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Optimal management of the flood risks of floodplain development

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ABSTRACT

This paper presents a model of the problem on floodplain development, exploring the conditions that are both necessary and sufficient for development to be optimal. The model is calibrated for a particular catchment, the Ouse catchment in the United Kingdom, and is used both to estimate the expected impact of floodplain development and to explore the impact of alternative policy instruments. We find that the use of price-based instruments that signal the expected flood damage cost of floodplain development has the potential to lead to outcomes close to the social optimum. The finding is robust to two types of uncertainty: model error about the relation between precipitation and flood-risk and measurement error about the benefits of developed floodplains.

1. Introduction

Flood risks are defined as the probability of flooding multiplied by the damage expected if flooding occurs. In the last three decades, flood risks in many European countries have increased sharply (Black and Burns, 2002; Munich Re, 2005). While this may reflect changes in the probability of inundation due to changing climatic conditions (te Linde et al., 2010), it is largely the result of the development of floodplains for commercial, industrial or residential use (Holway and Burby, 1990; Burby, 2001; de Moel and Aerts, 2011). Floodplains are low lands adjoining a channel, river, stream or watercourse, including riverine or riparian wetlands (Mitsch and Gosselink, 2000; Smith and Smith, 2001). It is expected that they will be inundated by floodwater over some timescale (Bedient and Huber, 2002). In fact, they are frequently defined by the probability that they will be inundated in any given year. Their development affects both the expected damage if flooding occurs and the likelihood that flooding will occur. In lowland river reaches floods can be dangerous if floodplains are intensively developed (De Martino et al., 2012).

The move toward risk-based flood management and away from flood protection standards has seen the development of a range of flood risk models (Messner et al., 2007). Most distinguish between the following elements: the flood hazard measured by inundation depth, the exposure associated with different land uses, the value at risk in each land use (the value of assets put at risk by flooding), and the relation between inundation depth and damage (de Moel and Aerts, 2011). The last three relate to the expected damage if flooding occurs. Development of floodplains increases the value of risk from flooding, while changes in land structure and land cover affect both the likelihood of inundation, and the damage expected at different inundation levels (Tockner and Stanford, 2002; Hall et al., 2005). Although these elements of flood risk are not independent of each other, they are typically the result of decisions taken by agents who do not consider the effect of their actions on others. In this paper we consider the socially optimal management of flood risk, given that the private activities involved in floodplain development have interdependent impacts on the value at risk, the probability of flooding, and the damage expected if flooding occurs.

Undeveloped floodplains yield a number of environmental, ecological and hydrological services, including water quality enhancement through their role as nutrient sinks for runoff from uplands (van den Bergh et al., 2004), habitat provision (Emerton et al., 1998; Mitsch and Gosselink, 2000; Thonon and Klok, 2007), the mitigation of flood risk through the regulation of water discharge volume (Ogawa and Male, 1986; Turner, 1991; Crooks et al., 2001; De Martino et al., 2012) and ground water recharge (Dister et al., 1990; Gren et al., 1995). The impact of development on these services is generally 'external' to the market. That is, the effect of development on the flood control functions of floodplains is neglected in the market transactions involved in development decisions. Developers have little incentive to take account of the impact of their actions on the flood risks faced by others at the same location or at downstream locations on the river. The result is that floodplains may be 'overdeveloped' relative to the social optimum.

Historically, flood risks have been managed through the regulated flood protection. The most common solutions included regulatory restrictions on either the level or type of development permitted in floodplains (zoning), and hard engineering of watercourses to contain floodwaters through bunds, levees, dykes, weirs or embankments.

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Economists generally approach the problem of externality in a different way, focusing instead on the rights to use, control and exchange resources (Alchian and Demsetz, 1973; Bromley, 1991). The economic solution to externalities whose effects impact particular people frequently lies in the assignment of property rights to those effects. The externality can then be internalized through transactions between the right-holders. The economic solution to externalities whose effects are in the nature of public goods or bads (affecting all people) frequently lies in the use of incentives — user fees or charges that reflect the social cost of the externality.

