1 \times 10^6 m^3$ and is small when compared to the largest dam planned for the basin, Kafin Zaki, with an envisaged total storage of $2{,}700 \times 10^6 m^3$ (HJRBDA, 1987). The purpose of the Kafin Zaki dam is to provide irrigation water to 84,000 hectares.

In addition to large-scale irrigation schemes, a number of channelisation schemes have been proposed (IWACO,1985; Chifana 1985). The IWACO (1985) plan consists of the construction of a new river channel that would shorten the length of the Hadejia River by 50% and allow navigation, hydro-power and fish ponds through the provision of control structures. The water would be utilized for irrigation, hydro-electric power and town water supply predominantly between Gashua and Geidam although water would be supplied to Nguru lake and 6,800 hectares of irrigation along the Burum Gana as well. Chifana (1985) also suggested the need for a new channel (with an annual capacity of $400 \times 10^6 m^3$) for the Hadejia River, intended to carry water from Hadejia town to Geidam. The water supply would be used for irrigation downstream of Gashua and upstream of Katagum and for rice cultivation in the *fadamas* around Hadejia. However, Hollis and Thompson (1993) note that groundwater, small-scale irrigation, wetland cultivation and pastoralism would be affected by the implementation of these channelisation schemes.

2. 4 The Hadejia-Jama'are floodplain and wetlands

Downstream of these developments, in the dusty, dry environment of northeastern Nigeria, the Hadejia-Nguru wetlands are an important source of food and the most essential resource of all - water. "Water is life" is a commonly heard refrain throughout the region. The source of the seasonal floods which maintain these wetlands, is the excess water carried down by the rivers during the rainy season. This water rejuvenates the floodplain, providing new soil and moisture. Floodplain activities have adapted to suit this cycle, making use of the floodwaters and the fadamas in an ingenious way, taking advantage of a combination of the wetland's resources. However, as discussed in the previous section, this water is also needed upstream. As populations of cities like Kano grow and the water demands of the urban areas increase, more water will be diverted further upstream, resulting in a reduction of the flow in the rivers as they pass through the floodplain. Competing uses for water from the Hadejia and Jama'are rivers divert water away from the floodplain to feed these upstream projects. In order to understand the full implications of upstream developments on the downstream portion of the river basin, we first examine the nature of wetlands within the tropics, and in particular, the role they play in maintaining life in semi-arid regions.

Wetlands have been identified as important ecosystems which provide a wide range of ecological and hydrological functions and are some of the most productive ecosystems on the Earth (Adamus and Stockwell, 1983; Mitsch and Gosselink, 1993). Although a number of definitions exist and are used to describe wetland ecosystems, these ecosystems are essentially distinguished by the presence of water, either at the surface or within the root zone; they often have unique soil conditions that differ from adjacent uplands; they support vegetation adapted to the wet conditions and are characterized by an absence of flooding intolerant vegetation (Mitsch and Gosselink, 1993).

Wetlands provide a multitude of direct benefits to populations as well as indirect benefits through ecosystem functioning. Ecosystem functions provide goods and services, maintaining the health, safety and welfare of populations directly and indirectly dependent on them. Cultural uniqueness, heritage value and maintenance of biodiversity are also attributes of certain wetlands. There is now an expansive literature on the functions and values of wetlands, reflecting the shift in attitude over the decades from wetlands being considered wastelands and harbouring disease, to wetlands being regarded as productive ecosystems of considerable economic and cultural value (Sather and Smith, 1984; Maltby, 1986; Adamus and Stockwell, 1993; Dugan, 1993; Mitsch and Gosselink, 1993). Some of the important values of wetlands identified by these studies are:

- groundwater recharge
- groundwater discharge
- flood storage and de-synchronisation
- shoreline anchoring and dissipation of erosive forces
- sediment trapping
- nutrient retention and removal
- food chain support
- habitat for fisheries
- habitat for wildlife
- active recreation, passive recreation and heritage value
- regional and global value in maintaining global cycles of nitrogen, methane, sulphur and carbon dioxide
- stabilization of micro-climates
- communication and transportation

The particular role played by any one wetland will vary since not all wetlands perform all the functions listed above. The degree to which a wetland may perform these functions will also differ since the ability of a wetland to carry out these functions depend on the physical and biological characteristics of the wetland (Hollis and Acreman, 1994). Nonetheless, a wetland in its natural state is a multi-functional and therefore, a multi-benefit resource. Floodplain wetlands are associated with groundwater recharge or discharge in particular, and although floodplains may exhibit either or both of these functions, they play an important role in maintaining groundwater regimes.

The floodplain wetlands of the Hadejia-Jama'are Basin are located at the downstream end of the Hadejia-Jama'are River Basin around and just upstream of the confluence of the two rivers (Figure 2.1). At the town of Gashua the area drained by the Hadejia and Jama'are is 61,120 km^2 (Hollis *et al.* 1993). The wetlands are maintained by the regular flooding of the two rivers which meet to form the Komadugu Yobe river, flowing northeast into Lake Chad. The floodplain is formed by the waters of the Hadejia and Jama'are rivers which meet to form the Komadugu-Yobe river, flowing northeast into Lake Chad.

Historically, the floodplain of the Hadejia and Jama'are rivers may have spanned an area of over 2,000 km^2 at peak flood (Thompson and Goes, 1997). Inundations begin in July and peak flood extents are attained in August/September (HNWCP,1992; Thompson, 1995; see figure 2.1).

The climate of the region is dominated by the annual migration of the Inter Tropical Convergence Zone (ITCZ) which reaches its most northerly position above Nigeria in August. The influence of the ITCZ produces distinct wet and dry seasons. The peak rainfall months in northeastern Nigeria are June-August and the mean annual rainfall for Nguru for the period 1942-1990 was 487mm (Thompson and Hollis, 1995). The rivers have periods of no flow in the dry season (October-April) and 80% of the total annual runoff occurs in August and September.

Figure 2.3 shows a cross-section of the underlying geological structure in the Hadejia-Nguru wetlands. The Chad Formation is a freshwater argillaceous sequence and is permeable. The Basement Complex is however an impermeable Pre-Cambrian granitic and metamorphic strata and is found mainly in the upper part of the basin (Hollis *et al.*,1993). The Hadejia and Jama'are rise in areas underlain by the impermeable Basement Complex and begin to lose water when they start to flow across the Chad Formation. Schultz (1976) suggests that these losses occur due to :

- water held in interdune depressions, oxbows and *fadamas* and subsequently removed by evaporation or infiltration
- evaporation and evapotranspiration losses
- groundwater recharge
- removal by non-returning channels
- abstraction for crop irrigation

The flood waters of the Hadejia and Jama'are rivers accumulate in low-lying areas known as *fadamas* in Hausa, which then provide valuable opportunities for grazing, agriculture and other economic uses. *Fadamas* have been defined as land which is seasonally waterlogged or flooded (Turner, 1977). These areas are waterlogged or flooded during the wet season and gradually dry out until they are flooded again during the next wet season. *Fadamas* are used extensively for fishing, farming and grazing, with the uses varying in accordance with the seasonal changes in flood extent.

In 1993, a study of the hydrological and economic environment of the Hadejia-Nguru[2] wetlands noted that these wetlands support a wide range of economic activities, including wet and dry season agriculture, fishing, fuelwood collection, livestock rearing and forestry (Hollis *et al.*, 1993; Adams, 1993a, b & c; Thomas *et al.*, 1993). The wetlands are, in addition, a valuable site for wildlife conservation and, in particular, for waterfowl. Table 2.3 summarizes the available key floodplain resources and the main methods of utilization within the wetlands.

Table 2.3 Resource utilization

Resource	Utilization
Water	Domestic use, irrigation, livestock watering, navigation
Vegetation	Food, thatching material, ropes, fuel
Land (fadamas and upland),soil	Flooded agriculture, irrigated agriculture, dryland farming, building material
Fish	Fishing, important source of protein
Birds, reptiles, amphibians	Food, hunting, tourism, minor trade

The flood cycle is very important in the order and intensity of activities undertaken. In agriculture, the seasonal rise and fall of floodwaters results in the establishment of four cropping systems, namely, rainfed upland cropping, *fadama* or flood cultivation, recession farming and irrigated cropping (Table 2.4).

Rainfed upland farm lands are called *tudu* in Hausa. This type of farming entails mainly bullrush millet and sorghum or guinea corn. These two crops make up a large proportion of the agricultural production of the area and are dominant in the diet of the villagers. Planting occurs with the beginning of the rains in early June and the growing season lasts for 100 to 120 days (Adams and Hollis, 1988; Kimmage and Adams, 1992).

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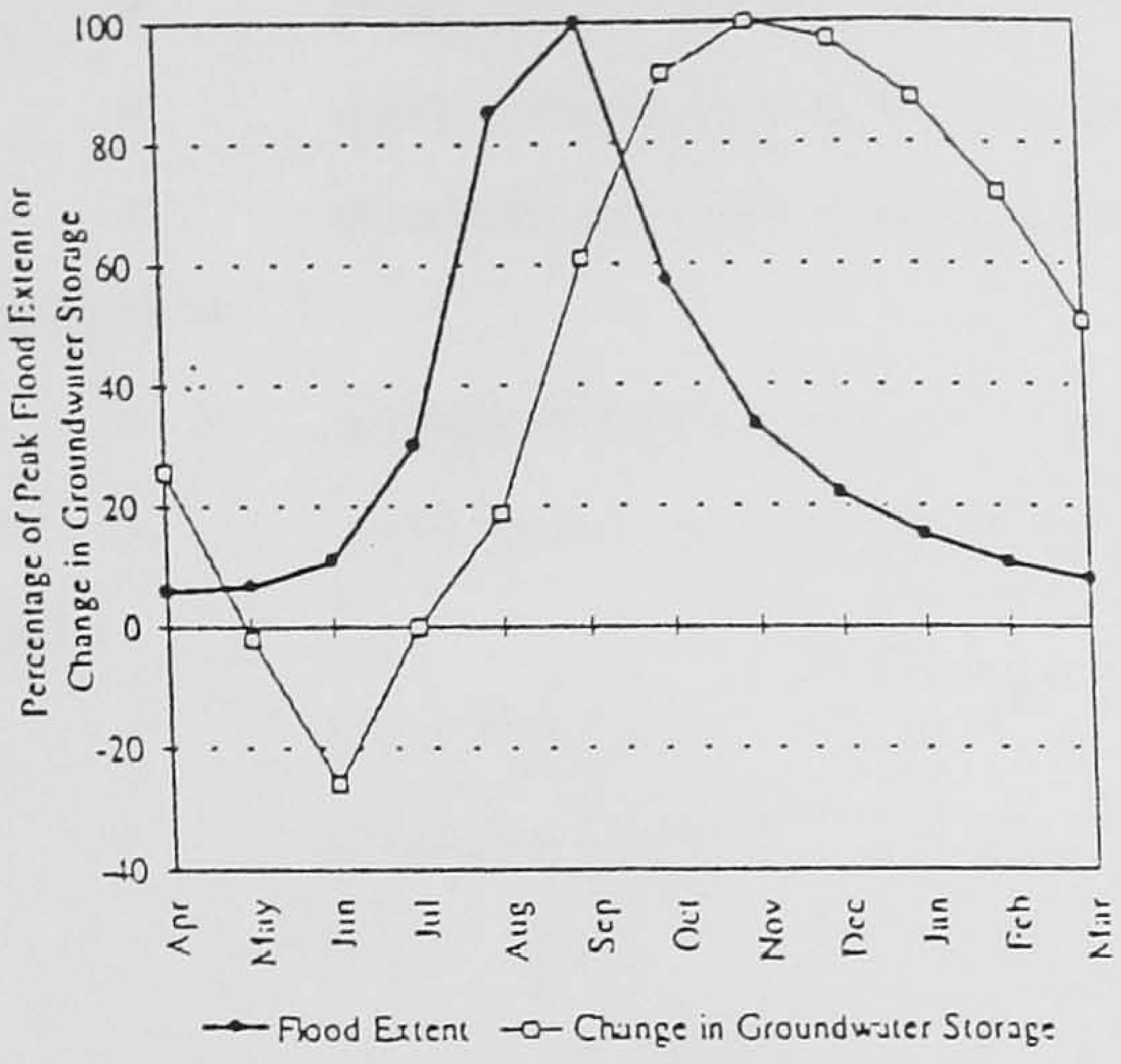
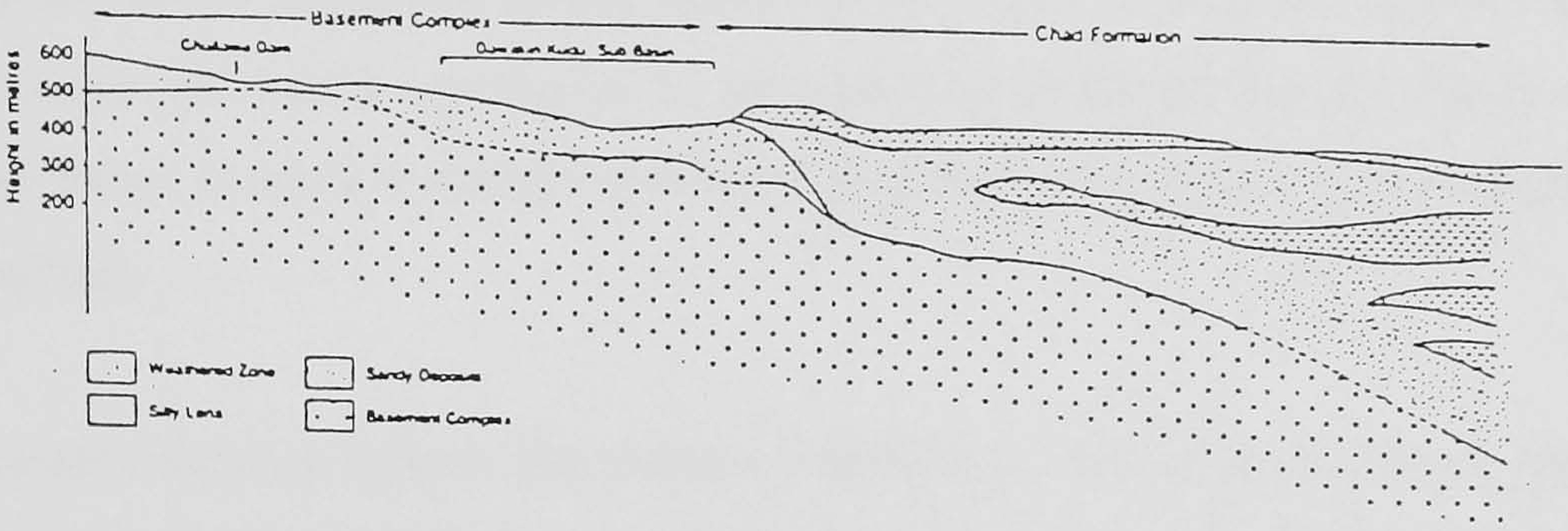
[2] The Hadejia-Jama'are wetlands refer to the entire Basin, including the area beyond the town of Gashua in the northeast, whereas Hadejia-Nguru is the term used to describe the wetlands between Gashua and Hadejia towns.

Figure 2.2 Annual inundation and groundwater regimes



Source: Thompson and Goes (1997)

Figure 2.3 Geological cross-section through the Chad formation



Source: Hollis et al., 1993

Table 2.4 Agricultural technologies

A. Flood cropping
- rising flood cropping (planted before flood rises)
- decrue cropping (residual soil moisture cropping)
- flood defence cropping (with bunds)

B. Stream diversion
- permanent stream diversion or canal supply
- storm spate diversion (rainwater harvesting)

C. Lift irrigation
- from openwater
- from groundwater
  - well
    - -bucket
    - -shadoof
    - -animal powered
    - -motorized
  - tubewell (generally < 9-10 metres depth)
  - borehole (up to 30 metres depth)

Source: adapted from Adams, 1992

Flood cultivation is an important aspect of farming in the floodplain and *fadama* lands are highly priced possessions. Rice cultivation and some sorghum is grown. The land is prepared during the dry season and planted with the onset of the rains. By the time the land is flooded, the rice is expected to be tall enough to withstand the inundation and not get swept away. Farmers sometimes construct defensive bunds to prevent flood damage to the rice plants.

Recession farming follows the *fadama* cultivation. As the floods recede the exposed *fadama* land is planted with recession crops such as beans, cotton or cassava. These crops utilize the residual moisture in the soil.

Dry season irrigated farming has been traditionally practised in the area with irrigation technologies such as shadoofs (Adams, 1993). These irrigated or *lambu* lands are now increasingly (since the 1980's) being irrigated with the use of small petrol powered pumps, which can lift water relatively short distances from river channels or from shallow groundwater within the wetlands (see chapter 6 for further details on irrigated agriculture using small pumps for groundwater abstraction).

Pastoralists use the wetlands seasonally, moving into the wetlands as the surrounding rangelands dry out. Grazing within the wetlands is crucial for the cattle and livestock owned by the nomadic Fulani populations and by some sedentary farmers. It is estimated that the Fulani herds may number around 250,000 animals (Rodenburg, 1987). During the dry season the Fulani from both the north and the south of the wetlands move their camps and their herds on to the seasonally exposed grasslands. The wetlands are a part of the seasonal cycle of migration undertaken by the nomadic Fulani and traditionally, the Fulani and farmers have had a tense but cordial relationship. Certain traditions such as allowing the Fulani herds to graze on the last of the harvest crops in return for some compensation are still practised, although these are becoming increasingly rare and wrought with conflict.

Fisheries, fuel, fibre and food resources are important products of the wetlands. Mathes (1990) and Thomas *et al.*, (1993) note that the wetlands have long been recognized as an important centre of fish production in the region. Fishing is undertaken mainly during the flooded season although some villages and individuals fish throughout the year. The main fishing period begins at the start of the dry season when fish return to areas of permanent water and are more concentrated (Thomas *et al.*, 1993; 1996). The intensity of fishing activity varies between different parts of the wetland, with some villages specializing in fishing. Thomas *et al.*, (1993) estimated that the annual fish production from the wetlands may vary between 1,620 and 8,100 metric tonnes, and may well be an underestimate. NEAZDP (1991) estimated annual catch as 10,000 to 14,000 metric tonnes.

The floodplain is also a producer of large quantities of doum palm, reeds and sedges (Kalawachi, 1995). Polet and Shaibu (in prep.) estimate that the annual value of doum palm produced from the area may be around 35 million Naira[3]. A recent study by Eaton and Sarch (1996) provides additional information on the wild food resources found within the wetlands and the extensive use of these resources by the wetland populations.

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[3] 88 Naira = 1$

2.4.1 Water use within the floodplain

Water is used directly from fadamas, from the rivers and from groundwater resources. The majority of the floodplain villages draw their drinking water from hand dug village wells (Kimmage and Adams, 1992). A few villages near rivers may rely more heavily on river water. In addition to the direct removal of water from the river channel both upstream and within the wetlands, significant modifications to the hydrological regime are also made during the river's passage through the floodplain, due to the flooding pattern of the river and landscape characteristics (Thompson and Hollis, 1995). This includes infiltration of water into the ground as shown earlier in figure 2.4. Hydrological studies conducted on the wetlands have concluded that the wetlands are particularly important for the recharge of the shallow and deeper aquifers of the Lake Chad Formation which is facilitated by the wet season flooding of the wetlands (Schultz, 1976; Diyam, 1987; cited in Thompson and Hollis,1995).

The majority of the estimated population of nearly one and a half million people within the wetlands, depend on groundwater. With reference to the important function performed by these wetlands Hollis *et al.*, (1993), state:

> "There is no doubt that groundwater recharge comes mainly from the inundation of the fadamas and floodplain and not from the river channels themselves. Much literature refers wrongly [to] 'losses' with the implication that reductions in river flow represents water going to waste. In fact, the reduction in flow in rivers crossing the Chad formation is an essential natural process which supports a range of productive ecological and human activities including potable water supplies to villages over a wide area." pp 67.

As is shown in chapters 5 and 6, groundwater resources are used extensively within the floodplain and are of significant economic importance.

2.5 Managing water resources within the Komadugu river basin

In recent decades, the Hadejia-Jama'are wetlands have been affected by drought conditions and by upstream water resource schemes. These developments have had an impact on the extent and pattern of flooding within the wetlands. The hydrological regime of the wetlands has been changed either through the construction of dams which alter the timing and the size of flood flows or through the diversion of surface water and abstraction of groundwater for irrigation (Hollis and Thompson, 1993; Thompson and Hollis, 1995) Figure 2.1 shown earlier shows the larger schemes upstream of the wetlands. A number of developments downstream of these dams and the economic activities of the wetland communities will be affected by the decrease in water supply to the area. Thomas *et al.*, (1993) have also indicated that documented declines in the floodplain's fisheries are related to the reduced flooding resulting from the recent drought conditions and the operation of the Tiga reservoir located upstream on the Hadejia river.

It is possible that the upstream areas have gained significantly from these projects, thereby justifying downstream losses to some extent. However, the impact of the projects on upstream populations has also been ambiguous. Over 13,000 farmers were relocated for the building of Tiga dam and over 100,000 people may have to be moved and compensated for the completion of KRIP (Wallace, 1981). The overall aim of these irrigation schemes was to provide wheat and vegetables for the growing urban population. Farming within the scheme is undertaken on holdings of between 1-2 ha grouped into 12 ha blocks in which coordination of farming activities is expected. Wheat now accounts for around half of the area cultivated. Dry season production of wheat and tomatoes has resulted in the reduction of crop diversity, at the expense of sorghum and millet. Sorgum was discouraged in irrigated area because its cropping patterns interfered with wheat production. Traditional crops such as sorghum and millet were often grown by women farmers and the project has been criticised for denying women access into the irrigation-based agriculture, while rendering their traditional practices obsolete (Jackson, 1985). The reduction in subsistence crops and in women's income (from the extra crop sold in local markets) may also have resulted in poorer health and nutrition for their families.

The performance of such large schemes has generally been rather poor and there are considerable short-falls between actual productivity and targets laid down at their conception (Iliasu and Alsop, 1985). Aminu-Kano *et al.* (1993) note that the Federal Military Government has spent about US$ 3 billion on irrigation development through the RBD, although only 70,000 ha are under large-scale irrigation (Pradhan, 1993).

Finally, there are a number of changes in factor and relations of production for farmers affected by the scheme which have made farmers with access to land, money and labour better off while smaller farmers have been forced off the land (Wallace, 1981). Furthermore, the project based approach has been criticised for failing to include other aspects of rural welfare such as health, education and clean water supply.

2.5.1 Hydrological studies

The impacts of uncoordinated planning has however been felt most sharply within the wetlands where reduced flooding or untimely release of water has caused damage to crops, reduced water supply during dry seasons and caused changes in ecological conditions. By use of a hydrological model of the floodplain, Thompson and Hollis (1995) suggest that the potential hydrological impacts of the completion of the proposed dams and irrigation schemes would affect the productivity of downstream wetlands in terms of less land and less pastures as well as lower groundwater tables. The hydrological model of the river basin is employed to simulate a range of scenarios involving various actual and planned irrigation investments on the Hadejia and Jama'are Rivers. The likely impact of each scenario in terms of reduced flood extent is then estimated[4]. Table 2.5 depicts the various hydrological scenarios.

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[4] Details of the hydrological model and simulations can be found in Thompson, J.R. and Hollis, G.E. 1995.

Table 2.5 Scenarios for Upstream Projects in the Hadejia-Jama'are River Basin

Scenario (Time Period)	Dams	Regulated Releases ($10^6 m^3$)	Irrigation Schemes
1 (1974-1985)	Tiga	Naturalised Wudil flow (1974-1985)	No KRIP-I
1a (1974-1990)	Tiga	Naturalised Wudil flow (1974-1990)	No KRIP-I
2 (1964-1985)	Tiga	None	KRIP-I at 27 000 ha
3 (1964-1985)	Tiga	400 in August for sustaining floodplain	KRIP-I at 14 000 ha
4 (1964-1985)	Tiga	None	KRIP-I at 27 000 ha
	Challawa Gorge	348 yr^{-1} * for downstream users	
	Small dams on Hadejia tributaries		
5 (1964-1985)	Tiga	None	KRIP-I at 27 000 ha
	Challawa Gorge	348 yr^{-1} * for HVP	
	Small dams on Hadejia tributaries		
	Kafin Zaki	None	84 000 ha
	HVP	None	12 500 ha
6 (1964-1985)	Tiga	350 in August	KRIP-I at 14 000 ha
	Challawa Gorge	248 yr^{-1} * and 100 in July	
	Small dams on Hadejia tributaries		
	Kafin Zaki	100 per month: Oct-Mar and 550 in August	None
	HVP	Barrage open in August	8 000 ha

Notes: * Distributed based on Haskoning, 1977

KRIP-I = Kano River Irrigation Project Phase I

HVP = Hadejia Valley Project

Source: Barbier and Thompson, 1997

Scenarios 1 and 1a represent the production of naturalised discharge data for the Hadejia River at the Wudil gauging station downstream of Tiga Dam, under two alternative discharge assumptions. The remaining five scenarios represent the impacts of a range of operating regimes for various combinations of the proposed water resource schemes. The simulation periods for these scenarios are limited to either 1964-1985 or 1964-87. The impacts of the different scenarios are evaluated by assuming that the dams and irrigation schemes were operational at the start of the simulation period and continued to function in the same manner throughout this period.

Scenario 2 investigates the impacts of extending the KRIP-I to its planned full extent of 22,000 hectares. This scenario does not allow for any downstream releases. In contrast, Scenario 3 simulates the impacts of limiting irrigation water to KRIP-I to the existing 14,000 hectares and releasing a regulated flood in August to sustain inundation within the floodplain. Scenario 4 adds the impact of Challawa Gorge and the simulated operating regime involves the year-round release of water for use along the Hadejia River. This scenario repeats the simulation of Tiga Dam and KRIP-I used in Scenario 2, and the added effect of small dams on tributaries downstream of Tiga and Challawa Gorge dams are simulated by reducing the inflows from these tributaries by 25%. Scenario 5 simulates the full development of the four water resource schemes. In this scenario there are no regulated releases except from Challawa Gorge Dam which releases a relatively stable volume of water for use on the Hadejia Valley Project. The final scenario represents an attempt to allow for the full range of the schemes and in addition to maintain a regulated flooding regime for the floodplain. In the case of the Jama'are River, this scenario envisages the construction of Kafin Zaki but no diversions for formal irrigation.

2.5.2 Economic studies

The Barbier, Adams and Kimmage (1993) economic valuation study of the wetlands resources was a response to early concerns raised by hydrological studies of the wetlands. Barbier *et al.* (1993) concluded that the net present value of the agricultural, fishing and fuelwood benefits of the wetlands was between 849 and 1,276 Naira per hectare in 1991, a value much higher than the estimated NPV of the Kano River Irrigation Project (KRIP). The study showed that both on an area and water use basis the total production from *fadamas* of the Hadejia-Nguru Wetlands far exceeds that derived from KRIP. However, the study was unable to measure the value of the groundwater recharge function performed by the annual flooding of the wetlands, although it concluded that the groundwater recharge function is probably the most important function performed by these wetlands. Barbier *et al.* (1993) for example showed that both on an area and water use basis the total production from *fadamas* of the Hadejia-Nguru Wetlands exceeds that derived from KRIP (Table 2.6).

Table 2.6 Present Annual Value Net Economic Benefits*: KRIP and Fadamas

Present Value Net Economic Benefits from Overall Land-Use System	
Kano River Irrigation Project	233 Naira ha^{-1}
Hadejia-Nguru Wetlands	1276 Naira ha^{-1}
Present Value Net Economic Benefits per 000m^3 of Water Used	
Kano River Irrigation Project	0.3 Naira
Hadejia-Nguru Wetlands	565 Naira

** assumes a discount rate of 8% over 50 years and based on 1989-90 values*
Source: adapted from tables 10.4, 10.6 and 10.8 in Barbier et al., (1993).

The above study clearly established a positive value for floodplain agriculture in the wetlands. Barbier and Thompson (1997) expands on the above analysis and suggests that the construction of the proposed dams would have a large impact on floodplain production. In Table 2.7, the estimated floodplain losses are indicated for Scenarios 2-6 compared to the baseline Scenarios 1 and 1a. The high productivity of the floodplain is evident in the losses in economic benefits due to changes in flood extent for all scenarios are large, ranging from US$2.2 - 20.8 million. Scenario 3, which yields the lowest upstream irrigation gains, also has the least impact in terms of floodplain losses, whereas Scenario 5 has both the highest irrigation gains and floodplain losses.

The hydrological simulations are combined with the economic estimates of floodplain agricultural, fishing and fuelwood benefits and the returns to the Kano River Irrigation Project - Phase 1 (KRIP-I) (Barbier *et al.*,1993). These are used to determine for each scenario the likely overall gains in terms of economic benefits of additional upstream irrigation production versus the subsequent losses in floodplain benefits from reduced flooding. Table 2.7 below also depicts the net balance between losses of floodplain production benefits and gains in the value of large-scale irrigation production as well as the proportionate comparison of irrigation gains to floodplain losses. Barbier and Thompson (1997) confirm that in all the scenarios the additional value of production from large-scale irrigation schemes does not replace the lost production attributable to the downstream wetlands, since it is evident that gains in irrigation values account for at most around 17% of the losses in floodplain benefits.

Table 2.7 **Scenarios 2-6 Compared with Naturalized Scenarios 1 and 1a: Losses in Floodplain Benefits versus Gains in Irrigated Production, Net Present Value**

		Scenario 1			Scenario 1a		
	Irrigation Benefits [1] a/	**Floodplain Loss** [2] b/	**Net Loss** [2] - [1]	**[1] as % of** [2]	**Floodplain Loss** [3] b/	**Net Loss** [3] - [1]	**[3] as % of** [2]
Scenario 2	682,983	-4,045,024	-3,362,041	16.88	-5,671,973	-4,988,990	12.04
Scenario 3	354,139	-2,558,051	-2,203,912	13.84	-4,184,999	-3,830,860	8.46
Scenario 4	682,963	-7,117,291	-6,434,328	9.60	-8,744,240	-8,061,277	7.81
Scenario 5	3,124,015	-23,377,302	-20,253,287	13.36	-24,004,251	-20,880,236	13.01
Scenario 6	556,505	-15,432,952	-14,876,447	3.61	-17,059,901	-16,503,396	3.26

Notes: a/ Based on the mean of the net present values of per hectare production benefits for the Kano River Irrigation Project Phase I applied to the gains in total irrigation area. (US$ 1989/90 Prices)
b/ Based on the mean of the net present values of total benefits for the Hadejia-Jama'are floodplain averaged over the actual peak flood extent for the wetlands of 112,817 ha in 1989/90 and applied to the differences in mean peak flood extent.

Source: Barbier and Thompson, 1997

Barbier and Thompson (1997) conclude that the expansion of the existing irrigation schemes within the river basin results in negative net benefits and that the planned construction of Kafin Zaki Dam and extensive large-scale formal irrigation schemes within the Jama'are Valley are inappropriate developments for this part of the basin. The effects of the construction of the Kafin Zaki Dam and formal irrigation within the basin may be mitigated to some extent by the introduction of a regulated flooding regime (Scenario 6) which would reduce the scale of this negative balance to around US$14.8-16.5 million. However, the overall combined value of production from irrigation and the floodplain would still fall well below the levels experienced if the additional upstream schemes were not constructed.

Irrigation benefits in upstream areas may increase as a result of improved management practices and improved farming techniques, and it is therefore possible that the above noted net losses may be lower. This is likely since the full potential of the upstream projects has not been reached and particularly since the above analysis includes only the net benefits from KRIP Phase I. However, the above analysis does not include the impact of these developments on the groundwater regime and associated welfare losses. As noted earlier, hydrological studies of the area suggest that maintainence of groundwater resources is possibly the most important function performed by the flooding and may have implications for areas beyond the wetlands as well. Therefore, although the estimation of the full benefits of all the upstream projects is beyond the scope of this thesis, estimating the indirect benefits of the wetlands, in terms of providing groundwater recharge, could serve to improve the analysis and contribute to future work on the evaluation of the upstream projects as well as to the more general area of valuing ecosystem functions.

We can estimate groundwater changes based on each of the above noted scenarios. In calculating changes in groundwater levels we consider the base scenario as being 5000 km^2 of flood extent. No estimates of the area of the alluvial aquifers are currently available. Therefore a range of aquifer areas have been used in the calculations presented in Table 2.8. Changes in flood extent predicted from the simulated results of scenarios 2 - 6 are used to calculate changes in groundwater elevation using the regression relationships between flood extent and water table change depicted in table 2.8 below:

Table 2.8 Summary of relationship between flood extent and water table change

Scenario	Final Storage ($10^{6}m^3$)	Change in Storage ($10^{6}m^3$)	Difference in Storage from Naturalised Conditions ($10^{6}m^3$) Scenario 1	Scenario 1a	WT Elevation (from 100 m)	Change in WT Elevation (m)	Difference in WT Elevation Conditions (m) from Scenario 1	Scenario 1a
Actual	4294.27	5705.73	-16.13	-136.30	93.80	6.20	-0.02	-0.15
Scenario 1	4310.40	5689.60	x	x	93.82	6.18	x	x
Scenario 1a	4430.57	5569.43	x	x	93.95	6.05	x	x
Scenario 2	3291.21	6708.79	-1019.19	-1139.36	92.69	7.31	-1.13	-1.27
Scenario 3	3573.75	6426.25	-736.65	-856.81	93.00	7.00	-0.82	-0.95
Scenario 4	3227.05	6772.95	-1083.35	-1203.52	92.61	7.39	-1.21	-1.34
Scenario 5	459.74	9540.26	-3850.66	-3970.83	89.54	10.46	-4.28	-4.41
Scenario 6	3226.53	6773.47	-1083.86	-1204.03	92.61	7.39	-1.21	-1.34

Source: Thompson and Goes, 1997 and Thompson, pers. communication

The monthly change in water table elevation (column 3) is calculated for each scenario by setting the initial groundwater elevation at an arbitrary level of 100 m a.s.l (metres at sea level). The monthly changes in water level were evaluated for each month of the simulation period using $\Delta WT = \frac{EGR}{S_y}$ where *WT* is the height of the water table, *EGR* is the equivalent groundwater recharge (m) and S_y is the specific yield of the aquifer (set at 15%). This is the depth of water which is added to (or removed from) the aquifer throughout its spatial extent. *EGR* does not equal the change in water table elevation since this depth of water must be incorporated within the pore spaces of the aquifer. Column 4 is the difference in groundwater levels for each scenario, when compared to the water table elevation under scenario 1 and scenario 1a (Thompson and Goes, 1997 and Thompson, 1998, pers. communication).

Although a range of aquifer areas have been used in the above calculations, it is suggested that the area of the alluvial aquifer is likely to be towards the higher end of this range (Thompson and Goes, 1997). It is clear that all the scenarios will result in changes in excess of 1 metre. In chapters 5 and 6 therefore we hypothesise a drop in groundwater level by 1 metre as a result of decreased recharge and calculate associated welfare changes in agricultural production and domestic water consumption.

2.6 Conclusions

This chapter has discussed the water diversion schemes affecting water flow in the Hadejia and Jama'are rivers and traditional water use systems within the floodplain wetlands. In the next chapter, an optimal control model is developed to maximize the net benefits of the water use alternatives and related benefits. It is evident from the above presented background of the study area that, at least in terms of agricultural production, point estimates of net average benefits from water use in downstream and upstream areas of the river basin do exist. However, the analysis continues to lack the necessary data for valuing the groundwater recharge function of the wetlands. The comparison of net benefits from water use within the Komadugu Yobe basin is not complete without a representative value for groundwater recharge, identified as the most important ecosystem function performed by the Hadejia-Jama'are floodplain.

The economic valuation study presented in chapters 4 and 5 identifies domestic water consumption and agricultural use as two of the main uses of groundwater within the floodplain. In chapter 7 we return to the policy implications of the valuation studies, with regard to the construction of some of the water projects detailed here. We use Tables 2.7 and 2.8 in conjunction with the results from chapters 5 and 6 to draw some general conclusions regarding the welfare impacts of water project development within the Komadugu-Yobe river basin.

Chapter 3

An Optimal Control Approach to Floodplain Management

3.1 Introduction

The model developed in this chapter will draw on literature on river basin planning and optimal use of groundwater resources to examine water resource management in the Komadugu-Yobe river basin in Northern Nigeria described in chapter 2. The physical system is first described briefly and the economic components of water resource use within the river basin are identified. Two optimal control models are then developed to maximise net benefits of water used in productive activities across the river basin, subject to the physical and economic constraints defined.

In order to maximise the net present value of water resource use in a river basin, such as the Komadugu -Yobe river basin, both upstream and downstream development options, and surface water-groundwater interactions are considered. The three main uses of water resources within the river basin can be identified as: 1) irrigation for agricultural production in upstream areas; 2) downstream floodplain uses including agriculture, fishing and forestry; and 3) groundwater abstraction for irrigation and drinking water supplies. Groundwater resources are maintained through the regular inundation of the floodplain wetlands and recharge of these resources is therefore an important indirect benefit of the wetlands. The basin wide economic value of water resources therefore includes benefits derived from upstream uses, floodplain use and groundwater recharge.

The aim of this chapter is to explicitly show the effect of ignoring the value of the wetlands in providing indirect benefits through continued ecosystem functions, such as groundwater recharge. The two models presented in this chapter consider the benefits of water use for upstream diversions as well as the direct and indirect benefits derived from the wetlands. The first model presents the problem as a simple maximisation of net benefits derived from upstream use of water and net benefits derived from the direct benefits of the wetlands. The second model expands on this model to include the value of groundwater use. The analysis shows that including the value of groundwater use reduces the rate of diversion for upstream uses over time.

The following sections present a review of the underlying hydrological and economic concepts that motivate this analysis. Some of the relevant literature on river basin planning and optimal control models of resource use is introduced in section 3.2. Water use within the river basin is then described in section 3.3, using an economic framework of resource utilisation. The specific economic and hydrological relationships required to develop the optimal control models are introduced. The two models are then presented consecutively, with the second model incorporating net benefits derived from groundwater use in the objective function. The dynamics of the system are examined in section 3.4 using comparative statics where the impact of including or ignoring the value of groundwater use is examined with respect to changes in the rate of upstream diversions over time.

3.2 Underlying concepts

There are two broad areas of literature relevant to the present modelling process. These areas cover river basin planning concepts and optimal control models of surface and groundwater resource use.

The "water budget" or "water balance" is an integral management tool used in river basin and watershed planning. The water budget essentially refers to the balancing of inputs and outputs of water (in any form) that affect the river basin or watershed. However, the water budget is used to make development decisions at a particular section of the river basin and has little to say about water flow in other portions of the affected waterway. In fact, river basin characteristics and streamflow are important environmental factors which, in conjunction with other physical effects such as diversions for irrigation, determine infiltration rates, flood flows and other variables. Upstream reservoirs and dams interrupt the continuous transfer of water and sediment, changing the channel flow regime, sediment transport rates, channel morphology, water quality, water temperatures and dissolved oxygen levels in downstream portions of the river (Wilcock, 1988).

By far the greatest use of water from rivers, wetlands and aquifers is for irrigated agriculture. Agriculture accounts for nearly three-quarters of the total global consumption of water (Thanh, 1990). Upstream irrigation projects are often developed to divert water to areas where agricultural production is limited largely by the availability of water. Although there are clearly benefits associated with such developments, there may also be important impacts on downstream areas which need to be considered. In their discussion of the management of the Colorado River Basin, El-Ashry and Gibbons (1986) state that "in a sense, developing and using the Colorado River water to irrigate low-valued crops in the Upper Basin is a double insult: the total basin-wide economic return to water could be increased if more of it were allowed to flow downstream to be used eventually in the Lower Basin, and the salinity problem would decrease."pp 32

The development of upstream dam and irrigation projects on the Hadejia and Jama'are rivers has resulted in diversion of water from the rivers, resulting in less water reaching the downstream wetlands. The impact of upstream diversions on flood extent within the wetlands has been studied by hydrologists and a hydrological model of the river basin has been developed to simulate a range of hydrological scenarios for the water allocation within the river basin (Hollis and Thompson, 1993). These scenarios are developed by estimating water demand in upstream areas based on dam storage potential and irrigation projects such as KRIP and HVP (see chapter 2 for more detail on these irrigation schemes and dams; Hollis *et al.*, 1993; Barbier and Thompson, 1997). Based on these scenarios and simulations of flood extent within the wetlands, an economic valuation of benefits derived from upstream and floodplain water use indicates that dam construction and channelisation will adversely affect floodplain production and may not be viable (Barbier and Thompson, 1997). However, these simulations are based not on optimal use of water within the river basin but on inferred demand for water in upstream areas and a perceived need to maintain a minimum level of flooding within the wetlands. In fact, any constraint placed on surface water flow from the upper to the lower watershed must ensure that the marginal benefit of flow to the lower watershed should equal the marginal cost to the upper watershed. The hydrological model (Hollis and Thompson, 1993; Thompson, 1996) places constraints based on water demands at an arbitrary point in time and not on optimal allocation rules based on efficiency.