In recent years a growing body of literature has promoted the development of economic incentives to support socially efficient watershed management in cases where private decisions generate significant upstream-downstream externalities. Preeminent among these instruments are payments for ecosystem services (Engel et al., 2008; Wunder et al., 2008; Arriagada and Perrings, 2011; Kinzig et al., 2011). There has been some interest in the development of tradable risk permits (Chang, 2008; Chang and Leentvaar, 2008), but economic instruments of this sort have not generally been applied to the management of flood risks. In this paper we consider the potential for economic instruments in managing the flood risk externalities of floodplain development. We do this in the context of a model of floodplain externalities calibrated on data on a particular river basin in the UK Ouse/Humber system—one of two areas (>10 hectads) in the UK where more than 50% of the land area lies in indicative floodplains (Hall et al., 2005). The Ouse catchment is located in Yorkshire, which is in fact delineated by the River Ouse and tributaries. The river system experiences regular flood events that are related to land use change both in the floodplains and elsewhere in the catchment. The catchment area is about 424,279 ha.

Using a numerical, discrete time dynamic model of the principal hydrological, ecological and economic processes involved, we evaluate the efficiency (and cost effectiveness) of economic instruments designed to internalize the flood risk externalities of floodplain development (and to reduce the cost of meeting floodplain development or restoration targets). Since payments for ecosystem services are a particular example of a broader class of economic instruments, we consider, in addition, a system of land use taxes, and two types of marketable permits. These are compared with the direct control of floodplain development through zoning.

2. A generic model of floodplain development

The basic unit of analysis in the model is the area of floodplain developed in each of a number of sub-basins. The extent of the developed floodplain in the ith of n sub-basins at time t is denoted by X_t^i. These are the state variables of the problem. Sub-basin index numbers follow the direction of flow: i.e. i is in ascending order from upstream to downstream. Private development/restoration of the floodplain in the ith sub-basin at time t is given by y_t^i, which can be indirectly affected by economic incentive mechanisms and directly by zoning regulations. The dynamics of floodplain development in the ith sub-basin may accordingly be described by the equation:

$$X_{t+1}^i - X_t^i = y_t^i. \tag{1}$$

The flood risk associated with the level of floodplain development in the ith sub-basin at time t, given prevailing climatic conditions, R_t (an independent and identically distributed random variable) is denoted:

$$D_t^i = D^i\left(X_t^i, X_t^{i+1}, \ldots, X_t^n, R_t\right). \tag{2}$$

It comprises the expected damage from inundation in sub-basin i and in all sub-basins affected by sub-basin i. This is conditioned by the level of floodplain development sub-basins both above and below the ith sub-basin. Upstream development in $X_t^1, \ldots, X_t^{i-1}$ affects the probability of flooding in ith and downstream sub-basins. Downstream development in $X_t^{i+1}, \ldots, X_t^n$, affects both the probability and the value of flood events downstream of the ith sub-basin. Floodplain development in sub-basins upstream of i is assumed to have a negative impact on flood risk in i due to the loss of floodplain capacity in those sub-basins. Similarly, floodplain development in i is assumed to have a negative impact on flood risk in sub-basins downstream of i for the same reason.

The privately optimal rate of floodplain development in sub-basin i is the solution to a problem of the form:

$$\max_{y_t^i} E\left\{\sum_{t=0}^{T-1} \rho^t \pi^i\left(y^i, X_t^i, D_t^i, R_t\right) + \rho^T \pi^i\left(X_T^i\right)\right\} \tag{3}$$

in which $\rho = \frac{1}{1+\delta}$ is a discount factor, δ being the discount rate (a proxy for the rate of return on alternative assets). Eq. (3) is optimized subject to Eq. (1) and initial conditions X_0^i. Developers choose a development trajectory so as to maximize the discounted profits to be had from floodplain development during their planning horizon, denoted by T, together with the “scrap value” of that development at the end of the horizon. Note that the “scrap value” is in fact the value of the developed floodplain for all time beyond T. Using the Lagrangian function for the certainty-equivalent of the problem in Eq. (3), the first order necessary conditions for the floodplain development trajectory to be privately optimal include:

$$\begin{aligned} L_{y_t^i} &= \rho^t\left[\frac{d\pi^i}{dy^i} + \rho\lambda_{t+1}^i\right] = 0 \\ L_{X_t^i} &= \left[\frac{d\pi^i}{dX_t^i} + \frac{d\pi^i}{dD_t^i}\frac{dD_t^i}{dX_t^i} + \rho\lambda_{t+1}^i - \lambda_t^i\right] = 0 \\ L_{\rho\lambda_{t+1}^i} &= \rho^t\left[X_t^i + y_t^i - X_{t+1}^i\right] = 0 \end{aligned} \tag{4}$$

and

$$\begin{aligned} \lambda_T^i &= \pi^i\left(X_T^i\right) \\ X_0^i &= X^i(0). \end{aligned} \tag{5}$$

From the conditions on y_t^i and X_t^i in Eq. (4) it can be shown that in the steady state

$$\delta = \left[\frac{\frac{d\pi^i}{dX_t^i} - \frac{d\pi^i}{dD_t^i}\frac{dD_t^i}{dX_t^i}}{\frac{d\pi^i}{dy^i}}\right] \tag{6}$$

i.e. that private developers will invest up to the point at which the marginal return on floodplain development is equal to the return on alternative assets. They will take account of the impact of floodplain development on flood risks, $d D_t^i / d X_t^i$, but only to the extent that flood risks affect their profits, $d\pi^i / d D_t^i$. That is, private developers will neglect the impact of floodplain development in sub-basin i on flood risks in sub-basins elsewhere in the system.

We now consider the social problem this raises. We suppose that there exists an authority assumed to have responsibility for managing the floodplain (which we arbitrarily call the floodplain authority). In the UK in general, and in the area explored in this paper in particular, the responsible authority is the Environment Agency (Environment Agency, 2008). The formal problem for the floodplain authority is to maximize the expected social utility of floodplain development in all sub-basins and over the authority's planning horizon. For convenience we suppose this to be the same as the private developers' horizon, although this need not be the case. The problem has the following form:

$$\max_{y_t^i} E\left\{\sum_{t=0}^{T-1}\sum_{i=1}^{n}\rho^t U\left[\pi^i\left(y^i, X_t^i, D_t^i, R_t\right)\right] + \rho^T U\left[\pi^i\left(X_T^i\right)\right]\right\}. \quad (7)$$

Eq. (7) describes the expected social utility of the net benefits of floodplain development, during the planning period plus the expected social utility of the state of the system at the end of the planning period. The inclusion of all members of the community means that this problem includes the wider effects of private floodplain development on flood risk everywhere. The utility function, $U(\cdot)$, is assumed to be strictly concave and twice differentiable in income: i.e. $U_\pi = \frac{dU}{d\pi} > 0$, $U_{\pi\pi} = \frac{d^2U}{d\pi^2} < 0$.

Solving this problem in the same manner yields the following equivalent to Eq. (6):

$$\delta = \left[\frac{\frac{dU}{d\pi^i}\left(\frac{d\pi^i}{dX_t{}^i} - \frac{d\pi^i}{dD_t{}^i}\frac{dD_t{}^i}{dX_t{}^i}\right) + \sum_j \frac{dU}{d\pi^j}\frac{d\pi^j}{dD_t{}^j}\frac{dD_t{}^j}{dX_t{}^i}}{\frac{dU}{d\pi^i}\left(\frac{d\pi^i}{dy^i}\right)}\right]. \quad (8)$$

In addition to the terms appearing in the solution to the private problem of floodplain development, this includes the impact of development in sub-basin i on the wellbeing of people in downstream sub-basins: $\sum_{j>i}\frac{dU}{d\pi^j}\frac{d\pi^j}{dD_t^j}\frac{dD_t^j}{dX_t^i}$. Investment in floodplains should increase up to the point at which the marginal return on development net of social flood risk is equal to the return on alternative assets.

In principle, there are many instruments that are capable of ensuring that private floodplain development does not exceed the socially efficient level—the level at which this condition holds. These include both quantitative restrictions on floodplain development, usually based on some form of zoning, and development limits combined with the establishment of markets, in a variant of the familiar cap and trade systems from pollution control. Alternatives to such quantitative restrictions include a range of economic instruments including taxes, subsidies, user charges, access fees, payments for ecosystem services and so on. In this paper we consider the potential efficiency for both quantitative restrictions (with and without supporting markets) and economic instruments.