The approach taken by ecological-economic or hydrological-economic models integrate concepts from both hydrology and economics and develop a more complete analysis of water resource management. A resource system such as a wetland is characterised by a set of functions defined by the utilisation of the resource and the resultant ecological and economic linkages. The nature of the interaction between the bio-physical and economic characteristics of the system is determined both by the supply and the demand of the resource. Typically, in optimal control models, production decisions are influenced by the application of environmental constraints and the interaction of the physical and economic systems is modelled as a problem of maximising the discounted flow of net social benefits to society over time.

Water resource allocation is basically a special case of natural resource allocation problems encompassing stocks and flows of the resource. From the social welfare point of view therefore, the maximisation of long run benefits from the resource can be accomplished by the efficient allocation of the resource among the competing uses in present and future periods. Resource allocation between uses is, however, also governed by the physical or hydrological state of the system.

Economic-ecological models of groundwater use generally consider that the physical behaviour of an aquifer is determined by its storage capacity, recharge, water depth and water quality, all of which will be affected by changes in its hydrological or physical characteristics, whether natural or human instigated (Burt, 1967; Saleth, 1991; Provencher and Burt, 1994). Some literature also exists on the conjunctive use of surface and groundwater resources and is in fact becoming the dominant literature in this area. Where there is interaction between ground and surface water bodies, it has been noted by Burt (1976) that "the inherently random nature of surface water supplies and the natural recharge to an aquifer give ground stocks an important role as a contingent supply for times when the flow components of supply are below average. Optimal intertemporal allocation of groundwater used conjunctively with surface water will impute a higher value to the surface water than it would have in an unmanaged basin." pp. 76. Similarly, Tsur and Graham Tomasi (1991) refer to this as the "buffer value of groundwater" and define it as "the difference between the maximal value of a stock of groundwater under uncertainty and its maximal value under certainty where the supply of surface water is stabilised at its mean." pp.201.

Whereas most of the literature studies the use of ground and surface water on the same parcel of land, the models developed in this chapter assume that floodwater and groundwater are used on different parcels of land. Although this is not strictly true, since floodwater and groundwater do serve the same general area, shallow tubewell irrigation using groundwater occurs only during the dry season, when the floods have receded, and so we assume that the benefits derived from flood and groundwater are spatially separated. In the next section, the underlying economic and hydrological relationships within the Komadugu-Yobe river basin are discussed. These relationships will be used to develop relevant hydrological-economic optimal control models for the river basin.

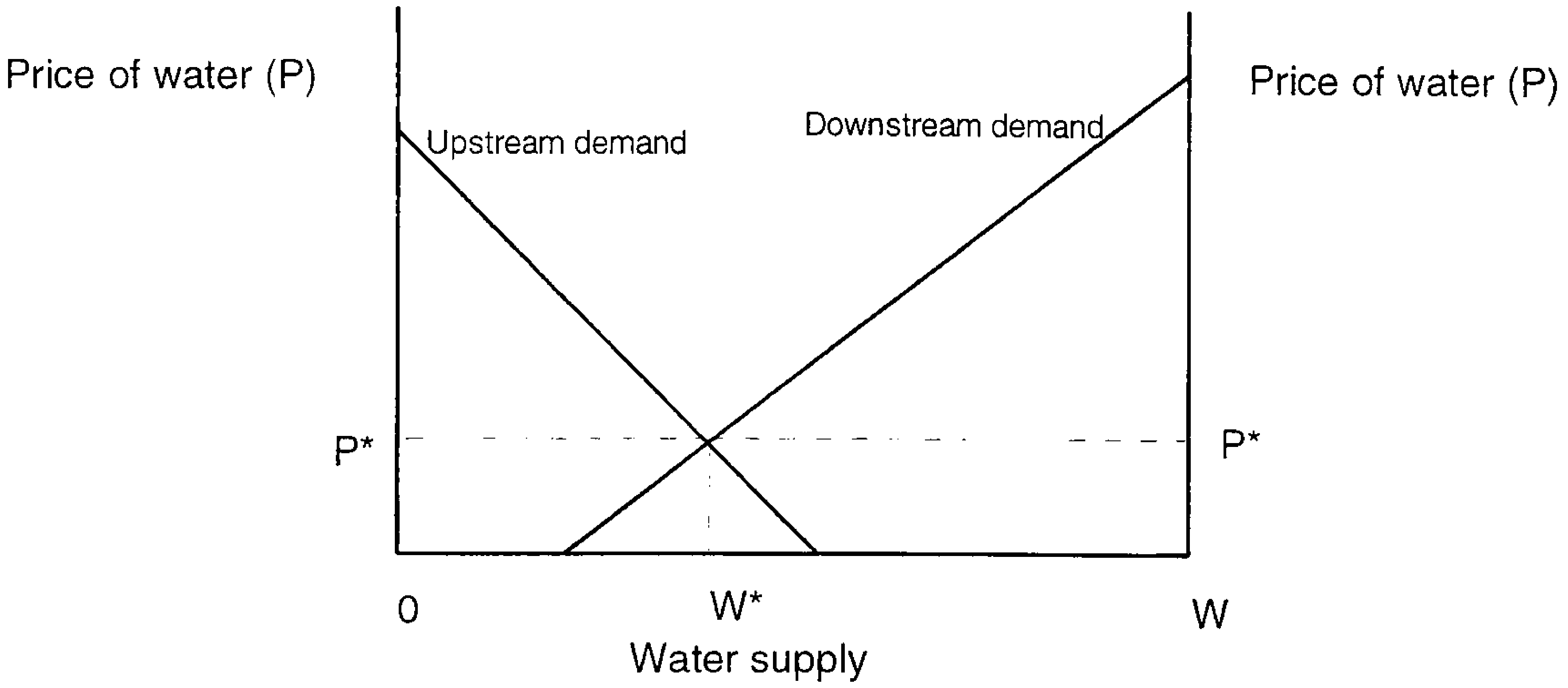
3.3 Optimal water allocation in the Komadugu-Yobe river basin

The Hadejia-Nguru wetlands are maintained by the regular flooding of the Hadejia and Jama'are rivers. However, as described in chapter 2, irrigation projects and drinking water supply projects in areas upstream of the wetlands are supplied by water diverted from the rivers. This diverted river flow feeds the upstream projects but the resulting decreased river flow results in reduced flooding within the wetlands. Reduced flooding, as has been noted in chapter two, could imply reduced groundwater recharge and lower water tables within the wetlands. We can therefore expect that increasing competition from upstream uses and declining groundwater tables will affect the benefits derived from water use in floodplain agriculture and groundwater irrigated agriculture within the wetlands. On the other hand, irrigated agriculture and water supply schemes in upstream areas have an associated social welfare and this must be considered by water allocation decisions as well.

The hydrology of the system in the Komadugu-Yobe river basin can be described by a river which supports upstream diversions and a floodplain wetland, and the wetland recharges an aquifer. The river basin covers an area over 84,000 km^2. The regional demand for water comes from two main areas and is supplied by surface and groundwater resources. Competing uses of water resources therefore require information on the net benefits derived from their use. In the first instance, an optimal control model is used to maximise joint benefits from water diversions and from floodplain benefits. The model is then extended to include net benefits derived from water supply from the shallow aquifer. Groundwater management in the Hadejia-Nguru wetlands is characterised as a renewable resource management problem since the aquifer is recharged through precipitation and seepage from the overlying wetlands.

In a static analysis, economically efficient water allocation will occur when the marginal values of water use in upstream and downstream areas are equated and equal to the marginal costs of supplying water. This is seen in figure 3.1, where price of water (*P*) is the cost of supplying water:

Figure 3.1 Optimal allocation of water in a river basin: a static analysis



In the above graphical representation, *W** is the equilibrium point at which price is equal to demand. Hence, if the total water available is *W*, optimal water allocation would be *OW** for upstream users and *WW**for downstream users. However, when resource prices are not observable, the above simple analysis cannot be used. In the case of the Komadugu-Yobe river basin where there are no market prices for water supply and little or no information exists on demand functions for water used within the river basin, we need to use a different approach. Due to the complexities of the water resource system and the interdependent nature of the various components, intertemporal optimal allocation of water between uses within the river basin (whether actual or proposed) is difficult in the absence of proper market signals.

It is therefore most appropriate to define the entire system as a welfare maximisation problem with the objective of maximising net benefits of water used within the entire system. In 1993 participants from the Federal Ministry of Water Resources and Rural

Development, the River Basin Development Authorities, State Governments, and conservation and development organisations took part in a workshop held at Kuru and organised by the Hadejia-Nguru Wetlands Conservation Project and the National Institute for Strategic Studies (NIPSS, 1993). The recommendations arising from this workshop included that the existing dams within the basin should be operated to "satisfy the water supply, irrigation, groundwater recharge and flooding requirements of both upstream and downstream communities" (NIPSS, 1993, pp 41). Since developing a water management plan for the Komadugu-Yobe river basin is a key objective for the area and one that involves various river basin development authorities, the analysis presented in this chapter could serve to aid in the process. We use a dynamic approach in the models presented below because the planner is concerned with the rate of diversion of water from the flood, with a view to maximizing the present discounted value of the flow of net benefits. The dynamic approach also allows us to analyse the time path of diversion of water for upstream uses and changes in the flood stock for downstream users.

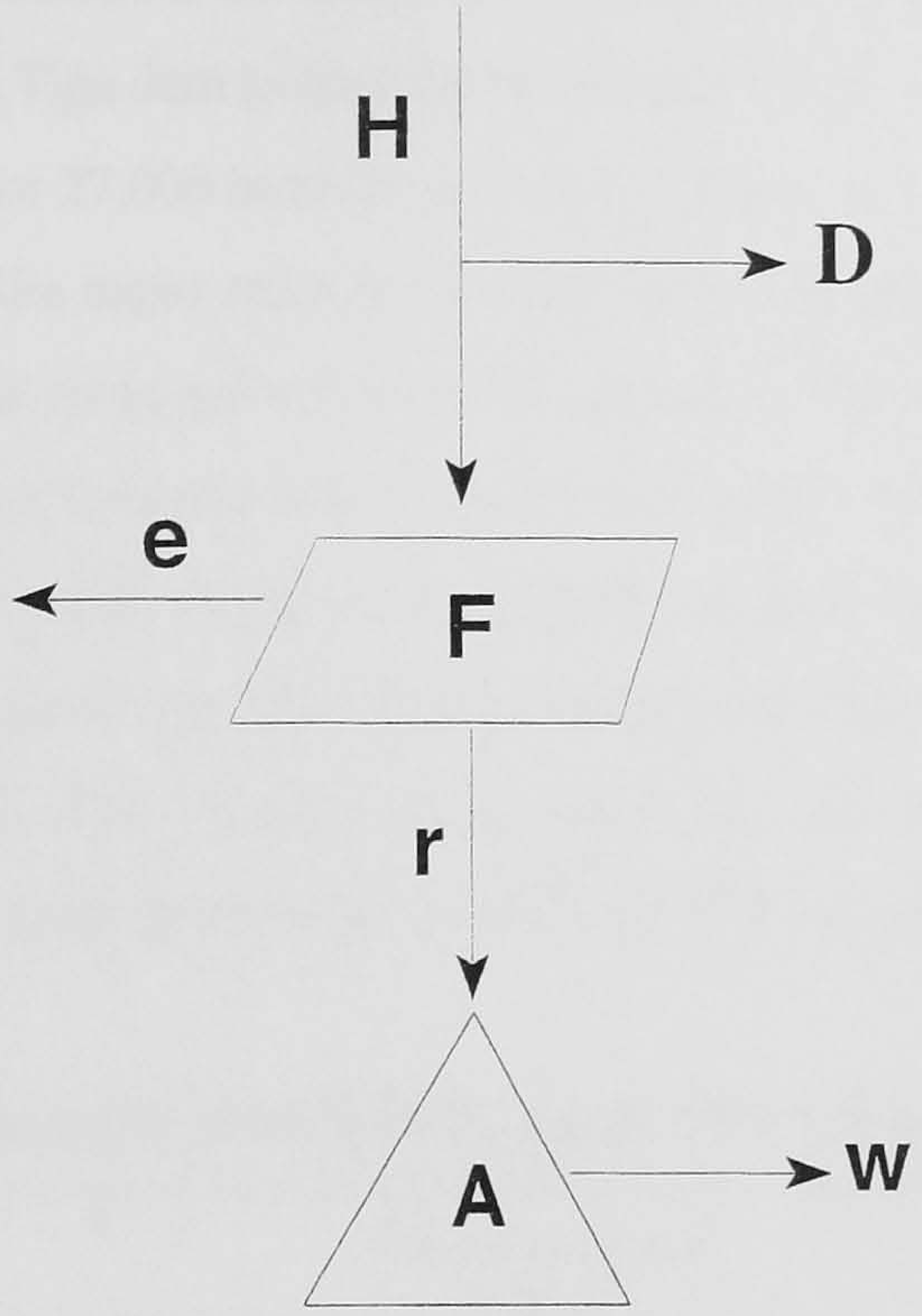
We base our analysis on the underlying production functions and cost functions associated with water use in upstream and downstream activities. An optimal control model framework is used to illustrate how the net benefits of water use can be maximised across the river basin. The interaction of the physical and economic systems is therefore defined as a problem of maximising the discounted flow of net social benefits over time. The net benefits (both direct and indirect benefits) derived from diverted water and flood water are maximised based on the physical and economic constraints for each sub-system, described in greater detail below.

The schematic flow diagram shown in Figure 3.2 shows the key hydrological linkages between water uses and sources of water within the Komadugu-Yobe river basin. These linkages form the basis of the optimal control models developed below. Diversion from river flow (H) is represented by D. This diversion determines the flood extent (F) which is a crucial source of recharge (r) to the underlying groundwater aquifer (A). As the next sections describe, upstream economic activities, i.e., irrigated agricultural production, is dependent on the amount of diverted water which is determined by the rate of diversion $D(t)$. Floodplain productive activities are dependent on the stock of flood $F(t)$, net of all losses due to evaporation, while downstream uses dependent on groundwater (i.e., irrigated agricultural production and domestic water consumption) are affected by $W(t)$, the rate of abstraction where t is the time period. In the models developed below, $D(t)$ and $W(t)$ are flow variables; F and A are stock variables. Model one maximises net benefits of water used in upstream and downstream areas without taking into account groundwater use and model two includes the value of groundwater use. The results of the two models are then analysed and discussed further in section 3.4.

3.3.1 Water use within the river basin

Within the river basin there are two main uses of surface water which may be differentiated spatially as upstream use and downstream or floodplain use. In addition, there is extensive use of groundwater resources in the downstream portion of the river basin. A number of productive activities utilise these water resources and are therefore dependent on the hydrological linkages illustrated in Figure 3.2 above. The value of water used in these activities is of interest to us in understanding how benefits within the river basin may be affected by water allocation policies. In this section therefore we examine the main uses of water in upstream production and floodplain production, including benefits derived from groundwater abstraction.

Figure 3.2 Schematic diagram showing the hydrological linkages within the Komadugu-Yobe river basin



Symbols:

H	:	river flow
D	:	diverted flow from river
F	:	extent of flood
e	:	evaporation rate from floodplain
r	:	recharge rate from floodplain to aquifer
A	:	groundwater, net of losses due to evapotranspiration and regional flow
W	:	withdrawal from aquifer

Upstream production

The principal threat to the floodplain comes from extensive upstream irrigation schemes. The largest of these schemes is the Kano River Irrigation Project (KRIP) with water supplies being provided by the Tiga dam located on the Hadejia River. The KRIP project is designed to provide irrigation for 27,000 hectares in the first phase and an additional 40,000 hectares in the second phase. The major crops grown during the wet season are rice, maize, cowpeas, and millet and the main crops grown in the dry season are tomatoes and wheat. The second major irrigation scheme is the Hadejia Valley Project (HVP) which is still under construction and is intended to provide irrigation for 12,500 hectares when completed. The HVP is supplied by the Challawa Gorge dam located upstream of Kano. The dam is also expected to provide water for other riparian users and Kano city water supply. The estimated monthly and annual water demand by KRIP and HVP are presented in table 3.1 below.

Table 3.1 Water demand from KRIP(I) and HVP ($10^6 m^3$)

	Monthly demand ($10^6 m^3$)												Annual demand
	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	
KRIP (I)	35.9	20.5	22.8	16.4	10.5	37.6	37.1	22.3	29.6	53.3	57.4	46.9	390
HVP	52.6	41.0	35.5	18.2	5.4	29.4	34.4	26.5	29.0	38.5	44.3	59.2	414

Source: Diyam (1996)

We assume that the main productive use of water diverted by these schemes is in agriculture. Agricultural production in upstream areas is assumed to depend upon the current rate of diversion, $D(t)$, and the cumulative amount of diverted water at time t, $\int_0^t D(t)dt$, as well as on a number of other variable inputs. We make this assumption because the dams constructed along the river hold large quantities of water in reservoirs. These reservoirs are then used to provide irrigation water to upstream farmers. If the total amount of water diverted to upstream areas increases, this could happen either through filled reservoirs or new dams being constructed. We therefore expect that the total irrigated area in upstream areas could increase. Furthermore, since newly irrigated areas would respond favourably to water inputs, the more water diverted in the current period, the higher will be the aggregate output. Farmers are assumed to be price takers, i.e., we expect that the price effects resulting from changes in crop acreage would be small. As indicated in Figure 3.2, the change in the extent of downstream flooding will be determined by the cumulative amount of water diverted upstream, i.e., $F(t)-F(0) = -\int_0^t D(t)dt$

Upstream production for farmers can thus be described by the following production technology:

$$Y_1 = f_1(x_i,...x_j,D,F(0)-F(t)) \qquad \mathbf{(3.1)}$$

where: $F(t) = F(0) - \int_0^t D(t)dt \ ; F(0) = F_0; D(0) = 0$

Y_l : an agricultural good

x_i: variable inputs (for $i = 1,...j$)

$D(t)$: diverted river flow used as water input

$dY_l/dD > 0$;

$dY_l/d[F(0)-F(t)] > 0$

$Y_l(.)'' < 0$

Note that the subscript t has been dropped for notational convenience. We assume that the production function for the agricultural good Y_l is increasing, concave and twice differentiable. The partial derivative, $dY_l/d[F(0)-F(t)]$, is positive, suggesting that aggregate agricultural production increases with an increase in the total amount of water diverted up to time t. This implies that every time water is diverted, the total amount of water available for irrigation in upstream areas increases, thus, effectively, increasing total irrigated area used in upstream agricultural production. However, it is also argued that newly irrigated areas generally receive a greater boost to yields initially with a new injection of water input (Carruthers and Clark, 1981). Thus, the more water diverted in the current period, the higher the aggregate output and $dY_l/dD > 0$.

If we consider that the price of the agricultural output, P_a, varies according to the inverse demand curve for the good, i.e.,

$$P_a = P_a(Y_1) \qquad \text{where} \quad P_a^{/}(Y_1) < 0 \tag{3.2}$$

and we assume that $P_a(Y_1)$ is a reasonable approximation to the income compensated demand curve, then the net benefits from *Y(t)* are measured as the area under the demand curve integrated from 0 to *Y(t)*, less the costs of inputs. That is to say, our welfare measure, S_i, is the sum of consumer and producer surplus associated with the production of *Y*, and can be expressed by the net benefit function $B^1(D, F(0)-F(t))$, where:

$$B^1(D,F(0)-F(t)) = \int_0^{Y_1} P_a(Y_1)dY_1 - \mathbf{c}_x\mathbf{x}_J - c_1 D \tag{3.3}$$

for all *i* and where $\mathbf{c}_x\mathbf{x}_J$ is the vector of costs associated with the use of variable inputs in the production process[1]. Since there is a social opportunity cost associated with diverting this water, $c_1 D > 0$. Note, however, that in actual production decisions, farmers in upstream areas face no water charges[2].

Floodplain production

As has been noted earlier (see chapter 2 for greater detail), the Hadejia-Nguru wetlands are highly productive in terms of agricultural production and other resources. The change in flood extent in the wetlands, as is shown in Figure 3.2, is determined by the level of diversion. In addition, floodplain water may be lost due to evaporation and infiltration to groundwater. It is the remaining water net of evaporation and infiltration losses that is then available for floodplain activities such as floodplain and recession agriculture, fishing and forestry.

For the purpose of our analysis, we assume that floodplain agriculture is the main productive

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[1] For convenience of notation this is written as $\mathbf{c}_x\mathbf{x}_J$ for all the agricultural production functions described later in this chapter. However, each production function will have its own, unique vector of associated input costs.

[2] If there are no water use charges for farmers *and* no externalities, then we could assume zero costs of diversion, i.e. $c_1 D = 0$, by further noting that investments in pipes, dams etc., have already been made.

use of water within the floodplain and we further assume that evaporation losses are accounted for in the level of F. Hence, F represents the maximum amount of water stored on the floodplain at time t, net of evaporation losses and available for use by floodplain activities.

The water available on the floodplain (F) is used with other inputs ($x_i...x_j$) to produce an agricultural good (Y_2)[3]. This is described in chapter 2 as floodplain and recession agriculture where farmers utilise flooded areas and soil moisture to grow crops. Farmers are assumed to be price takers and produce agricultural goods similar to those produced by upstream farmers, i.e., vegetables such as tomatoes, onions and grains such as wheat, rice, millet. We therefore use the same notation to describe costs associated with the use of variable inputs in the production process for floodplain agriculture.

We assume that the production function for the agricultural good Y_2 is increasing, concave and twice differentiable with respect to its inputs and can be expressed as:

$$Y_2 = f_2(x_i,\dots,x_j,F) \tag{3.4}$$

Since Y_1 and Y_2 are similar agricultural products and are both produced for the same local and regional markets, we assume that both upstream and floodplain producers face the same inverse demand schedule for agricultural production, i.e., $P_a(Y_1) = P_a(Y_2) = P_a(Y)$. The net benefit or welfare function for floodplain agriculture, $B^2(F)$ is expressed as:

$$B^2(F)=\int_0^{Y_2} P_a(Y_2)dY_2-\mathbf{c_x x_J} \tag{3.5}$$

where the benefits derived from the floodplain agriculture are the value of the production less the costs of variable inputs, assuming constant prices. Note that since that the floodplain water is not diverted and is used *in-situ*, there are no costs of diversion associated with this sector.

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[3] The other main uses of floodwater are fishing and forestry. Net benefits from these activities can be similarly described by appropriate production functions. However, to keep the analysis simple and to maintain symmetry between the sectors we include only agricultural production in the model.

Production activities using groundwater

As noted in chapter 2, the floodplain provides various environmental benefits such as groundwater recharge and habitat for migratory waterfowl (Hollis *et al.*, 1993). These environmental benefits are *indirect* benefits deriving from the regular inundation of the floodplain. Groundwater recharge is regarded as possibly the most important environmental function supported by the wetlands.

Groundwater is used within the wetlands for two main uses, namely, dry season agricultural production and domestic water consumption. Irrigation is carried out mainly with the use of small pumps and shallow tubewells and draws water from the shallow aquifer within the wetlands. Domestic water use also relies on the shallow aquifer, and water is abstracted from village wells. We define W as the total volume of water abstracted from groundwater, w_1 as water abstracted for use in dry season irrigated agriculture and w_2 as water abstracted from groundwater to meet domestic demand within the wetlands, where:

$$W = w_1 + w_2 \tag{3.6}$$

Irrigated agricultural production

Water abstracted for irrigation (w_1) is combined with other resources $(x)_i$ and is used to produce an agricultural good (Y_3)[4].

$$Y_3 = f_3(x_i,\ldots,x_j,w_1) \tag{3.7}$$

In this case, because of the use of shallow tubewells to abstract water, there is a cost associated with water abstraction for irrigation. This pumping cost is represented by $c_{w1}(r)$. Pumping costs are assumed to vary inversely with the height of the water table. We assume that costs are depended on the recharge rate since lower water levels in the aquifer would result in higher pumping costs, assuming no technological change (see chapter 6 for further discussion and for an estimation of the welfare effect of a change in the recharge rate on agricultural production dependent on groundwater abstraction).

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[4] Note that we assume that the diverted water, the flood and the groundwater serve distinct areas. The area irrigated by flooding is not irrigated by groundwater abstraction and vice versa.

We assume that an inverse demand curve for this sector exists and is also equal to $P_a(Y)$. The benefit function associated with agricultural production using groundwater, $B^3(w_1)$, can then be expressed as:

$$B^3(w_1)=\int_0^{Y_3}(P_a(Y_3)dY_3-\mathbf{c}_x\mathbf{x}_J-c_{w_1}(r)w_1) \qquad \textbf{(3.8)}$$

where P_a is the per unit price for the agricultural good Y_3, $\mathbf{c}_x\mathbf{x}_J$ is the vector of costs associated with inputs.

Domestic water consumption

Groundwater is also used for domestic use and as drinking water. Water is abstracted using a simple technology comprised of a rope and a rubber bucket. Households may collect their water or alternatively may purchase it from vendors. Vendors however also use the same technology and the same village wells to abstract water. Hence we assume that abstracted water (w_2) is combined with household labour (L) to meet water demand for domestic consumption.

$$Y_4=f_4(L,w_2) \qquad \textbf{(3.9)}$$

Let P_w be the shadow price of water used for domestic consumption. Then $P_w(w_2)$ is the inverse demand for groundwater abstracted for domestic consumption. The benefit function for this use is $B^4(w_2)$ and is described as:

$$B^4(w_2)=\int_0^{w_2}P_w(w_2)dw_2-c_{w_2}(r)w_2 \qquad \textbf{(3.10)}$$

where $c_{w2}(r)$ is the cost of abstracting w_2, and $\partial c_{w2}/\partial r<0$. This cost represents the opportunity cost to the household of abstracting water from village wells. For those households who collect water themselves, this cost is the opportunity cost of labour used in other productive household activities. For households purchasing their water c_{w2} represents the delivery cost of vended water to the households. We assume that there are no other variable costs associated with c_{w2}. Abstraction costs from the aquifer depend inversely on the height of the water table and as this will affect the level of water in village wells, we assume costs are a decreasing function of recharge (see chapter 5 for a further discussion and for an estimation of the welfare effects resulting in increases in abstraction costs due to changes in recharge rate).

3.3.2 Hydrological linkages within the floodplain

The previous section defines the economic relationships which define productive activities across three main sectors within the river basin and Figure 3.2 generalizes the key hydrological relationships between these sectors. The physical/hydrological relationships underlying these production sectors form the basis of the optimal control models developed in this chapter. These linkages are therefore described in this section in terms of how they affect hydrological conditions within each sector, and across the sectors.

Equations governing the floodplain

We assume that flooding changes in each time period, with changes in flooding affected by the level of diversion in the present period. Diversions from the flood are taking place continuously, e.g., by varying the level of water held behind a dam, and the only factor determining the rate of change in the level of flooding on the floodplain is the control variable $D(t)$, which is the level of diversion in time t. The flood stock is therefore equal to the initial flood stock, $F(0)$, less the total amount of diverted water.

$$F(t) = F(0) - \int_0^t D(t)dt \qquad \textbf{(3.11)}$$

Differentiating (3.11) with respect to time, the equation of motion for the flood stock is given by[5]:

$$\begin{aligned} \dot{F} &= -D(t) \\ F(t), D(t) &\geq 0 \\ F(0) &= F_0 \end{aligned} \qquad \textbf{(3.12)}$$

Equation (3.12) describes the change in flood stock over time and defines the initial stock of flood. It also dictates that there can be no negative values for diversions or for the flood

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[5] A dot above a variable denotes the time rate of change of that variable, i.e., $\dot{F}(t) = \partial F(t)/dt$

stock. Furthermore, if $F(t) = 0$, $D(t)$ must also equal 0, implying that $\dot{F}=0$.

Equations governing the aquifer

In an aquifer, abstraction costs are seen to rise as the water table falls and, under an uncontrolled regime, even if the social benefits of the water exceed extraction costs, these costs may be economically excessive. Change in stock is therefore a function of abstraction rate and recharge (for a renewable aquifer). The recharge rate of an aquifer may be increasing, constant or decreasing at any time depending on a number of physical and hydrological constraints. The effect of a fall in water table is subsequently reflected in increasing marginal costs of extraction in economic-hydrological models.[6]

We use the basic groundwater model (see for example Burt, 1967; Gisser and Sanchez, 1980) and assume that groundwater stocks adjust over time in response to withdrawals and recharge (in the case of a renewable aquifer).[7] The equation of motion defines changes in aquifer stock levels (A) and is normally a function of recharge and withdrawal.

Recharge ($r(t)$) is decreasing and concave with respect to stock and $r(\bar{A})=0$, where $\bar{A}$ is the maximum level of storage in the aquifer. As the aquifer stock declines, recharge increases at a diminishing rate. While there may also be some level of seepage from irrigated fields, and this may also be viewed as groundwater recharge, this aspect of recharge is not included here.

As noted earlier, recharge in the Hadejia-Nguru wetlands is a function of flood extent. The basic groundwater model is therefore modified to allow for the additional influence on the recharge rate caused by the extent of available flood, F, in each period. Since recharge is a function of flood extent, by including F as an argument in the above equation, we ensure

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[6] Given a level of technology (e.g., the capacity of pumping equipment), lower aquifer stocks would reduce the efficiency of the technology and reduce the amount of water that can be pumped during a fixed period t. Similarly, for a given groundwater level, the lower the technological capacity of the pumps, the smaller the amount of water that can be pumped. We will return to these issues in chapter 6, in the valuation of the recharge function in agricultural production.

[7] Annual losses from groundwater storage may also occur due to regional groundwater flow and phreatophytic evapotransipration. However, since these are fairly constant, estimated as 500 $10^6 m^3$ per year for regional groundwater flow and as 1,000 $10^6 m^3$ per year for evapotranspiration (Hollis *et al.*, 1993), we assume that changes in groundwater levels is net of these losses. These losses are taken into account when calculating changes in water table elevations in chapter 2, table 2.8.

that the indirect benefits from flooding are captured by changes in the production or benefits derived from A, the groundwater stock.

$$\begin{gathered}\dot{A}=r(A,F)-w(t)\\ r(A)\geq 0 \;\forall\; A<\bar{A};\; r(\bar{A})=0\\ r_{AF}=0; r_{F}=k\end{gathered} \quad (3.13)$$

We assume that $r(A,F)$ is separable and $r_{AF} = 0$.

3.3.3 Optimal resource allocation

We assume the existence of a central planner who is interested in investing optimally in a water distribution system, i.e., in maximising the net benefits of water used upstream and within the wetlands. The water allocation problem is then presented as an optimal control model, where the sum of discounted net benefits is maximised over an infinite planning horizon, subject to all the relevant physical and economic constraints described above.

Two models are developed in this section. The first model ignores the value of groundwater and includes direct floodplain benefits and upstream benefits in the objective function. The second model is developed to illustrate the effect of including the indirect benefits of the wetlands in terms of supporting productive activities using groundwater. The two models are compared to show the effects of including rather than excluding indirect and direct benefits of the floodplain in basin wide water allocation decisions.

Model 1: maximizing net benefits from upstream and floodplain water uses.

We begin by presenting a simple one stock and one control model, where the objective is to maximise net benefits from upstream and downstream water uses. We ignore the use of groundwater in this first model. In this problem, therefore, water can be allocated to two different locations: upstream and to the floodplain. The social objective is to maximise the net benefits from water use in upstream areas (through $D(t)$) and water available for use on the floodplain ($F(t)$) subject to constraints.

$$\underset{D(t)}{Max}=\int_{0}^{\infty} e^{-\delta t}\left[B^{1}(D,F(0)-F(t))+B^{2}(F)\right]dt \quad (3.14)$$

subject to:

$\dot{F} = -D(t)$

$F(t), D(t) \geq 0$

$F(0) = F_0$

$B^2(F)$, $B^1(D, [F(0)-F(t)])$ are as defined above; and δ is the social rate of time preference.

$\lim_{t \to \infty} e^{-\delta t} \mu_1(t) = 0$

Note that we have dropped the time indices for convenience; $B^1(D, [F(0)-F(t)] = B^1(D(t), [F(0)-F(t)]$ and $B^2(F) = B^2(F(t))$.

The conditions for optimality are observed from the current value Hamiltonian which is formulated as below. Our control variable is $D(t)$ and the stock variable is $F(t)$. μ_1 is the current value of the co-state variable. The co-state variable can be interpreted as the shadow price of the stock (flood) at any time t.

$$H(D,F,\mu_1) = B^1(D,F(0)-F(t)) + B^2(F) - \mu_1(D) \tag{3.15}$$

The Hamiltonian can be defined as the total value accruing to society from the net value of the resource in current use and change in the total value of the stock. Applying the maximum principle and assuming an interior solution, we derive first order conditions to satisfy an optimal diversion regime and retrieve the equation of motion for the stock variable as follows:

$$\frac{\partial H}{\partial D} = B_D^1 - \mu_1 = 0, \quad D(t) > 0 \qquad \Rightarrow B_D^1 = P_a(Y_1)\frac{\partial Y_1}{\partial D} - c_1 = \mu_1 \tag{3.16}$$

$$\begin{aligned} \dot{\mu} - \delta\mu_1 &= -\frac{\partial H}{\partial F} = -B_F^2 + B_F^1 \\ \Rightarrow \quad \dot{\mu}_1 - \delta\mu_1 &= P_a(Y_2)\frac{\partial Y_2}{\partial (F)} + P_a(Y_1)\frac{\partial Y_1}{\partial [F(0)-F(t)]} \end{aligned} \tag{3.17}$$

$$where \quad B_F^1 = -\frac{\partial B^1}{\partial F(0)-F(t)} < 0, \quad B_F^2 > 0$$

$$\frac{\partial H}{\partial \mu_1} = -D = \dot{F} \tag{3.18}$$

Equation (3.16) indicates that at the optimum, the marginal benefits from diverting water away from the floodplain, in terms of consumer and producer surplus are equal to the opportunity cost of the resulting loss in flood extent, μ_1. This opportunity cost (μ_1) is therefore a measure of the future floodplain benefits forgone by a decision to divert today. Equation (3.17) implies that the flood should be diverted up to the point where the marginal benefits of downstream flooding are equal to the opportunity cost of allowing the flooding to occur and accumulate. The marginal benefits include any capital gains plus the benefits of current floodplain production, B^2_F. The opportunity costs include the interest payment term, $\delta\mu$, plus (B^1_F), which represents the opportunity cost of reduced accumulated diversion. This term is negatively signed because an increase in $F(t)$ implies a lower amount of total water diversion $(F(0)-F(t))$, resulting in losses in net benefits from upstream areas, i.e., $B^1_F<0$. Equation (3.18) returns the equation of motion for the stock variable.

Solving the above first order conditions and the equilibrium conditions of the model, allows us to determine optimal time path solutions D*, F* and μ*. Here we are less concerned with deriving the steady state equilibrium than with the more relevant problem of examining the conditions determining the optimal rate of change in water allocation between upstream and downstream uses. Hence, taking the time derivative of (3.16) and substituting into (3.17) and noting that $\mu_1 = B_D$, we get:

$$\dot{\mu}_1 = \delta B^1_D + B^1_F - B^2_F = \dot{D} B^1_{DD} \tag{3.19}$$

This expression for the rate of change in water diversion along the optimal path can be re-written as:

$$\dot{D} = \frac{\delta B_D^1 - B_F^2 + B_F^1}{B_{DD}^1} = \frac{\delta\left(P_a(Y_1)\frac{\partial Y_1}{\partial D} - c_1 \right) - P_a(Y_2)\frac{\partial Y_2}{\partial (F)} + P_a(Y_1)\frac{\partial Y_1}{\partial [F(0)-F(t)]}}{P_a^{\prime}(Y_1)\left(\frac{\partial Y_1}{\partial D} \right)^2 + P_a(Y_1)\frac{\partial^2 Y_1}{\partial D^2}} \tag{3.20}$$

The sign of $\dot{D}$ along the optimal path can be derived from (3.20) and by recalling that $B_{DD}<0$:

$$\dot{D} \begin{smallmatrix} < \\ = \\ > \end{smallmatrix} 0 \ if \ \frac{B_F^2}{\delta} \begin{smallmatrix} < \\ = \\ > \end{smallmatrix} B_D^1 + \frac{B_F^1}{\delta} \tag{3.21}$$

That is, the change in the optimal rate of diversion is determined by whether or not the present value benefits of the floodplain, $\frac{B_F^2}{\delta}$, exceed the present value benefits of diverting water for upstream irrigation, $(B_D^1 + \frac{B_F^1}{\delta})$.

We would normally expect the rate of diversion to fall over time, i.e., $\dot{D}<0$, so that the diversion rate is higher today relative to the future, and therefore, the discounted net benefits from diversion would exceed the net benefits from flooding. The rate of diversion will *increase* over time if the present value of the net benefits from diversion are less than the benefits from flooding. However, given that flood extent, *F*, is finite, it is feasible for $\dot{D}>0$ only for the initial periods and the rate of diversion must eventually fall. One feasible optimal path for the rate of diversion for this first model is shown in figure 3.3 and depicted as $D^1(t)$. Note that in the long run, as $t \to \infty$, $D^1(t)$ goes to zero.

Model 2: Maximising net benefits of water use, including groundwater use

We extend model 1 by accounting for the net benefits derived from utilising groundwater in the welfare maximisation problem. This also introduces a new state and control variable, namely, groundwater stock and the abstraction of groundwater. We include the use of groundwater resources for drinking water and irrigated agriculture. The associated net benefit functions for groundwater use are as described earlier in (3.8) and (3.10). Note that in this model the recharge rate, *r*, is no longer an exogenous parameter but a function of the area of flood extent, F, as well as a function of groundwater stock, A, i.e., $r = r(A,F)$.

The objective function (3.14) can now be expressed as:

$$\underset{D(t),w_1(t),w_2(t)}{Max} = \int_0^\infty e^{-\delta t}\left[B^1(D,F(0)-F(t)) + B^2(F) + B^3(w_1) + B^4(w_2)\right]dt \qquad (3.22)$$

subject to:

$$\dot{A} = r(A,F) - w(t)$$
$$w(t) = w_1(t) + w_2(t)$$

$$\dot{F} = -D(t)$$

$$\lim_{t\to\infty} e^{-\delta t}\mu_1(t) = 0$$

The corresponding Hamiltonian is expressed as:

$$H = B^1(D,F(0)-F(t)) + B^2(F) + B^3(w_1) + B^4(w_2) - \mu_1(D) + \mu_2(r(A,F) - w_1 - w_2) \qquad (3.23)$$

In our problem, there are two main decisions to be made regarding 1) the rate of diversion and 2) the abstraction rate from groundwater resources. Our control variables are $D(t)$, $w_1(t)$ and $w_2(t)$ and stock variables are F and A. The co-state variable (μ_2) captures the value of a marginal change in the resource stock, i.e., it is the shadow price of the groundwater resource. Applying the maximum principle, we derive the following first order conditions:

$$\frac{\partial H}{\partial D} = B_D^1 - \mu_1 \Rightarrow P_a(Y_1)\frac{\partial Y_1}{\partial D} - c_1 = \mu_1 \qquad (3.24)$$

$$\frac{\partial H}{\partial w_1} = B_{w_1}^3 = \mu_2 \Rightarrow P_a(Y_3)\frac{\partial Y_3}{\partial w_1} - c_{w_1}(r(A,F)) = \mu_2 \qquad (3.25)$$

$$\frac{\partial H}{\partial w_2} = B^4{}_{w_2} = \mu_2 \Rightarrow P_w(w_2) - c_{w_2}(r(A,F)) = \mu_2 \qquad (3.26)$$

$$\dot{\mu}_1 - \delta\mu_1 = \frac{-\partial H}{\partial F} = -B_F^2 + B_F^1 + \left(\frac{\partial c_{w_1}}{\partial r} w_1 + \frac{\partial c_{w_2}}{\partial r} w_2 - \mu_2 \right) r_F$$

$$\Rightarrow \dot{\mu}_1 - \delta\mu_1 = -P_a(Y_2)\frac{\partial Y_2}{\partial F} + P_a(Y_1)\frac{\partial Y_1}{\partial[F(0)-F(t)]} + \left(\frac{\partial c_{w_1}}{\partial r} w_1 + \frac{\partial c_{w_2}}{\partial r} w_2 \;\; -\mu_2 \right) r_F \qquad \textbf{(3.27)}$$

$$\textit{where} \quad B_F^1 = -\frac{\partial B^1}{\partial(F(0)-F(t)} < 0,\; B_F^1 > 0,\; \frac{\partial c_{w_1}}{\partial r} < 0,\; \frac{\partial c_{w_2}}{\partial r} < 0$$

$$\dot{\mu}_2 - \delta\mu_2 = -\frac{\partial H}{\partial A} = -\mu_2 r_A + \frac{\partial c_{w_1}}{\partial r} r_A + \frac{\partial c_{w_2}}{\partial r} r_A \qquad \textbf{(3.28)}$$

$$\frac{\partial H}{\partial \mu_1} = -D = \dot{F} \qquad \textbf{(3.29)}$$

$$\frac{\partial H}{\partial \mu_2} = r(F,A) - w_1 - w_2 = \dot{A} \qquad \textbf{(3.30)}$$

Note that (3.27) is different from (3.17) by virtue of including the extra terms, $\mu_2 r_F$ and the marginal reductions in costs of abstracting w_1 or w_2 due to an increase in the rate of groundwater recharge, due to additional flooding, r_F. From (3.25) or (3.26) we further note that the shadow price of groundwater is equal to the net benefits derived from water use in the form of w_1 or w_2, i.e., $\mu_2 = B_{w1} = B_{w2}$. This confirms that the indirect benefit of the additional downstream flooding can be measured by the marginal net benefits gained in terms of agricultural production or domestic water consumption, which are dependent on groundwater sources recharged by the floodplain. From (3.25) and (3.26) we can therefore define $\mu_2 r_F$ as the value of a marginal change in recharge, in terms of additional returns to downstream productive activities dependent on groundwater abstraction. Equation (3.27) therefore implies that the flood should be diverted up to the point where the marginal benefits of downstream flooding are equal to the opportunity cost of allowing the flooding to occur and accumulate.