All quantitative restrictions involve some form of zoning that directly regulates the allowable area of floodplain development, and that captures the effect of measures to remove land from development (through restoration of areas formerly designated as residential, commercial or industrial) or to develop more land (through conversion of areas formerly designated as 'natural' floodplains). In principle, if it is possible to calculate the socially optimal level of floodplain development it is also possible to regulate the area zoned for development to coincide with this. What it is not generally possible to do, however, is to make this sensitive to changes in either economic or environmental conditions.

In practice, the potential change in the extent of floodplain development at any point in time depends partly on the area zoned for development or restoration, and partly on a set of institutional conditions that limit the rate at which land can be converted. We define the limits to the amount of land that can be reallocated in any one period as follows:

$$\max\left\{-X_t^i, \bar{y}^{ri}\right\} \le y_t^i \le \min\left\{\bar{y}^{di}, L_F^i - X_t^i\right\}, i = 1, \ldots, n \quad (9)$$

in which $\bar{y}^{di}(>0)$ is the maximum allowable development in the ith sub-basin in any one period; $\bar{y}^{ri}(<0)$ is the maximum allowable restoration in the ith sub-basin in any one period; and. L_F^i is the total area of floodplains in the ith sub-basin.

The main alternatives to zoning-based quantitative restrictions are market-based economic instruments. Since the privately optimal level of investment is a function of the return on development in floodplains, it may be expected to respond to policies that change the rate of return on floodplain development. In addition to zoning restrictions on y_t^i therefore, we also consider the use of two economic instruments: land use taxes, which we denote τ_t^i, and payments for ecosystem services, which we denote σ_t^i. In addition, we consider both simple quantitative restrictions and the development limits that are supported by a set of transferable development rights.

3. Calibration of the model

We calibrate the model using data on the Ouse catchment in North Yorkshire, UK (Mori, 2006; Mori, 2010). Fig. 1 maps the 100-year floodplains of the Ouse catchment. Land uses within the floodplains have changed substantially in the last five decades. In particular, land that was previously committed to agriculture or left fallow has been developed for commercial, industrial or residential use.

Selection of the sub-basins to be included in the model was based on the location of hydrological gauging stations. These are indicated in Fig. 2, which shows the map of the sub-basins in the Ouse catchment, and the location of hydrological gauging stations. The individual sub-basins are located upstream of each gauging station.

The relationship between precipitation and water discharge in each sub-basin is calculated using the hydrological program, HEC-HMS. The model has been applied to many different river systems in order to solve a wide range of management problems, including the problem studied in this paper: floodplain regulation (USACE, 2001). It is also sufficiently flexible that modeler has a choice of hydrological or hydraulic sub-models depending on the nature of system and the availability of observed and measured data. The HEC-HMS model projects the runoff associated with particular levels of precipitation in dendritic watershed systems, based on a number of empirically estimated hydraulic models. The parameter values in HEC-HMS are selected by maximizing the goodness-of-fit between observed and simulated discharge flows, using observed data on precipitation and discharge. Each sub-basin is characterized by the dominant land use, and by precipitation. The probability of flood events in that sub-basin is estimated from rainfall data (10 years), topographical, and land-cover conditions. We assume the frequency of floods to be highly correlated with the frequency of high rainfall events. Once we have estimated the flood probability, we are then able to estimate a flood damage cost function. This depends on the relationship between precipitation, the area of developed floodplain and water discharge volume, and between water discharge volume and flood damage within and downstream of the reference sub-basin. In our model, the damage at any given level of floodplain development is determined by flood depth. The expected flood risk is then calculated by simulating the damage costs associated with a range of development levels. For the Ouse–Humber catchment this was obtained from 60 observations on the expected costs associated with different levels of floodplain development.

The flood risk sub-model reflects four core assumptions. First, there are unidirectional spatial externalities. The damage in a particular location is a function of the area of developed floodplain in that location and locations upstream (as long as the external impacts of upstream development are not trivial). Second, an increase in the area of developed floodplain in either that location or in locations upstream increases the expected cost of flooding. Third, differences in hydrological conditions and development patterns will lead to differences in flood risks. Fourth, the expected cost of flooding is determined by peak stages that are determined by floodplain development levels in the reference zone and upstream.

Our criteria for choosing between alternative functional forms in the flood risk sub-models are: (1) that they satisfy these assumptions; (2) that the adjusted R-squared (coefficient of determination) is sufficiently high; (3) that independent variables are statistically significant (at least at the 10% significance level) based on t-tests and F-tests; (4) that the

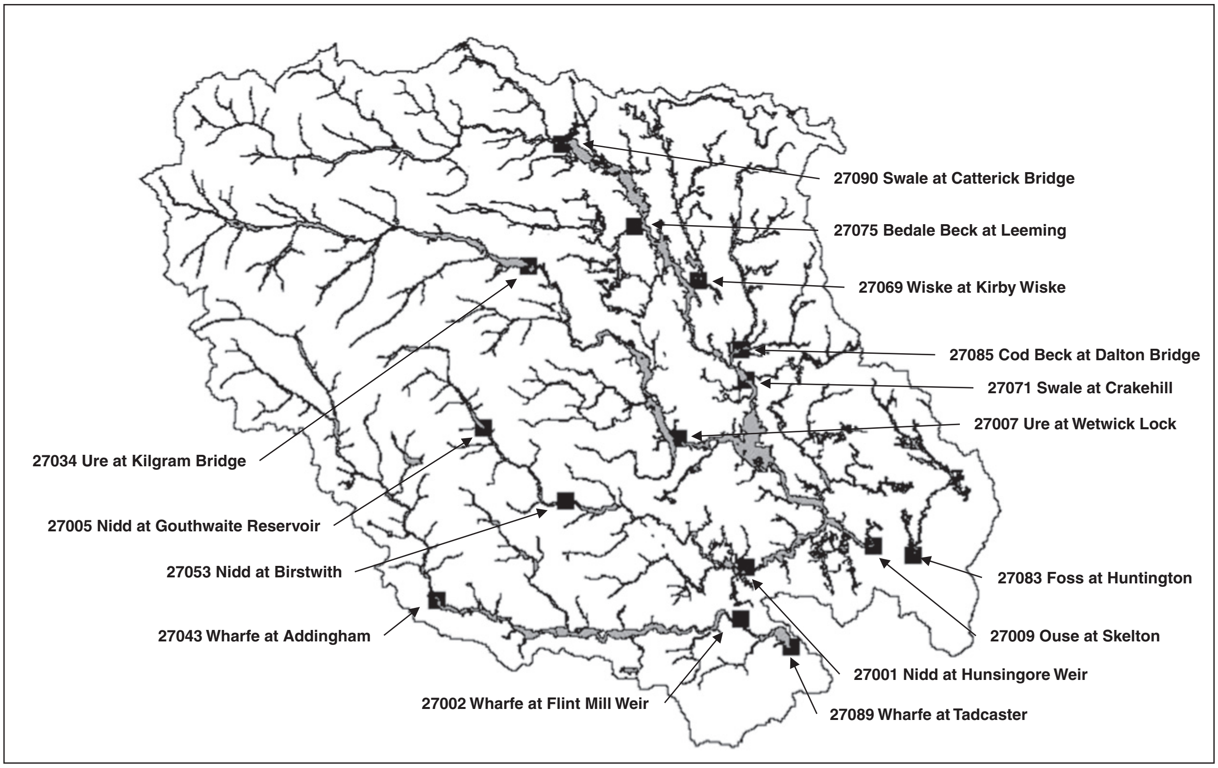

Fig. 1. Floodplain map in the Ouse catchment in North Yorkshire UK.
Source: The Map is created from OS Land-Form PANORAMATM DTM [1:50,000] (EDINA Digimap) and Indicative Floodplain Map 2001 [1:10,000] (Environment Agency) by use of ArcGIS. Note: The numbers in the map indicate hydrological gauging stations. The names of gauging stations are provided by names of river and place.

sufficiency conditions are satisfied; and (5) that RESET (regression specification error test) or the Davidson–MacKinnon test are satisfied. Application of these criteria yield the flood risk functions for each sub-basin reported in Table 1.