However, compared with model 1, the marginal floodplain benefits in model 2 include capital gains and the benefits of current floodplain production, B^2_F as well as the value of a marginal change in recharge to downstream uses of groundwater ($\mu_2 r_F$) less the marginal changes in costs of abstracting $w_1$or w_2, due to changes in r. The sum of these terms $(\mu_2 - w_1 \frac{\partial c_{w_1}}{\partial r} - w_2 \frac{\partial c_{w_2}}{\partial r}) r_F$ can be defined as the indirect benefits from an increase in the recharge function of the floodplain wetlands. The opportunity costs of maintaining F in (3.27) are the same as in (3.17) and are comprised of the sum of the interest payment term, $\delta\mu$, and the opportunity cost of reduced accumulated diversion, (B^1_F).

Hydrological data from the Komadugu-Yobe river basin suggest that the relationship between flooding and groundwater recharge is linear and dependent solely on flood extent within the wetlands (Thompson and Goes, 1997). Based on this evidence, we define $r(A) = 0$, for model 2. This relationship implies that $r_A = 0$ and equation (3.28) simplifies to:

$$\dot{\mu}_2/\mu_2 = \delta \qquad \textbf{(3.28')}$$

implying that the shadow price of the groundwater stock is constant over time and that the its rate of change is equal to the discount rate,δ.

As shown for the previous model, we derive the following expression for the optimal rate of diversion of water for model 2, from downstream to upstream areas, from (3.25), (3.27) and (3.28) and from noting that $B_D^1=\mu_1$. Thus,

$$\dot{\mu}_1=\delta B_D^1-B_F^2+B_F^1+\left(\frac{\partial c_{w_1}}{\partial r}+\frac{\partial c_{w_2}}{\partial r}-\mu_2\right)r_F = \dot{D}B_{DD}^1 \tag{3.31}$$

It follows therefore that the rate of change in water diversion along the optimal path is determined by the following condition:

$$\dot{D} = \frac{\delta\left(P_a(Y_1)\frac{\partial Y_1}{\partial D}-c_1\right)-\left(P_a(Y_2)\frac{\partial Y_2}{\partial F}\right)+\left(P_a(Y_1)\frac{\partial Y_1}{\partial[F(0)-F(t)]}\right)-\left(\frac{\partial c_{w_1}}{\partial r}+\frac{\partial c_{w_2}}{\partial r}-P_a(Y_3)\frac{\partial Y_3}{\partial w_1}+c_{w_1}\right)r_F}{P_a'(Y_1)\left(\frac{\partial Y_1}{\partial D}\right)^2+P_a(Y_1)\frac{\partial^2 Y_1}{\partial D^2}} \tag{3.32}$$

This implies that:

$$\dot{D}\ \begin{matrix}<\\=\\>\end{matrix}\ 0\ \mathit{if}\ \frac{B_F^2}{\delta}+\frac{\left(\mu_2-\frac{\partial c_{w_1}}{\partial r}-\frac{\partial c_{w_2}}{\partial r}\right)r_F}{\delta}\ \begin{matrix}<\\=\\>\end{matrix}\ B_D^1+\frac{B_F^1}{\delta} \tag{3.33}$$

Equation (3.33) tells us that if the present value net benefits from diverted water are higher than net direct and indirect benefits from the floodplain wetlands, then it implies that the rate of diversion falls over time. We would normally expect the rate of diversion to fall over time, i.e., $\dot{D}<0$, so that the diversion rate is higher today relative to the future, and therefore, the discounted net benefits from diversion would exceed the net benefits from flooding. The rate of diversion will *increase* over time if the present value net benefits from diversion are less than the benefits from flooding. However, as in model 1, given that flood extent, F, is finite, it is feasible for $\dot{D}>0$ only for the initial periods and the rate of diversion must eventually fall.

Note the similarities between equations (3.20) and (3.32). Clearly, in the second model, the optimal path for *D(t)* is affected by two types of present value benefits derived from the floodplain, namely, discounted production benefits, $\frac{B_F^2}{\delta}$ and discounted floodplain recharge benefits, $\frac{\left(\mu_2 - \frac{\partial c_{w_1}}{\partial r} - \frac{\partial c_{w_2}}{\partial r}\right) r_F}{\delta}$. The first model ignores the impacts of diversion on floodplain recharge of groundwater stocks. This difference is further examined in section 3.4.1.

3.4 Comparing the dynamics of the two models

In order to appreciate the difference between the two models presented above and to analyse more completely the effect of including the value of indirect benefits derived from the downstream wetlands, we compare the dynamics of the two models in this section. In particular we look at the effect of including or ignoring benefits from groundwater use on the diversion path *D(t)* and the role of the recharge rate in affecting the diversion path.

3.4.1 Analysing the diversion path D(t)

We examine the diversion path for *D(t)* in both the models presented above and to distinguish between the optimal diversion paths of the two models, we define $D(t) = D^{(1)}(t)$ for model 1 and $D(t) = D^{(2)}(t)$ for model 2. Following Dasgupta and Heal (1974) and Barbier (1994), we note that since *D* is a factor of production in upstream agriculture, there exits a derived demand curve for the flow of the resource *D(t)* and since this input is obtained for upstream production by diverting water away from the downstream floodplain, this derived demand will be given by $D(\mu_{1t}, t)$ where μ_1 can be interpreted as the shadow price of the diverted flood stock. We assume for simplicity that the demand curve does not shift over time. Therefore, assuming a constant elasticity of demand we can describe the demand for *D(t)* as:

$$D(t) = \mu_1(t)^{-1/\alpha} \quad \text{where } \alpha > 0 \tag{3.34}$$

Deriving $D^{(1)}(t)$ for model 1[8]

We first carry out our analysis of the diversion path for model 1, defining $D(t)$ as $D^{(1)}(t)$. Integrating the co-state equation of motion, (3.17), we get:

$$\begin{aligned} \mu_1^{(1)}(t) &= \mu_{1_0}^{(1)} e^{\delta t} - \int (B_F^2 - B_F^1)\,dt \\ \textit{where} \quad & \mu_{1_0} = \mu_1(0) \end{aligned} \qquad \textbf{(3.35)}$$

Substituting (3.35) into (3.34),we obtain the following expression for $D(t)$,which is denoted as $D^{(1)}(t)$ in model 1:

$$D^{(1)}(t) = \left(\mu_{1_0}^{(1)} e^{\delta t} - \int (B_F^2 - B_F^1)\,dt \right)^{(-1/\alpha)} \qquad \textbf{(3.36)}$$

The expression $\int (B_F^2 - B_F^1)\,dt$ implicitly suggests that the undiscounted value of the net benefits, $(B^2{}_F - B^1{}_F)$, will change over time. From (3.17) and noting that $\mu_{1_0} = \mu_1(0)$, we derive the optimal starting shadow price for the initial level of diversion as:

$$\mu_{1_0}^{(1)} = \frac{B_F^1 - B_F^2}{\delta} \qquad \textbf{(3.37)}$$

Deriving $D^2(t)$ for model 2

For the second model we define $D(t)$ as $D^2(t)$. This model includes the interaction of groundwater resources within the floodplain and is therefore influenced by the relationship between flood extent and groundwater recharge. Based on hydrological data, the relationship between flood extent and groundwater recharge (r) is found to be linear (Thompson and Goes, 1997). The marginal change of recharge due to a marginal change in flood extent, $\partial r/\partial F$ or r_F, is therefore a constant.

Assuming then that $r_F = k$, we note from (3.25) that :

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[8] To distinguish between the models, the superscript (1) is used to refer to model 1 and (2) to denote model 2.

$$\mu_{1_0}^{(2)}=(\mu_{0_1}^{(2)})e^{\delta t}-\int(B_F^2-B_F^1)dt-\int k\mu_2 dt+\int\left[\frac{\partial c_{w_1}}{\partial r}w_1+\frac{\partial c_{w_2}}{\partial r}w_2\right]kdt \tag{3.38}$$

However, we also know from (3.26') that $\mu_2^1(t)=\mu_{2_0}^1 e^{\delta t}$. Therefore it follows from the expression $\int k\mu_2 dt$ that $\int k\mu_{2_0}e^{\delta t}dt=\dfrac{k\mu_{2_0}e^{\delta t}}{\delta}$. It follows from (3.34) and (3.38) that:

$$D^{(2)}(t)=\left[\mu_{0_1}^{(2)}e^{\delta t}-\int(B_F^2-B_F^1)dt-\frac{k\mu_{2_0}}{\delta}e^{\delta t}+\int\left[\frac{\partial c_{w_1}}{\partial r}w_1+\frac{\partial c_{w_2}}{\partial r}w_2\right]kdt\right]^{-1/\alpha} \tag{3.39}$$

Furthermore, from (3.37) and by recalling that $\mu_1(0)=\mu_{1_0}$, the optimal level of μ_{1_0} can be defined as:

$$\mu_{1_0}^{(2)} = \frac{B_F^1-B_F^2+(\mu_2-\frac{\partial c_w}{\partial r}w_1-\frac{\partial c_w}{\partial r}w_2)r_F}{\delta} \tag{3.40}$$

Comparing (3.37) and (3.40) and assuming that the marginal benefits $(B_F^1-B_F^2)$ are equal in the two models, it is clear that $\mu_{1_0}^{(2)} > \mu_{1_0}^{(1)}$ if the net benefits from a marginal increase in recharge $\left(\mu_2-\frac{\partial c_{w_1}}{\partial r}w_1-\frac{\partial c_{w_2}}{\partial r}w_2\right)r_F$ are positive. This implies that the shadow prices of the initial level of diversion, corresponding to the optimal diversion trajectories for the two models, are different and thus *$D^{(1)}(t)$* > *$D^{(2)}(t)$* at least initially at t = 0.

From (3.37) and (3.40) we have established that the optimal starting prices for the two paths are different, with $\mu_{1_0}^{(1)} < \mu_{1_0}^{(2)}$. This implies that *$D^{(2)}(t)$* starts at a lower level of diversion than *$D^{(1)}(t)$*. Returning to our first order conditions for the two models, we note from examining (3.19) and (3.31) that $\dot{\mu}_1^{(1)} > \dot{\mu}_1^{(2)}$. Thus it is clear that the shadow price for the initial level of diversion in model 1 changes at a higher rate along the optimal diversion trajectory than the shadow price for diversion in model 2. From (3.19) and (3.31) it is further clear that the slope of *$D^{(1)}(t)$* is steeper than the slope of *$D^{(2)}(t)$*.

Given the non-negativity constraint $F(t) \geq 0$ it is clear that the flood stock is not necessarily exhausted in the long run, i.e., as $t \rightarrow \infty$. Hence, as t tends to ∞, the stock could tend to either zero or to some constant. If we assume that there always remains some amount of flood at $t = \infty$, then the path $D^{(1)}(t)$ may always be higher than $D^{(2)}(t)$, and $D^{(1)}(t) = D^{(2)}(t) = 0$ at $t = \infty$. This result is shown in figure 3.3.

If, however, the stock tends to zero at time $t \rightarrow \infty$ then the curves must cross each other at some point in time and the optimal path for $D^{(1)}(t)$ will cut $D^{(2)}(t)$ from above. The two paths will converge as $t \rightarrow \infty$. The conditions for this may be described by considering equations (3.36) and (3.37) from which we note that:

$$D^{(1)}(t) \overset{>}{\underset{<}{=}} D^{(2)}(t) \;\; if \;\; \mu_{1_0}^{(1)} e^{\delta t} - \int (B_F^2 - B_F^1) dt \overset{<}{\underset{>}{=}} \mu_{1_0}^{(2)} e^{\delta t} - \int (B_F^2 - B_F^1) dt - \frac{k\mu_0}{\delta} e^{\delta t} + \int [\frac{\partial c_{w_1}}{\partial r} w_1 + \frac{\partial c_{w_2}}{\partial r} w_2] k dt \qquad \textbf{(3.41)}$$

or more simply from (3.34) we note that:

$$D^{(1)}(t) \overset{>}{\underset{<}{=}} D^{(2)}(t) \;\; if \;\; \mu_1^{(1)}(t) \overset{<}{\underset{>}{=}} \mu_1^{(2)}(t) \qquad \textbf{(3.42)}$$

This implies that as the shadow price μ_1 for diverted flood in model 1 increases over time, the diversion rates will fall but remain higher than diversion rates in model 2 up until such time that the shadow price of diverted flood becomes higher for model 1 than for model 2. We expect this to be the case in later periods since the stock in model 2 is being used up at a slower rate. Hence, as $t \rightarrow \infty$, and if the stock tends to zero, we expect the diversion paths to cross. If the flood stock is not exhausted as $t \rightarrow \infty$, and in addition the shadow price in model 1 is always lower than the shadow price in model 2, then the paths will not cross and will converge as $t \rightarrow \infty$ (figure 3.3).

3.4.2 The role of the recharge rate

The time rate of change in $D(t)$ along the optimal path is given by equation (3.20) for the first model and by equation (3.32) for the more complete model. The previous section has shown how the optimal path would shift if we were to include the value of indirect benefits in the objective function. Since indirect benefits are directly dependent on recharge and indirectly on the flood stock, in this section we investigate the role of the recharge rate in influencing the optimal paths of the two models.

In model 1 we have considered recharge as exogenous and it does not therefore affect diversion decisions. Hence partial differentiation of (3.20) with respect to r gives us:

$$\frac{\partial \dot{D}^{(1)}(t)}{\partial r} = 0 \qquad \textbf{(3.43)}$$

This implies that the slope of $D^{(1)}(t)$ is not affected by a change in the recharge rate. In model 2, however, r is included as a function of flood extent F as well as a function of groundwater stock, i.e., $r = (A,F)$. Therefore, we expect that an exogenous change in r would affect the decision to divert water away from the floodplain. Since the relationship between recharge rate and flood extent is found to be linear by hydrological studies of the Komadugu-Yobe river basin, $r_A = 0$ and the effect of a marginal change in the recharge rate r is represented by a change in k, defined as the marginal rate of recharge of the groundwater stock due to a change in flood extent, i.e., $r_F = k$. From (3.31) we note that:

$$\frac{\partial \dot{D}^{(2)}(t)}{\partial r_F} = \frac{\partial \dot{D}^{(2)}(t)}{\partial k} = \frac{\left[-\mu_2 + \frac{\partial c_{w_1}}{\partial r} w_1 + \frac{\partial c_{w_2}}{\partial r} w_2\right]}{B_{DD}^{1}} > 0 \qquad \textbf{(3.44)}$$

This result implies that the higher the recharge rate, the lower the rate of increase in diversions. Hence, assuming that diversion starts out high and declines over time, a higher recharge rate would make the optimal path of $D^{(2)}(t)$ flatter, while a lower recharge rate would make the optimal path steeper. This result is shown graphically in figure 3.4 where the dotted line indicates that with a higher recharge rate the optimal rate of diversion will be flatter for model 2. Therefore less flood will be diverted in initial periods relative to future periods.

Figure 3.3 Effect of indirect benefits on the optimal path for *D(t)*

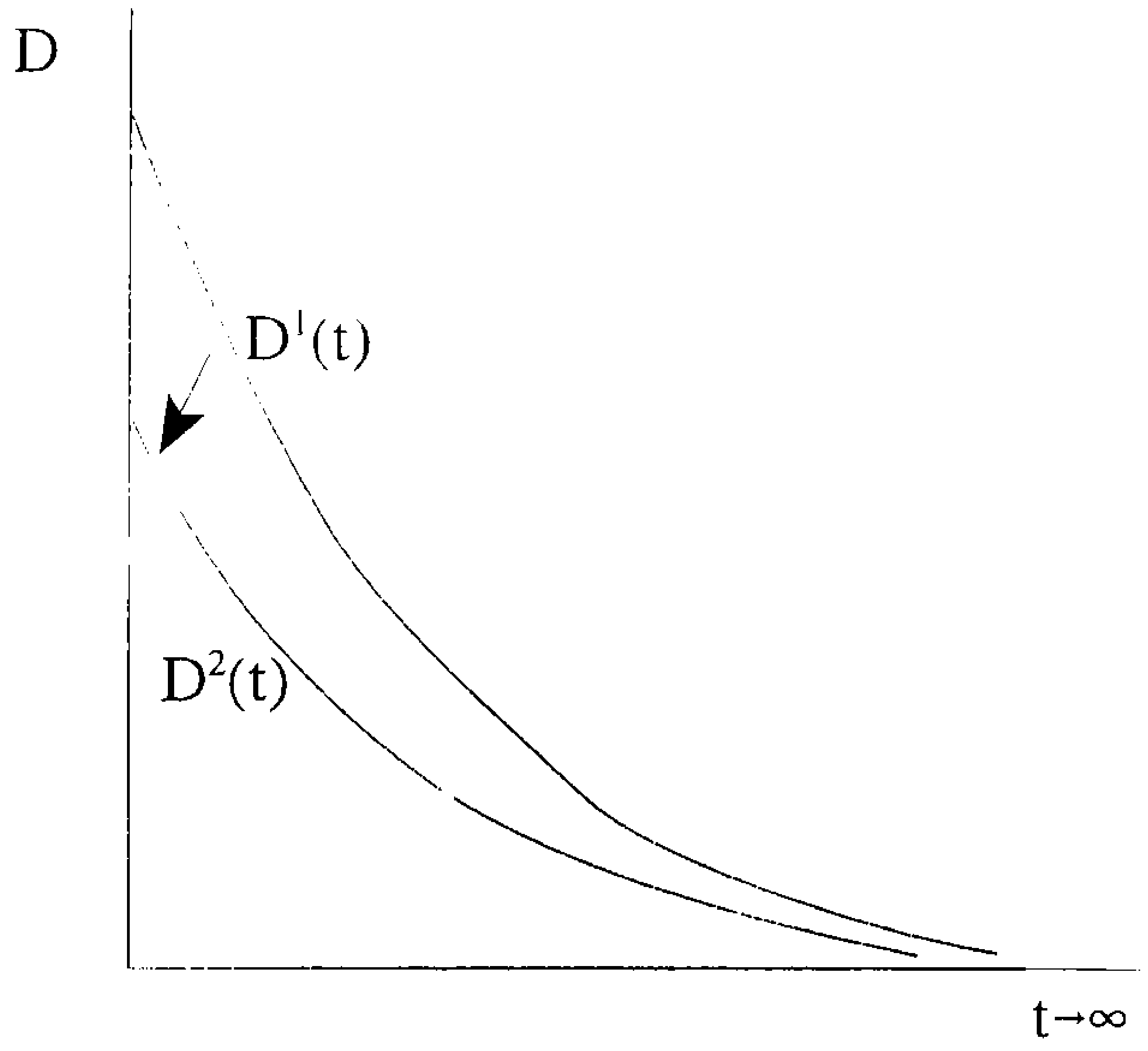
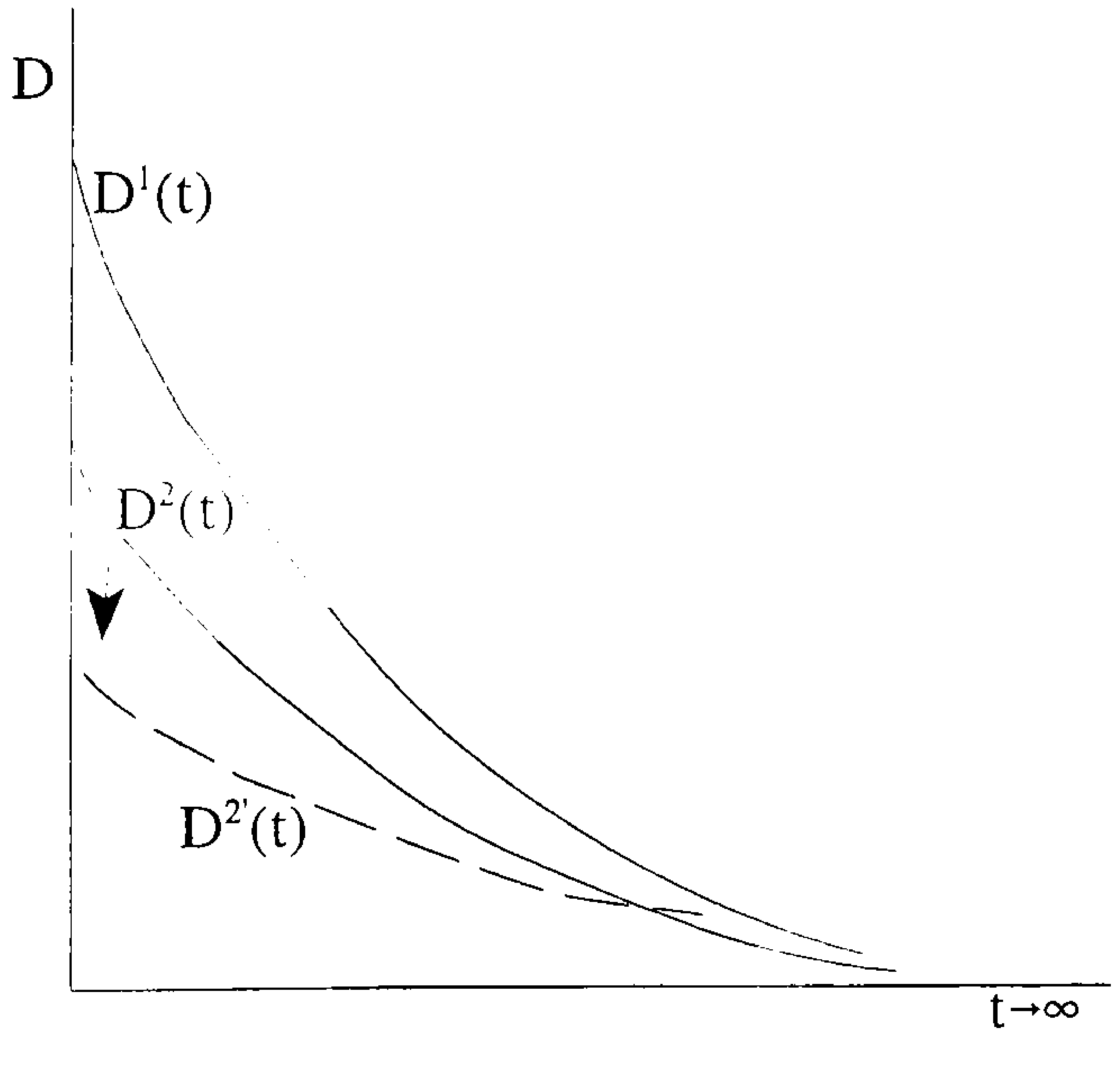


Figure 3.4 Effect of recharge rate on the optimal path for *D(t)*



3.5 Conclusions

This chapter has shown that the inclusion of indirect benefits of the wetlands, such as groundwater recharge, affects the time path of diversion. The results show that the optimal path of diversion will be lower in initial periods if the indirect benefits of the wetlands are accounted for. Subsequently, since the rate of change in the optimal shadow price of diversion as specified in model 1 is higher, the optimal path of diversion in model 1 will fall faster, to levels below the optimal path of diversion given by model 2. Path $D^1(t)$ therefore results in the diversion of more flood in initial periods while path $D^2(t)$ diverts less flood in initial periods, allowing more flood to be diverted in later periods than is possible under path $D^1(t)$. It has been argued that a social planner interested in maximising the basin wide economic value of water used within the river basin would use the second model rather than the first model, facing a higher initial shadow price for diversion of water from downstream to upstream areas. Furthermore, it is shown that a change in the marginal rate of recharge will flatten the optimal rate of diversion in the second model resulting in lower rates of diversion in initial periods.

As emphasised by this chapter, if the magnitude of the economic value of the indirect benefits is significantly large, including them in the maximisation problem can impact on both the level of diversion and its rate of change. However, the indirect benefits of most ecosystems are poorly understood and their economic valuation is seldom carried out. Quantifying net benefits from indirect benefits such as groundwater recharge would therefore assist policy decisions regarding the level of diversions and in determining the time path of the diversion rate.

To test for positive values deriving from indirect benefits, chapters 5 and 6 present two valuation studies to attempt to capture the partial value of the indirect benefits of the Hadejia-Nguru wetlands. The next chapter, chapter 4, therefore presents a literature review of valuation methodologies that are considered relevant to the valuation of indirect benefits, focusing on those techniques employed in the analysis carried out later in chapters 5 and 6.

Chapter 4

Theoretical Background and Empirical Studies on the Valuation of Ecosystem Functions

4.1 Introduction: Valuing the Environment

The assignment of monetary values to economic goods and services is a normal and necessary result of economic activity. Assigning monetary values to environmental resources, particularly those for which there are no market values, is however, a somewhat more difficult concept for many people to accept. Yet, without attempting to value environmental goods and services, we essentially allow the opportunity for them to be mismanaged. For example, as discussed in chapter 3, knowing whether or not the value of indirect benefits derived from downstream wetlands are positive, could have a significant impact on the decision to divert water from downstream to upstream areas. It becomes necessary therefore to measure the value of indirect benefits in order to inform policy decisions affecting water allocation within the river basin.

This chapter will discuss various theoretical approaches developed in the literature to value environmental resources and ecosystems. It will then examine in greater detail the application of some of these valuation approaches, addressing some of the data problems and cross-disciplinary issues that often hinder the proper valuation of environmental systems. The main aim of the chapter is therefore to discuss the appropriateness of using valuation techniques developed further in chapters 5 and 6, in the context of the available literature on the valuation of indirect use benefits.

4.2 Types of values

Human society can derive value from an ecological system either from using resources directly in meeting production and consumption needs or by indirectly using or relying on environmental functions characteristic of that ecosystem. This utilitarian approach to valuation allows values to both direct and indirect uses, consumptive and non-consumptive uses and if satisfaction is derived, allows for the measurement of non-use values as well. Demand for ecological systems therefore derives from the goods and services supported by these systems. In addition, resources and ecosystems may have value independent of their use value, direct or indirect. The concept of total economic value (TEV) is an all-encompassing term, which includes use values and non-use values of environmental systems.

Krutilla (1967) initially noted the difference between use and non-use values of environmental resources. Goods and services obtained through extraction from or by interaction with the ecosystem have a use value which may be measurable. Use values are themselves grouped according to whether these are direct or indirect. Use value may derive from the direct use of goods and services, such as food resources, or from the indirect use of the ecosystem services, such as flood control. In general, the direct use of marketed products of ecosystems is easier to measure since a market value exists and may be adjusted for distortions. In contrast, regulatory ecological functions, such as groundwater recharge or discharge, may have indirect use values which may be reflected in the economic activities these functions support. If an environmental function can be related to the support or maintenance of an economic activity, then the indirect use value of an environmental function can be recovered from observing the change in the value of production or consumption of that activity. The indirect use value of an environmental function is therefore related to the change in the value of production or consumption of an activity or property that it is protecting or supporting (Barbier, 1994).

The idea of non-use benefits is motivated by the concern that even after all of the various benefits associated with using an environmental amenity have been estimated and entered into the benefit estimation, something important may have been missed (Randall, 1991). Non-use values are usually further divided into option value and existence value. Option value is applied to situations in which individuals are faced with uncertainty regarding the susceptibility of the ecosystem to irreversible change[1]. Existence value is defined as the intrinsic value placed on resources or amenities by individuals who wish to see these resources preserved in their own right. It is also referred to as the value placed by the individual on the assurance of the future availability of the resource or amenity (Krutilla and Fisher, 1975; Randall, 1991).

Gren *et al.,* (1994), also in reference to wetland values, divide the total production output of a wetland system into a) primary values and b) secondary values. They refer to the

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[1] Weisbrod (1964) argues that the true measure of consumer benefits would actually exceed expected consumer surplus because of the consumer's willingness to pay to some amount to preserve an option value. See Bishop (1986), Smith (1983) and Smith and Desvousges (1988), amongst others, for theoretical discussions and the empirical difficulties associated with measuring option value.

primary value as the "glue" value of the system, ensuring its own development and maintenance. Total secondary value, referring to the exports of the system to human society, is therefore dependent on the successful build up of the primary value, i.e., on the proper functioning of the system. Each secondary value is dependent on the maintenance of the multi-functional system (Gren *et al.*, 1994).

Also in reference to tropical wetland use, Barbier (1994) suggests that direct uses would include both consumptive use of the resource such as livestock grazing, fuelwood collection, forestry, agriculture, water use, hunting and fishing) and non-consumptive uses of wetland services such as recreation tourism, *in situ* research and education and navigation along water courses. Direct uses could therefore include commercial and non-commercial activities, some of which could be important for the subsistence needs of local people.

In addition, various regulatory ecological functions have indirect value. The functional characteristics of ecosystems are defined by de Groot (1992) as "the capacity of natural processes and components to provide goods and services that satisfy human needs (directly and/or indirectly)" pp 152. This concept, which focuses on the functional interactions between the natural system and human society, distinguishes between four categories of environmental functions, namely:

- Regulation functions - relating to the capacity of natural and semi-natural ecosystems to regulate essential ecological processes and life support systems to maintain a healthy environment.
- Carrier functions - relating to the space and medium provided by these ecosystems in which human activities such as habitation, cultivation and recreation may be carried out.
- Production functions - relating to the resources provided by natural systems for human consumptive and productive activities, and;
- Information functions - relating to the aspects of natural systems which provide opportunities for reflection, cognitive development and aesthetic experience.

These classification approaches are important in that they are attempts at identifying the characteristics of the link between human or societal preferences and the resource.

Concepts such as primary value and existence value are based on a perceived value placed by human society on maintaining the resource intact. However, as has been noted by Krutilla and Fisher (1975) individuals may express a positive existence value for an environment because they want to preserve the environment for the benefit of their heirs, i.e., the existence value is derived from a bequest motivation. McConnell (1983) however notes that the fact that existence value may be motivated by a bequest value only underlines the argument that resources are valued for their use. Bequest value simply indicates that the use may be expressed by a different generation rather than the present one. Others, such as Randall and Stoll (1983) have further noted that use values can be derived through 'vicarious consumption' implying that the user and the resource do not have to be in close proximity. These arguments suggest that values expressed as existence value or 'primary value' as defined by Gren *et al.,* for wetlands, are really composite values and breaking them down into various types of use values may well be possible. In some cases, valuing both use and non-use values for a particular resource could therefore result in over-estimating its total economic value.

For this reason, this thesis focuses on the indirect use value of wetland by identifying the role of environmental functions in maintaining and providing for the consumptive and productive needs of societies. The physical (and non-physical) characteristics of an ecosystem can be affected by the impact of human use of resources. In turn, the ecological functioning of the system is affected by changes in its physical (or non-physical) structure. It is important therefore that when attempting to value the use values of resources or functions that the links between the function and its manifestation in the consumptive or productive process be recognized in order to measure both direct and indirect values accurately. However, since human's use ecosystems in various direct and indirect ways and the use of a resource may be affected by both spatial and temporal factors, it is not always easy to establish the nature of the link or how humans derive a value from the ecosystem function. The success of a valuation approach depends in part on our ability to accurately identify the link between the ecosystem function and human productive and consumptive processes.

4.2.1 Measuring welfare change

Once the physical linkages are made clear, the valuation exercise must identify the economic linkages and understand what aspect of the consumptive or non-consumptive activity provides satisfaction to human societies and how best to measure this satisfaction. The economic concept of value discussed in this thesis has its foundations in neoclassical welfare economics. The economic value of changes in environmental resources and systems is derived from measuring the effects of such changes on human welfare. The value an individual places on a resource influence his/her behaviour by changing their choices to consume certain goods, or by inducing adaptive behaviour. It is contended that the existence and non-use value concepts may be similarly measured since individuals may value the intrinsic survival rights of species and/or ecosystems and this concern may be reflected in the valuation framework.[2]

Welfare theory is based on the theory of individual preferences. Individuals make choices based on the utility they derive from these choices. Hence inferences about welfare may be drawn from observing the individual choices amongst alternative bundles of goods and services (Freeman, 1993; Just *et al.*, 1982; Varian; 1984).

The theory of revealed preference allows the prediction of the consumer's behaviour and allows the deduction of the consumer's utility function based on her or his observed choices amongst commodity bundles (Henderson and Quandt, 1980; Varian, 1992). If x^1 and x^2 are alternatives belonging the set of preferences ψ and if the individual prefers x^1 to x^2, then we can say that $x^1 \geq x^2$. If the individual prefers x^2 to x^1 or is indifferent between them, then we say that $x^1 \leq x^2$. And if the individual is indifferent between them then $x^1 \sim x^2$. Thus the indifference curves for a single individual may be constructed and the utility function can be expressed as :

$$U = U(X,Q) \qquad \textbf{(4.1)}$$

where X is a vector of marketed goods and services and Q is the quality of the environment. The consumer's best choice is then made where an indifference curve is tangent to the

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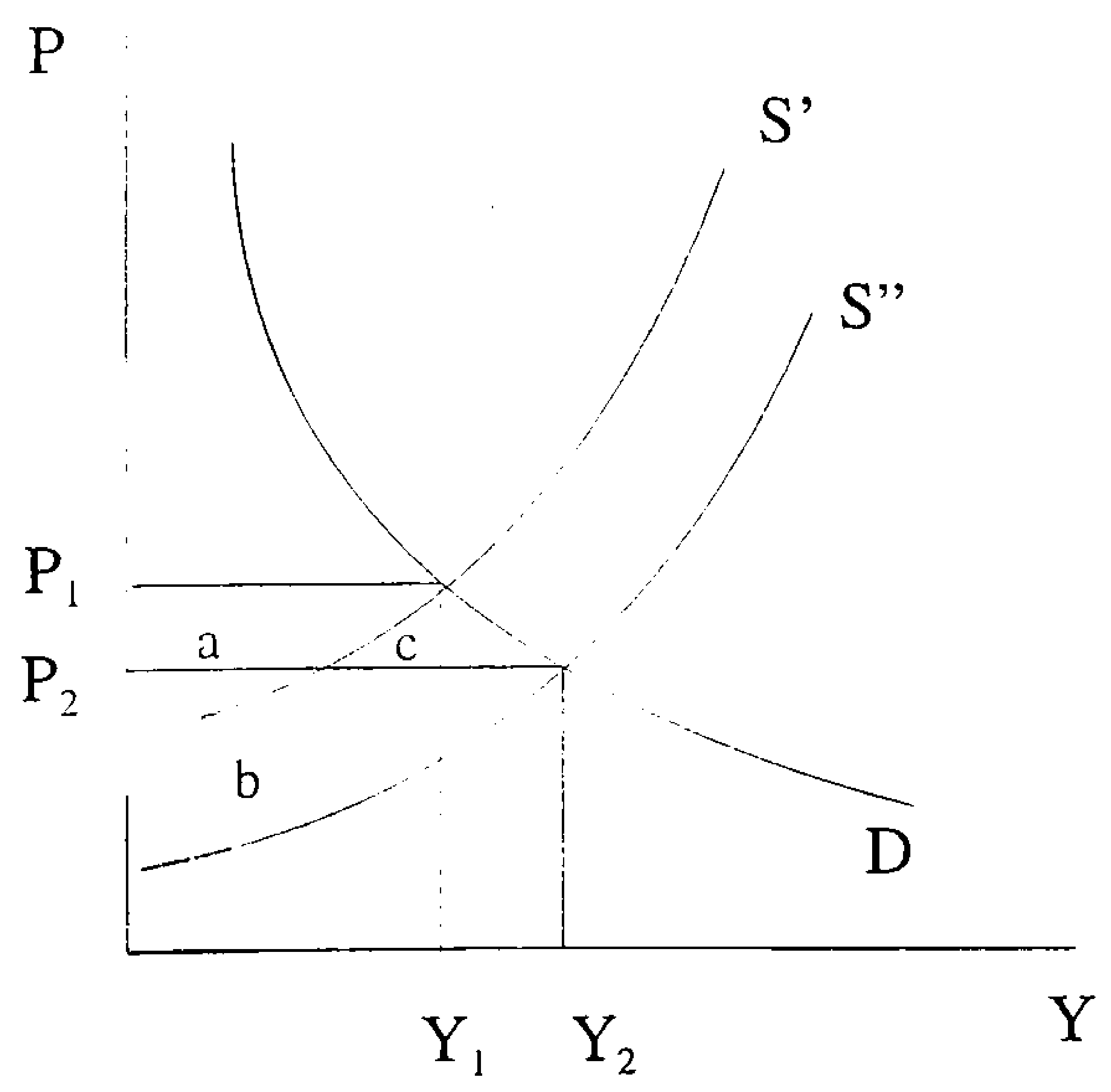
[2] For a more complete discussion on non-use values see Krutilla, 1967; Krutilla and Fisher, 1995; Randall, 1991; Freeman, 1993.

consumer's budget constraint.

The economic value of changes in environmental resources and services is derived from measuring the effects of these changes in human welfare. In revealed preference models, valuation questions posed as changes in parameters exogenous to the individual, reveal welfare effects or willingness to pay measures through the individual's response to these parameter changes (Bockstael, 1995).

The theoretically preferred measure of welfare change used in chapters 5 and 6, is the area under the demand curve, measuring the change in combined consumer and producer surplus. This area is bounded by the demand curve and the old and new supply curves. Figure 4.1 shows the case for a downward shift in the supply curve of some good X, the production of which is affected by a change in environmental quality. The benefit to consumers of the good X can be approximated by the change in consumer surplus or the area a+c. Change in producer surplus is approximated by the area b-a, which implies that the total welfare gain due to the downward shift in the supply curve is equal to the area b+c. The identification of demand for an environmental good is therefore necessary in order not to overestimate the benefits of an environmental improvement and, as noted by Freeman (1991), the impacts of market conditions and regulatory policies are also important.

Figure 4.1 **Consumer surplus and producer surplus measures with a downward shift in the supply curve**



There are various measures of welfare change, deriving from the use of Hicksian (compensated) demand curves and Marshallian (uncompensated) demand curves. Ordinary consumer's surplus is measured by the area under the Marshallian ordinary demand curve and above the horizontal price line. Other measures, namely, compensating variation, equivalent variation, compensating surplus and equivalent surplus measures are measured under the Hicksian demand curve. The Marshallian consumer surplus is usually taken to lie somewhere between the compensating variation and equivalent variation measures of welfare change (Freeman, 1993), unless preferences are homothetic, in which case it is a valid indicator of welfare change (Deaton and Muellbaur, 1980). The Marshallian consumer surplus measure is often adopted because ordinary demand curves are easily observed whereas income compensated demand curves are not. It has been noted that if ordinary demand functions reflect utility-maximising behaviour, then utility functions can be recovered using duality theory and compensating variation or equivalent variation measures may be derived directly from the ordinary demand functions (Hausman, 1981; Vartia, 1983).

4.3 Observed behaviour and hypothetical methods

Many environmental resources are not traded in markets and so preferences for the quantity, quality and other attributes of the resource are not revealed through simple observations of market prices and traded quantities. Hence, some of the most challenging methodological issues associated with valuing environmental resources stem from changes in the characteristics of these resources. Valuation methods can broadly be divided into direct and indirect methods. Direct methods, both observed and hypothetical, use data which is directly related to valuing the environmental good in question, to derive benefit measures. Indirect methods on the other hand use responses and revealed preferences which are indirectly related to the environmental good of interest, but which are then used to derive values for that good. The classification below further subdivides direct and indirect methods into observed and hypothetical methods. Because the valuation of an environmental function requires information on the physical and behavioural linkages between that function and demand, a combination of some of the methods noted below could be used to derive a value for the recharge function of the wetlands.

Table 4.1 A categorisation of valuation methods

	Observed/Revealed preference	Hypothetical/Stated preference
Direct methods	Competitive market prices Simulated markets Referendum Production function	Bidding games Contingent valuation method
Indirect methods	Travel cost Hedonic property values Avoidance expenditures Referendum voting Household production function	Contingent referendum Contingent ranking Contingent behaviour

Source : Adapted from Mitchell and Carson (1989):75 and Freeman (1993):24

Direct observed methods include the use of competitive market prices and the use of results from simulated markets set up specifically to learn about the individual values and preferences. These observations are based on actual choices made by people who are assumed to be maximizing their utility, subject to the relevant constraints, and who are free to choose the quantity of good at a given price. The data therefore reveal values directly in monetary units since the choices are made on the basis of observed market prices. However, few public goods have functioning or complete markets from which one could derive such data. Where prices do exist, they must be corrected for distortions arising from market or policy failures.