To get a first approximation of the benefits of ecosystem services (excluding flood mitigation) from floodplains we exploit existing synthetic research on the value of wetlands (Heimlich et al., 1998; Woodward and Wui, 2001). More particularly, we use estimates from Woodward and Wui (2001). They analyze 46 existing studies of ecosystem services in 39 wetlands. We make use of all the explanatory dummy variables (except for year) in Woodward and Wui's option A model, assigning a 'zero' weight to 'coastal', 'flood', 'storm' and 'producer's surplus' and a 'unit' weight to the others. This is because our focus is on fluvial floodplains. This yields the following function:

$$\ln(V) = 8.635 - 0.168 \cdot \ln(x_a)$$

in which V denotes the benefit of ecosystem services per acre in 1990 USD. Converting the units into hectares and GBP, yields the following estimate of the opportunity cost of floodplain conversion in terms of ecosystem services other than flood mitigation (see Table 1).

$$B\left(X^i\right) = 0.55978\left(L_F^i - X^i\right)e^{8.48302 - 0.168 \cdot \ln\left(L_F^i - X^i\right)} \qquad (10)$$

To estimate the net benefits of developed floodplains we suppose that the rents generated by economic activities on developed lands are capitalized into property prices. If the market for land is complete and efficient, the price of residential land coincides with the present value of the future rents that the landowner can earn. That is, we calculate economic rents per hectare of developed land from the relation:

$$P_0{}^i = \sum_{t=0}^{\infty} \frac{R^i}{(1+\delta)^t} = \frac{R^i}{\delta} \qquad (11)$$

where

P_0^i present land price in the ith sub-basin
R^i economic rent in the ith sub-basin
δ the discount rate (real interest rate)

Fig. 2. Geographical map of sub-basins in the Ouse catchment.
Source: This geographical map is created from GIS data of EDINA Digimap (OS Strategi and Land-Form Panorama [DEM]). Note: The numbers in the map indicate hydrological gauging stations.

Table 1
Calibrated functions.

Function	Calibration method	Data
Cost function of flood risk $D^i\left(X_t^i, X_t^j; R_t\right) = \alpha^i\left(X_t^i\right)^2 + \sum_j \beta^{ij} X_t^j$ NB: Refer to Appendix about parameter values for all sub-basins.	Creation of map of sub-basins and rivers on ArcGIS (GIS software program). Hydrological simulations on a sub-model in HEC-HMS (USACE). Calculation of Base Flow Index on the basis of the method of Gustard et al. (1992). Calculation of physical parameters such as the imperviousness, river length energy slope and so on by ArcGIS Technique of hydraulic geometry to estimate cross section coordinates of rivers (Hey and Thorne, 1986; Knighton, 1998) Frequency analysis of precipitation. Econometrics (regression analysis)	GIS data: EDINA Digimap (OS Strategi, Land-Form Panorama [DEM], OS Land-Line. Plus and OS Land-Form PROFILE DTM); Land Cover Map of Great Britain 1990 (LCM 1990); and Indicative Floodplain Map 2001 [1:10,000] (Environment Agency). Time-series data on precipitation from hydrological gauging stations during 1990–2006 (CEH, Met Office and BADC, UK). Time series data on daily river flow data from rain gauging stations during 1990–2006 (CEH, UK). Manning's N value (Thomas, 1986; Coon, 1998; Bedient and Huber, 2002). Standard data on the relationship between flood depth and damages (Penning-Rowsell et al., 2003, 2005a, 2005b).
Net benefit function of developed floodplains $rX_t^i = 14030.80048X_t^i + B(X_t^i)$	Derivation of economic rents from NPV (using a theoretical logic based on an assumption of efficient market)	Data on residential land prices (Inland Revenue Valuation Office, UK). Annual average of 4 UK banks' base rates (Bank of England). RPI (UK National Statistics)
Benefit function of ecosystem services (implies opportunity costs due to floodplain development) $B(X_t^i) = 0.55978(L_F^i - X_t^i)e^{8.48302 - 0.168\ \ln(L_F^i - X_t^i)}$	Benefit transfer method	Woodward and Wui (2001).
Control cost of floodplain development and restoration $C(y_t^i) = \begin{cases} 1914.63735y_t^i & (y_t^i \geq 0) \\ 19146.37353y_t^i & (y_t^i < 0) \end{cases}$	Assumptions and cost transfer.	Data on cost of floodplain restoration (Edwards and Abivardi, 1997; Gutrich and Hitzhusen, 2004; Kissimmee River Restoration Project).
Constraints on control variables $\max\{-X_t^i, 10\,\text{ha}\} \leq y_t^i \leq \min\{100\,\text{ha}, L_F^i - X_t^i\}$	Assumptions	

The net return on floodplain development is then equal to the sum of (11) and (10), r being the rate of return on X_t^i: i.e.

$$rX_t^i = \delta P_0^i X_t^i + B^i\left(X_t^i\right). \tag{12}$$

The cost of floodplain development (or restoration) is site-specific, but in general we expect restoration to be more costly than development (Mitsch and Gosselink, 2000; Edwards and Abivardi, 1997).[1] Since there are no data on restoration costs in the Ouse catchment, we make the highly conservative 'starting' assumption that restoration costs are ten times as large as development costs. Sensitivity tests showed that the 'starting' assumption influences the area of floodplains that it is optimal to develop, but does not affect the ranking between management strategies.

Table 1 summarizes the data and methods used in calibrating the model. The supplementary material reports both program codes for the GAMS model, and the parameter values that result from its calibration on these data.

To evaluate the flood-risk externalities associated with this level of floodplain development we calculated the socially optimal steady-state level of floodplain development, using GAMS IDE version 21.3, assuming a time horizon of $T = 30$ (years) and a discount rate of 5% for both the private and social problems (see Appendix). The size of the floodplain in each sub-basin, the current level of floodplain development and the optimal level of floodplain development are indicated in Table 2. We obtained interior solutions in all but two sub-basins. For the two sub-basins in which we obtained corner solutions (sub-basins 27005 and 27053) the optimal solution implies no floodplain development. From a flood risk perspective, most 'downstream' sub-basins (27001, 27002, 27007, 27009, 27034, 27043, 27071, 27083, 27085 and 27089) still allow significant scope for further floodplain development. However, we found that overdevelopment of floodplains (relative to the social optimum) currently occurs in 5 'upstream' sub-basins: 27005, 27053, 27069, 27075 and 27090.

Fig. 3 shows the socially and privately optimal development paths for floodplains in all sub-basins. We note that the convergence path, in all cases, is limited by the constraints imposed on the rate at which land can be converted from one state to another. The socially optimal area of developed floodplains differs from the privately optimal area in all sub-basins by the end of the planning horizon by an amount that reflects the external costs of flood-risk (and the other ecosystem services lost due to floodplain development). The socially optimal level of development is larger than the current area of floodplain development in all those sub-basins where the benefits of potential development would be expected to exceed the damage due to the increased risk of flooding. It is smaller

Table 2
Optimal and current size of developed floodplains.

Subbasin	Optimal size of developed floodplains (ha)	Current size of developed floodplains (ha)	Size of floodplains (ha)
27001	239.19083	99.39369	1356.91346
27002	1987.28207	217.13234	2402.75427
27005	0 [−39.99124]	14.38793	204.67004
27007	503.39352	155.26437	2447.00171
27009	1426.77342	308.46632	6639.46521
27034	108.47819	51.12944	2451.61496
27043	161.96300	27.69161	1257.75186
27053	0 [−4836.83615]	7.97054	347.13385
27069	38.67005	101.62420	1338.21609
27071	685.14809	306.14877	3595.16936
27075	24.88389	63.81431	1029.10755
27083	1116.83288	106.27285	1119.66767
27085	119.85753	60.06330	1149.58292
27089	318.88009	35.18348	443.79102
27090	32.49644	67.09430	1632.33813

The values in brackets are calculated values, based on optimality conditions obtained from the model.

[1] Edwards and Abivardi (1997) compare the wetland restoration cost with the potential value of the restored land, and conclude that the former is at least around 100 times as large as the latter.