Indirect observed methods are also based on actual behaviour reflecting utility maximization. Observations of choices made by an individual, i.e., demand for a quantity of a good or service at each price, provide clues to the value placed by that individual on the environmental good or service. The value of the non-market amenity is derived from the market data available for the good with which it is linked. Methods such as hedonic pricing and travel cost methods have been applied by a number of studies to environmental valuation in developed countries but are more difficult to apply to developing countries where property markets are not as well developed. However, the travel cost method has been employed to study the demand for environmental goods by tourists visiting developing countries. Brown and Henry (1993) for example, use the travel-cost method to measure the viewing value of elephants to North American and European tourists visiting safari parks in Kenya.

An example of indirect valuation in a developing country context is presented in Mu *et al.*, (1990). This study uses a discrete-choice contingent valuation approach combined with a water demand model to estimate factors which affect the household's decision to choose one water source over another. Households in Ukundu, Kenya were found to be obtaining water by one of three different sources, namely, kiosk water, vended water or pumps. The study finds that household decisions are influenced by time taken for collecting water from the different sources, the price of water and the number of women in the household. Income is found to be a relatively unimportant variable. The study uses collection time as an indicator of the opportunity cost associated with collecting water.

In a similar approach, Whittington *et al.*, 1990 present two approaches for valuing time spent in collecting water. The prices of water charged by kiosks and by vendors were found to be the same for all households. However, the study notes that time taken to collect water from kiosks and from wells varies according to the location of households in relation to these water sources. A discrete choice behavioural model is used together with a random utility model to determine the probabilities associated with preferences for different types of water services. A multinomial logit model is used to estimate parameters for key variables which are then used to estimate the value of time spent in collecting water.

Direct hypothetical methods involve asking people directly about the values they place on an environmental service or good, e.g., by asking them willingness-to-pay (WTP) questions. These WTP questions may be based on a scenario reflecting a physical or price change in the environmental service. Contingent valuation (CV) surveys are used to assess how people react to hypothetical changes in some environmental resource. "Contingent valuation devices involve asking individuals, in survey or experimental settings, to reveal their personal valuations of increments (or decrements) in unpriced goods by using contingent markets...Contingent markets elicit contingent choices." (Randall *et al.*, 1983). CV surveys of relevant populations are used to determine willingness to pay (WTP)or willingness to accept (WTA) a certain situation with regard to a specific environmental resource. Sensitivity analysis conducted on the data collected can also reflect on the criteria that are important in affecting preferences of these households. The CV should therefore elicit information on household characteristics, prices, water sources used by the household, and WTP for different scenarios for water supply.

Indirect hypothetical methods are relevant to this study, in particular the use of contingent behaviour surveys to determine preferences for environmental goods. Contingent behaviour questions focus on hypothetical *behaviour* to determine preferences for environmental goods and services. Contingent rankings asks individuals to rank alternatives in order of preference while contingent referendum asks individuals to make their selection of one alternative from a set of two hypothetical alternatives. These methods therefore rely on the individual to make an ordinal ranking of alternatives rather than asking them to choose or state monetary values.

For the remainder of this chapter we will focus on a discussion of two methodologies, namely, the household production function and production function approaches. The valuation studies presented in chapters 5 and 6 are based on these valuation approaches.

4.3.1 Valuing the environment as an input

Freeman (1993) notes that welfare changes may be defined due to:
1) changes in the prices individuals pay for goods bought in markets
2) changes in the prices they receive for their factors of production
3) changes in the quantities or qualities of non-marketed goods
4) changes in the risk individuals face.

The third point is the focus of this chapter and we will discuss the use of production function and household production function approaches in the context of quantity changes of non-marketed, environmental services.

The valuation of direct use values (i.e., benefits derived from the direct use of a wetland's resources) and indirect use values (deriving from environmental functions) require different approaches. Direct use values are generally measured by observing commercial uses of resources or services derived from wetlands and by applying market prices or shadow prices. The valuation of indirect use values deriving from environmental functions requires that the linkages between these functions and dependent economic production activities are known or at least estimable.

While the assignment of monetary values to economic goods and services is acceptable to most people, assigning monetary values to environmental resources, particularly in order to capture non-use values, invokes moral and ethical arguments which may not and perhaps need not, be resolved. Nonetheless, indirect uses of environmental systems require some form of value assignment, in terms of both establishing the physical/ecological linkages that make such uses possible, as well as by measuring the derived economic benefits from these uses.

Valuation techniques based on the household production function and production function approaches have been advocated in the valuation literature as appropriate techniques to use when the services of an environmental resource are inputs in the production of some marketed or marketable good.

Applications of the general production function approach in derived demand studies such as a household's demand for environmental amenities, is known as the household production function approach (Smith, 1991). Travel cost and averting behaviour models are examples of this approach. The household production function approach was developed on the pioneering work of Becker (1965) and Lancaster (1966) on the theory of consumer choice. This approach is based on the observation that households derive utility from goods produced through combining purchased goods with household labour or time. The household can be analysed therefore as a producer which combines purchased goods and time as inputs into a household production function to produce some commodity (see Hori (1975) for an early application). By explicitly incorporating non-marketed environmental goods in the modelling of consumer preferences, valuation techniques based on the household production function approach can relate household expenditures on private goods to the derived demand for environmental goods.

The household production function may be described by the following utility function:

$$U = U(\mathbf{Q}, f(x_i, W)) \qquad \mathbf{(4.2)}$$

where **Q** is a vector of privately consumed goods, with known prices and quantities. The production function $f(x_i, W)$ for $i = 1,\dots k$, describes the production of a good q by the household using both a private good x and an environmental good W as inputs. The household is then expected to maximise this utility function subject to a budget constraint and the derived demand function for the environmental good can be estimated.

Agricultural household models are similarly developed based on this microeconomic approach where the household is essentially treated as a firm, combining labour with purchased inputs to produce multiple crops partly for sale and partly for own-consumption (Singh *et al.*, 1986). These models provide an analytical framework within which the household is assumed to maximise a utility function such as:

$$U=U(X_a,X_m,X_l) \qquad \textbf{(4.3)}$$

where X_a is an agricultural good, X_m is a market purchased good and X_l is the amount of leisure enjoyed by the household. The household maximises the above utility function subject to a budget constraint and a time constraint. The household also faces a specified production function :

$$Q_a=Q(L,V,A,K) \qquad \textbf{(4.4)}$$

where L is the household total labour input, V is a variable input (fertilizer for example), A is the household's land endowment (fixed) and K is its fixed stock of capital. This approach therefore allows the modelling of consumption and production decisions in a single framework. Clearly, however, the modelling approach is data intensive. In an application using a modified agricultural household production approach, in areas of Northern Nigeria, Freeman *et al.*, (1997) examine the effect of trade restrictions and fertilizer subsidies on environmental degradation. They model the impact on the environment through the effects of the trade policies and subsidies on household cropping decisions and input use, and use social accounting matrices (SAMs) for this purpose. Households are assumed to maximize a utility function similar to equation 4.3 above, subject to a full income constraint. Household produced agricultural commodities which are marketed are also included in the model. The study finds that cereal production dominates household production decisions and requires a high input of fertilizer. Household cropping choices and input use decisions reflected in the model are affected by trade policies which determine domestic relative prices of cereals versus legumes, a fertilizer subsidy which increases relative profitability of maize production and a technological change which increases the competitive position of maize (Freeman *et al.*, 1997).

In the more general case of the household production function, the production function approach allows us to capture the indirect use value of environmental goods in the production of some marketable goods. Mäler (1992) develops the use of the production function for estimating the value of an environmental resource when the output of the production function is measurable. If the output is measurable and the production function can be defined as for example:

$$q=f(x_1,\ldots,x_k,W) \quad \textbf{(4.5)}$$

where q is the output, $x_1,\ldots x_k$ are inputs of goods and services and W is the input of the unpriced environmental resource, then the economic value of a small change in the resource supply (holding all other prices constant) is the value of the production change that will accompany the change in the resource availability[3]. The welfare change is the sum of the consumer and producer surplus measures. However, if the production units are small relative to the market for the final output, and they are essentially price-takers, it can be assumed that product and variable input prices will remain fixed after a change in the environmental resource, W. In this case the benefits of a change in W will accrue to the producers (Freeman, 1993).

The appropriate basis for determining the value of the environmental good W is therefore to view it as a *factor input* in the production process (Ellis and Fisher, 1987; Mäler, 1992; Freeman, 1993; Barbier, 1994). The impact on the product supply of a change in an

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[3] If the output q cannot be measured directly, then either a marketed substitute may be used, if it exists, or possible complementary or substitutability between the resource and other inputs must be explicitly defined (see Mäler 1992 for a more complete discussion).

ecosystem function depends therefore on the demand for the product and the shift in the supply curve of the factor input. For example, services such as a wetlands ability to improve the quality of drinking water (Ellis and Fisher, 1987), enters into the utility function indirectly through the consumption of the final good, drinking water. Since wetlands can be said to reduce the cost of water treatment by removing or settling pollutants, this cost can be represented as a shift in the marginal cost or supply curve for fresh water along a given demand curve.

Whereas Ellis and Fisher (1987) discuss only the case where the output is marketed, Mäler (1991;1992) shows that the production function approach, where the unpriced environmental good enters as an input into the production process, may be applied differently based on whether the output is measurable or not measurable. He also makes the difference in non-measurable output between substitutability and complementarity of the output with a measurable good to further explore the possibility of using the production function approach for different situations.

The production function approach provides a useful way in which to value environmental functions. However, the pervasive lack of adequate data on how an environmental function is linked to the production of other goods often means that the welfare analysis may need to make a number of assumptions. Nonetheless, there may be sufficient information on related variables which could help strengthen the validity of these assumptions. As noted earlier, Mäler (1992) also shows that not knowing the functional form of the production function may not impede analysis, provided certain assumptions, such as substitutability or complementarity of the output with a measurable good, can be made. Furthermore, as the valuation study presented in chapter 5 shows, data requirements for the use of the household production approach may also be met by combing stated preference and revealed preference data.

Point (1994) further expands on this approach of including the environmental factor into the production process. He notes that since any environmental variation, directed towards production has an effect which depends on the role played by the environmental factor in the production technology, there are four main specification possibilities:

- simple input acting as fixed factor, denoted as:

$$q = f(x_i, W) \quad for\ i = 1,\ldots,n \tag{4.6}$$

where W is the environmental factor, q is the output and x_i are marketed inputs. Examples of this production technology are quality and quantity of water available for irrigation and air pollution. Ellis and Fisher (1987) provide an example of this approach, building on an earlier study by Lynne *et al.,* (1981). Lynne *et al.*, (1981) develop a bioeconomic model in which human effort and wetlands are distinct inputs into production of blue crab off the Florida Gulf Coast (see below).

- factor affecting a specific input, expressed as:

$$q = f(x_1, \ldots x_i(W) \ldots x_n) \quad for\ i = 1,\ldots,n \tag{4.7}$$

where $x_i(W)$ is the input under the influence of the environmental factor. See chapter 6 for an application of this formulation of the production function.

- factor affecting the product, expressed as:

$$q = Wf(x_i) \quad for\ i = 1,\ldots,n \tag{4.8}$$

where in this case, W, the environmental factor, affects the entire production function. This is a special case of (4.8) and may be applied to the case of pollution where the reduction in environmental quality may be assumed to affect the entire production technology.

- factor affected by a specific input, expressed as:

$$q = f(x_i) \quad where\ E(x_i) < E^* \quad for\ i = 1,\ldots,n \tag{4.9}$$

here the impact of the environmental factor is felt through a limitation in the use of an input x_i. Examples include cases where standards may be set which restrict the use of a particular input, based on a quality or quantity standard for the environmental input, e.g., pesticide use and water quality standards.

Lynne *et al.*, (1981) as noted above, model the population of blue crab as a function of wetland acreage. Hence wetlands appear as an input in the production function for crabs, defining the carrying capacity for crabs. They calculate a marginal product for an acre of wetlands based on their approximation of the production function. The Lynne *et al.*, study uses fish population dynamics modelling approach to link marsh size (i.e., wetland area) to the population of blue crab. The suggest therefore that B_t (maximum potential biomass of blue crab) is a function of marsh area:

$$B_t = f(M_{t-1}) \tag{4.10}$$

where the acreage of marsh (M_{t-1}) is a proxy for the services of the marsh, available in year t-1. The limitations of this study in terms of accurate welfare measures is discussed in Ellis and Fisher (1987) (see above) and in terms of management regimes and institutional factors by Freeman (1991). Freeman (1991) notes that the values imputed to the wetlands are influenced by market conditions and by institutional arrangements that determine the conditions of access and rate of utilization of the blue crab fishery. Under conditions of open access, for example, rents in the fishery would be dissipated and that price would be equated to average costs, rather than to marginal costs as would be the case under optimal regulation of the fishery. As a result, under open access conditions, there is zero producer surplus and any change in wetland area would affect only consumer surplus.

Anderson (1987) provides an empirical application in a developing country, of the change in production approach. The study values the effects of afforestation (shelterbelts and farm forestry) in Northern Nigeria. The project output was assessed in terms of 1) increases in agricultural output, 2) increases in livestock products and 3) increases in tree products (especially fuelwood production). The effect of afforestation on these three outputs is assessed by making certain assumption regarding the effect of planting on wind velocity, soil fertility, livestock feed (in terms of crop residue, farm trees and shrubs) and on wood and fruit production. In addition, the maturity of the shelterbelts was also taken into account since the trees are expected to have different effects on the production functions for the three outputs, depending on the height of the shelterbelt.

In the study, Anderson analyses farm forestry and shelterbelts separately. He finds that the rate of buildup of benefits between the two options is different and the yield affects are smaller for farm forestry. Anderson (1987) presents a number of scenarios such as low yield/high cost, high yield/high cost, no erosion, rapid erosion, soil restoration and a jump in yield, to further test the viability of a shelterbelt afforestation project. He concludes through this analysis that shelterbelts have significantly higher costs than farm forestry programmes but the latter carry higher risks of poor returns.

Narain and Fisher (1994) use a similar production function approach to model the value of the Anolis lizard. They estimate crop production functions for various crops and assume that the contribution of the lizard as a pest control is reflected in the production function as a shift in the intercept term. For example, they estimate, the production function for sugar is expected to shift by 1000 percent for a one per cent decrease in the lizard population. Although this approach develops the appropriate production functions for the crops, it is unable to actually predict the change in output due to changes in lizard population because of the lack of information about the lizard populations and its contribution as a pest control for agricultural crops. This paper particularly highlights the problems of poor data on resources that are the subject of the valuation exercise.

Often however, more than one valuation approach may be required to derive values for the ecological function of interest to the researcher. Gren *et al.*, 1994 employ contingent valuation, production function and replacement cost methods to arrive at the value of the nitrogen abatement function of wetlands on the island of Gotland in Sweden. Similarly, Hammack and Brown (1974), employ results from contingent valuation surveys combined with production functions for duck production by prairie wetlands in North America. Results obtained from these data are then combined with a bio-economic model for the prairie wetlands in order to elicit the optimal number of prairie potholes.

The studies which use various modifications of the production function approach show the different ways in which environmental functions may be valued. It is clear from examining them however, that the lack of adequate data on how the environmental function is linked to the production of other goods often means that the welfare analysis must make a number of assumptions, which may be inaccurate. Nonetheless, there may be sufficient information on related variables which could help strengthen the validity of these assumptions. If however, the production technology has to be defined, it has been suggested that detailed data collection would be required to gather information on household patterns of expenditures, time allocations, commodity prices and wage rates, as well as measures of levels of (or changes in) environmental quality experienced by these households (Bockstael and McConnell, 1983; Smith, 1991; Barbier, 1994). The difficulty of collecting such detailed data has meant that there are few applications of this approach, particularly in developing countries.

4.3.2 Applications of studies combing revealed preference/stated preference data

There are some ways to get around this daunting task of collecting appropriate data for the household production function approach. Augmenting revealed preference data, collected through market observations or surveys, with data collected through indirect survey methods of contingent valuation or contingent behaviour can be used to provide adequate information for the required analysis. This technique of combing stated preference and revealed preference data has been used by a number of studies in transportation research (Henscher and Bradley, 1993, Morikawa *et al.*, 1990; Ben-Akiva and Morikawa, 1990).

Contingent valuation methods have been applied to a number of issues in developing countries to estimate values for non-marketed resources such as environmental resources or social services. Contingent valuation has also been applied to study the demand for water supply and sanitation facilities in Haiti (Whittington *et al.*, 1990), Ghana (Boadu, 1992 and Whittington *et al.*, 1993), Philippines (Bohm *et al.*, 1993), Pakistan (Altaf *et al.*, 1993) amongst others. These studies have mainly looked at the willingness to pay for improved or alternative water supply or sanitation services.

Most studies combining observed and hypothetical data have used the method of contingent valuation to obtain their hypothetical data. A few, such as Adamowicz *et al.*, (1994) and Englin and Cameron (1996) have used contingent behaviour techniques to obtain the hypothetical data. Pooled stated preference and revealed preference data has been used to value environmental amenities by a few studies such as Adamowicz *et al.*, (1994), Cameron (1992) and Englin and Cameron (1996). Stated preference approaches such as contingent behaviour can be combined with revealed preference data to augment observed data. Adamowicz *et al.*, (1994), amongst others, note that:

1) stated preference data can help reduce collinearity that may be present in the revealed preference data set and attribute effects, which were previously weakly identified due to collinearity, may become more clearly identified by pooling the data; and that
2) stated preference questions can address a wider range of proposed changes which revealed preference data cannot record.

Furthermore, it is argued that people may be better at predicting what they would *do* in a hypothetical situation rather than whether they would pay some hypothetical price, as is required, for example, by a contingent valuation referendum survey and that it may also be easier for respondents to predict their prospective behaviour rather than to estimate their total willingness to pay for an environmental resource (Englin and Cameron, 1996). Contingent behaviour data precludes the need to return to households over a number a years to collect time series data which may result in expensive research and fail to meet the urgent environmental and social concerns prevalent in many parts of the developing world.

4.4 Conclusions

This chapter has focused on empirical and theoretical studies addressing the valuation of environmental functions, specifically as inputs into the production of other, marketed or marketable goods. In the next two chapters some of tools described here will be used to value the ground water recharge function of the Hadejia-Nguru wetlands. The approaches presented in these studies draws on the experiences of some of the studies reviewed in this chapter. By applying some of the methodological aspects described above, the following two chapters provide new insights into the possibilities and difficulties of applying indirect valuation techniques in developing countries.

Chapter 5

Valuing Groundwater Recharge: A Modified Household Production Function

5.1 Introduction

The wetlands of the Hadejia-Jama'are floodplain described in chapter 2 are under threat by planned upstream water resource schemes which could drastically reduce the flooding within the wetlands. The annual flooding of the Hadejia and Jama'are rivers create and maintain these wetlands which are known in the local Hausa language as *fadamas*[1]. The wetlands have been found to be of significant economic importance in terms of floodplain activities (Barbier *et al.*, 1993). In addition, hydrological studies of the wetlands have concluded that the annual recharge of the underlying aquifer is an important environmental function performed by the regular flooding of the wetlands and surveys of the wetlands have also shown that dependence of the wetland populations on groundwater for drinking water and other household uses is very high (see chapter 2 and Hollis *et al.*, 1993a).

However, as shown in chapter 3, the opportunity cost of diverting water for upstream developments and other water diversion schemes which may affect the flood extent within the wetlands needs to be incorporated into development plans for the river basin. Although the economic importance of floodplain activities has been partially evaluated (Barbier and Thompson, 1997; Barbier *et al.*, 1993), the environmental function of groundwater recharge performed by the wetlands, remains unvalued. The aim of this chapter is to value this recharge function through an analysis of domestic consumption of groundwater resources. Some of the valuation techniques discussed in chapter 4 will be applied and further developed in this chapter for this purpose. Chapter 6 will value the contribution of the wetland recharge function to irrigated agriculture within the wetlands.

Observations of water demand are based on a dry season survey carried out during 1995-1996. As noted earlier in chapter 4, the methodological difficulty of determining a demand schedule for each household, given few observations, may be overcome with the use of pooling observed (revealed preference data) data with contingent behaviour (stated preference) data, also collected during the same time period. The present study identified two areas within the wetlands and collected data on both observed prices and quantities, and

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[1] *Fadamas* are low-lying areas which become waterlogged or flooded during the wet season and gradually dry out until they are flooded again during the next wet season.

collection times for each household within the sample, as well as other relevant socio-economic information. The contingent behaviour data was collected by varying prices and collection times and recording household response.

Three types of households, defined by their water procurement preferences, were identified as (i) households which collect all their water, (ii) those which purchase all their water and (iii) those which both purchase and collect the water consumed by the household.[2] Households do not sell the water they collect and any water collected by a household is solely for its own consumption. Given these household types, a behavioural model using a household production function approach is developed to model demand for collected and purchased water. A panel is formed by pooling the hypothetical and observed data to augment the information on demand for purchased and/or collected water, thereby allowing us to determine demand schedules for each household, in each 'market'. Water demand for collected water and purchased water is estimated using panel data comprised of the pooled data. Random effects and seemingly unrelated regressions are used to address panel data econometric issues and error correlation issues. Welfare change is then calculated based on the results of the demand estimation and on hypothetical reductions in the groundwater recharge rate, to obtain a value for the groundwater recharge function of the wetlands.

5.2 The study area

Three villages in the Madachi *fadama* and one village in the Sugum *fadama* were chosen for the economic valuation study, based on the hydrological evidence that these villages rely on groundwater recharged mainly by wetlands (see figures 5.1 and 5.2). The flooding of the Madachi *fadama* is caused by the floodwaters of the Hadejia river. The village of Sugum is located in the eastern part of the wetlands and is influenced by the flooding of the Jama'are river. Villagers prefer to use well water for drinking, cooking and cleaning. Other activities such as watering of animals, washing clothes and utensils and house building may sometimes use water from the *fadamas* in addition to well water.

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[2] For the remainder of this chapter we will refer to these groups as (i) collect only; (ii) purchase only; and (iii) collect and purchase households.

Figure 5.1 Study area within the Hadejia-Nguru wetlands (villages around the Madachi *fadama*)

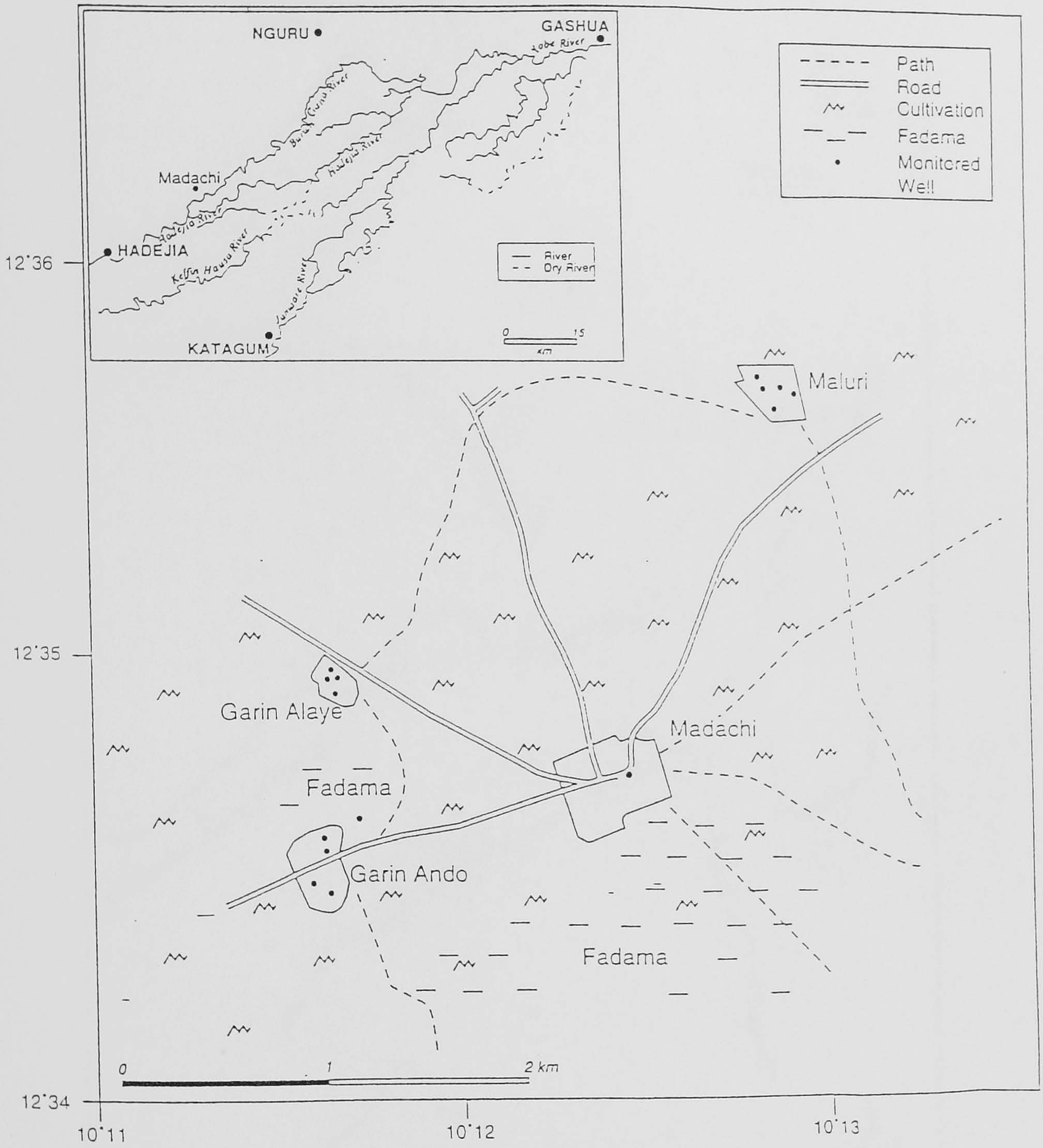
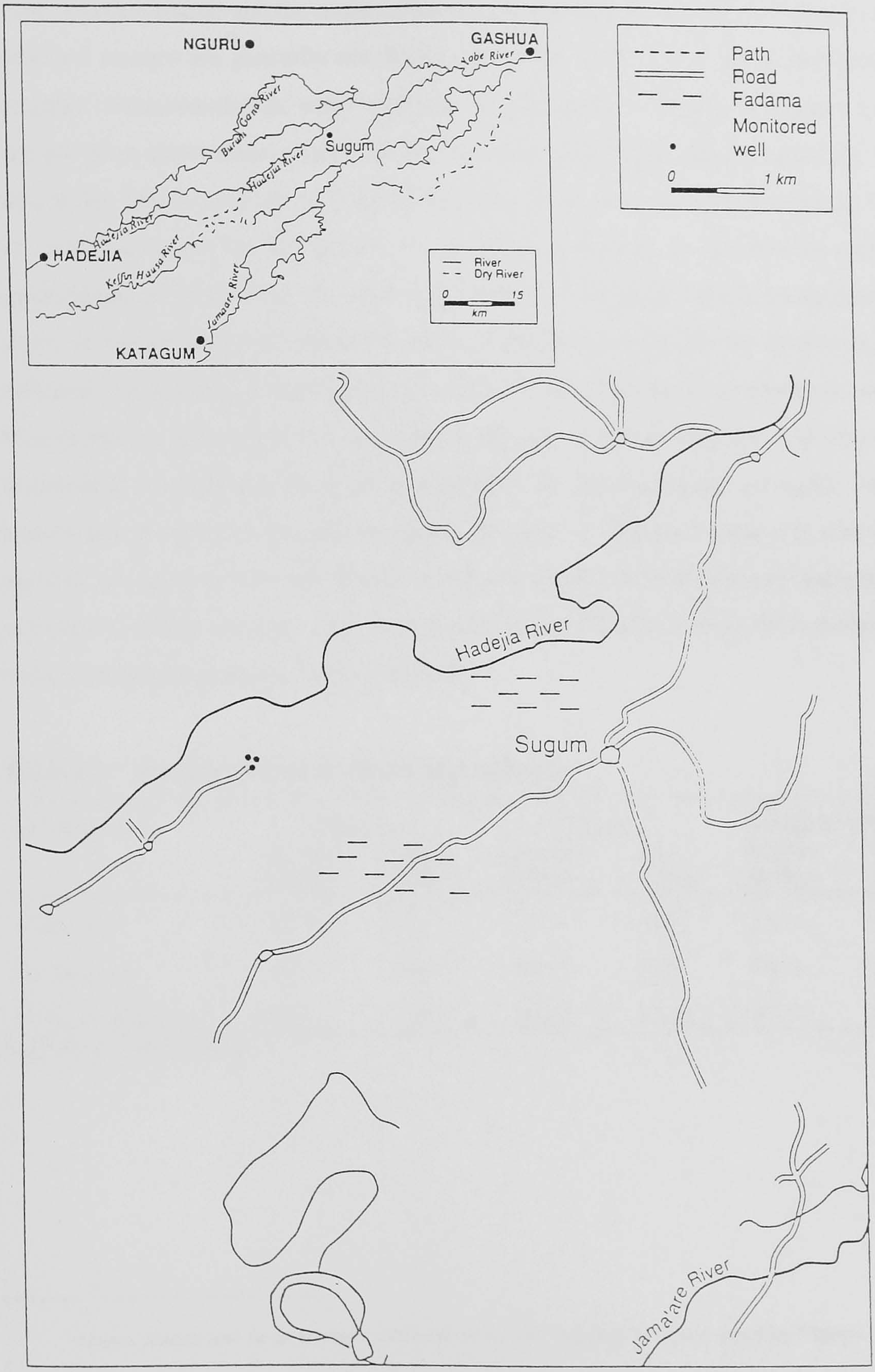


Figure 5.2 Study area within the Hadejia-Nguru wetlands (the Sugum *fadama*)



5.2.1 Water collection

The Madachi area is predominantly Hausa or Kanuri while the village of Sugum is Bede[3]. Both areas are Islamic and the communities practice 'purdah' or seclusion of married women. Married women are generally not allowed to move outside their compound and in the majority of the households, water is fetched by men and/or children. In Sugum, the Bede culture does allow some women to move outside their home and consequently not all households practice purdah. In households where wives were found to be sharing the task of collecting water for the household, an effort was made to involve the women in participating in the surveys. In most cases, however, the head of the household collected water in the morning and additional water requirements were met by smaller quantities collected by household members later in the day or supplied by independent vendors. Households in the sample do not collect and sell water themselves[4]. Distances from households to wells and back were measured for all households surveyed, including households observed to be purchasing all their water. The time taken for a household member to travel to the well, collect water and return to the house was measured and recorded as collection time. The mean distances and collection times per household type in each village are given in Table 5.1 below.

Table 5.1 Average distances and collection times

Household type	Madachi		Sugum		Average for both sites	
	Distance (metres)	Time (mins)	Distance (metres)	Time (mins)	Distance (metres)	Time (mins)
Collect only	207.8	9.2	279	9.89	239.5	9.52
Purchase only	209.1	8.14	280.73	12.73	248.12	10.62
Collect and Purchase	230.9	12.2	234.86	11.94	235.62	12.06

Sample size: 130 households

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[3] Hausa, Kanuri and Bede are three different ethnic and language groups in northern Nigeria.

[4] Young children may occasionally collect and sell small quantities of water but the quantity sold is insignificant and the frequency of this activity is difficult to ascertain.

Water purchasing

All the villages are familiar with the vending of water and the price of water in the villages ranged between 2.00-5.00 Naira[5] per 36 litres. Water is delivered to households by vendors who collect the water from the village wells using the same technology used by households who collect their own water. There are no restrictions on the vendors' use of the village wells. The water vendors are often Fulani men from Niger who migrate to villages within the wetlands and stay for periods of a few months at a time. They are accepted as guests into a household and may stay as long as the household is able to support them.

Capital outlay for the purchase of a *sanda* (comprising of two tins, one pole and string) is Naira 350. Price changes due to decreased water levels in wells are evident in the price increase during the dry season. A survey of the vendors who were present in the villages (sample size = 7) was carried out to investigate the effect of changing water levels on the price and availability of vended water. In reply to whether there would be a price increase if the water levels in the wells were to fall, the vendors unanimously stated that they would increase the price by 1-2 Naira for a 25% increase in their (average) collection time[6].

5.2.2 Consumption and storage of water in houses

Water is stored in large earthen pots within the compound. Most houses have at least two containers and many have five or six. The use of these containers makes it easier to calculate the quantity of water used by each household per day since the standard of measurement in all the villages was based on the volume of water contained by one tin, equivalent to 18 litres of water. Daily water consumption per household was calculated by recording the number of times each container was filled and how many tins it could take. Collect and purchase households clearly consume more water than the other households and are almost evenly divided in the amounts they purchase and collect.

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[5] Exchange rate (March 1996) Naira 88 = $1

[6] For vendors, the time taken to collect and deliver water varies with water depth and with distance to the purchasing household. Hence average collection times were estimated for vendors by taking the average of time taken for collection and delivery to a random sample of households within each village.

Table 5.2 Average water consumption (litres per day)

Household type	Total water consumption	Collected water	Purchased water
Purchase only	153.31	0	153.31
Collect only	221.81	221.81	0
Purchase and collect	285.98	153.90	132.23
Mean	232.28	144.57	87.77

Sample size = 130 households

5.2.3 Household characteristics

Aside from differences in water consumption levels, purchase only, collect only and purchase and collect households are also differentiated by employment, income levels and other household characteristics. Table 5.3 provides information on the occupation and sources of income of the households as well as other indicators of wealth. A higher percentage of households which only purchase water are involved in local trading and the civil service, in addition to farming and fishing activities. The occupational differences between collect only households and the other two household types are more marked than those between purchase only and purchase and collect households. These differences are also revealed in the water demand analysis in section 5.3.

Wealth indicators such as the number of size of land holdings show that purchase only households have a lower level of larger land holdings, compared with households which only collect their water. However, this is probably consistent with the findings that households which purchase only state local trading and the civil service as important occupations and income sources. Purchase and collect households have a higher average monthly income as well as larger households than purchase only or collect only households. Collect only households are clearly poorer in terms of monthly income levels and the level of monthly savings.

Table 5.3 Household characteristics

Variable	purchase only	collect only	purchase and collect
Occupation[7] (%)			
• farming/fishing only	23.2	40.2	19.9
• trader	34.4	28.6	32.6
• civil service	36.0	19.2	26.9
• other	6.4	12.0	20.5
Land holding (parcels of land)			
• 0-1	0.0	1.9	0.0
• 2-4	48.0	13.9	24.0
• 5-7	47.2	69.5	48.6
• >7	4.8	14.7	27.4
Average monthly income (Naira)	4656.48	2653.46	7322.73
Average monthly expenditure	3365.21	2074.58	4024.50
Household size	8.83	8.77	10.60
Ratio of children to adults[8]	1.4	1.35	1.35

Notes: Sample size = 130
Average size of landholdings =1.59acres

5.3 The behavioural model

As described in the previous section, the households in the study area were found to be either collecting all their water, purchasing all their water or doing a bit of both. Households do not collect and sell water, all water collected by a household is consumed by the household and water is purchased from independent vendors. In this section we develop a behavioural model to estimate water demanded by the different types of households. Since households are observed to be collecting, purchasing or doing both, we need to account for this behaviour in our demand estimation. We describe why households may choose their preferred method of water procurement. We also show in this section and in Appendix 5.1, the basic demand equations that can be derived from the behavioural model. In addition, we argue that, given changes in the price of vended water or collection

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[7] This refers to the main occupation of the household. Nearly everyone engages in farming and fishing to some extent. Those in the farming/fishing category depend solely on these activities for household income whereas traders and civil servants are farmers and/or fisherman who derive a larger share of their income from trading or employment in the public sector. The category other refers to activities such as tailoring, mat making and driving of motorcycle taxis.

[8] The household is usually an extended family and in addition, each man may have up to 4 wives and usually at least 2.

times, households may switch from their present method of water procurement (e.g., collecting only) to another method (e.g., collecting and purchasing).

5.3.1 A model of household water consumption

We begin with a general model in which it is assumed that a household has the choice of both collecting and purchasing its water. The household allocates its labour between income generating activities or water collection. Hence, members of the household can either spend their time collecting (producing) water, or in some other income generating activity. In addition to consuming water, the household also purchases a composite good Q, with price P. Labour is allocated between water collection and time spent in income generating activities. Thus the household maximizes its utility subject to a labour and budget constraint. Assuming that Q is our numeraire good, the problem can be written as:

$$Max\ U = U(Q,W) \qquad \textbf{(5.1)}$$

$$\begin{aligned} &s.t.\ \ W = W_p + W_c; \qquad W_c, W_p \geq 0 \\ &where\ W_c = \frac{L_w}{\alpha} \end{aligned} \qquad \textbf{(5.2)}$$

and

$$Y(L_0 - L_w, z) - P_w W_p = Q \quad (budget\ constraint) \qquad \textbf{(5.3)}$$

where:

Q = numeraire good with price P = 1
W = total water demand by household
L_0 = total household labour
L_w = labour used in collecting water
P_w = price of vended water, exogenous
W_c = quantity of water collected by household
W_p = quantity of water purchased by household
Y = household income
z = household characteristics, exogenous factors affecting income generation
α = time cost of collecting water

We assume that water collection displays constant returns to labour (L_w/α), (as long as groundwater levels remain constant) and production of other goods is affected by diminishing returns to labour. Since $W_c = L_w/\alpha$, Q can be rewritten as $Y(L_0\text{-}Wc\alpha,\ z)\text{-}\ P_wW_p$, and by substituting into the utility function, the maximization problem for the general case is written as:

$$\underset{W_c, W_p}{Max}\ U[Y(L_0 - W_c\alpha,\ z) - P_wW_p,\ W_p + W_c] \tag{5.4}$$

The Lagrangian for this problem is:

$$\mathcal{L} = U[Y(L_0 - W_c\alpha\ ,\ z) - P_wW_p, W_p + W_c] \qquad U'(.)>0, U''(.)<0 \tag{5.5}$$

with the following first order Khun-Tucker conditions:

$$\frac{\partial \mathcal{L}}{\partial W_c} = U_w - \alpha U_Q Y_L(z) \leq 0, \quad W_c \geq 0, \quad W_c\left[\frac{\partial \mathcal{L}}{\partial W_c}\right] = 0 \tag{5.6}$$

$$\frac{\partial \mathcal{L}}{\partial W_p} = U_w - P_wU_Q \leq 0, \quad W_p \geq 0, \quad W_p\left[\frac{\partial \mathcal{L}}{\partial W_p}\right] = 0 \tag{5.7}$$

implying that the household will consume W_c or W_p until the marginal utility of consuming the good is less than the marginal utility of producing or purchasing the good. As there are non-negativity constraints on the choice variables W_c and W_p , either may equal zero according to the relative prices P_w and α which is determined by the household's productivity of labour. Since W_p and W_c are perfect substitutes in consumption (but not in production), a household can make three choices depending on the relative prices :

1) W_p and $W_c > 0$ (interior solution)
2) $W_p = 0$ (collect only corner solution)
3) $W_c = 0$ (purchase only corner solution)

Interior solution

If an interior solution exists, then W_p and $W_c > 0$ and from (5.6) and (5.7) we obtain the following condition:

$$\frac{U_w}{U_Q} = \alpha Y_L(z) = P_w \tag{5.8}$$

i.e., for an interior solution to exist, the utility maximizing household will set $\alpha Y_L(z) = P_w$. At this point, the household's marginal productivity of labour (time) spent in producing water is equal to the price of vended water. That is to say, the relative prices of collected water and purchased water are equal. The household is therefore indifferent (at the margin) between purchasing and collecting water (see Figure 5.3). Note that $Y_L(z)$ implies that the marginal product of labour is a function of household characteristics, z. In addition note that Y is a function of labour L and we include L as a parameter in the vector z to simplify notation.

The household's demand for collected and purchased water (W_c and W_p) can now be approximated by combining the conditions for an interior solution (5.8) with the budget constraint (5.3) and by solving for W_c and W_p, where:

$$W_c = W_c(P_w, \alpha, z) \tag{5.9}$$

$$W_p = W_p(P_w, \alpha, z) \tag{5.10}$$

Using the first order (linear) Taylor series expansion[9], linear demand functions for W_c and W_p are approximated as:

$$W_c = c_1 + \frac{\partial W_c}{\partial P_w} P_w + \frac{\partial W_c}{\partial \alpha} \alpha + \frac{\partial W_c}{\partial z} z + \varepsilon_1 \tag{5.11}$$

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[9] $Y = f(x^0) + \sum_i f_i(x^0)(x_i - x_i^0)$ where $f_i(x^0) = f'(x^0)$; $x_i^0 = 0$

$$W_p = c_2 + \frac{\partial W_p}{\partial P_w}P_w + \frac{\partial W_p}{\partial \alpha}\alpha + \frac{\partial W_p}{\partial z}z + \varepsilon_2 \qquad \textbf{(5.12)}$$

Appendix 5.1 provides a detailed discussion of the comparative static effects of changes in α, z and P_w on the first order conditions of the interior solution. Appendix 5.1 also shows how these can be used to derive demand functions and details the derivation of the linear approximations to equations (5.9) and (5.10).

Corner solutions

As noted earlier, there are two possible corner solutions to the household demand problem. For the corner solution where the household collects all its water, $W_p = 0$. Hence equation (5.7) is no longer applicable. For this household, $\alpha Y_L(z) < P_w$ at the optimum, i.e., the shadow price of labour employed in collecting water is less than the price of vended water:

$$\frac{U_w}{U_Q} = \alpha Y_L(z),\ \alpha Y_L(L-\alpha W_c^*,z) < P_w,\ W_p = 0 \qquad \textbf{(5.8')}$$

The household will therefore collect water up to the point where the marginal rate of substitution between water and the agricultural good, Q, is equal to the marginal opportunity cost of time spent in collecting water (figure 5.4). For these household, the price of purchasing water is always higher than the shadow price of collecting water. The comparative static effects of a change in α and z on the demand for collected water is shown in Appendix 5.1.

In the case of the purchase only corner solution, where the household chooses not to collect any water, $W_c = 0$ and it follows that $\alpha Y_L(z) > P_w$. That is, households will purchase all their water if the opportunity cost of their time spent collecting water is higher than the price of vended water (figure 5.5). Equation (5.6) is therefore no longer relevant, and the first order condition (5.8) is modified to:

$$\frac{U_w}{U_Q} = \alpha Y_L(z),\ \alpha Y_L(L_0-\alpha W_c^*,z) > P_w,\ W_c = 0 \qquad \textbf{(5.8'')}$$

For this household, the shadow price of labour employed in collecting water is always more than the price of vended water. Thus, the household will decide to purchase water up to the point where the marginal rate of substitution between water and the agricultural good, Q, equals the price of water. The comparative static effects of a change in α and z on the demand for purchased water is shown in Appendix 5.1.

The linear demand functions for estimating $W_{c\,(\mathrm{corner})}$ and $W_{p\,(\mathrm{corner})}$ are thus :

$$W_{c_{corner}} = \frac{1}{L_{11}}[c_3 L_{11} + \gamma_1 \alpha + \gamma_2 z] + \varepsilon_3 \qquad \textbf{(5.13)}$$

$$W_{p_{corner}} = \frac{1}{L_{22}}[c_4 L_{22} + \delta_1 P_w + \delta_2 z] + \varepsilon_4 \qquad \textbf{(5.14)}$$

where L_{11} and L_{22} are as defined as in Appendix 5.1.

Hence, as is shown in Appendix 5.1, for the case where $Y_L(z) = Y_L$, the linear demand functions for estimating W_c and W_p in the interior solution are:

$$W_c' = \frac{L_{22}}{Det}[c_1 Det/L_{22} + (\beta_1 + \gamma_1)\alpha + (\beta_2 + \gamma_2)z + \beta_3 P_w] + \varepsilon_1 \qquad \textbf{(5.15)}$$

$$W_p' = \frac{L_{11}}{Det}[c_2 Det/L_{11} + (\beta_4 + \delta_1)P_w + (\beta_5 + \delta_2)z + \beta_6 \alpha] + \varepsilon_2 \qquad \textbf{(5.16)}$$

It follows that if $\beta_1 = \beta_2 = \beta_3 = 0$ then $W_c' \approx W_{c(\mathrm{corner})}$ in (5.13) and if $\beta_3 = \beta_4 = \beta_5 = 0$ then $W_p' \approx W_{p(\mathrm{corner})}$ in (5.14).

Switching behaviour

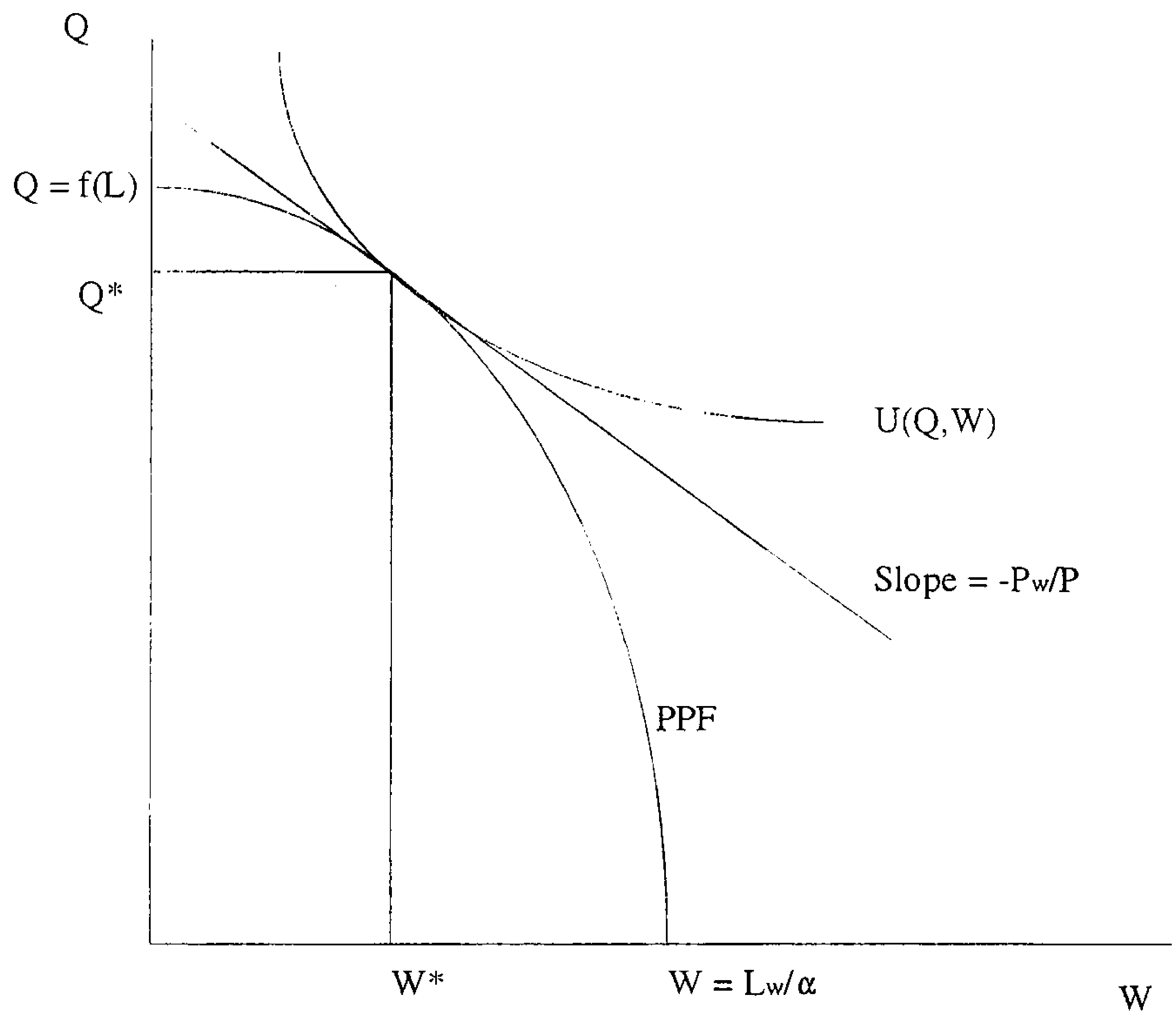
A comparison of conditions (5.8), (5.8') and (5.8'') indicate how changes in α or P_w may induce a household to switch from one water procurement method to another. The shadow price of collecting water is determined for a household by the alternative use of the household's labour and other household characteristics which may affect income generation.

Therefore, if household characteristics change or if α or P_w change, a household may switch from one water procurement method to another. For example, assume we observe a household purchasing all its water at price $P_w{}^0$. Assuming α for this household remains constant, there may exist a price $P_w{}^s$, where $P_w{}^s > P_w{}^0$, at which this household would start collecting some of its water while continuing to purchase the rest. At this point the household operates in both the collected water and purchased water markets. If we consider further that there exists a price $P_w{}^*$ where $P_w{}^* > P_w{}^s$; and $P_w{}^*$ is the choke price for the household's demand for purchased water, then beyond this price the household is not willing to pay for vended water and will operate solely in the collected water market. At this point condition (5.8') describes the behaviour of this household.

The same process could be observed in the behaviour of a household initially described by (5.8'). Holding P_w constant, of we allow α_0 for this household to increase, there may exist a shadow price α^s where $\alpha^s > \alpha_0$ and at which point the household purchases some of its water. The behaviour of this household is described by (5.8) at this point. There may also exist a choke shadow price for collecting water where $\alpha^* > \alpha^s$, after which the household leaves the market for collected water and is observed to be purchasing all its water, thereby defined by (5.8″). Hence these households are reacting to relative prices in the two markets and are expected to adjust their behaviour based on changes in household characteristics or the values of these relative prices.

In the next section and in Appendix 5.1, therefore, we derive demand functions which estimate demand functions in the two markets for collected and vended water. The demand for collected water is the total demand by collect only households and collect and purchase households whereas the demand for purchased water is the total demand by purchase only and collect and purchase households. As seen below in section 5.3.2, by using dummy variables to differentiate between household types, the effect of explanatory variables on the demand for collected water and purchased water can be differentiated for interior and corner solution households.

Figure 5.3 Graphical representation of the interior solution



W* and Q* are optimal levels of goods W and Q where W = collected + purchased water.

Figure 5.4 Graphical representation of the collect only corner solution

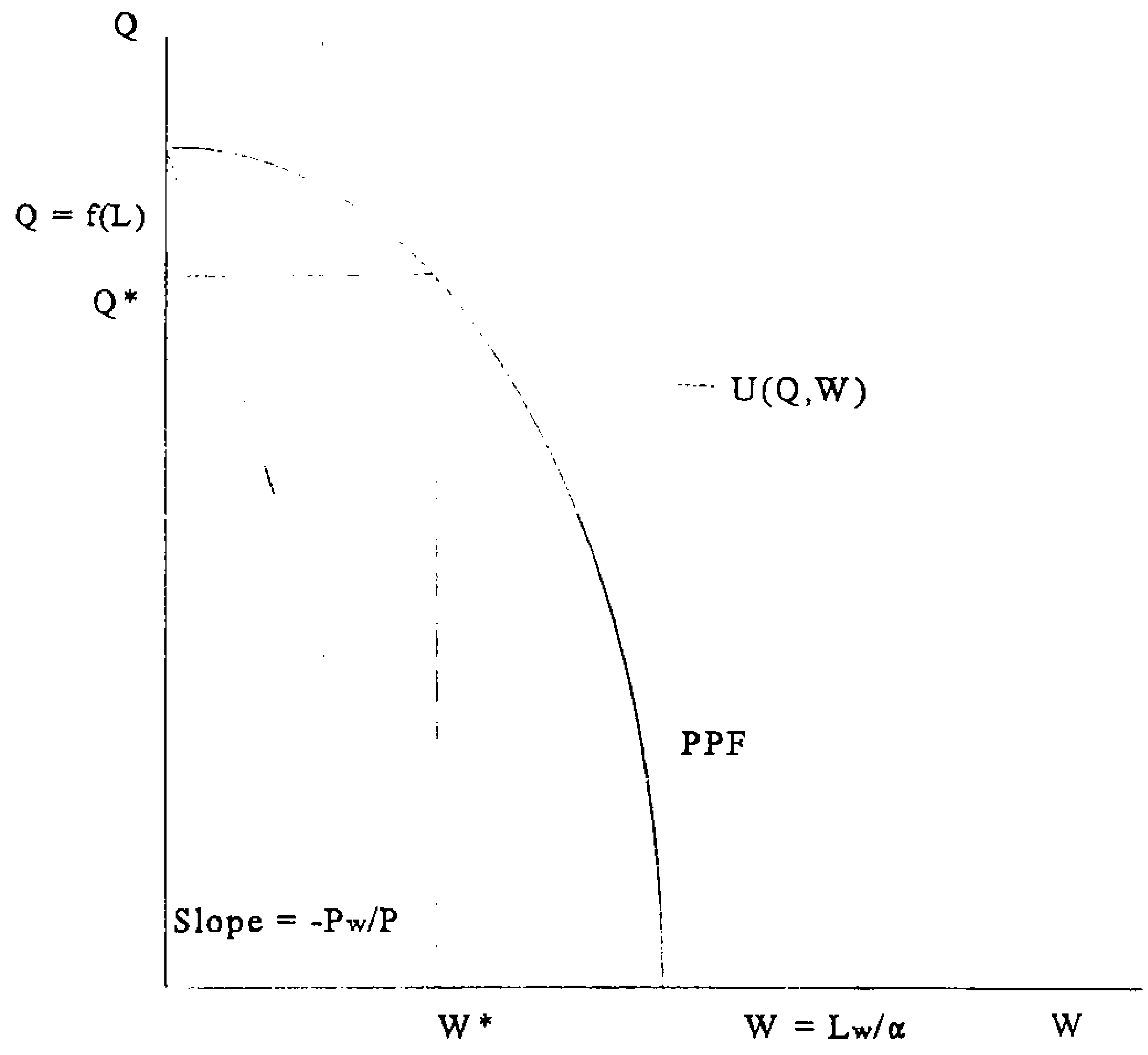
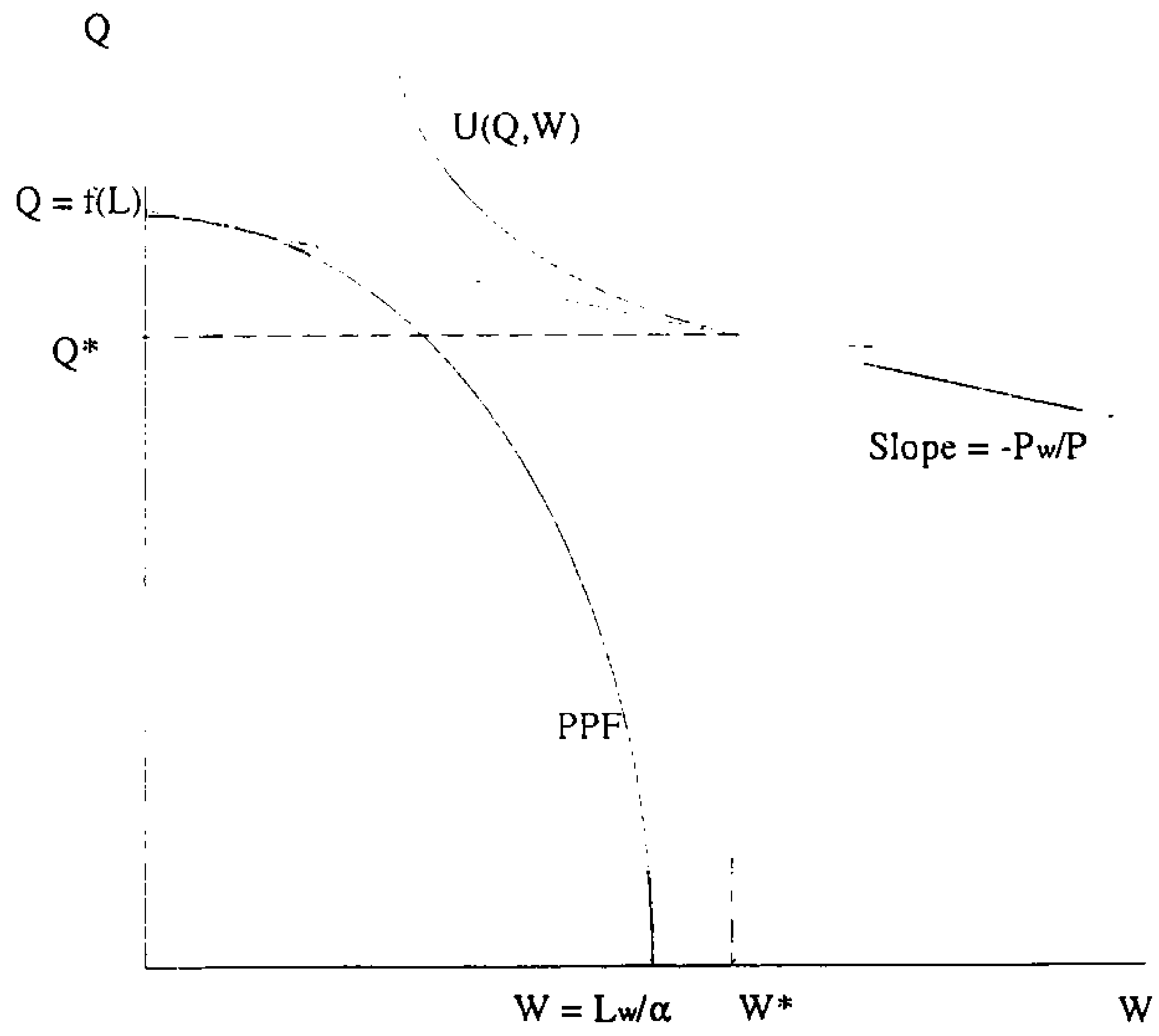


Figure 5.5 Graphical representation of the purchase only corner solution



5.3.2 Derivation of demand equations

From (5.11) we note that $Y = Y(L_0 - W c\alpha, z)$, and from the first order conditions we know that the marginal product of household labour is a function of household characteristics, i.e., $\partial Y/\partial L = Y_L(z)$. Each household's ability to convert labour into income is affected by the characteristics of that household. We include this effect by using varying parameters, where there is interaction between collection time and household characteristics variables. Hence, incorporating the varying parameter terms, as shown explicitly in Appendix 5.1, the demand functions to be estimated in the next section are:

Demand for collected water by collect only and collect and purchase households:

$$W_c^{//} = c_1 + a_1\alpha + a_2 D_c\alpha + a_3\alpha z + a_4 D_c\alpha z + a_5 z + a_6 D_c z + a_7 D_c P_w + \varepsilon_1 \qquad \textbf{(5.11')}$$

Demand for purchased water by purchase only and collect and purchase households:

$$W_p^{//} = c_2 + b_1 P_w + b_2 D_p P_w + b_3 D_p\alpha + b_4 D_p\alpha z + b_5 z + b_6 D_p z + \varepsilon_2 \qquad \textbf{(5.12')}$$

where :

$$a_1 = \frac{L_{22}}{Det}\theta_0;\ a_2 = \frac{L_{22}}{Det}\pi_0;\ a_3 = \frac{L_{22}}{Det}\theta_1;\ a_4 = \frac{L_{22}}{Det}\pi_1;\ a_5 = \frac{L_{22}}{Det}\gamma_2;\ a_6 = \frac{L_{22}}{Det}\beta_2;\ a_7 = \frac{L_{22}}{Det}\beta_3$$

$$b_1 = \frac{L_{11}}{Det}\delta_1;\ b_2 = \frac{L_{11}}{Det}\beta_4;\ b_3 = \frac{L_{11}}{Det}\zeta_0;\ b_4 = \frac{L_{11}}{Det}\zeta_1;\ b_5 = \frac{L_{11}}{Det}\delta_2;\ b_6 = \frac{L_{11}}{Det}\beta_5$$

where L_{11} and L_{22} and the determinant terms are as defined in Appendix 5.1. D_c and D_p refer to dummy variables used to differentiate between household observed to be at corner solutions and those observed to be at interior solutions. $D_c = 1$ if the household collects and purchases and 0 otherwise; $D_p = 1$ of the household collects and purchases and 0 otherwise. The demand for collected water and purchased water are estimated separately and the coefficients for the corner solutions and interior solution can be differentiated with the use of dummy variables in the estimation procedure.

In the next section, the demand functions in (5.11') and (5.12') will be estimated using the panel data compiled from pooling stated and revealed preference data.

5.4 Augmenting observed data with contingent behaviour data

The previous section developed a behavioural model and approximated linearised demand functions for the estimation of collected and purchased water. To construct a demand schedule for each household we use data collected from the Madachi and Sugum areas. This data is constructed by pooling observed and contingent behaviour data on water demand, household characteristics, price of vended water and water collection times for each household.

Pooling observed data with hypothetical data provides information on revealed preferences (observed data) and stated preferences (hypothetical data). Demand analysis based on actual market transactions *and* hypothetical questions has been used to a considerable extent in travel demand literature[10]. Such analysis has also been used to value environmental amenities (Adamowicz *et al.*,(1994); Cameron (1992); Englin and Cameron (1996)) although most studies combining observed and hypothetical data have applied the method of contingent valuation to obtain their hypothetical data. Adamowicz *et al.*, (1994) and Englin and Cameron (1996) use contingent behaviour (CB) techniques to obtain the hypothetical data, noting that "the true demand...by an individual should be reflected in both her observed behaviour (revealed preferences) and her responses to the contingent behaviour questions posed in the survey (stated preferences)" (Englin and Cameron, 1996).

5.4.1 The contingent behaviour survey method

This study uses the stated preference technique of contingent *behaviour* rather than

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[10] See for example Henscher and Bradley (1993), Morikawa *et al.*, (1990), Ben-Akiva and Morikawa (1990)

contingent valuation. The CB survey used in this study asked respondents questions such as: will you continue to purchase/collect/collect and purchase water if your collection time/price per collection unit of water were to change by a certain amount? The CB questions therefore focused on hypothetical *behaviour* to understand the effects of changes in relative prices (water collection and water purchasing prices) on the household's decision to buy or collect water rather than on asking willingness to pay or willingness to accept questions.

The survey gradually changed prices or collection times, asking the respondent to decide the household's behaviour with each change. By doing this, the data can be used to represent a demand schedule for each household. The data records the relative price levels (price of vended water to collection time) at the point at which the household switches (if it switches) from its preferred water procurement choice to some other pattern. These switching prices are reached by most respondents as the collection times or prices are increased during the CB exercise and indicate a change in the household's original choice of being a collect/purchase or collect and purchase household. A follow up question asked respondents to consider how many units of water their household would buy/collect given their change in behaviour (as a response to changes in the relative prices), thus allowing us to trace the demand curve for quantities demanded at different prices, by individual households. Specifically, households were asked the following sets of questions:

Purchase only: P_w was increased or collection time was decreased. With each increase or decrease the respondent was asked if s/he would continue to purchase water. If yes, a follow up question established how much would be purchased and how much collected, if any, and if no, how much would s/he collect.

Collect only: P_w was decreased or collection time was increased. With each price reduction or time increase the respondent was asked whether s/he would continue to collect water. If yes, how much would be collected and how much purchased if any, and if no, how much would be purchased.

Collect and Purchase: P_w was first increased and then decreased and similarly collection time was decreased and then increased to determine the price/time at which the household would switch to being either a collect only or a purchase only household. With each adjustment in price or time the respondent was asked whether s/he would continue to collect and purchase water. The quantity purchased and/or collected at each price and time was recorded.

Note that when households choose to leave the market for collected or purchased water they could switch from one corner solution to another without passing through a 'transition period' of collecting and purchasing. In fact, our sample shows that very few households expressed a willingness to do this. The majority of our sample households observed initially to be at a corner, reacted to changes in relative prices by choosing to purchase and collect water before they would completely leave the market at some maximum price they were willing to pay.

5.4.2 Demand models and estimation procedures

As described in section 5.3, we assume there are two markets for water, i.e., one market for water collected by households (with price α) and one market for water purchased from vendors (with price P_w). As shown in the previous section and in Appendix 5.1, the linear demand functions with varying parameters can be estimated by (5.11') and (5.12') below.

Demand for collected water by collect only and collect and purchase households is given by:

$$W_c = c_1 + a_1\alpha + a_2 D_c \alpha + a_3 \alpha z + a_4 D_c \alpha z + a_5 z + a_6 D_c z + a_7 D_c P_w + \varepsilon_1 \qquad \textbf{(5.11')}$$

and the demand for purchased water by purchase only and purchase and collect households is given by:

$$W_p = c_2 + b_1 Pw + b_2 D_p Pw + b_3 D_p \alpha + b_4 D_p \alpha z + b_5 z + b_6 D_p z + \varepsilon_2 \qquad \textbf{(5.12')}$$

where:

W_c = demand for collected water (collected by the household for own consumption)

W_p = demand for purchased water

α = collection time (for 36 litres of water per trip)
P_w = price charged by vendor per 36 litres of water
z = exogenous factors affecting income generation including household characteristics such as household size, children/adult ratio, occupation
αz = interaction between collection time and certain household characteristics.
D_c = dummy variable where $D_c=0$ if household is collect only and 1 if household both collects and purchases its water.
D_p = dummy variable where $D_p=0$ if household is purchase only and 1 if household both collects and purchases its water.
$\varepsilon_{1,2}$ = random errors associated with each demand function

The mean values of the primary variables are given in Table 5.4. A full list of the variables used in estimating (5.11') and (5.12') is listed in Table 5.5.

These demand equations indicate that there are four possible demands in the two markets comprising of a demand for collected water by collect only households, a demand for collected water by collect and purchase households, a demand for purchased water by purchase only households and a demand for purchased water by collect and purchase households. As noted in the previous section, by using dummy variables to differentiate between household types, the effect of explanatory variables on the demand for collected water and purchased water can be differentiated for interior and corner solution households. The contingent behaviour data is used to record the change or switch in the household's behaviour. For example, a household which is observed to be collecting may switch its behaviour to collecting and purchasing during the course of the CB survey. In the estimation, therefore, the observed behaviour of this household selects it as a collect household and gives it the dummy variable value of 0. At the instance this household switches to collecting and purchasing, the dummy variable value is 1. If this household were to switch over completely to purchasing water, it is selected out of the sample for collected water demand altogether and recorded as a purchasing household.

In the derivation of the theoretical model, it was assumed that the marginal productivity of labour allocated to other activities is influenced by household characteristics. Interactive or varying parameter terms are therefore included in the estimation procedure (see Appendix 5.1; equations A5.18-A5.24). The interaction terms such as TRADCOL and CSCOL are included to capture the effect of the marginal productivity of labour used in other activities and thus on collection time. Similarly, KDCT captures the effect of a household characteristic such as the ratio of adults to children, on α. By varying the parameters in this way we are able to better capture the effects of household characteristics in the estimation of water demand.

The panel data were created by pooling the observed responses and the hypothetical responses. Before proceeding with the joint estimation of the pooled data, we check to establish whether the two sets of data (hypothetical and observed) are derived from a similar underlying demand preference structure (Hsiao, 1986). Following Gujarati (1995), we use the dummy variable approach to test if the two data sets are derived from the same preference structure. Dummy variables are used to differentiate between the contingent behaviour data and the observed data. The null hypothesis of equality between the coefficients of the hypothetical transactions: Ho : $\beta = 0$, was tested. This tests the interaction of the data type dummy variable (a constant term shifter) and the interaction of the dummy variable with the other variables (the slope shifters). None of the coefficients of the contingent behaviour variables in the demand equation were found to be significantly different from 0. The null hypothesis is therefore not rejected and it is assumed that the two data sets are derived from the same preference structure[11].

Before proceeding with the estimation of the demand functions we have to consider two potential sources of error. An OLS regression of the dependent variable on a constant and a set of independent variables would simply pool the data, ignoring any difference in the number of observations per individual. However, we have several observations for the same household and since there are a number of time invariant variables, such as household size, the error structure is likely to be correlated across observation for the same household. In addition, the number of observations per household varies. Although the observations for each household are not tied to different time periods and are therefore not affected by different exogenous factors, a one factor model, using GLS, is more appropriate in unbalanced panel data, where the number of observations per individual vary (Baltagi,1995; Greene ,1991). The one-factor model is, in general, given by:

$$\begin{aligned} y_{ir} &= a + X_{ir}b + u_{ir} \\ u_{ir} &= \mu_i + v_{ir} \end{aligned}$$

where μ_i are the unobserved disturbances and v_{ir} are the remaining disturbances. The random effects model is estimated by two step GLS. The results of this regression are reported in tables 5.6 and 5.7.

A second error structure problem we consider derives from the fact that households which collect and purchase are included in the estimation of both demand functions (purchased

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[11] In the literature on pooling stated preference (SP) and revealed preference (RP) data, there is also discussion of difference in variance between the two data. Morikawa (1989) suggests scaling the variance of the observed effects associated with the SP data so that the equality of variances across the RP and SP components of a pooled model is reinstated. Henscher and Bradley (1993) state that the "equality of variances is a permissible empirical outcome, but not one to be assumed ex ante."

water and collected water) and the error term across the two equations may be correlated. We assume an error structure where a decision taken by household i is correlated with the same decision across the two equations. The error structure is thus assumed to be of the form:

$$W_{ir}^{c}=X_{irc}\beta_{c}+\varepsilon_{irc}$$

$$W_{ir}^{p}=X_{irp}\beta_{p}+\varepsilon_{irp} \qquad \textit{for each } r$$

Seemingly unrelated regression estimation (SUR) techniques were used to address this issue of error correlation across equations (Greene, 1992)[12]. Combining the data types, we obtain a total of 836 observations, including 706 observations based on the contingent behaviour data. The demand for purchased water was estimated using 556 observations and the demand for collected water was estimated using 590 observations. For the SUR estimation, all 836 observations are used. These results are reported along with the random effects model results in tables 5.6 and 5.7.

Table 5.4 Mean Values for primary variables

(Collected water)

Variable	OBS only	CB only	All Observations
PPL	2.89	3.95	3.79
COLTME	10.84	19.29	18.04
WCOL	186.50	150.68	156.00

(Purchased water)

Variable	OBS only	CB only	All Observations
PPL	2.77	5.76	5.33
COLTME	11.54	14.45	14.04
WPUR	139.78	125.31	127.37

OBS = observed data ; CB = contingent behaviour data

5.4.3 Empirical Analysis

The demand functions in (5.11') and (5.12') were first estimated using the random effects model and the results are reported in Tables 5.6 and 5.7. As noted earlier, we also estimate the demand functions using seemingly unrelated regressions (SUR) because of the possible correlation across the error terms of the two demand functions. These results are reported along with the random effects model results, in Tables 5.6 and 5.7.

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[12] The SUR model used in this chapter estimates the demand equations (5.11') and (5.12'). The disturbances across equations are allowed to be freely correlated. The full number of observations (836) are used to estimate each equation, however the demand for each household observed to be demanding zero quantity of either vended or collected water is recorded as such (see Greene, 1982).

Table 5.5 Table of Variable Names

Variable Name	Definition
Dependent Variables	
WPUR	Purchased water
WCOL	Collected water
Price variables	
PPL	Per litre Price of vended water
DMPPL	Household dummy variable * PPL
COLTME	Collection time
DMCOL	Household dummy variable *COLTME
Household Characteristic Variables (excluding Occupation)	
KDSADT	Ratio of children to adults in household
DMKDS	Household dummy variable[1] * KDSADT
HHSIZE	Household size
DMHSIZE	Household dummy variable *HHSIZE
Occupation Variables[2]	
TRADE	Occupation dummy variable, Trader
DMTRDE	Household dummy variable * TRADE
CS	Occupation dummy variable, civil service
DMCS	Household dummy variable *CS
OTHER	Occupation dummy variable, e.g., tailor
DMOTHR	Household dummy variable*OTHER
Varying Parameter Variables[1]	
TRADCOL	TRADE * COLTME
DMTCOL	Household dummy variable * TRADCOL
CSCOL	CS * COLTME
DMCSCOL	Household dummy variable * CSCOL
KDCT	KDSADT * COLTME
DKCT	Household dummy variable * KDCT

[1] Household dummy variables refer to D_c and D_p in (5.11) and (5.12) respectively.

[2] Not all occupation variables are used in the estimations to overcome the problem of singular matrixes.

Table 5.6 Demand for collected water : dependent variable = WCOL

Explanatory variables	Random effects model	SUR
DMPPL	97.883** (1.968)	53.771 (1.283)
COLTME	1.040 (1.243)	-0.286 (1.297)
DMCOL	-2.289*** (2.285)	-3.187*** (4.737)
KDSADT	7.150 (0.737)	-7.032 (1.102)
DMKDS	-21.453* (1.935)	-33.513*** (4.322)
HHSIZE	12.764*** (12.519)	6.586*** (8.452)
DMHSIZE	-4.997*** (5.120)	-1.803 (1.498)
TRADE	107.50*** (5.403)	32.815** (2.415)
DMTRDE	-51.197** (2.153)	19.149 (1.165)
CS	16.949 (0.739)	2.846 (0.205)
DMCS	-19.772 (0.724)	6.728 (0.583)
OTHER	-7.768 (0.340)	-28.778* (1.664)
DMOTHR	-42.206* (1.878)	-7.418 (0.657)
CSCOL	-0.960 (0.761)	-0.241 (0.313)
DMCSCOL	1.081 (0.709)	0.615 (0.602)
TRADCOL	0.949 (0.867)	3.222*** (4.606)
DMTCOL	-1.309 (1.037)	-3.699*** (3.942)
KDCT	-0.602 (1.176)	-0.025 (0.089)
DKCT	1.086* (1.706)	1.543*** (3.263)
Constant	70.421*** (3.536)	140.16*** (8.688)
Observations	590	836
Adjusted R^2	0.36	0.64

(t-statistics in parenthesis; *** 1% significance level, ** 5% significance level; * 10% significance level)

Note: Not all occupation variables are used in the varying parameters to overcome the problem of singular matrixes. We have dropped the interaction term OTHER*COLTME for this purpose.

Table 5.7 Demand for purchased water : dependent variable = WPUR

Explanatory variables	Random effects model	SUR
PPL	-114.59* (2.354)	-166.69*** (5.478)
DMPPL	4.8324 (0.074)	-3.583 (0.055)
DMCOL	-0.468 (0.618)	1.687* (1.741)
KDSADT	1.987 (0.241)	5.454 (0.800)
DMKDS	1.365 (0.128)	22.982* (1.879)
HHSIZE	9.371*** (8.827)	3.701*** (4.221)
DMHSIZE	-7.116*** (6.339)	-0.586 (0.542)
TRADE	84.547*** (5.20)	55.550*** (3.943)
DMTRDE	-88.578*** (4.159)	-25.273 (0.988)
CS	11.987 (0.720)	28.158* (1.892)
DMCS	-41.818* (1.884)	-35.985 (1.337)
OTHER	-6.573 (0.264)	22.633 (1.161)
DMOTHR	7.497 (0.301)	-9.981 (0.418)
DMTCOL	1.464* (1.904)	0.917 (0.889)
DMCSCOL	0.890 (0.932)	0.575 (0.45)
DKCT	0.0299 (0.067)	-0.843 (1.428)
Constant	106.56*** (5.630)	48.396*** (2.968)
Observations	556	836
Adjusted R^2	0.22	0.11

(t-statistics in parenthesis; *** 1% significance level, ** 5% significance level; * 10% significance level)
Note: Not all occupation variables are used in the varying parameters to overcome the problem of singular matrixes. We have dropped the interaction term OTHER*COLTME for this purpose.

We restrict our discussion of the econometric results to the estimates obtained from the SUR model. This is because the SUR model accounts for the correlation in error terms across the two demand equations and performs better than the random effects model in terms of generating the expected signs for the differential slope coefficients of the price variables.

Using the dummy variables D_p and D_c, we can transform (5.11') and (5.12') into the following 4 demand functions:

Collected water demand by collect only households:

$$W_c^1 = c_1 + a_1\alpha + a_3\alpha z + a_5 z + \varepsilon_1$$

Collected water demand by collect and purchase households:

$$W_c^2 = c_1 + (a_1 + D_c a_2)\alpha + (a_3 + D_c a_4)\alpha z + (a_5 + D_c a_6)z + D_c a_7 P_w + \varepsilon_1$$

Purchased water demand by purchase only households:

$$W_p^1 = c_2 + b_1 P_w + b_5 z + \varepsilon_2$$

Purchased water demand by collect and purchase households:

$$W_p^2 = c_2 + (b_1 + D_p b_2)P_w + D_p(b_3 + D_p b_4 z)\alpha + (b_5 + D_p b_6)z + \varepsilon_2$$

Our regression results yield estimates for the coefficients in these four linear demand estimations across the two markets for collected and purchased water. From the econometric results in tables 5.6 and 5.7, the explicit demand functions are written as follows:

Collected water demand by collect only households:

$$W_c^1 = 140.16-(0.286)COLTME-(0.241)CSCOL+(3.222)TRADCOL+(-0.025)KDCT+ (2.846)CS+(32.815)TRADE-(28.776)OTHER+(6.586)HHSIZE-(7.032)KDSADT \tag{5.11a}$$

Collected water demand by collect and purchase households:

$$\begin{aligned} W_c^2 = {} & 140.16+(-0.286-3.186)COLTME+(0.615-0.241)CSCOL+(3.222-3.699) \\ & TRADCOL+(1.543-0.025)KDCT+(2.846+6.728)\ CS+(32.815+19.149)TRADE \\ & +(-28.776-7.418)OTHER+(6.586-1.803)HHSIZE\ +(-7.032-33.513)KDSADT \\ & +(53.771)DMPPL \end{aligned} \tag{5.11b}$$

Purchased water demand by purchase only households:

$$W_P^1 = 48.396-(166.69)PPL+(55.55)TRADE+(28.158)CS+(22.633)OTHER+(3.701)HHSIZE+ (5.454)KDSADT \tag{5.12a}$$

Purchased water demand by collect and purchase households:

$$\begin{aligned} W_P^2 = {} & 48.396+(-166.69-3.583)PPL+(1.687)DMCOLL+(0.917)DMTCOL+(0.575)DMCSCOL \\ & -(0.843)DKCT\ +(55.55-25.273)TRADE+(28.158-35.985)CS+(22.633-9.981)OTHER+ \\ & (3.701-0.586)HHSIZE+(5.454+22.982)KDSADT \end{aligned} \tag{5.12b}$$

Analysing demand for collected water

From Table 5.6 and equations (5.11a) and (5.12b) we note that the coefficients on the non-interactive price variables carry the expected signs. While DMCOL is highly significant (at the 1% significance level), DMPPL and COLTME are both significant at the 20% level. These results indicate that with an increase in α, the demand for collected water would fall for both collect and collect and purchase households. Differentiating across these households according to occupation groups we find that traders and civil service groups from both household types have a strong preference for collected water. In fact, traders in purchase and collect households have a stronger preference for collected water than their demand for purchased water (since the value of the differential slope coefficient for TRADE is higher, and positive, for the demand by these households for collected water than it is for purchased water). The civil service and OTHER occupation groups from collect only households have a downward sloping demand for collected water.

Household size has a positive effect on demand for collected water, although this is a slightly lower effect for collect and purchase households. KDCT has a negative but insignificant effect on demand for collected water by collect only households but has a highly significant and positive effect for collect and purchase households.

Amongst the interactive variables for the demand for collected water, the coefficient for DKCT is positive and significant for the demand for collected water by purchase and collect households. This is in contrast to the results obtained from the slope differentials for KDSADT or COLTME. However, the absolute value of the coefficient on DKCT is smaller than for these variables, suggesting that demand for collected water is still downward sloping for these households. The negative effect of KDCT for collect only households, suggests that with higher collection times or a higher ratio of children to adults, these households would have a downward sloping demand curve.

An interesting result is that KDSADT and DMKDS both have negative coefficients for the estimation of demand for collected water by collect and purchase households. This is in contrast to the results we obtain for the estimation of demand for purchased water by these households. For collect and purchase households therefore this indicates that the effect of a higher ratio of children to adults would reduce their demand for collected water but would increase their demand for purchased water. Across the household groups it appears that with a higher ratio of children to adults, there is a higher preference for purchased water rather than collected water. This is possibly due to the lower amount of adult labour available in the household and therefore a higher opportunity cost of spending labour collecting water.

Analysing demand for purchased water

From Table 5.7 and equations (5.12a) and (5.12b) we see that the coefficients for the price variables, i.e., PPL and DMPPL carry the expected signs indicating a propensity by both collect and purchase households and purchase only households to decrease their demand for purchased water with an increase in price. DMCOL is significant at the 20% level and indicates a preference for collect and purchase households to demand purchased water with an increase in their collection times.

The households can also be differentiated by occupation. For the default occupation group of fishing and farming only, the demand for purchased water is downward sloping for both purchase only and purchase and collect households. As shown in (5.12a), the large and positive coefficient value for trading households from the purchase only group suggests a strong preference for purchased water. The coefficient for trading households from collect and purchase households, is somewhat smaller but still has an overall positive effect on the demand for purchased water by these households (see 5.12b). Similar results are obtained for the occupation group OTHER. However, the coefficient for purchase only civil service households is positive whereas the coefficient for this occupation group has a negative impact on the demand curve for collect and purchase households.

The varying parameter variables have coefficients with low significance levels. The coefficients on DMCSCOL and DMTCOL suggest however, that purchase and collect households involved in trading and civil service occupations would demand more vended water if collection times were to rise. This supports the substitution effect of DMCOL for purchase and collect households. The household size and ratio of children to adults variables also carry the expected signs, indicating a higher demand for purchased water with larger households or higher ratio of children to adults within a household. However, the effect of DKCT on demand for purchased water is negative (with low significance) and counter-intuitive.

Summary of price effects

Since (5.8), (5.8') and (5.8") suggest that a household's decision to collect and/or purchase water is affected by relative prices in the two markets, in addition to household characteristics, we are interested in examining the own-price and cross-price effects on these three household types. The econometric results show that the effect of a change in price on the demand for collected water by collect only households is smaller in absolute terms than the effect of a change in α on the demand for collected water by purchase and collect households. The effect of a price change on the demand for purchased water by purchase only households is similar to the effect of a price change on the demand for purchased water by purchase and collect households. The effect of a change in price for vended water on the demand for collected water by purchase and collect households is positive. These are given in table 5.9 and as reference, the proportions of each occupational group across the household types are given in table 5.8 .

Table 5.8 Proportion of occupational groups in each household type

Variable	purchase only	collect only	purchase and collect
Occupation (%)			
• trader	34.4	19.2	32.6
• civil service	36.0	28.6	26.9
• Rep[1]	29.6	52.2	40.4

Table 5.9 Price effects on demand

	Collect only		Purchase only		Collect and Purchase			
	$\partial Wc/\partial\alpha$	$\partial Wc/\partial P_w$	$\partial Wp/\partial P_w$	$\partial Wp/\partial\alpha$	$\partial Wc/\partial\alpha$	$\partial Wc/\partial P_w$	$\partial Wp/\partial\alpha$	$\partial Wp/\partial P_w$
Trader	2.91	0	-166.69	0	-2.43	53.77	1.76	-170.27
Civil service	-0.55	0	-166.69	0	-1.58	53.77	1.42	-170.27
Rep[1].	-0.31	0	-166.69	0	-1.95	53.77	1.68	-170.27

[1] Representative household, including fishing, farming and other occupations

The above results for the effect of a change in α on the demand for collected water by traders in collect only households is positive. These account for 28.6% of collect only household in the sample. It is possible that collect only traders are trading in agricultural goods and since they are also the group with larger land holdings, they are likely to remain in the village whereas traders from the other two household categories may be travelling away from the village for their trading activities. Hence, traders from collect only households may always prefer to collect than purchase water. The upward sloping demand curve for these households is however a counter-intuitive result and is possibly due to factors unexplained by the model. However, the demand for collected water by collect and purchase households in this occupational group gives us the expected effect. The demand curves for these households are downward sloping, indicating that they demand less collected water with an increase in their collection times.

From Table 5.9 we also note that the absolute value of $\partial Wp/\partial P_w$ for purchase only households is smaller than the corresponding value for collect and purchase households. Calculating price elasticities for these households at average values of P_w and WPUR, we find that the price elasticity of demand for all collect and purchase households (-0.073) is marginally higher (in absolute terms) than the price elasticity of demand for purchase only households (-0.067), implying that the slope of (5.12b) is flatter than that for (5.12a). With respect to cross-price effects, we note that the values for $\partial Wc/\partial P_w$ for collect and purchase households are also greater than the corresponding value for collect only households, as is the case for $\partial Wp/\partial \alpha$ values. Therefore the slopes of the demand curves for collected water and purchased water for collect and purchase households are more elastic with respect to changes in the price of vended water or α than they are for the other two household groups.

5.5 Estimating the value of the recharge function

Having estimated water demand functions for collected water and purchased water, the next step is to calculate the welfare effects of a change in groundwater levels. As described in chapter 2 , the hydrological evidence for the relationship between flood extent and recharge to wells shows some fluctuation with flood extent and mean water depth in village wells. Reduced flooding in the wetlands will result in lower recharge rates and hence changes in groundwater levels in wells. Changes in groundwater levels are therefore expected to affect collection time (α) and price of vended water (P_w), assuming all other household characteristics remain constant.

5.5.1 Welfare estimation

Welfare changes are calculated as changes in consumer surplus, i.e., as the change in the area behind a household's ordinary demand curve between the relevant "prices". The estimated demand functions in the previous section are Marshallian demand functions. The consumer surplus measure is an approximation of the welfare change measures associated with the Hicksian demand curve. Since the income effects of the price changes for individual households are not known, the compensated demand curves cannot be derived. We assume therefore that the consumer surplus of the ordinary demand function is a reasonable estimate of consumer welfare[13].

The primary question this chapter set out to answer was : what are the welfare effects of a change in the flood extent (and therefore groundwater recharge rates) within the wetlands. Based on aerial surveys, the flood extent in the wetlands in 1994/5 was approximately 78.03 km^2 and in 1995/6 the flood extent was recorded at 56.91 km^2. The resulting change in water table elevations was approximately 1 metre, from 2.50 in 1994/5 to 1.47 metres in 1995/6 (Thompson and Goes, 1997). Furthermore, as shown in chapter 2, decreased recharge due to reduced flooding caused by any of the dam scenarios presented in table 2.6, will result in decreases in groundwater levels by at least 1 metre.

To value the change in the recharge function due to reduced flooding within the wetlands, we therefore hypothesize a decrease of 1 metre in level of water in the village wells, resulting in an increased collecting time of 25% and an increase in the price of vended water of approximately 1 Naira. These critical assumptions are based on the evidence provided by the survey data on the relationship between collection time and well water levels and on the change in price indicated by vendors as likely to occur, in the event of a 1 metre decrease in water levels.

Using the estimated demand structure we can calculate the welfare effects due to changes in collection time, where the change in collection time is due to a change in groundwater recharge to the village well, and a change in the price of vended water. Using the sample of observed households, we calculate the change in consumer surplus for each household due to a change from (α^0, P_w^0) to (α', P_w'). Change in consumer surplus is calculated for individual households, and average consumer surplus is calculated as the average of the sample. Since we are using ordinary demand curves to calculate changes in consumer surplus, we recognise that changes in surplus may depend on the order in which prices change. We can define two possible price change paths as:

- a change in collection time followed by a change in price of vended water
- a change in the price of vended water followed by a change in collection time.

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[13] Consumer surplus will be a reasonable estimate of a multi-price change on welfare if the resulting income effects are small (Just *et al.*, 1982). We expect that this is likely for the price change we are concerned with here.

However, the relatively small price changes we consider in calculating welfare changes do not result in switching behaviour in our sample, we calculate consumer surplus change for the three household groups using the demand functions[14] given by (5.11a), (5.11b), (5.12a) and (5.12b).

We integrate under the demand functions given by (5.11a), (5.11b), (5.12a) and (5.12b) and by varying the value for α for (5.11a) and (5.11b) and P_w for (5.12a) and (5.12b). For collect and purchase households we first vary α, holding P_w constant and calculate welfare change by integrating under equation (5.11b). We then increase P_w and using the new α value calculate welfare change by integrating under equation (5.12b). We then aggregate consumer surplus values for purchase and collect households across the two markets The consumer surplus change is calculated for each household in this manner. The average consumer surplus loss per household type is given in table 5.9.[15]

Table 5.10 Consumer surplus changes (in Naira) per household type for a 25% increase in collection time and a 1 Naira increase in the price of vended water

Households	Consumer surplus change
Purchase only	2.86
Collect only	12.09
Purchase and collect	19.93
Average for all households	10.62
(sample size = 130)	

Extrapolating these results to the population of the floodplain we estimate the following

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[14] If the price change is large enough to induce switching behaviour, the consumer surplus calculations are no longer simply integrating under the demand curve but must account for the kink in the household's aggregate demand curve for water, by calculating CS under each linear segment of the demand schedule for each household. Our price changes are relatively small and do not induce switching behaviour within either market.

[15] We argue that the shadow value of time spent collecting water cannot be equal to the year-round agricultural wage rate since dry season farming is not as widespread as floodplain recession agriculture and full employment conditions will not prevail throughout the year. The average household is expected to work 10 hours per day, if all the agricultural land available is fully employed. However since only 33.7% of the total agricultural land can be used during the dry season farming, we expect the average household to be able to work approximately 3 hours per day at the prevailing agricultural wage. Since the dry season lasts for 6 out of 12 months, we use the following weighting to calculate a daily agricultural wage for the average household: 0.337/10 x 6/12 x 80. We estimate an hourly wage of 13.48 Naira or a per minute value of 0.225 Naira as our shadow value of time during the dry season.

changes in consumer surplus for the wetland populations:

Table 5.11 Consumer surplus changes for wetlands per household type for a 25% increase in collection time and a 1 Naira increase in the price of vended water

Household type	No. of representative households in wetlands	Welfare change per household (in Naira)	Welfare change for the wetlands (in Naira)
Purchase only	22,650	2.86	64,779
Collect only	57,013	12.09	689,287
Purchase and collect	28,302	19.93	564,059
All households	107,965	10.62	1,146,588

88 Naira = 1 US$ (1994/5 prices)

Given an average consumption of 232 litres per household (24 litres per capita) the recharge function has a value of 0.046 Naira per litre of water consumed by households per day. These results suggest that the value of the recharge function is 1,146,588 Naira or US$ 13,029 per day for the wetlands. The average welfare change for a 1 metre change in water levels is approximately 10.62 Naira or US$ 0.12 per household. This amounts to a daily loss of approximately 0.23% of monthly income for purchase only households, 0.4% of monthly income for collect only households and 0.14% of monthly income for purchase and collect households. Based on the household specific welfare figures given in table 5.9 however, these percentage figures are 0.06% for purchase only households, 0.45% for collect only households and approximately 0.27 % for purchase and collect households.

In chapter 3 it was shown that including the value of indirect benefits in water resource policies for the Komadugu-Yobe river basin could have a significant effect on the rate of diversion for upstream uses. Although the analysis presented in this chapter is static and covers only a single dry season within the wetlands, the results of the valuation process show that the failure of the wetlands to provide the existing daily level of recharge would result in a substantial economic loss for wetland populations presently deriving benefit from groundwater use for domestic consumption. In fact, the value of the groundwater recharge may be much higher than that reported by this study, given that without the presence of the groundwater resources many villages might have to relocate. This chapter provides a partial estimate of the value of the recharge function to wetland populations and in chapter 6 we examine the value of the recharge function in agricultural production within the wetlands.

Appendix 5.1

Using the first order (linear) Taylor series expansion[16], linear demand functions for W_c and W_p are approximated as:

$$W_c = c_1 + \frac{\partial W_c}{\partial P_w}P_w + \frac{\partial W_c}{\partial \alpha}\alpha + \frac{\partial W_c}{\partial z}z + \varepsilon_1 \qquad \textbf{(A5.1)}$$

$$W_p = c_2 + \frac{\partial W_p}{\partial P_w}P_w + \frac{\partial W_p}{\partial \alpha}\alpha + \frac{\partial W_p}{\partial z}z + \varepsilon_2 \qquad \textbf{(A5.2)}$$

We can define $F^1(W_c, Wp; Pw, \alpha, z) = \partial\mathcal{L}/\partial W_c = 0$ and $F^2(W_c, Wp; Pw, \alpha, z) = \partial\mathcal{L}/\partial W_p = 0$. To find the effect of changes in α, z and P on W_c and W_p, we totally differentiate the first order conditions:

$$\frac{\partial F^1}{\partial W_c}dW_c + \frac{\partial F^1}{\partial W_p}dW_p + \frac{\partial F^1}{\partial P_w}dP_w + \frac{\partial F^1}{\partial \alpha}d\alpha + \frac{\partial F^1}{\partial z}dz = 0 \qquad \textbf{(A5.3)}$$

$$\frac{\partial F^2}{\partial W_c}dW_c + \frac{\partial F^2}{\partial W_p}dW_p + \frac{\partial F^2}{\partial P_w}dP_w + \frac{\partial F^2}{\partial \alpha}d\alpha + \frac{\partial F^2}{\partial z}dz = 0 \qquad \textbf{(A5.4)}$$

The Hessian is defined as :

$$[H] = \begin{bmatrix} \dfrac{\partial^2\mathcal{L}}{\partial W_c^2} & \dfrac{\partial^2\mathcal{L}}{\partial W_c \partial W_p} \\ \dfrac{\partial^2\mathcal{L}}{\partial W_c \partial W_p} & \dfrac{\partial^2\mathcal{L}}{\partial W_p^2} \end{bmatrix} = \begin{bmatrix} L_{11} & L_{12} \\ L_{21} & L_{22} \end{bmatrix}$$

We can rewrite (A5.3) and (A5.4) as

$$L_{11}dW_c + L_{12}dW_p = -\frac{\partial F^1}{\partial P_w}dP_w - \frac{\partial F^1}{\partial \alpha}d\alpha - \frac{\partial F^1}{\partial z}dz \qquad \textbf{(A5.5)}$$

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[16] $Y = f(x^0) + \sum_i f_i(x^0)(x_i - x_i^0)$ where $f_i(x^0) = f'(x^0)$; $x_i^0 = 0$

$$L_{21}dW_c + L_{22}dW_p = -\frac{\partial F^2}{\partial P_w}dP_w - \frac{\partial F^2}{\partial \alpha}d\alpha - \frac{\partial F^2}{\partial z}dz \qquad \textbf{(A5.6)}$$

and solve for the partials using Cramer's rule as:

$$\begin{aligned} \frac{\partial W_c}{\partial P_w} &= \frac{L_{12}\partial F^2/\partial P_w - L_{22}\partial F^1/\partial P_w}{Det} & \frac{\partial W_p}{\partial P_w} &= \frac{L_{21}\partial F^1/\partial P_w - L_{11}\partial F^2/\partial P_w}{Det} \\ \frac{\partial W_c}{\partial \alpha} &= \frac{L_{12}\partial F^2/\partial \alpha - L_{22}\partial F^1/\partial \alpha}{Det} & \frac{\partial W_p}{\partial \alpha} &= \frac{L_{21}\partial F^1/\partial \alpha - L_{11}\partial F^2/\partial \alpha}{Det} \\ \frac{\partial W_c}{\partial z} &= \frac{L_{12}\partial F^2/\partial z - L_{22}\partial F^1/\partial z}{Det} & \frac{\partial W_p}{\partial z} &= \frac{L_{21}\partial F^1/\partial z - L_{11}\partial F^2/\partial z}{Det} \end{aligned} \qquad \textbf{(A5.7)}$$

where $Det = L_{22}L_{11} - (L_{12})^2$

Collect only corner solution

The first order conditions for the interior solution are derived in the main text of the chapter as equations (5.6), (5.7) and (5.8). For the corner solution where the household collects all its water, $W_p = 0$. Hence equation (5.7) is no longer applicable. For this household, $\alpha Y_L(z) < P_w$ always holds, i.e., the shadow price of labour employed in collecting water is always less than the price of vended water:

$$\frac{U_w}{U_Q} = \alpha Y_L(z), \ \alpha Y_L(z) < P_w, \ W_p = 0 \qquad \textbf{(5.8')}$$

The household will therefore collect water up to the point where the marginal rate of substitution between water and the agricultural good, Q, is equal to the marginal opportunity cost of time spent in collecting water. Hence, only the linearised demand function (5.11) is relevant and the effects of a change in α and z on the demand for collected water is:

$$L_{11}dW_c = -\frac{\partial F^1}{\partial \alpha}d\alpha - \frac{\partial F^1}{\partial z}dz \qquad \textbf{(A5.8)}$$

Rearranging (A5.8) yields the following comparative statics expressions:

$$\frac{\partial W_c}{\partial \alpha} = -\frac{\partial F^1/\partial \alpha}{L_{11}} \quad , \quad \frac{\partial W_c}{\partial z} = -\frac{\partial F^1/\partial z}{L_{11}} \quad , \quad \frac{\partial W_c}{\partial P_w} = 0 \qquad \textbf{(A5.9)}$$

Purchase only corner solution

In the case of the other corner solution, where households choose not to collect any water, $\alpha Y_L(z) > P_w$. That is, households will purchase all their water if the opportunity cost of their time spent collecting water is higher than the price of vended water. Equation (5.6) is therefore no longer relevant for these households and the first order condition for the household which purchases all its water:

$$\frac{U_w}{U_Q} = \alpha Y_L(z),\ \alpha Y_L(z) < P_w,\ W_p = 0 \qquad \textbf{(5.8')}$$

For this household, the shadow price of labour employed in collecting water is always less than the price of vended water. Thus, the household will decide to purchase water up to the point where the marginal rate of substitution between water and the agricultural good, Q, equals the price of water. Hence, only the linearised demand function (5.12) is relevant and the effects of a change in P_w and z on the demand for collected water are:

$$L_{22} dW_p = -\frac{\partial F^2}{\partial P_w} dP_w - \frac{\partial F^2}{\partial z} dz \qquad \textbf{(A5.10)}$$

Consequently,

$$\frac{\partial W_p}{\partial P_w} = -\frac{\partial F^2/\partial P_w}{L_{22}} \quad , \quad \frac{\partial W_p}{\partial z} = -\frac{\partial F^2/\partial z}{L_{22}} \quad , \quad \frac{\partial W_p}{\partial \alpha} = 0 \qquad \textbf{(A5.11)}$$

Returning to the comparative statics expressions for the two corner solutions, we define the following expressions:

$$\gamma_1 = -\frac{\partial F^1}{\partial \alpha} \ ; \ \gamma_2 = -\frac{\partial F^1}{\partial z} \text{ and } \delta_1 = -\frac{\partial F^2}{\partial P_w} \ ; \ \delta_2 = -\frac{\partial F^2}{\partial z} \qquad \textbf{(A5.12)}$$

We observe that these partials are actually imbedded in the expressions in (A5.7), i.e., the parameters for the corner solutions are part of the parameters for the interior solution. Rearranging terms, it follows that the additional parameters required with the above corner solution terms, to retrieve the interior solution comparative static effects shown in (A5.7) are:

$$\beta_1 = \frac{L_{12}\partial F^2/\partial\alpha}{L_{22}} \; ; \; \beta_2 = \frac{L_{12}\partial F^2/\partial z}{L_{22}} \; ; \; \beta_3 = \frac{L_{12}\partial F^2/\partial P_w}{L_{22}} - \partial F^1/\partial P_w \tag{A5.13}$$

$$\beta_4 = \frac{L_{21}\partial F^1/\partial P_w}{L_{11}} \; ; \; \beta_5 = \frac{L_{21}\partial F^1/\partial z}{L_{11}} \; ; \; \beta_6 = \frac{L_{21}\partial F^1/\partial\alpha}{L_{11}} - \partial F^2/\partial\alpha$$

The linear demand functions for estimating $W_{c\,(corner)}$ and $W_{p\,(corner)}$ are thus :

$$W_{c_{corner}} = \frac{1}{L_{11}}[c_3L_{11} + \gamma_1\alpha + \gamma_2 z] + \varepsilon_3 \tag{A5.14}$$

$$W_{p_{corner}} = \frac{1}{L_{22}}[c_4L_{22} + \delta_1P_w + \delta_2 z] + \varepsilon_4 \tag{A5.15}$$

and the linear demand functions for estimating W_c and W_p in the interior solution are:

$$W_c' = \frac{L_{22}}{Det}\,[c_1Det/L_{22} + (\beta_1 + \gamma_1)\alpha + (\beta_2 + \gamma_2)z + \beta_3P_w] + \varepsilon_1 \tag{A5.16}$$

$$W_p' = \frac{L_{11}}{Det}[c_2Det/L_{11} + (\beta_4 + \delta_1)P_w + (\beta_5 + \delta_2)z + \beta_6\alpha] + \varepsilon_2 \tag{A5.17}$$

It follows that if $\beta_1 = \beta_2 = \beta_3 = 0$ then $W_c' \approx W_{c(corner)}$ in (A5.14) and if $\beta_3 = \beta_4 = \beta_5 = 0$ then $W_p' \approx W_{p(corner)}$ in (A5.15).

Using (A5.16) and (A5.17), the demand for collected and purchased water can be estimated separately and the coefficients for the corner solutions and interior solution can be differentiated with the use of dummy variables in the estimation procedure.

Varying parameters model

The above model is applicable for the case where $Y_L(z) = Y_L$. However, in the model developed in this chapter, $Y = Y(L_0 - W_c\alpha, z)$, and from the first order conditions we know that the marginal product of household labour is a function of household characteristics, i.e., $\partial Y/\partial L = Y_L(z)$. Each household's ability to convert labour into income is affected by the characteristics of that household. This suggests that the comparative static effects for α in (A5.14), (A5.16) and (A5.17) are now:

$$\gamma_1 = -\partial F^1/\partial\alpha = -U_{wQ}Y_L(z)W_c^* - U_QY_L(z) + U_{QQ}(Y_L)^2(z)W_c^*\alpha + U_QY_{LL}(z)W_c^*\alpha \qquad \textbf{(A5.18)}$$

$$\begin{aligned}\beta_6 &= \frac{L_{12}(\partial F^1/\partial\alpha)}{L_{11}} - (\partial F^2/\partial\alpha)\\ &= \frac{L_{12}[-U_{wQ}Y_L(z)W_c^* - U_QY_L(z) + U_{QQ}(Y_L)^2(z)\alpha W_c^* + U_QY_{LL}(z)W_c^*\alpha]}{L_{11}}\\ &\qquad + U_{wQ}Y_L(z)W_c^* - P_wU_{QQ}Y_L(z)W_c^*\end{aligned} \qquad \textbf{(A5.19)}$$

$$\beta_1 = \frac{L_{12}\partial F^2/\partial\alpha}{L_{22}} = \frac{L_{12}[-U_{wQ}Y_L(z)W_c^* + P_wU_{QQ}Y_L(z)W_c^*]}{L_{22}} \qquad \textbf{(A5.20)}$$

where W_c^* = the optimal level of collected water. The expressions for γ_1, β_1 and β_6 suggest that the coefficients on α for collect households and collect and purchase households are each functions of z. Assuming that the relationship between z and α is linear we can express γ_1, β_1 and β_6 as :

$$\gamma_1 = f(z) = \theta_0 + \theta_1 z \qquad \textbf{(A5.21)}$$

$$\beta_1 = g(z) = \pi_0 + \pi_1 z \qquad \textbf{(A5.22)}$$

$$\beta_6 = h(z) = \zeta_0 + \zeta_1 z \qquad \textbf{(A5.23)}$$

where θ_0, π_0 and ζ_0 are the coefficients on α and θ_1, π_1, and ζ_1 are the coefficients on an interaction or varying parameter term αz. Hence, incorporating the varying parameter terms, the demand functions to be estimated are:

$$W_c^{//} = c_1 + a_1\alpha + a_2 D_c\alpha + a_3\alpha z + a_4 D_c\alpha z + a_5 z + a_6 D_c z + a_7 D_c P_w + \varepsilon_1 \qquad \textbf{(A5.24)}$$

$$W_p^{//} = c_2 + b_1 P_w + b_2 D_p P_w + b_3 D_p\alpha + b_4 D_p\alpha z + b_5 z + b_6 D_p z + \varepsilon_2 \qquad \textbf{(A5.25)}$$

where :

$$a_1 = \frac{L_{22}}{Det}\theta_0;\ a_2 = \frac{L_{22}}{Det}\pi_0;\ a_3 = \frac{L_{22}}{Det}\theta_1\ ;\ a_4 = \frac{L_{22}}{Det}\pi_1;\ a_5 = \frac{L_{22}}{Det}\gamma_2;\ a_6 = \frac{L_{22}}{Det}\beta_2;\ a_7 = \frac{L_{22}}{Det}\beta_3$$

$$b_1 = \frac{L_{11}}{Det}\delta_1;\ b_2 = \frac{L_{11}}{Det}\beta_4;\ b_3 = \frac{L_{11}}{Det}\zeta_0\ ;\ b_4 = \frac{L_{11}}{Det}\zeta_1;\ b_5 = \frac{L_{11}}{Det}\delta_2;\ b_6 = \frac{L_{11}}{Det}\beta_5$$

(A5.24) and (A5.25) are given in the main text of the chapter as equations (5.11') and (5.12')..

Chapter 6

Using the Production Function Approach to Value Groundwater Recharge

6.1 Introduction

The Hadejia-Nguru wetlands described in greater detail in Chapter 2 are formed by the floodwaters of the region's two principal rivers, the Hadejia and the Jama'are. The rivers exhibit ephemeral flow patterns with periods of no flow in the dry season (October - April). Almost 80% of the total annual runoff occurs in August/September. (Thompson and Hollis, 1995). During this period, waterlogged areas known as *fadamas* are formed and are important not only for fishing and agricultural activities, making these some of the most productive areas in Northern Nigeria, but also for providing recharge to the underlying aquifers (Schultz, 1976; Diyam, 1987). Water from these aquifers is used for domestic consumption (see chapter 5) and for irrigation during the dry season.

As has been detailed in the preceding chapters, many water diversion schemes have been constructed or are planned upstream of these wetlands. These schemes will divert floodwater away from the wetlands, reducing the annual flooding within the floodplain (Hollis *et al.*, 1993). The economic value of the opportunity costs associated with diverting this water away from the wetlands has not been fully realized and incorporated into the development plans for this region. Barbier *et al.*, (1993) and Barbier and Thompson (1997) have shown that the economic value of the wetlands, in terms of floodplain agriculture and fishing, could be significant and affected by the construction of new dams and water diversion schemes. Hydrologists have noted, however, that an important environmental function of these wetlands is in recharging the groundwater resources of the area (Schultz, 1976; Diyam, 1987; Thompson and Hollis, 1995).

The previous chapter carried out a partial valuation of the groundwater resources and the indirect benefits of groundwater recharge, using a domestic water analysis and a modified household production function approach. The aim of this chapter is to partially value the groundwater recharge function of the wetlands by applying the production function approach to analysing groundwater use in irrigated agriculture.[1] The groundwater recharge function is assumed to support dry season agricultural production which is dependent on

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[1] Throughout this paper, irrigated agriculture refers to irrigation with groundwater pumped up from the shallow aquifer with the use of small tubewells.

groundwater abstraction for irrigation. Using survey data on agricultural production in the floodplain, this paper first carries out an economic valuation of agricultural production, per hectare of irrigated land. Following approaches advocated in the valuation literature (Barbier, 1994; Freeman, 1993; Mäler, 1992; Ellis and Fisher, 1987), we value the recharge function (through water input) as an environmental input in dry season agricultural production. Two welfare change measures are derived and related to the recharge function of the wetland. Welfare change is then calculated using the estimated production functions and hypothetical changes in groundwater level.

6.2 Groundwater use in irrigated dry season farming

Agriculture in the Hadejia-Jama'are floodplain involves both dryland and *fadama* farming (see chapter 2 for more detail). These areas are flooded during the wet season and gradually dry out until they are flooded again during the next wet season. This cycle provide valuable opportunities for grazing, agriculture and other economic uses. Floodplain activities have adapted to make use of the floodwaters and the *fadamas* in an ingenious way, taking advantage of a combination of the wetland's resources (see chapter 2).

Total cultivated area in the floodplain is estimated as 230,000 hectares of which approximately 77,500 hectares is dry season farming and 152,500 hectares is wet season farming (Barbier, *et al.*, 1993). Upland or dryland farming is rain-fed, and millet, sorghum and cow-melon are cultivated. *Fadama* farming is mainly rice cultivation. In addition, there are irrigated lands where vegetables may be grown during the dry season. The three main types of irrigation technologies used in this area are identified by Adams (1993) as ditch irrigation, shadoof irrigation and pump irrigation. Pumps may be used to pump water from flooded areas, rivers or groundwater resources. This study focuses on pump irrigation using water from shallow aquifers. Irrigation farming begins in October, after the floods have receded, and continues up until March/April. The crops grown using this irrigation technology include tomatoes, sweet and chili peppers, onions, spring onions, wheat, and to a lesser extent, sweet potatoes, irrigated rice, lettuce and garlic. The floodplain has experienced a dramatic rise in small-scale irrigation following the introduction of small petrol powered pumps for surface water irrigation and tubewells to tap the shallow aquifers under the floodplain (Kaigama and Omeje, 1994; Kimmage and Adams, 1992). Diyam (1987) suggests that shallow aquifers could irrigate 19,000 hectares within the wetlands through the use of these small tubewells. Although the extent of small scale tubewell irrigation within the Hadejia-Jama'are wetlands is not well documented, it appears to be changing rapidly due to changes in hydrological conditions, economic conditions, government initiatives, and in particular due to the policies of the World Bank supported Agricultural Development Programs (ADPs) which have promoted the use of small irrigation pumps through subsidies and/or loans for tubewell drilling and pump purchase. NEAZDP (1994) suggests that the annual increase in cropped area within the wetlands is at least 10% and could be higher in areas where water and suitable land is available.

The expansion of dry season cultivation in the area has resulted from the increased availability of small-scale irrigation technology and higher producer prices for some dry-season crops such as peppers, onions and wheat. In the influence area of the Madachi *fadama*, the recent increase in tubewell irrigation is clearly visible in the large numbers of irrigated fields producing off-season grains such as irrigated rice and wheat and high value perishables such as tomatoes, onions and pepper. The availability of pumps has also resulted in irrigation of certain dry-season crops such as sweet potato, to increase yields, and farmers in the area are experimenting with new commercial crops such as lettuce and garlic. Availability of, and access to, groundwater resources ensures the farmers a more secure and year-round water supply for these crops.

The growth of tubewells in this area is expected to continue to increase and although there is at present apparently little concern for the over-exploitation of this resource, this optimism is based on relatively little data on aquifer recharge and the effect of increased or reduced flooding of fadama areas. The Jigawa state ADP (JARDA) has provided loans to farmers in the Madachi area to purchase pumps and drill boreholes. Most of the pumps in this area have been supplied over the past 2-3 years. On average, each farmer was given a loan of N 19,500 [2](1992 prices) for the purchase of a pump and for drilling costs.

Cropping patterns in the area have changed due to these credit and technological facilities

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[2] 1US$ = 88Naira

as well as due to changing hydrological conditions. Increasing dependence on small-scale irrigation for dry season crops may result in increased sensitivity of small farmers to changes in prices and market demand. However, farming in this area is generally subsistence and to hedge against uncertainty farmers practice multi-cropping and intercropping. Farmers are therefore assumed to be mainly subsistence oriented agricultural households, also producing cash crops.

6.3 Economic valuation of dry season irrigated agriculture

Production data on crops grown in the study area are based on the results of field surveys carried out in four villages in the Madachi *fadama* (see Figure 1) from November 1995 - March 1996. The four villages of Madachi, Garin Ando, Garin Alaye and Maluri are believed to be representative of the villages in the fadama, comprising a range of large, medium and small farmers. A total of 37 farms were surveyed for crop production data. In addition, the entire influence area of the Madachi *fadama* was surveyed to establish the number of operational tubewells in the area (HNWCP, 1996). A total of 309 operational tubewells were counted during this survey period.

Figure 6.1 The Madachi *fadama* influence area within the Hadejia-Nguru wetlands

The agricultural survey of farmers in the Madachi *fadama* established wheat, tomatoes and pepper as the main cash crops being cultivated (Table 6.1). Okra and eggplant (the latter is grown in large quantities where there is surface irrigation) are also grown but mainly for home consumption and in small quantities.

Table 6.1 Main commercial crops cultivated in survey villages

Crop	Percentage of farmers surveyed growing crop
Grains	
Wheat	56.7%
Rice	42.4%
Vegetables	
Onions	36.4%
Spring Onions	15.6%
Tomatoes	60.6%
Pepper (sweet)	27.3%
Pepper (chilli)	9.1%
Tubers	
Sweet potatoes	12.1%

The total area of small scale irrigation using groundwater resources within the Madachi *fadama* and its influence area is estimated to be around 66 km^2, or approximately 6,600 hectares[3]. The value of the output from the farms surveyed as shown in Table 6.2 below. Financial prices for the outputs are estimated from market surveys conducted between December 1995 and May 1996 and from survey findings of farmgate prices received by farmers. Outputs are based on harvest figures reported in sacks or bundles by farmers and converted to weight measures, based on results from the market survey. Economic prices for the grains are calculated from World Bank data on commodity prices. For non-tradeables (i.e., vegetables and tubers), the standard conversion factor is approximately 1 and no additional adjustment is considered necessary since most of the economy uses the black market rate of N88 to 1US$ for its transactions and faces no foreign exchange premium.

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[3] This figure is based on Thompson and Goes (1997) which states that the influence area of the Madachi fadama may be estimated as 136 km^2, assuming a minimum of 1 km radius of influence. Since the largest extent of the actual swamp area has been estimated as 78 km^2, we estimate an area of 66 km^2 as being serviced by the recharge from the fadama and as being available for agricultural activities.

Table 6.2 Economic valuation of irrigated agriculture for survey villages (area:20.23ha)

Crop	Output (kg)	Financial Price (per kg)	Economic Price (per kg)	Financial Benefits (N)	Economic Benefits (N)
Wheat	57,250.00	22.00	6.86	1,259,500	392,964
Rice	29,070.00	12.50	12.3	363,375	357,561
Tomatoes	11,030.25	25.60	25.60	282,374	282,374
Onions	21,336.00	4.80	4.80	102,413	102,413
Spring Onions	3,280.00	6.25	6.25	20,500	20,500
Sweet Pepper	2,607.00	50.10	50.10	130,611	130,611
Chilli Pepper	1,423.75	22.00	22.00	31,323	31,323
Sweet Potatoes	1,400.00	5.10	5.10	7,140	7,140
Total	127,397.00			2,197,235.40	1,324,886

Financial Benefits per ha (N/ha)	108,612.7
Gross Economic Benefits per ha (N/ha)	65,491.15
Costs of inputs (N/ha)	29,183.38
Net Economic Benefits per ha (N/ha)	36,307.7

Exchange Rate N88=$1

The per hectare value for irrigated agriculture in the Madachi area is estimated as 36,308 Naira or US$ 412.5 per hectares. For an approximate area of 6,600 hectares, the economic value of dry season irrigated agriculture from the Madachi fadama and influence area is estimated as 2.39 x 10^8 Naira or US$ 2,723,077.

6.4 The production function approach and crop-water relationships

This section will develop the underlying general welfare estimation theory based on the production function approach described in the recent literature on valuation (see Barbier, 1994; Freeman, 1993; Mäler, 1991). The specific production functions for wheat and vegetables based on the production and input data collected by the survey are estimated in section 6.5. Based on this analysis and the production functions, welfare estimates related to a change in water input are calculated in section 6.6.

6.4.1 Production function approach

We begin by assuming that farmers produce $i = 1,...,n$ crops, irrigated by groundwater. Let y_i be the aggregate output of the i^{th} crop produced by the farmers. The production of y_i

requires a water input W_i, abstracted through shallow tubewells, and $j = 1,\ldots,J$ of other variable inputs (e.g., fertilizers, seed, labour), which we denote as $x_i,\ldots x_J$ or in vector form as $\mathbf{X}_J$. Because of the relationship between recharge and the level of water in the aquifer, we also assume that the amount of water available to the farmer for abstraction is dependent on the groundwater level, R. The aggregate production function for crop i can be expressed as:

$$y_i = y_i(x_{i1},\ldots,x_{iJ},W_i(R)) \qquad for all i \tag{6.1}$$

and the associated costs of producing y_i are:

$$C_i = C_x X_J + c_w(R)W_i \qquad for all i \tag{6.2}$$

where C_i is the minimum costs associated with producing y_i during a single growing season, c_w is the cost of pumping water and $\mathbf{C}_x$ is a vector of $c_{xi},\ldots c_{xJ}$, strictly positive, input prices associated with the variable inputs $x_{i1},\ldots x_{iJ}$. Note that we assume c_w is an increasing function of the groundwater level, R, to allow for the possibility of increased pumping costs from greater depths, i.e., $c_w > 0$, $c_w \geq 0$.

We first assume that there exists an inverse demand curve for the aggregate crop output, y_i:

$$P_i = P_i(y_i) \qquad for all i \tag{6.3}$$

where P_i is the market price for y_i, and all other marketed input prices are assumed constant.

Denoting S_i as the social welfare arising from producing y_i, S_i is measured as the area under the demand curve (6.3), less the cost of the inputs used in production[4]:

$$S_i = S_i(x_{i1},\ldots x_{iJ}, W_i(R); c_w(R)) = \int_0^{y_1} P_i(u)du - C_x X_J - c_w(R)W_i \qquad for all i,j \tag{6.4}$$

---

[4] We assume here that the demand function in (6.3) is compensated, so that consumer welfare can be measured by the appropriate areas; or that the consumer surplus estimate of the ordinary demand function is a reasonable estimate of consumer welfare. See Freeman (1993) for a discussion.

To maximize (6.4) we find the optimal values of input x_{ij} and water input W_i through setting the following first order conditions to zero:

$$\frac{\partial S_i}{\partial x_{ij}} = P_i(y_i)\frac{\partial y_i}{\partial x_{ij}} - c_{xj} = 0 \qquad for\,all\,i,j \tag{6.5}$$

$$\frac{\partial S_i}{\partial W_i} = P_i(y_i)\frac{\partial y_i}{\partial W_i} - c_w(R) = 0 \qquad for\,all\,i \tag{6.6}$$

Equations (6.5) and (6.6) are the standard optimality conditions indicating that the socially efficient level of input use occurs where the value of the marginal product of each input equals its price. If each farmer is a price-taker, then this welfare optimum is also the competitive equilibrium. We assume that this is the case.

The first order conditions in (6.5) and (6.6) can be used to define optimal input demand functions for all other inputs as $x_{ij}^* = x_{ij}^*(c_{xj}, c_w(R), R)$ and for water as $W_i^* = W_i^*(c_{xj}, c_w(R), R)$. In turn, the optimal production and welfare functions are defined as

$y_i^* = y_i^*(x_i^*, \ldots, x_J^*, W_i^*(R))$ and $S_i^* = S_i^*(x_{i1}^*, \ldots, x_{iJ}^*, W_i^*(R); c_w(R))$[5].

From the above relationships, we are interested in solving explicitly for the effects on social welfare of a change in groundwater levels, R, due to a fall in recharge rates. This effect is observed in the production function through an impact on water input, w_i. We assume that all other inputs are held constant and at their optimal levels, and that all input and output prices, with the exception of c_w, are unchanged. It therefore follows from the envelope theorem that:

---

[5] Asterisks denote optimally chosen quantities.

$$\begin{aligned}\frac{dS_i}{dR} &= \frac{\partial S_i}{\partial x_{ij}}\frac{\partial x_{ij}}{\partial c_w}\frac{\partial c_w}{\partial R} + \frac{\partial S_i}{\partial x_{ij}}\frac{\partial x_{ij}}{\partial R} + \frac{\partial S_i}{\partial W_i}\frac{\partial W_i}{\partial c_w}\frac{\partial c_w}{\partial R} + \frac{\partial S_i}{\partial W_i}\frac{\partial W_i}{\partial R} \\ &= \frac{\partial S_i}{\partial W_i}\left(\frac{\partial W_i}{\partial c_w}.\frac{\partial c_w}{\partial R} + \frac{\partial W_i}{\partial R}\right)\Bigg|_{x_{ij}=x_{ij}^*}\end{aligned} \qquad \textbf{(6.7)}$$

Applying (6.7) to the welfare function in (6.4) we obtain:

$$\frac{dS_i}{dR} = \left(P_i(y_i^*)\frac{\partial y_i}{\partial W_i} - c_w\right)\left(\frac{\partial W_i}{\partial c_w}\frac{\partial c_w}{\partial R} + \frac{\partial W_i}{\partial R}\right) - W_i^*\left(\frac{\partial c_w}{\partial R}\right) \qquad \textbf{(6.8)}$$

The net welfare change is therefore the effect of a change in groundwater levels on the value of the marginal product of water in production, less the per unit cost of a change in water input. The marginal change in pumping costs also affects the total costs of water pumped ($W_i^*\frac{\partial c_w}{\partial R}$). The effect of a change in water input due to a change in groundwater levels occurs both directly ($\partial W/\partial R$) and indirectly through the marginal effect of a change in pumping costs on water input ($\frac{\partial W_i}{\partial c_w}\frac{\partial c_w}{\partial R}$). For a non-marginal change in groundwater levels, the welfare change can be found by integrating (6.8) over R_o (old level) to R_l (new level).

$$\frac{dS_i}{dR} = (S_{Rl})-(S_{R0}) = \int_{R_0}^{R_1}\left[\left(P_i(y_i^*)\frac{\partial y_i}{\partial W_i} - c_w\right)\left(\frac{\partial W_i}{\partial c_w}\frac{\partial c_w}{\partial R} + \frac{\partial W_i}{\partial R}\right) - W_i^*\frac{\partial c_w}{\partial R}\right]dR \qquad \textbf{(6.9)}$$

Thus our welfare change measure associated with a change in naturally recharged groundwater is the resulting change in the value of production less the impacts on pumping costs. As long as per unit pumping costs are not prohibitively high, one would expect an increase in groundwater levels (to a point) to lead to a welfare benefit, or at least to maintain the initial welfare levels, whereas a decrease in groundwater levels would result in a welfare loss, either due to increased pumping costs and/or change in productivity.

If we now assume that farmers face the same production and cost relationships (6.1) and (6.2) for each crop i and are price takers, then it is possible to aggregate (6.9) from the welfare effects of a change in groundwater levels for the individual farmer. Let there be

$1,\ldots k$ farmers producing y_{ik} output of crop i and using w_{ik} water inputs. It follows that:

$$\frac{dS_i}{dR} = \sum_{k=1}^{K}\frac{dS_{ik}}{dR} = \sum_{k=1}^{K}\int_{R_0}^{R_1}\left[\left(P_i(y_i^*)\frac{\partial y_{ik}}{\partial W_{ik}} - c_{w_k}\right)\left(\frac{\partial W_{ik}}{\partial c_{w_k}}\frac{\partial c_{w_k}}{\partial R} + \frac{\partial W_{ik}}{\partial R}\right) - W_{ik}^*\left(\frac{\partial c_{w_k}}{\partial R}\right)\right]dR \quad \textbf{(6.10)}$$

Thus the welfare effects of a change in groundwater levels on the aggregate production of crop i can be determined from the resulting change in the marginal (net) profits of water use faced by the k^{th} farmer, aggregated across all K farmers.

However, in order to implement the welfare measures in (6.9) and (6.10) note that we need to know the production function for each crop, as well as how the equilibrium output changes with R and how levels of inputs change with R. As these equations indicate, this measure of welfare requires integration along a path and we must therefore know the functional forms for each of the expressions in (6.9) and (6.10). Alternatively, we could also measure welfare change directly from our measure of social welfare, S_i, in equation (6.4) above. This would imply:

$$\frac{dS}{dR} = (S_{R_1}) - (S_{R_0}) = \int_0^{y_1} P_i(y_i^*)dy - \boldsymbol{C}_x X_j^* - c_w(R_1)W_i^*(R_1) - \int_0^{y_0} P_i(y_i^*)dy + \boldsymbol{C}_x X_j^* + c_w(R)W_i^*(R_0) \quad \textbf{(6.11)}$$

$$for\,all\,i,j$$

where y_0 is the initial output level and y_1 is the final output level. To use (6.11) as a welfare measure we would also need to estimate production functions for each crop and calculate optimal levels of inputs and output levels. We return to these welfare measures in section 6.6 where, using the information from the production functions, we will use both measures to calculate welfare change for our sample of wheat and vegetable farmers.

6.4.2 Irrigation inputs and crop yields

Before we proceed to the estimation of production functions we need to understand the nature of the groundwater technology used in this area in relation to groundwater recharge and hence, water input into crop production. Assessing the importance of groundwater recharge in maintaining groundwater at levels suitable for irrigated agriculture requires that we know i) the water-yield relationships influencing the crops and ii) the technological ability of the pumps to pump water. This section will briefly examine the literature on crop-water production functions and discuss the role of pumping technology used by the farmers, in determining pumping costs.

The extent to which crop yields will be affected will depend on a number of factors including:

1) The stage of crop development affected by reduced or no availability of irrigation water
2) The sensitivity of the crop to fluctuations in water availability
3) Climatic factors such as evaporation rates
4) Soil factors, including soil type and soil moisture
5) Length of growing period

Figure 6.2 below depicts seasonal crop response to variable water input showing zones of increasing returns (0,W), diminishing returns (W_1,W_2) and negative returns (>W_2).

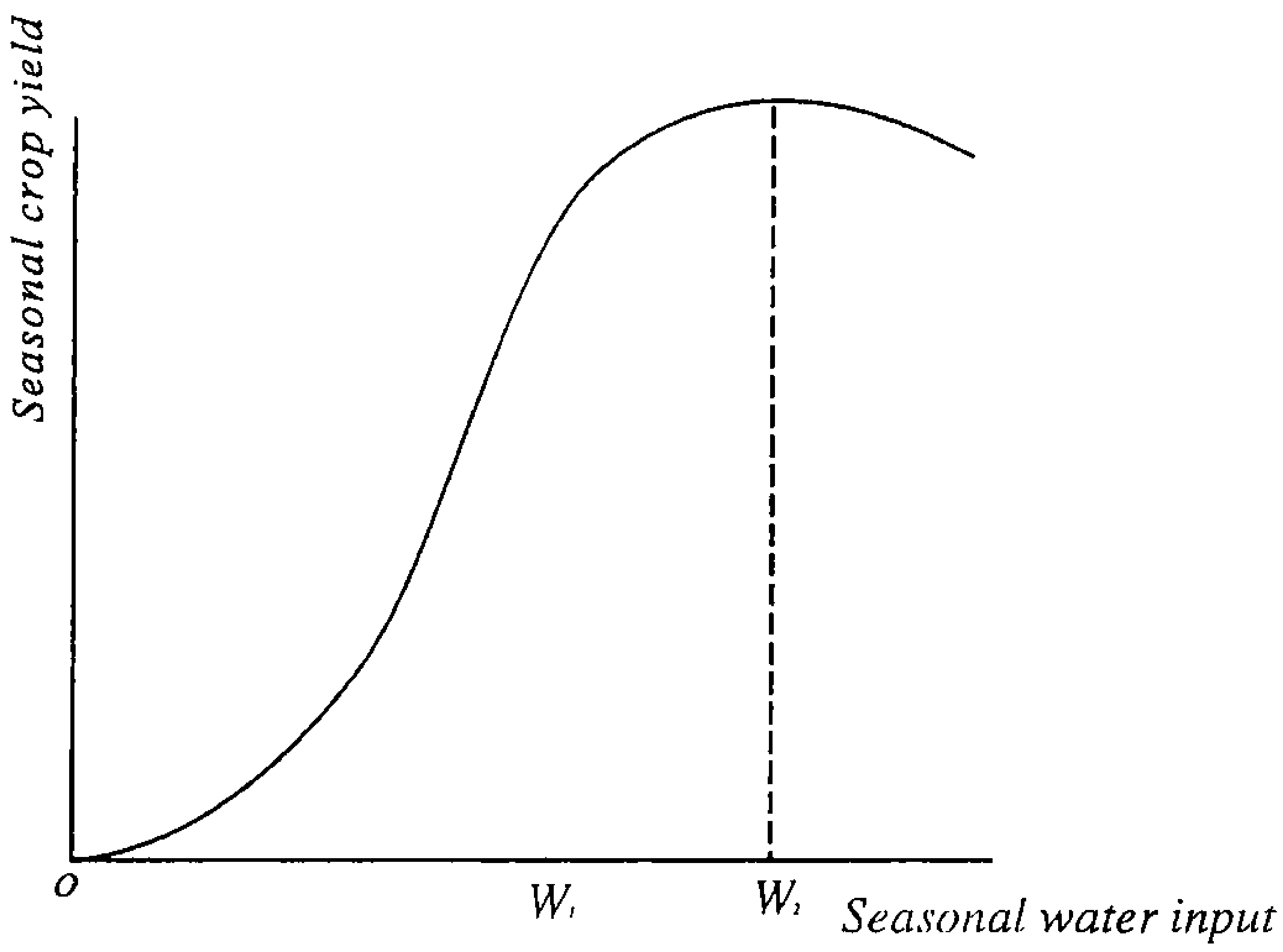

Figure 6.2 Crop-water relationships (adapted from Carruthers and Clark, 1981)

Various functional forms have been used to describe production technologies using data from field experiments and from observed farm data. The simplest conception of crop response to water application is the linear response. This is most likely when the range of application of the variable inputs is small. The log-linear relationship using a Cobb-Douglas production function has also been used to estimate crop-water relationships, although, as noted by Hexem and Heady (1978), a maximum product is not defined by the Cobb-Douglas and consequently, a decreasing total product (e.g., at high levels of water application) is not possible. A polynomial function such as a quadratic or Gompertz function would allow estimation of the effect of increasing input levels and diminishing marginal returns, as would a Cobb-Douglas translog function, particularly when a wider range of inputs is considered (Hexem and Heady, 1978; Carruthers and Clark, 1981).[6] Since the survey data contains information on actual quantities and market prices of inputs used and yields, it reflects optimization behaviour on the part of the farmers and is therefore more than a physical relationship between the inputs - it reflects economic decisions as well. Hence, production functions for the crops are estimated using the survey data[7].

A second issue we consider before estimating production functions and welfare changes is the technological relationship between groundwater levels and tubewells. A typical tubewell consists of a length of pipe sunk into the ground below the maximum depth to the water table. This maximum depth should be such that during pumping, the aquifer's water level does not fall below the pipe's reach. If the rate of withdrawal from the aquifer exceeds the recharge, and groundwater levels do not recover to the original base level, the use of the shallow tubewell will need to be abandoned.[8]

For the purpose of this study, there are two possible effects of a fall in groundwater levels:

(i) as groundwater falls below a certain level, the costs of pumping water are likely to rise, and

(ii) if groundwater levels fall below the maximum depth of the sunk tubewells, then the

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[6] Existing crop-input functions such as Mitscherlich - Spillman functions are used to estimate effects of changes in water input, given that the application of all other inputs remain constant. These functional forms obey the von Liebig law of the minimum which asserts that there may be non-substitution between some nutrients and a yield plateau. Mitscherlich proposed an exponential functional form specified as: $y_i = m\,(1 - ke^{-\beta a_i})$; where y_i is the observed yield and a_i is the growth factor of the crop. m is defined as the asymptotic yield plateau. The Von Liebig function assumes that output increases linearly in the input up to some maximum. These functional forms have been used with experimental data to study the input-crop production relationship. Experimental data would need to be generated to find the maximum for each input. Yield and output data generated by these agronomic experiments do not, however, reflect optimizing behaviour and we use market generated and farm data for the production function estimation.

[7] Cost functions are not estimated, although the literature advocates the estimation of cost function in lieu of production function whenever possible. The cost data in this case is less reliable than the physical data since some or all of the inputs are purchased at subsidy prices, market prices or black market prices.

[8] However, increased costs of pumping from a greater depth may cause pumping to be curtailed until a new groundwater level is established. Because the farmer is forced to stop pumping, water levels may recover, allowing some sporadic pumping throughout the season. This introduces uncertainty into the problem and makes it a dynamic problem. This is beyond the scope of the present paper.

farmer will have to cease pumping for the rest of the dry season and thus agricultural production will fall and may even cease.

Figures 6.3 and 6.4 are used to depict these effects. Figure 6.3 describes the effect of changing groundwater levels on the marginal costs of pumping water and Figure 6.4 depicts the effect of changing groundwater levels on the farmer's production possibilities frontier. Water inputs are denoted by W and other inputs by X, while groundwater levels are denoted by R. For case (i) to occur, we expect that the speed of the pump will be affected by a drop in groundwater levels but water will still be available to the farmer using the given technology. The pumps being used in the floodplain are surface mounted pumps, and it is likely that at depths approaching 7 metres (denoted as R_1 in figure 6.3), these pumps will slow down because of the increase in lift and costs will rise from the point where $R > R_0$. To maintain water input levels, the farmer would have to increase pumping hours, thereby essentially incurring higher costs of production (C_2). However, the farmer may be able to continue production despite higher pumping costs. Using the data on pumping hours and the specifications of the pumps being used, we estimate that as water levels drop from 6m to 7m, pump speeds will decrease from 37,636 litres/hour to 26,434 litres/hour (approximately 30% decrease in speed).[9]

The tubewells in the study area are sunk to depths of approximately 9 metres. This implies that the groundwater table would have to fall to a level greater than 9 metres (R_s in figure 6.3) before water pumping capabilities fall to zero, i.e., for case (ii) to occur. If this occurs, and assuming that all other inputs are held constant, the farmer normally producing at point A (W_0,X_0) is forced to operate at point B, defined by (W_1,X_0) in figure 6.4. The farmer's production possibilities frontier (PPF) moves in because of a fall in depth beyond 9 metres. The farmer cannot maintain his original level of utility (U_0) and move to point C at (W_1,X_1) because this point lies outside the production possibilities frontier (since the farmer cannot change input decisions during the season). The farmer will move to a lower level of utility

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[9] Although theoretically per unit costs of pumping water should be constant for the given technology, surface mounted pumps are less efficient at groundwater depths approaching 7 metres. If costs are constant the welfare change for the farmer would be measured by: $\frac{dS_i}{dR} = \int_{R_0}^{R_1} \left[\left(P_i(y_i^*) \frac{\partial y_i}{\partial W_i} - c_{w_i} \right) \left(\frac{\partial W_i}{\partial R} \right) \right] dR$.

(U_l) and operate at point B and produce a lower output, or not produce at all.[10] At R_s, the discontinuity that sets in due to technological limitations, in effect drives the cost of pumping water to infinity for the farmer. This non-convexity in the cost curve may be offset by technological innovation. However, given the present level of technology, if the water levels stay below 9 metres, the farmer will not be able to irrigate at all and the associated drop in yield can be calculated from the production function by setting water input to zero. This is only expected to occur in the wetlands if there is a long period of very low flooding and no technological change.

We use this information to calculate the unit pumping cost at the new groundwater level, R_2. As figure 6.3 shows, $C_w(R) = C_0$ for levels of $R \leq R_0$. Pumping costs increase thereafter. By linearising the cost function between R_0 (6 metres) and R_1 (7 metres) in figure 6.3, we derive the functional relationship between pumping costs, C_w and groundwater level R for $R_0 \leq R \leq R_1$ as:

$$\begin{aligned} C_w(R) &= a + bR \\ where\ a &= -19.56;\ b = 5.34 \end{aligned} \qquad \textbf{(6.12)}$$

This functional form, with the values for a and b as noted above, only describes the portion of the curve between R_0 and R_1 in figure 6.3. We can estimate the change in pumping costs due to a fall in groundwater levels using the above relationship and the welfare measure in (6.9). Increases in pumping costs will also affect the level of water input during the growing season and optimal levels of water input and associated change in output levels can be calculated from the production functions, estimated in section 6.5, and the optimality conditions in (6.5) and (6.6).

In the next section we estimate production functions for wheat and vegetables as a final step in calculating welfare change for a drop in groundwater recharge and associated groundwater levels in the Madachi *fadama*.

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[10] Note that we are assuming no technology shifts in this case. While this may seem unreasonable we argue that in the short run the farmer is unable to change technologies. There are high financial costs associated with the change in technology to deeper boreholes and very few farmers were observed to be using the deep boreholes for irrigation. The small pumps are subsidized and are being promoted by government and bilateral organizations.

Figure 6.3 Water pumping costs as a function of groundwater level

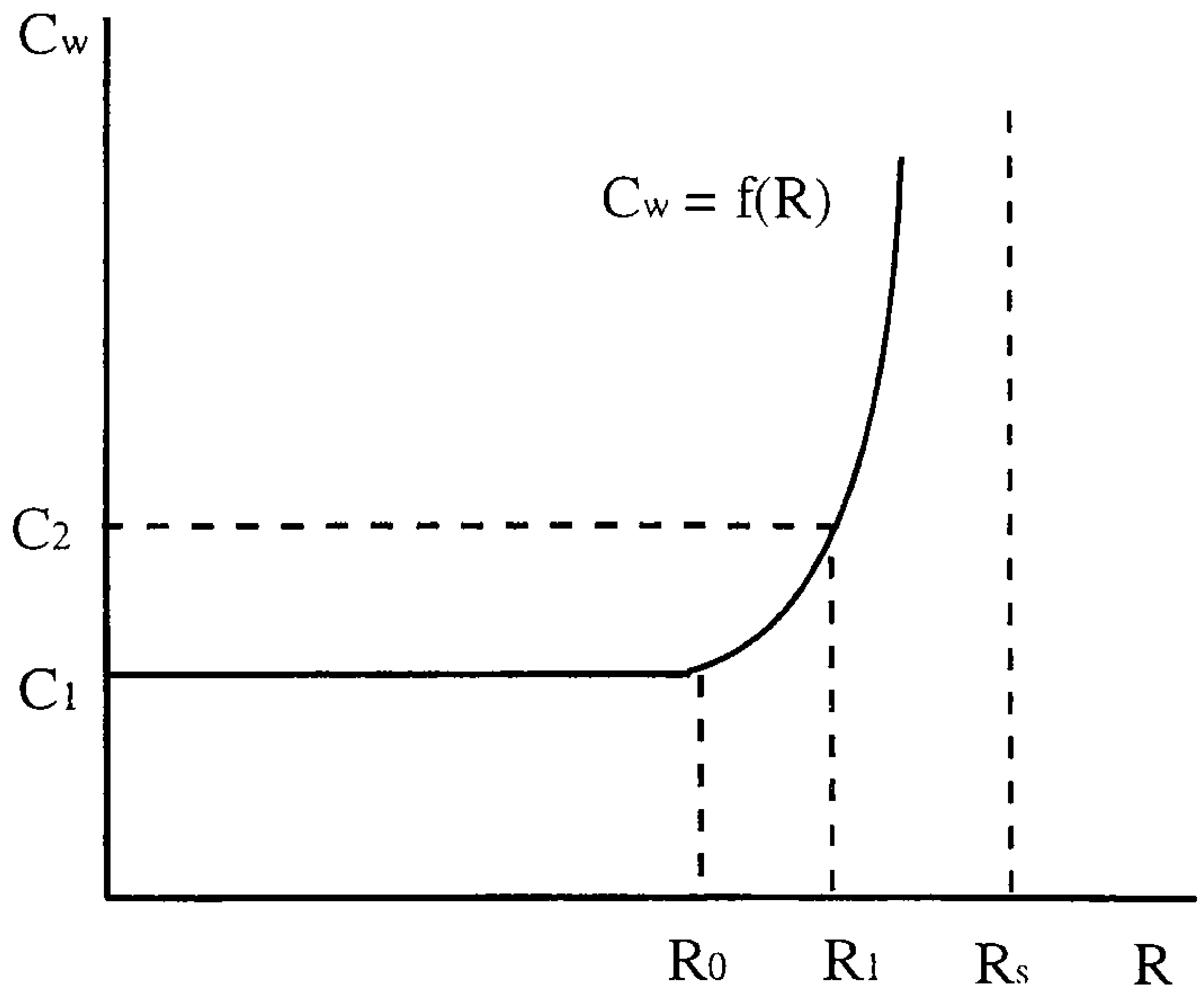
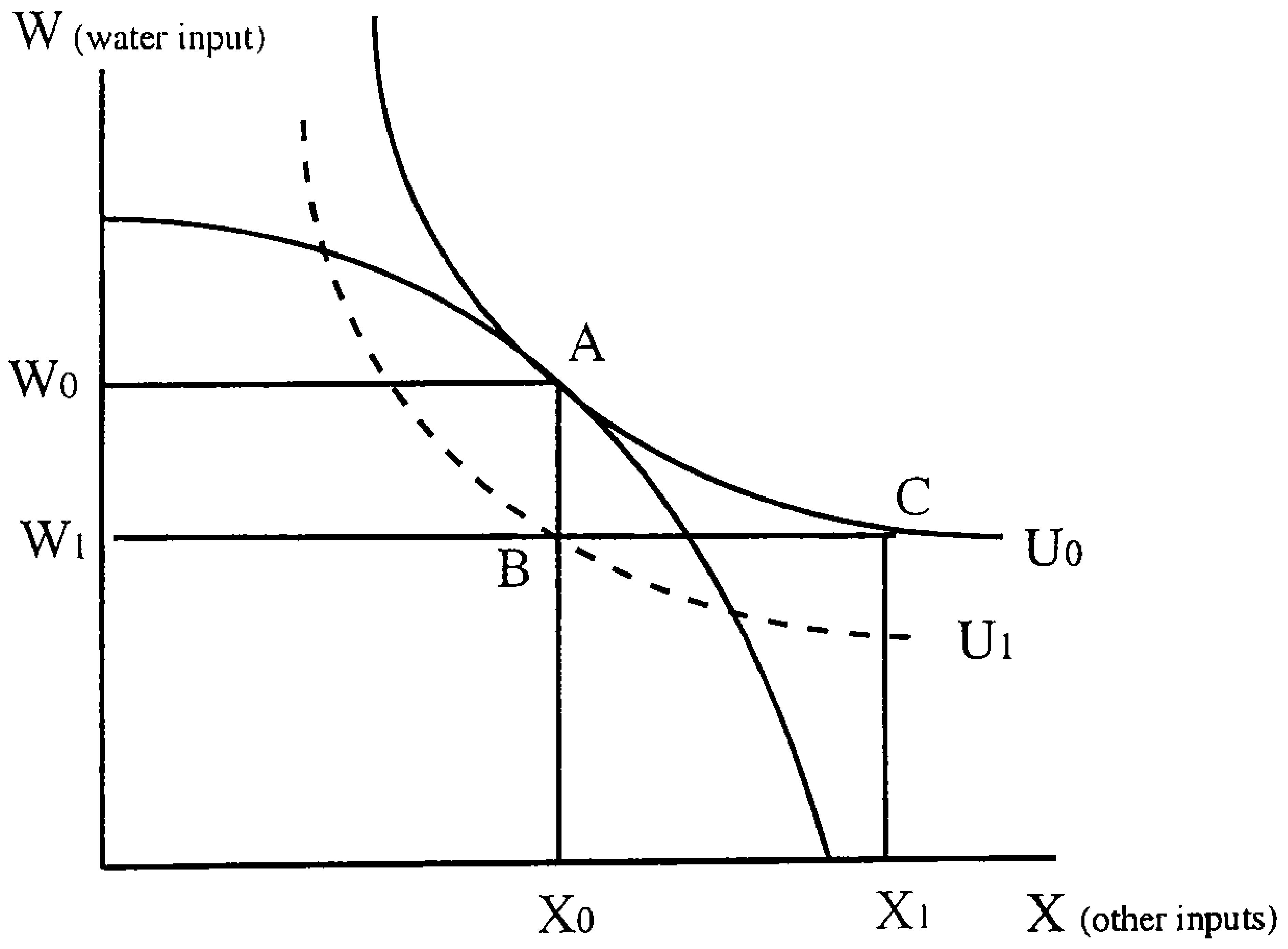


Figure 6.4 Effect of a non-marginal change in water table depth on the production possibilities frontier



6.5 Estimating production functions for wheat and vegetables

In the production functions estimated below, we assume that the output depends on a vector of purchased goods and water inputs. The farmers in the Madachi area grow mainly wheat, irrigated rice and vegetables. The crops are divided into these three groups because of the different nature of irrigation, fertilizer application and other farming decisions. Wheat and rice are generally grown earlier in the season and vegetables are grown well into the dry season. In the following sections, we estimate production relationships for wheat and vegetables only since irrigated rice is grown by very few farmers in the sample[11].

We consider linear and log-linear functional forms for wheat and vegetable production, using the production data collected by the agricultural survey within the Madachi *fadama*. The linear form assumes constant marginal products and excludes any interaction between the inputs. Although the lack of interaction terms is restrictive, we observe in the literature that linear relationships are likely, particularly for wheat production and with low levels of inputs. We therefore apply this functional form to the production function for wheat and vegetables. The log-linear form assumes constant input elasticity and variable marginal products. Note that the coefficients estimated by using this form represent output elasticities of individual variables and the sum of these elasticities indicates the nature of returns to scale.

The wheat production function

The production function for wheat is described as:

$$Y = f(L,B,S,F,W) \qquad \textbf{(6.13)}$$

where Y : total output of crop (kg)
L : land (hectares)
B : labour (workers)
S : seeds (kg)

---

[11] Since crop level data is often not available, many studies analyse farm level aggregated input demands. Although fixed factors, such as land, may cause jointness in the production process, we argue that crop level production functions can be estimated in this case for wheat and for vegetables since 1) crop level data was collected through the survey and is available and 2) vegetables are clearly grown only after the winter wheat production implying that input decisions may be considered as separate in terms of the production processes.

F : fertilizer (kg)
W : water application = irrigation (litres)

The production function was approximated using aggregate quantities as[12]:

1) a linear production function where: $Y = \alpha + \beta_1 L + \beta_2 B + \beta_3 S + \beta_4 F + \beta_5 W + \varepsilon_1$,

2) a log-linear function where: $\ln Y = \alpha + \beta_1 \ln L + \beta_2 B + \beta_3 \ln S + \beta_4 \ln F + \beta_5 \ln W + \varepsilon_2$,

and ε_i is the random disturbance associated with the production function.

The vegetable production function

The production function for vegetables was estimated as a single function since all the vegetables are grown at the same time (after the wheat has been harvested) or in quick succession and receive similar quantities of inputs. Data on seeds/seedlings was unreliable and this variable was dropped from the production function. The production function was approximated using aggregate quantities as:

1) a linear production function where: $Y = \alpha + \beta_1 L + \beta_2 B + \beta_3 F + \beta_4 W + \varepsilon_1$,

2) a log-linear function where: $\ln Y = \alpha + \beta_1 \ln L + \beta_2 B + \beta_3 \ln F + \beta_4 \ln W + \varepsilon_2$,

and ε_i is the random disturbance associated with the production function.

Table 6.4 reports the results for the linear and log-linear production functions for wheat production. The linear model has an adjusted R^2 of 0.93 and F statistic of 54.4. Both values

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[12] A quadratic function where:

$$Y = \alpha + \beta_1 L + \beta_2 B + \beta_3 S + \beta_4 F + \beta_5 W + \delta_1 L^2 + \delta_2 B^2 + \delta_3 S^2 + \delta_4 F^2 + \delta_5 W^2 + \gamma_1 BL + \gamma_2 LS + \gamma_3 LF + \gamma_4 LW + \gamma_5 SB + \gamma_6 FB + \gamma_7 BW + \gamma_8 SF + \gamma_9 SW + \gamma_{10} FW + \varepsilon_3$$

for the vegetable production function and

$$Y = \alpha + \beta_1 L + \beta_2 B + \beta_3 F + \beta_4 W + \delta_1 L^2 + \delta_2 B^2 + \delta_3 F^2 + \delta_4 W^2 + \gamma_1 BL + \gamma_2 LF + \gamma_3 LW + \gamma_4 FB + \gamma_5 BW + \gamma_6 FW + \varepsilon_3$$

for the wheat production function

may also be specified. However, the small sample size makes it impossible to include all the variables specified by the quadratic model in the estimation and this model was therefore discarded.

suggest a good fit. The Breusch - Pagan Lagrange Multiplier test is not significant for the linear model (critical value for LM $\chi^2 = 15.09$; with 4 d.f.), and we accept the hypothesis of homoscedasticity. However, the large, negatively signed and statistically significant value for the constant term would suggest that there may be misspecification of the functional form.

The log-linear functional form also performs well in terms of R^2 (0.9) and F statistics (37.49). The coefficients for LW and LF are found to be statistically significant in the log-linear model, with the expected signs. The Lagrange multiplier statistic is however significant for the log-linear model, indicating some heteroscedasticity in this model. The presence of this heteroscedasticity indicates that the least squares estimators are still unbiased but inefficient. Since the estimators of the variances are also biased we correct for the standard errors of the coefficients and find relatively small differences in the values.

According to the literature on crop-water production functions determined from experimental studies, wheat is often seen to have a linear or log-linear shape unlike other crops which may show diminishing returns at high levels of water application. Wheat may continue to show increasing returns up to fairly high levels of water application (Carruthers and Clark ,1981; Hexem and Heady, 1978). The log-linear model is considered as the most satisfactory version of the wheat production function although the small sample size may be inflating the model fit statistics.

Table 6.3 Table of Variable Names

Variable	**Definition**
Y	Output (kg)
L	Land (hectares)
B	Labour (workers)
F	Fertilizer (kg)
S	Seeds (kg)
W	Water (litres)
LY	LN (Y)
LL	LN (Land)
LB	LN(Labour)
LF	LN (Fertilizer)
LS	LN(Seeds)
LW	LN(Water)

Table 6.4 Results for the wheat production function

Variable	Linear	Log-linear
L	1993.7*** (2.865)	-
B	52.711 (0.824)	-
S	3.6165** (2.566)	-
F	71.581** (2.438)	-
W	11.610** (2.134)	-
LL	-	0.38 (1.442)
LB	-	-0.024 (0.156)
LS	-	0.026 (0.33)
LF	-	0.47*** (2.71)
LW	-	0.6885* (1.881)
Constant	-1662.5*** (3.598)	3.4** (2.39)
Adjusted R^2	0.93	0.9
F statistic	54.4	37.49
Breusch-Pagan χ^2	1.05 (d.f.5)	18.27 (d.f.5)
Observations	21	21

(t statistics in parenthesis; ***1% significance level; **5% significance level; *10% significance level)

Table 6.5 Results for the vegetable production function

Variable	Linear	Log-linear
L	-786.67 (-0.524)	-
B	282.76 (1.591)	-
F	265.04** (2.380)	-
W	5.8358** (2.433)	-
LL	-	0.231 (0.823)
LB	-	0.585** (2.206)
LF	-	0.593** (2.827)
LW	-	0.4268** (2.437)
Constant	-1449.4 (1.512)	3.13*** (11.439)
Adjusted R^2	0.55	0.66
F statistic	11.9	18.88
Breusch-Pagan χ^2	13.49 (d.f.5)	4.24 (d.f.5)
Observations	37	37

(t statistics in parenthesis; ***1% significance level; **5% significance level; *10% significance level)

Table 6.5 reports the econometric results for the functions estimation for vegetable production. The linear and log-linear models again perform well in terms of R^2 and F statistics. The Breusch - Pagan Lagrange Multiplier test is significant for the linear model ($\chi^2 = 13.49$; with 4 d.f.), and we reject the hypothesis of homoscedasticity. For the log-linear model, the Lagrange multiplier statistic is less than the critical value at the 5% significance level ($\chi^2 = 4.24$; with 4 d.f.), indicating no heteroscedasticity in this model. The coefficients on the variables LF, LB, LW and the constant term are statistically significant. The log-linear model is therefore accepted as the most satisfactory version of the vegetable production function.

6.6 Valuing the recharge function

Hydrological evidence for the relationship between flood extent and recharge to village wells show that there is some fluctuation with flood extent and mean water depth of the shallow aquifer. The effect of planned upstream water projects will have an impact on producer welfare within the wetlands through changes in flood extent therefore groundwater recharge. By hypothesising a drop in groundwater levels from 6 metres to 7 metres in depth (due to reduced recharge), we calculate the expected change in welfare associated with this reduction in recharge. This exogenous change affects the farmers decision making process *during* the farming season, i.e., after decisions on other inputs have already been taken. This is because the effect of the reduced recharge will not be felt until after the dry season agriculture has started.

Recall that in section 6.4.1, the welfare change measure for non-marginal changes in R (level of naturally recharged groundwater) was derived as:

$$\frac{dS_i}{dR} = \int_{R_0}^{R_1} \left[\left(P_i(y_i^*) \frac{\partial y_i}{\partial W_i} - c_w \right) \left(\frac{\partial W_i}{\partial c_w} \frac{\partial c_w}{\partial R} + \frac{\partial W_i}{\partial R} \right) - W_i^* \frac{\partial c_w}{\partial R} \right] dR \qquad \textbf{(6.9)}$$

This welfare change measure is used together with the results of the production function estimates to calculate welfare changes for individual farmers. We assume also that farmers in the Madachi area are price takers and hence face a 'horizontal' demand function, i.e.,

$P_i(y_i) = P_i$. From equation (6.10) we can calculate the welfare effects of a change in groundwater levels on the aggregate production of crop i across all K farmers.

From equation (6.9) we see that the effect of R on welfare is felt through a change in water input due to increased costs ($\frac{\partial W_i}{\partial c_w}$)and/or a change in water availability $\frac{\partial W_i}{\partial R}$. This second effect will occur only if a change in recharge were to cause a decline in groundwater levels below 9 m (see section 6.4.2 and figure 6.4 above). This is unlikely to happen within a single season and we do not therefore consider this aspect in calculating welfare change. Instead we consider the effect of changing pumping costs on water input and use the production function estimated earlier for the purpose of estimating welfare changes. However, in order to do so, we need to calculate $\frac{\partial W_i}{\partial c_w}$, the marginal change in water demand due to a marginal change in the cost of pumping.

In section 6.5 we estimated production functions for wheat and vegetable production. Holding all other inputs constant and noting that only water input will vary, we use the log linear production functions estimated in section 6.5, together with the optimality conditions in equations (6.5) and (6.6) to solve for W_i as:

$$P_i\alpha\beta_w L^{\beta_L} B^{\beta_B} S^{\beta_S} F^{\beta_F} W^{\beta_w - 1} = c_w \qquad \textbf{(6.6')}$$

$$W_i^* = \left(\frac{c_w}{P_i\alpha\beta_{w_i} L^{\beta_L} B^{\beta_B} S^{\beta_S} F^{\beta_F}}\right)^{\frac{1}{\beta_{w_i}-1}} \qquad \textbf{(6.14)}$$

where L,B, S and F are all the other inputs in the specified production function (for crop i) with estimated parameters $\beta_L, \beta_B, \beta_S$ and β_F.[13] We solve for $\frac{\partial W_i}{\partial c_w}$ as:

$$\frac{\partial W_i}{\partial c_w} = \frac{1}{\beta_w - 1}\left(\frac{c_w}{P\alpha\beta_w L^{\beta_L} B^{\beta_B} S^{\beta_S} F^{\beta_F}}\right)^{\frac{2-\beta_w}{\beta_w-1}} \frac{1}{P\alpha\beta_w L^{\beta_L} B^{\beta_B} S^{\beta_S} F^{\beta_F}} \qquad \textbf{(6.15)}$$

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[13] Note that for the vegetable production function, the variable S (seeds/seedlings) is not included and is therefore not included in the estimation of W_i either.

The above term is calculated for each individual farmer using the estimated values for the relevant parameters and constant terms and the market price of the crop.

We can now calculate welfare change due to a drop in groundwater levels to 7 metres, for individual farmers, using the welfare measures in equations (6.9) or (6.11) (see Appendix for the derivation of expressions used to calculate welfare changes). The production functions from section 6.5 are used to calculate the associated change in productivity due to a fall in recharge levels. We calculate optimal levels of water input from (6.14) and output levels from the production function. The average and total change in welfare for a drop in groundwater levels from 6 to 7 metres depth, using both welfare measures (6.9) and (6.11), are given below. From (6.9), the welfare change of a drop in groundwater levels (R) to 7 metres is calculated as given in table 6.6. From (11), the welfare change of a drop in groundwater levels (R) to 7 metres is calculated as in table 6.7.

Table 6.6 Welfare change for sample using equation (6.9)

Crop	Total welfare change (Naira)	Average welfare change per hectare	Total land (hectares)	Average land holding (hectares)
Wheat	551,201	54,459	10.51	0.645
Vegetables	105,916	3,566	29.7	0.803

Table 6.7 Welfare changes for sample using equation (6.11)

Crop	Total welfare change (Naira)	Average welfare change per hectare	Total land (hectares)	Average land holding (hectares)
Wheat	550,320	54,372	10.51	0.645
Vegetables	130,659	4,399	29.7	0.803

There is only a slight variation between the results from using the two welfare change measures. This may be due to the fact that (6.9) is an aggregation of marginal welfare changes whereas (6.11) is a calculation of the change in area bounded by the demand curve and the cost curve. The welfare change associated with the effects of groundwater loss on wheat production is very high. Although vegetable production is, in general, more water intensive, it appears that wheat production is more sensitive to changes in water input. Since wheat is a newly introduced crop in the area it displays a high yield response to water inputs. The elasticity of production to water inputs for wheat is therefore higher than it is in the case of vegetable production. However, vegetable production takes place well into the dry season and may be subject to even higher pumping costs for water if the water table falls below 7 metres during the dry season. To properly measure this welfare change we would, however, require full knowledge of the relationship between pumping costs and groundwater levels. Since there is little evidence that groundwater levels could fall much below 7 metres we have restricted our present analysis to this level for both wheat and vegetable production.

6.7 Conclusions and policy implications

The Madachi *fadama* affects an area of about 6,600 hectares. Although there are at least 963 tubewells installed in the area, only 309 were found to be currently operational (i.e., 32% of installed tubewells are operational). Based on the number of operational tubewells, we estimate the welfare effects of reduced recharge to the groundwater table across the farmers within the *fadama* who are presently using tubewells for dry season irrigated agriculture.

Approximately 56.7% of the farmers in this area grow wheat while 100% of the farmers grow vegetables. This implies that 56.7% of the farmers would be affected by the welfare change associated with growing wheat and vegetables and 43.3% would be affected by the welfare change associated with growing vegetables only. We assume there are a corresponding number of farmers for each of the 309 operational tubewells and conclude that there are 175 wheat and vegetable farmers and 134 vegetable farmers in the Madachi fadama influence area. We use the welfare change measures for a fall in groundwater levels from 6 to 7 metres depth from equation (6.9) for these calculations.

Table 6.8 Welfare change in the Madachi fadama in Naira

	Average welfare change per farmer	Total loss for Madachi farmers
Vegetable farmer	2,863	383,642
Wheat + Vegetable farmer	29,110	5,094,296

Exchange rate: 88 N=US$ 1

This study shows that irrigated agriculture using water from the shallow groundwater aquifer has a value of 36,308 Naira (413 US$) per hectares for the Madachi area. The change in welfare associated with a decrease in recharge to the aquifer is estimated as 2,863 Naira (US$ 32.5) for each vegetable farmer and as 29,110 Naira (US$ 331) for farmers growing wheat and vegetables. Average household income is estimated as Naira 3,155 per month and this welfare loss is approximately 7.56% of yearly income for vegetable farmers and 77% of yearly income for vegetable and wheat farmers. The total loss associated with the 1 metre change in naturally recharged groundwater levels (resulting in a decline of groundwater levels to approximately 7 metres) is estimated as 5,477,938 Naira (US$ 62,249) for the influence area of the Madachi *fadama*.

The welfare estimates for wheat are surprisingly high. It is argued that the reason for this is that wheat is a newly introduced crop within the wetlands and because of its recent introduction displays a high yield response to water inputs. Since our data is collected over a single dry season, this is evident in our results. Continued production of wheat within the wetlands could therefore be subject to declining yields over time and is therefore generally considered to be unsustainable within the wetlands over the long run (Barbier *et al.*, 1994) Therefore, we could disregard wheat production and estimate a welfare loss of 383,642 Naira or 4,360 US$ for the Madachi *fadama*.

Diyam (1987) suggested that shallow aquifers could irrigate 19,000 hectares within the wetlands through the use of small tubewells. Using this figure together with the average welfare change for the Madachi *fadama* (5,478 Naira/ha or US$ 62/ha), we estimate a welfare loss of 1.04 x 10^8 Naira or US$ 1,182,737 for the wetlands, due to a decrease in groundwater levels to approximately 7 metres in depth.[14] Again disregarding wheat production, the welfare loss associated with this change in groundwater levels, amounts to 82,832 US$ for the wetlands. Although there is considerable difference in the level of welfare loss with and without consideration of wheat production, the value of groundwater recharge in terms of irrigated agriculture is clearly positive and significantly large.

The emphasis on increasing tubewell irrigation within the wetlands is contradictory to

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[14] Note that this figure is based on 32% of installed tubewells actually working and could be much higher for a higher percentage of operational tubewells within the wetlands.

policies such as dam construction and channelization which might reduce the flooding within the wetlands. As previous studies have asserted, and as this study confirms, groundwater recharge is of considerable importance to wetland agriculture and reduced recharge resulting in lower levels of groundwater will result in a loss of welfare for the floodplain populations. Furthermore, this analysis has been conducted in the Madachi *fadama* which is a regularly inundated *fadama* with good groundwater stocks. It is very likely that in other areas of the wetlands where flooding is not as reliable as in Madachi, the effects of reduced recharge and rapid declines in groundwater levels will have more devastating effects.

It is also conceivable that given a dramatic fall in groundwater recharge, there may be a technological shift towards deeper tubewells and boreholes for irrigation. The 1994 groundwater report by NEAZDP suggests that many boreholes in the wetlands are sunk over 100m deep. In contrast, most of the village wells and shallow tubewells are less than 10 m deep. The boreholes may therefore be sunk in deeper aquifers. The exact relationship between the alluvial aquifers and the deeper aquifers of the Chad Formation is not known. In places there may be some connection between the two so that flooding within the wetlands may recharge the deeper aquifers as well. The move towards deeper boreholes in some parts of the wetlands appears to be both economically and politically motivated. Irrigation boreholes (sunk to levels greater than 10 metres depth) will transform the agriculture in the area and may offset any impact of falling groundwater levels in the shallow aquifer. However, given the lack of hydrological information regarding the hydrological pathways between the deeper aquifer and the shallow aquifer, the question of groundwater mining and hence, potentially unsustainable developments within the wetlands, cannot be ruled out. In the face of this uncertainty, the value of the shallow aquifers in irrigated agriculture, and consequently the value of the recharge function of the wetlands, must be recognized by policies affecting hydrological conditions within the floodplain.

The next chapter will discuss the implications of these results and the welfare change results from chapter 5 in the context of water allocation decisions within the river basin and the impacts of positive values for indirect benefits in terms of the analysis presented in chapter 3 and the hydrological scenarios described in chapter 2.

Appendix 6.1

Specifically, for each farmer the expression used in calculating welfare change from (6.11) is:

$$(S_{R1})-(S_{R0}) = (P_i y^1 - C_x X_J^* - c_w(R_1)W_i^*(R_1)) - (P_i y^0 + C_x X_J^* + c_w(R_0)W_i^*(R_0)$$

We use optimal values for water input levels, evaluated at the different unit costs of pumping c_1 and c_0, assuming all other inputs remain constant. Optimal levels of output, y^1 and y^0, are then calculated for each farmer at the estimated optimal water input levels. Similarly ,we integrate (6.9) over R, deriving the following expression:

$$\frac{dS}{dR} = \left[\frac{\left(\frac{1}{2}\beta_W \phi^\gamma R^2 a - \beta_W b \phi^\gamma R - \frac{(aR-b)^{\gamma+1}}{a(\gamma+1)} \right) \gamma a}{\phi^\gamma} - \frac{\left(\frac{aR}{\phi} - \frac{b}{\phi} \right)^{(\gamma+1)}}{\gamma+1} \phi \right]_{R_0=6}^{R_1=7}$$

Evaluating (6.9) for R = [6,7], we derive the following expression:

$$\frac{dS}{dR} = \frac{1}{2} \frac{\left(49\beta_W \phi^\gamma a^2 \gamma^2 + 49\beta_W \phi^\gamma a^2 \gamma - 14\beta_W b \phi^\gamma a \gamma^2 - 14\beta_W b \phi^\gamma a \gamma - 2\left(\frac{7a-b}{\phi} \right)^{\gamma+1} \phi \phi^\gamma - 2\gamma(7a-b)^{\gamma+1} \right)}{(\gamma+1)\phi^\gamma}$$
$$- \frac{\left(18\beta_w \phi^\gamma a^2 \gamma^2 + 18\beta_w \phi^\gamma a^2 \gamma - 6\beta_W b \phi^\gamma a \gamma^2 - 6\beta_W b \phi^\gamma a \gamma - \left(\frac{6a-b}{\phi} \right)^{\gamma+1} \phi \phi^\gamma - \gamma(6a-b)^{(\gamma+1)} \right)}{(\gamma+1)\phi^\gamma}$$

where a and b are as defined in (6.12); $\gamma = \frac{1}{\beta_W - 1}$; $\phi = P_i \alpha \beta_{w_i} L^{\beta_L} B^{\beta_B} S^{\beta_S} F^{\beta_F}$

Chapter 7

Conclusions and Research Directions

7.1 Introduction

The role of quantifying indirect environmental benefits in economic terms has been a central part of this thesis. Groundwater, while being an increasingly important source of water, is surprisingly undervalued in most economies. However, groundwater markets are emerging in some parts of the world to try and counter the inefficiencies created by the lack of adequate market and policy indicators regarding groundwater use. The conjunctive use of surface and groundwater resources is also increasingly being advocated to meet rising water use requirements and improve the efficient allocation of these resources. By and large, however, water management programs and policies concerning water use within river basins continue to under appreciate the interactions between surface water and groundwater resources, and particularly in developing economies, disregard the value of groundwater resources.

7.2 Main findings and conclusions

Although valuation of environmental resources remains a somewhat contentious issue, this thesis has shown that valuing indirect benefits of environmental systems contributes both to our understanding of how indirect benefits are derived and by whom, while at the same time allowing us to carry out a more complete analysis of resource distribution within a spatially linked resource system. In river basins such as the Komadugu-Yobe river basin discussed in this thesis, such valuation exercises allow us to address two important questions, namely:

1. Should indirect environmental values be used in policy decisions concerned with water allocation within the river basin?
2. Are the benefits of maintaining downstream groundwater resources (and in general, indirect benefits of environmental functions) positive and potentially greater than the opportunity costs of lower rates of upstream diversions?

Chapter 3 addresses the first of these two questions and presents a conceptual analysis of the impact of disregarding positive benefits of groundwater resources. The analysis shows that decisions rules governing water allocation within the river basin will be significantly affected when net benefits from groundwater use are included in the maximisation objective. It is further shown that the hydrological linkages between groundwater and surface water resources play a role in determining the magnitude of benefit changes and therefore affect allocation decisions. The inclusion of indirect benefits of the wetlands, such as groundwater recharge, affects the time path of diversion of water from downstream floodplain wetlands to upstream irrigation projects. It is clear that the relative sizes of net benefits derived from resource use across the river basin will determine the initial level of diversions. Subsequently, however, the time rate of change in diversions is affected by the relative sizes of upstream and downstream benefits as well.

An initial downward shift in the optimal path of diversion is expected to occur with the inclusion of indirect benefits in the formulation of the optimization problem, resulting in an overall welfare gain for society. It has been argued that a social planner would be interested in maximising the basin wide economic value of water and would therefore consider these indirect benefits, thereby choosing the optimal lower diversion path[1]. Thus, if the magnitude of the economic value of the indirect benefits is significantly large, including them in the maximisation problem can impact both the initial level of diversion and the time path of the rate of diversion.

The second of the above two questions is addressed by chapters 5 and 6. The results of these chapters underline the results of chapter 3 which suggest that the optimal path of diversion will shift down with the inclusion of indirect benefits in the formulation of the optimization problem. Using some of the valuation techniques described in chapter 4, chapters 5 and 6 provide partial estimates of the value of the groundwater recharge function of the Hadejia-Nguru wetlands, described as an important indirect benefit provided by the wetlands. It is shown that the recharge function of the wetlands is in fact an indirect benefit of significant economic value. Given an average consumption of 232 litres per household (24 litres per capita) the recharge function has a value of 0.046 Naira per litre of water consumed by households per day. The results from this analysis suggest that the value of

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[1] In practical terms this would mean that dam construction rates would be slower. It has been assumed in chapter 3 that the flood is non-renewable because dams, once contructed, are likely to remain in place for a long time. Therefore, the model developed in chapter 3 suggests that as diversion rates fall to zero over time, all the flood will be diverted to upstream areas, either by holding water in more reservoirs or by piping it to irrigation projects upstream.

the recharge function is 1,146,588 Naira or US$ 13,029 per day for the wetlands, in terms of domestic water consumption. The average welfare change for a 1 metre change in water levels is approximately 10.62 Naira or US$ 0.12 per household.

Chapter 6 finds that the total loss associated with the 1 metre change in naturally recharged groundwater levels (resulting in a decline of groundwater levels to approximately 7 metres) is 1.04 x 10^8 Naira or US$ 1,182,737 for the wetlands, due to a decrease in groundwater levels to approximately 7 metres in depth. Disregarding wheat production, the welfare loss associated with this change in groundwater levels, amounts to 82,832 US$ for the wetlands.

The valuation techniques presented in chapters five and six provide insights into the use of water resources within the wetlands and about the impacts of hydrological changes on wetland populations and resource use patterns. The valuation studies therefore address the first of the two above noted questions and establish a significant and positive value for the indirect benefits derived from the continued existence of the Hadejia-Nguru wetlands, in terms of groundwater use.

The applications of non-market valuation techniques used in chapters 5 and 6 however also indicate that there remain certain problems associated with attempting to value environmental functions. The most important problems concern the data restrictions of using valuation techniques such as the production function and household production function approaches. While the valuations carried out in this thesis have used farm or household level data and, particularly for chapter 5, have offered examples of how to augment existing data, long-term analysis in the absence of time series data is difficult. The valuation process however reflects activities in those areas of the wetlands where the hydrological data describing the link between recharge and flood extent is strongest.

Furthermore, although hydrological data within the wetlands is considerable and may indeed be one of the more complete studies of African floodplains available, the spatial variability of recharge rates within the floodplain is difficult to monitor and such data may take a considerably long time to collect. Meanwhile, however, some assessment of the relative values of downstream and upstream activities will have to be made in order to inform policy decisions regarding the construction of projects with significant hydrological and thus, economic, impacts within the river basin.

7.2.1 Revisiting the dams

The above discussed results form a complete picture when we return to the scenarios of planned water projects detailed in chapter 2. By using the measured values of indirect benefits derived from the wetlands, we can investigate the impacts of upstream projects on floodplain benefits, including direct and indirect benefits. Table 7.1 extends the analysis of previous economic studies to include the effect of welfare losses from reduced groundwater levels[2]. Equation (3.19) in chapter 3 tells us that the change in the rate of diversion is determined by whether or not the present value benefits of the floodplain exceed the present value benefits of diverting water upstream. The finding of Barbier and Thompson (1997), summarised in chapter 2, find that none of the proposed or functioning levels of diversion (in the form of dams) result in a situation where the net benefits of the floodplain are equal to or exceeded by the net benefits of diverting water to upstream areas.

Building on Barbier and Thompson (1997), Table 7.1 uses the welfare change values from chapter 6 together with the scenarios of dam construction detailed in chapter 2. The direct benefits are described as floodplain loss in table 7.1 and the indirect benefits are described as groundwater loss. Comparing net losses from direct floodplain benefits and from upstream projects (as is done in Barbier and Thompson, 1997) essentially addresses the relationship defined by equation (3.19) in chapter 3 which states that the rate of diversion is determined by whether or not the sum of net direct benefits from the floodplain exceeds the present value net benefits from diverted water. Table 7.1 instead compares losses from direct *and indirect* downstream benefits to upstream benefits and thereby addresses the relationship defined by equation (3.31) in chapter 3 which states that the rate of diversion is determined by whether or not the sum of net direct *and indirect* benefits from the

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[2] Welfare losses for groundwater irrigated agriculture are calculated by assuming that a welfare loss of 3566 Naira per hectare would occur over an area of 19,000 hectares within the floodplain. This is used together with estimated reductions in water table elevation under each scenario (see table 2.7, chapter 2). Net present values are calculated as in Barbier and Thompson, 1997, by assuming discount rates of 8% and 12%, each over a period of 30 and 50 years. This approach does not allow for technological changes and adaptive behaviour by farmers to adjust to decreased water tables. However, given the political and economic environment of the wetlands, we do not expect that technological changes would occur in the immediate aftermath of reduced water tables.

floodplain exceeds the present value net benefits from diverted water.

The welfare changes described by groundwater loss are based on changes in water table elevation, ranging from -0.82 metres to 4.41 metres as given by Table 2.7 in chapter 2. We refrain from including welfare loss for domestic water consumption in this analysis since the economic value of upstream projects reflects agricultural production only and does not include the value of water supply to Kano city from the upstream dams. Although Table 7.1 only considers the welfare losses from agricultural production, it is clear that the addition of welfare losses from the domestic water demand analysis in chapter 5 would add to the negative impacts on downstream welfare changes.

We are confident that these changes in water table elevation would result in similar increases in pumping costs and welfare losses as were calculated in chapter 6 for a 1 metre change in water table elevation since, with the exception of scenario 5, the remaining scenarios result in changes in groundwater levels of approximately 1 metre. Scenario 5 results in a large drop in water tables and is likely to have a dramatic effect on floodplain losses. Although we calculate welfare loss for scenario 5 based on welfare losses for a 1 metre decrease in water table elevations, in actual fact, given a decrease in water tables by more than 4 metres, we expect irrigated agriculture with the use of shallow tubewells to cease altogether, without recourse to technological change to enable water abstraction from a lower water table.

The estimated floodplain losses are large as shown in Table 7.1. In addition, welfare losses due to changes in groundwater recharge range from US$ 24,865-US$ 129,783 when compared to the baseline scenario 1 and from US$ 28,807-133,725 for baseline scenario 1a. Scenario 3 yields the lowest upstream gains and has the least impact on both floodplain and groundwater benefits while scenario 5 displays a high tradeoff between upstream and downstream areas, with high irrigation gains to upstream areas and higher direct and indirect downstream losses. For all the scenarios, the percentage gains in upstream irrigation production are also very low compared with downstream losses, accounting for at the most 16.74% of downstream losses under scenario 2.

These results suggest that in terms of a higher percentage of upstream production accounting for downstream losses scenario 2 fares best under baseline scenario1, while under baseline scenario 1a, scenario 5 performs best and scenario 3 performs better than 4. However, in terms of net losses, scenario 5 would result in extremely high losses of US$ 2.0-2.1 million.

The high net losses associated with scenarios 5 and 6 suggest that in terms of dam construction along the upstream stretches of the Hadejia and the Jama'are rivers, the full development of Tiga, Challawa Gorge, small dams on the Hadejia tributaries, Kafin Zaki and the development of the Hadejia Valley Project are unjustifiable in economic terms. However, downstream losses may be reduced by regulated flooding. Scenario 3 for example allows a large flood release from Tiga Dam aimed at mitigating adverse impacts of diversion on the floodplain. The result of allowing these floods to occur during the month of August is seen by comparing the net losses under scenarios 3 and 2. Both scenarios allow for the operation of Tiga Dam supplying water to the Kano River Irrigation Project (Phase I). In addition, scenario 3 allows for regulated flooding in August to sustain the floodplain and this results in a lower supply of water to KRIP-I. Scenario 2 allows full operation of the first phase of the KRIP irrigation project. The net economic losses from scenario 2 are higher than they are for scenario 3, indicating that although gains in upstream irrigation account for a higher percentage of floodplain losses under scenario 2, scenario 3 mitigates the adverse impacts of the dam by allowing regulated flooding in the floodplain.

The mitigating impact of regulated flooding is also seen in the comparison of net losses under scenarios 5 and 6. Scenario 5 does not allow for any regulated releases to augment flooding within the wetlands whereas scenario 6 allows regulated flooding from releases from Tiga Dam in August and monthly releases from Kafin Zaki (with additional releases in August). Although scenario 6 thereby restricts the amount of water Tiga Dam can supply KRIP-I, a significant drop in net losses between scenarios 5 and 6 indicates that regulated flooding to maintain floodplain and groundwater benefits has a mitigating impact on downstream losses. Given that upstream diversions are likely to continue despite the obviously large downstream losses, the mitigating effects of regulated flooding are essential for consideration by planners.

It is clear from the above analysis that at no point do net benefits from diversions equal, let alone exceed, the sum of the value of net direct and indirect benefits. Based on our conclusions in chapter 3 therefore, the current and proposed rates of diversion in the Komadugu-Yobe river basin are clearly sub-optimal and do not maximise the economic value of water within the river basin.

This analysis has shown therefore that compared to irrigation projects in upstream areas, arid floodplains play an important role in maintaining productive capacity, both in terms of the benefits derived from floodwaters and in terms of hydrological services such as the maintenance of groundwater regimes. Although the analysis must do more in terms of fully capturing the net benefits of upstream projects, including their use for providing drinking water to urban populations, the present analysis has shown that floodplain benefits are significant. These benefits are likely to be higher still if the cultural and social values of maintaining floodplain livelihoods are accounted for since the wetlands of the Hadejia-Jama'are river basin support both local and distant communities. For instance, perhaps the most important function provided by the wetlands, groundwater recharge, supports over one million people within the floodplain and also provides water for communities in areas beyond the wetlands, while the floodplain's role in the migration strategy of Fulani pastoralists extends its importance far beyond its geographical boundaries.

Yet, these wetlands, and other similar arid floodplains which support populations well adapted to flood cycles and maintain valuable environmental resources, are threatened by water development projects which continue to regard these areas as wastelands. Diverting water away from these areas, as this analysis shows, would in fact be wasteful, rendering the society economically and culturally worse off.

Table 7.1 **Scenarios for dams and losses in floodplain and groundwater use benefits versus gains in irrigated upstream production**

		Scenario 1				Scenario 1a			
	Irrigation Benefits [1] a	Floodplain Loss [2] b	Groundwater Welfare Loss [3] c	Net Loss [(2+3)-1]	[1] as % of [2+3]	Floodplain Loss [4] b	Groundwater Welfare Loss [5]	Net Loss [4+5] - [1]	[1] as% of [4+5]
Scenario 2	682,983	-4,045,024	-34,265	-3,396,306	16.74	-5,671,973	-38,510	-5,027,500	11.96
Scenario 3	354,139	-2,558,051	-24,865	-2,228,777	13.71	-4,184,999	-28,807	-3,859,667	8.40
Scenario 4	682,963	-7,117,291	-36,691	-6,471,019	9.55	-8,744,240	-40,633	-8,101,910	7.77
Scenario 5	3,124,015	-23,377,302	-129,783	-20,383,070	13.29	-24,004,251	-133,725	-21,013,961	12.94
Scenario 6	556,505	-15,432,952	-36,691	-14,913,138	3.60	-17,059,901	-40,633	-16,544,029	3.25

Notes:

a Based on the mean of the net present values of per hectare production benefits for the Kano River Irrigation Project Phase I applied to the gains in total irrigated area (Source: Barbier and Thompson, 1997)

b Based on the mean of the net present values of total benefits for the Hadejia-Jama'are floodplain averaged over the actual peak flood extent for the wetlands of 112,817 ha in 1989/1990 and applied to the differences in mean peak flood extent (Source: Barbier and Thompson, 1997)

c Based on the mean of the net present values of welfare loss from a 1 metre reduction in well levels in the Hadejia-Nguru wetlands (using discount rates of 5% and 8% with time horizons of 30 and 50 years for each discount rate), averaged over an area of 19,000 ha of land within the wetlands which could support groundwater irrigated agriculture. A welfare loss of Naira 3,566 per ha is used for all the scenarios.

Scenarios 1 and 1a represent the production of naturalised discharge data for the Hadejia River under two alternative discharge assumptions.
Scenario 2 investigates the impacts of extending the KRIP-I to its planned full extent of 22,000 hectares. This scenario does not allow for any downstream releases.
Scenario 3 simulates the impacts of limiting irrigation water to KRIP-I to the existing 14,000 hectares and releasing a regulated flood in August.
Scenario 4 adds the impact of Challawa Gorge and year-round release of water for use along the Hadejia River.
Scenario 5 simulates the full development of the four water resource schemes. There are no regulated releases except from Challawa Gorge Dam which releases a relatively stable volume of water for use on the Hadejia Valley Project.
Scenario 6 allows for the full range of the scheme, in addition to maintaining a regulated flooding regime for the floodplain. This scenario envisages the construction of Kafin Zaki but no diversions for formal irrigation.

7.3 Future research directions

This thesis provides an indication of the value of groundwater resources and the associated impacts of maintaining these resources on upstream activities. A number of interesting questions remain however. As shown in chapter 3, the undervaluation of wetland resources results in the intertemporal misallocation of resources. The valuation of the recharge function contributes to existing information regarding the economic value of the Hadejia-Jama'are wetlands and is therefore of relevance to wetland and water use policies that could affect the present flow of environmental services from these wetlands. It is not however a measure of the total value of the environmental functions performed by the wetlands and neither can it fully capture the value of the recharge function itself. In fact, the value of the groundwater recharge may be much higher than that reported by this study, given that without the presence of the groundwater resources many villages might have to relocate.

The main research interest lies in extending the use of some of the techniques used in this thesis to carry out dynamic valuation studies. Most value estimates of non-market resources in developing and industrialised countries are point estimates and there is little analysis done on how these benefits may change over time given changing preferences, population growth and the discovery and use of new resources and technologies. Predicting future benefits is greatly limited by the general lack of time series data but the use of pooled stated and revealed preference data as shown in this thesis offers the possibility of generating quasi-time series data on changing preferences and may be developed further to allow the prediction of future benefits with more accuracy than is presently possible.

Furthermore, the indirect benefits of groundwater recharge have been isolated for study in this thesis. However, most wetlands are multi-functional and therefore, multi-benefit resources. The interaction between direct and indirect benefits and the trade-offs between these benefits is an area where relatively little research has been carried out. Yet, competition for water resources and their spatial and temporal distribution, may occur not only between upstream and downstream areas but between the various attributes and functions of wetland resources as well. In addition, while the ecological value of surface water, in maintaining groundwater recharge, has been discussed in this thesis, the contribution of groundwater to ecological services has not been discussed. Groundwater processes affect the productivity of plant and animal species and may maintain base stream flow and the wetlands as well. Changes in groundwater quantity and quality may therefore impact the biodiversity of both land and water resources. These indirect benefits may be of significant importance to populations dependent on these resources.

Hence, the sustainability of the present trend towards increased abstraction of groundwater is also questionable. In areas such as the Hadejia-Nguru wetlands, the lack of well-defined and enforceable rights to extract groundwater makes it a potential open-access resource. While the competition for groundwater resources for irrigated agriculture and domestic water consumption is relatively insignificant at the present moment, this could, in the future, have potentially important implications regarding resource use and the imputed value of the recharge function. Research into the optimal use of groundwater resources and the conjunctive use of surface and groundwater resources to maximise the economic value of water resources within the river basin is therefore required.

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Appendices

APPENDIX A : HOUSEHOLD WATER USE SURVEY

The following version of the household water use survey was translated into Hausa with necessary changes in spacing and format to facilitate implementation. The style used in greetings respondents was changed in accordance with cultural requirements although the content of the introductory paragraph was maintained.

INTRODUCTION (to be spoken by the enumerator to the respondent)

My name is ____________. I am working with the HNWCP and we are carrying out a survey to understand the use and demand for water in this area. We are interested in understanding the importance of groundwater for your household and we would like to ask you a few questions about your use of water from wells. Your answers will help us understand the water situation in this area but they will not be used for any other purpose. We are not working for the government. There are no right or wrong answers to the questions we would like to ask you.

Will you allow us to interview you?

Yes ☐
No ☐

If the respondent answers no, thank him/her and stop the interview.
If the respondent answers yes the enumerator should continue to section A.

ENUMERATOR PLEASE RECORD :

1. Respondent's name ____________
2. Village name ____________
3. How many people are listening to the interview (do not count yourself and the respondent)? __________

SECTION A. BASIC OCCUPATIONAL/DEMOGRAPHIC DATA

A1. Which ethnic group do you belong to?

____

A2. How old are you?

16 - 20 years ☐
21-25 years ☐
26-35 years ☐
36 and over ☐

A3. Have you attended school?

Yes ☐ (go to a4)
No ☐

A4. Which level of school did you attend?

Koranic ☐

Primary ☐
Secondary ☐

A5. Are you the head of your household?
Yes ☐
No ☐

SECTION B. WATER USE

I would now like to ask you some questions about your water supply and use.

B1. What are the sources of water your household uses?

	Rainy Season	Dry Season
Well/Tubewell	☐	☐
River	☐	☐
Fadamas/ponds	☐	☐
Other (specify)	☐	☐ ________

B2. What do you use the water from the well or tubewell for?
Drinking ☐
Cooking ☐
Washing ☐
Cleaning ☐
Watering domestic livestock ☐
house building ☐
Other (specify) ____________

B3. During which season do you use more water from the well or tubewell?
Dry ☐ (go to b4)
Wet ☐
Same quantity used during both seasons ☐

B4. For which purposes do you use more water in the dry season?

Drinking ☐
Cooking ☐
Washing ☐
Cleaning ☐
Watering domestic livestock ☐
house building ☐
Other (specify) ____________

The enumerator should now ask the respondent if he/she can measure the container (s) used by the household to store water.

B5. How many water container(s) does the respondent have __________

B6. How many tins can each container take? __________

B7. Number of times the containers are filled per day __________

ENUMERATOR: For households which collect water ask B8:

B8. When do you usually fetch water?
morning
evening
night
other

ENUMERATOR : For households which purchase water ask B9:

B9. Why do you purchase water instead of collecting it?

B10. Total daily demand for water (B5)*(B6) *(B7) *18 litres =

ENUMERATOR: NOW ASK THE RESPONDENT TO SHOW YOU THE WELL THAT THEY USUALLY COLLECT WATER FROM (FOR PURCHASE ONLY HOUSEHOLDS ASK THEM WHICH WELL THEY WOULD PREFER TO GET THEIR WATER FROM) AND MEASURE THE TIME TAKEN TO WALK FROM THE RESPONDENT'S HOUSE TO THAT WELL AND THE DISTANCE.

B11. Distance from house to well and back _______feet

B12. Time taken to walk to the well, fill one sanda and come back to the house

____________minutes

[NOTE : ENUMERATOR WILL ASK THE RESPONDENT TO WALK TO THE WELL AND FILL ONE TIN OF WATER. THE TIME TAKEN FOR DOING THIS WILL BE MULTIPLIED BY 2 TO GET THE TIME TAKEN TO FETCH 1 SANDA (TWO TINS) OF WATER FROM THE WELL]

Enumerator: Note down well number ________

C. CONTINGENT BEHAVIOUR SECTION

ENUMERATOR: Is household
purchase only ☐
collect only ☐
collect and purchase ☐

FOR PURCHASE ONLY HOUSEHOLDS

ENUMERATOR: INTRODUCTION

I AM NOW GOING TO ASK YOU SOME QUESTIONS ABOUT YOUR DECISION TO BUY WATER OR COLLECT WATER. THESE QUESTIONS ARE BEING ASKED SO THAT WE CAN UNDERSTAND THE WATER SITUATION IN YOUR VILLAGE.

FROM THE EARLIER QUESTIONS YOU AND I KNOW THAT IT TAKES YOU [B12] MINUTES TO COLLECT 1 SANDA (TWO TINS) OF WATER FROM THE WELL. WE ALSO KNOW THAT YOUR HOUSEHOLD NEEDS [B10] TINS OF WATER PER DAY.

[ENUMERATOR WILL USE ANSWERS FROM SECTION B FOR THE ABOVE]

C1. How much are you presently paying for 1 sanda (two tins) of water?

________Naira per sanda

C2. Supposing the price of water were to increase in the following way (present scenarios in succession), how much water would you purchase?

Price per Sanda (Naira)	Collection time per trip (mins)	Are you still willing to Purchase some or all water demanded? (yes or no)	Quantity demanded (number of sandas)	
			Purchased	Collected
[C1]	[B12]	Yes	[B10]	0
[C1+2]	[B12]			
etc.	[B12]			
	[B12]			
	[B12]			
*	[B12]			

* ASK THE RESPONDENT AT WHAT PRICE HE WILL SWITCH TO COLLECTING ALL HIS WATER. WHEN THE RESPONDENT SAYS THAT HE WILL SWITCH TO **COLLECTING ALL** THE WATER DEMANDED BY THE HOUSEHOLD GO TO C3

.

Note: For example, if the starting price was 2 Naira, the next price offered would be 4 Naira, then 6 Naira and then 12 Naira

C3. Supposing the price remains at the present price [C1], and the time taken for collection decreases (present the following scenarios): how much water are you going to buy?

Price per sanda (Naira)	Collection time (per trip)	Are you still going to purchase some or all water demanded? (yes or no)	Quantity demanded (number of sandas)	
			Purchased	Collected
[C1]	[B12] mins	yes	[B10]	0
[C1]	7 mins			
[C1]	5 mins			
[C1]	*			

* ASK THE RESPONDENT WHAT IS THE LEAST AMOUNT OF TIME HE IS WILLING TO SPEND PER TRIP TO COLLECT ALL HIS WATER. WHEN THE HOUSEHOLD CHOOSES TO **COLLECT ALL** ITS WATER GO TO C4.

C4. If the price is [C1] Naira per sanda and collection time is ** mins per trip how much water will you collect?

Price	Collection time	Quantity demanded		
		Are you going to collect the same amount you were purchasing? (state initial amount)	More? (how much more)	Less? (how much less)
[C1]	** mins per trip			

** SWITCHING COLLECTION TIME FROM C3

FOR COLLECT ONLY HOUSEHOLDS:

ENUMERATOR : INTRODUCTION

I AM NOW GOING TO ASK YOU SOME QUESTIONS ABOUT YOUR DECISION TO BUY WATER OR COLLECT WATER. THESE QUESTIONS ARE BEING ASKED SO THAT WE CAN UNDERSTAND THE WATER SITUATION IN YOUR VILLAGE.

FROM THE EARLIER QUESTIONS YOU AND I KNOW THAT IT TAKES YOU [B12] MINUTES TO COLLECT 1 SANDA (TWO TINS) OF WATER FROM THE WELL. WE ALSO KNOW THAT YOUR HOUSEHOLD NEEDS [B10] TINS OF WATER PER DAY.

[ENUMERATOR WILL USE ANSWERS FROM SECTION B FOR THE ABOVE]

The price of having one sanda delivered to your house is around 5 Naira.

C1. Supposing the price is the same as the present, ie., 5 Naira, but the time taken for collection changes. (present the following scenarios) are you still going to collect water?

Price per Sanda (Naira)	Collection time (per trip)	Still willing to collect some or all water demanded? (yes or no)	Quantity demanded (number of sandas)	
			Purchased	Collected
5	[B12] mins			
5	20 mins			
5	30 mins			
5	*			

* ASK THE RESPONDENT WHAT IS THE MAXIMUM NUMBER OF MINUTES HE IS WILLING TO SPEND PER TRIP BEFORE HE SWITCHES TO PURCHASING ALL HIS WATER. WHEN THE RESPONDENT SWITCHES TO PURCHASING WATER ASK C2:

C2. If the collection time per trip is ** mins and price per sanda is 5 Naira, how much water are you going to buy?

Price	Collection time	Quantity demanded		
		Same as you were earlier collecting? (state initial amount)	More? (how much more)	Less? (how much less)
5	**mins per trip			

** COLLECTION TIME FROM C1

C3. Supposing the price per sanda decreases and collection time is [B12] per trip, (state scenarios) are you still willing to collect some or all of the water?

Price per Sanda (Naira)	Collection time (per trip)	Still willing to collect some or all water demanded? (yes or no)	Quantity demanded (number of sandas)	
			Purchased	Collected
5	[B12]			
3	[B12]			
2	[B12]			
*	[B12]			

* ASK THE RESPONDENT WHAT IS THE MAXIMUM HE IS WILLING TO PAY BEFORE HE WILL SWITCH TO BUYING ALL HIS WATER. WHEN THE RESPONDENT SWITCHES TO PURCHASING ALL THE WATER DEMANDED ASK C4:

C4. If the price of 1 sanda is ** Naira and collection time is [B12] mins, how much water are you going to buy?

Price	Collection time	Quantity demanded		
		Same amount as you were earlier collecting? (state initial amount)	More? (how much more)	Less? (how much less)
**	[B12] mins per trip			

**SWITCHING PRICE FROM C3

FOR COLLECT AND PURCHASE HOUSEHOLDS:

ENUMERATOR: INTRODUCTION

I AM NOW GOING TO ASK YOU SOME QUESTIONS ABOUT YOUR DECISION TO BUY WATER OR COLLECT WATER. THESE QUESTIONS ARE BEING ASKED SO THAT WE CAN UNDERSTAND THE WATER SITUATION IN YOUR VILLAGE. FROM THE EARLIER QUESTIONS YOU AND I KNOW THAT IT TAKES YOU [B12] MINUTES TO COLLECT 1 SANDA (TWO TINS) OF WATER FROM THE WELL. WE ALSO KNOW THAT YOUR HOUSEHOLD NEEDS [B10] TINS OF WATER PER DAY.

[ENUMERATOR WILL USE ANSWERS FROM SECTION B FOR THE ABOVE]

C1. How much are you presently paying for 1 sanda (two tins) of water?

________Naira per sanda

C2. If the price per sanda decreases (present the following scenarios) and collection time per trip is [B12] mins, are you going to collect any water?

Price per Sanda (Naira)	Collection time (per trip)	Still willing to collect some or all water demanded? (yes or no)	Quantity demanded (number of sandas)	
			Purchased	Collected
[C1]	[B12] mins			
3	[B12] mins			
2	[B12]			
*	[B12]			

* ASK THE RESPONDENT WHAT IS THE MAXIMUM HE IS WILLING TO PAY PER SANDA BEFORE HE SWITCHES TO PURCHASING **ALL** HIS WATER. WHEN THE RESPONDENT SWITCHES TO PURCHASING **ALL** ITS WATER ASK C3:

C3. If the price of 1 sanda is ** Naira, and collection time per trip is [B12] mins, how much water are you going to buy?

Price	Collection time	Quantity demanded		
		Same as you were earlier buying and collecting? (state initial amount)	More? (how much more)	Less? (how much less)
**	[B12] mins per trip			

** SWITCHING PRICE FROM C2

C4. If the price remains at [C1] Naira and the collection time changes (present scenarios) are you going to collect any water?

Price per Sanda (Naira)	Collection time (per trip)	Still willing to collect some or all water demanded? (yes or no)	Quantity demanded (number of sandas)	
			Purchased	Collected
[C1]	[B12]			
[C1]	20 mins			
[C1]	30 mins			
[C1]	*			

* ASK THE RESPONDENT WHAT IS THE MAXIMUM NUMBER OF MINUTES HE IS WILLING TO SPEND PER TRIP BEFORE HE SWITCHES TO PURCHASING ALL HIS WATER. WHEN THE RESPONDENT SWITCHES TO PURCHASING ALL HIS WATER ASK C4:

C5. So, if the price of 1 sanda is [C1] Naira and the collection time is ** mins per trip, how much water are you going to purchase?

Price	Collection time (mins per trip)	Quantity demanded		
		Same as you were earlier buying and collecting? (state initial amount)	More? (how much more)	Less? (how much less)
[C1]	**			

** SWITCHING COLLECTION TIME FROM C4

C6. Now supposing the price for 1 sanda increases (present scenarios) and collection time is [B12] mins, are you going to collect water?

Price per Sanda (Naira)	Collection time (per trip)	Still willing to collect some or all water demanded? (yes or no)	Quantity demanded (number of sandas)	
			Purchased	Collected
[C1]	[B12] mins	Yes		
10	[B12] mins			
*	[B12] mins			

* ASK THE RESPONDENT WHAT IS THE MAXIMUM HE IS WILLING TO PAY PER SANDA BEFORE HE SWITCHES TO COLLECTING **ALL** HIS WATER. WHEN THE RESPONDENT SWITCHES TO COLLECTING **ALL** ITS WATER ASK C7:

C7. If the price of 1 sanda is ** Naira and the collection time per trip is [B12] mins, how much water will you collect?

Price	Collection time	Quantity demanded		
		Same as you were earlier buying and collecting? (state initial amount)	More? (how much more)	Less? (how much less)
**	[B12] mins per trip			

**SWITCHING PRICE FROM C6

C8. If the price of 1 sanda remains at [C1] Naira and collection time per trip decreases (present scenarios), are you going to purchase any water?

Price per Sanda (Naira)	Collection time (mins per trip)	Still willing to purchase some or all water demanded? (yes or no)	Quantity demanded (number of sandas)	
			Purchased	Collected
[C1]	[B12] mins			
[C1]	7			
[C1]	5			
[C1]	*			

*IF HOUSEHOLD SWITCHES TO COLLECTING ALL ITS WATER ASK C9:

C9. If the price of 1 sanda is [C1] Naira and collection time is ** mins per trip, how much water will you collect?

Price	Collection time	Quantity demanded		
		Same as you were earlier buying and collecting? (state initial amount)	More? (how much more)	Less? (how much less)
[C1]	** mins per trip			

** SWITCHING TIME FROM C8

SECTION D: SOCIOECONOMIC CHARACTERISTICS

D1. How many people are there in your household?

Adults (above 16 years of age?) ________
Number of men ________
Number of women ________
Children ________

D2. How many parcels of land do you own?

1 ☐
2-4 ☐
5 or more ☐

D3. Do you have livestock?

yes ☐ (go to d4)
no ☐ (go to d5)

D4. How many?

	1-5	6-10	11-20	>20
Cattle	☐	☐	☐	☐
Goats/sheep	☐	☐	☐	☐
Poultry	☐	☐	☐	☐
Other (specify)	☐	☐	☐	☐

D5. Do you practice any of the following occupations:

Farming ☐
Fishing ☐
Mat making ☐
Local trading ☐
Other (specify) ☐ ______________

D6. What are the sources of income for the household? (rank)

Farming	☐
Fishing	☐
labouror	☐
trading	☐
Remittances/gifts	☐
Other	☐

D7. What is the household's total income per month?

500-1000 Naira/month	☐
1000-1500 Naira/month	☐
1500-2000 Naira/month	☐
2000-4000 Naira/month	☐
4000-6000 Naira/month	☐
6000 and more	☐

Seasonal income: Dry (rani) Hot (bazara) Wet (damina) Cold (kaka)

D8. What are the main items of expenditure for the household?

Food	☐
Agricultural inputs	☐
Clothing	☐
Water	☐
Fuelwood	☐
Other	☐

D9. How much do you spend on these items per month?

Food	_____
Agricultural inputs	_____
Water	_____
Clothing (per year)	_____
Fuelwood	_____
Other	_____

ENUMERATOR : Please thank the respondent for his/her time and conclude the interview.

Total time taken for the interview: ______________

ga/hhs/mar96

APPENDIX B: AGRICULTURAL SURVEY

The following version of the agricultural survey was translated into Hausa with necessary changes in spacing and format to facilitate implementation. The style used in greetings respondents was changed in accordance with cultural requirements although the content of the introductory paragraph was maintained.

Enumerator's name ____________________

Introduction (to be spoken by the enumerator to the respondent)

My name is ___________. I am working with the HNWCP and we are carrying out a survey to understand the use and demand for water in this area. We are interested in understanding the importance of groundwater for irrigation and we would like to ask you a few questions about your use of water from tubewells. Your answers will help us understand the water situation in this area but they will not be used for any other purpose. We are not working for the Government. There are no right or wrong answers to the questions we would like to ask you.

Will you allow us to interview you?
Yes ☐
No ☐

Enumerator: If respondent answers yes, continue to the next question, if no, thank the respondent and continue to next interview.

Enumerator :
1. How many people are listening at the interview? _________

SECTION A. Basic demographic data

a1. What is the name of the village you live in? ________________

a2. Which ethnic group do you belong to?
    Hausa ☐
    Kanuri ☐
    Fulani ☐
    Other (write down name) _________________

a3. How old are you?
    16 -20 years ☐
    21-25 years ☐
    26-35 years ☐
    36 -40 years ☐
    40 and over ☐

a4. Have you attended school?

Yes ☐ (Go to a5)
No ☐ (Go to a6)

a5. Which level of school did you attend?

Koranic	☐
Primary	☐
Secondary	☐
Higher institution	☐

a6. Are you the head of your household?

Yes ☐
No ☐ (if not, note down relationship to head of household)

B. Land Holdings

b1. How many parcels of land do you own?

one ☐
two ☐
three ☐
four ☐
other (specify) ________

b2. What is the **total** size of your land holding?

0-1 acre	☐
2-5 acres	☐
6-10 acres	☐
10 or more	☐

Note: this was later confirmed by measurements made by the survey team

b3. Do you practice mixed cropping?

yes ☐
no ☐

b3. What do you produce on your land?

Pepper	☐
Onions	☐
Wheat	☐
Maize	☐
Eggplant	☐
Tomatoes	☐
Cashews	☐
Fruit trees	☐
Other (specify)	☐ ________________________________

b4. What is being grown on this land at present?

____

C. Pump details

c1. What type of pump are you using?

____

Note : Enumerator should write down any other information available about the size and speed of the pump.

c2. What is the depth of the borehole?
1-1.5 pipes ☐
2-2.5 pipes ☐
3 pipes ☐
other ____________

c3. Do you own this pump or is it hired?
Owned ☐ (go to c4)
Hired ☐ (go to c7)

c4. How much did you spend on buying the pump?

____________Naira

c5. Did you receive any subsidies to purchase the pump?
Yes ☐(go to c6)
No ☐(go to c8)

c6. How much subsidy did you receive?

__________Naira

c7. How much does it cost you to hire the pump?

____________Naira per hour (if they only know the rate per day then note N/day)

c8. Who drilled the borehole?

____________ (name of organization)

c9. How much did you spend on drilling the borehole?

____________Naira

c10. Did you receive any assistance or subsidies for the drilling?
Yes ☐ (go to c11)
No ☐ (go to section D)

c11. Who provided the subsidy?

_________ (name of the organization providing assistance)

c12. How much subsidy did you receive for the drilling?

_________Naira

D. Irrigation

d1. How often do you irrigate the crop?

Every day ☐
Every 2 days ☐
Every 5 days ☐
Every week (7 days) ☐
Every 10 days ☐
Other (specify) ☐

d2. How many hours do you irrigate per day?

_____________hours/day

d3.What is the total number of days you will irrigate this crop over one season?

_____________days/season

Enumerator: if more than one crop is being grown and they receive irrigation for different number of days please note down total number of irrigation days for each crop.

____________days/season

____________days/season

E. Other inputs

e1. How much did you use of the following inputs:

crop_______

	per acre	total
Seeds		
Seedlings		
Fertilizer		

crop_______

	per acre	total
Seeds		
Seedlings		
Fertilizer		

e2. How many beds of seedlings did you use for this farm this season?

crop_______ seedling beds__________

crop_______ seedling beds__________

e3. How much will you spend this season on the following inputs:

crop _______

Seeds	________Naira
Seedlings	________Naira
Fertilizer	________Naira
Fuel/Petrol	________Naira

crop_______

Seeds	________Naira
Seedlings	________Naira
Fertilizer	________Naira
Fuel/Petrol	________Naira

Enumerator: if farmer only knows total amount spent for all crops then note down that the figures are for input costs for all the crops.

e4. Do you receive any subsidies/assistance for these inputs? If yes, how much?

crop_______

Seeds/Seedlings	________Naira
Fertilizer	________Naira
Fuel/Petrol	________Naira

crop_______

Seeds/Seedlings	________Naira
Fertilizer	________Naira
Fuel/Petrol	________Naira

e5. How many people do you expect to employ this season to work on your farm?

________men ________women

e6. How many days do you expect to employ them for?

________men ________women

e7. How much do you expect to pay for labour?

____________per day (men)

____________per day (women)

____________total labour costs for this season

F. Income

f1. How much do you expect to harvest this season?

crop _______sacks________

crop________sacks________

If more than one crop is being grown on the farm the enumerator should note down the expected harvest from each crop

f2. When do you expect to sell your crop?

After harvest ☐
Off season ☐

f3. How much do you expect to earn per sack?

After harvest________Naira/sack
Off-season ________Naira/sack

(If more than one crop is being grown on the farm the enumerator should note down the expected earning per sack for each crop)

The enumerator should now thank the respondent for his/her time and conclude the interview.