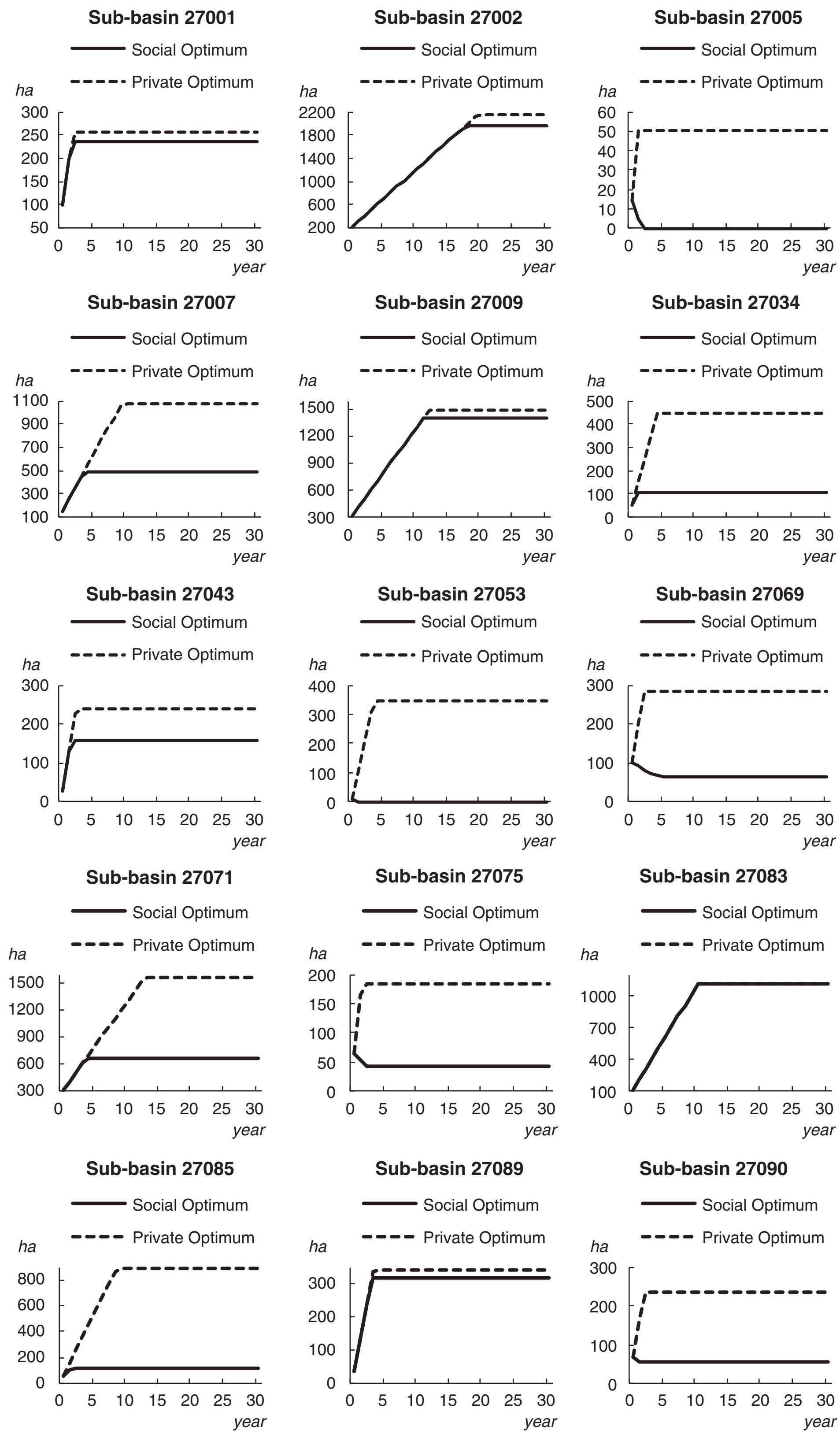

Fig. 3. Paths of area of developed floodplains under social and private optimization.

than the current area of floodplain development where the flood risks of current development outweigh the benefits conferred by that development.

The difference between private and social optima is a measure of the extent of the externalities of development. This difference varies significantly across sub-basins. Note, though, that in all cases where the socially optimal level of floodplain development is less than the current level, the difference between private and social optima is large. In fact, in all those cases, it would still be privately optimal to increase the level of development beyond the current level.

The sensitivity of the social optimum to the discount rate depends on whether the initial level of floodplain development is greater or less than the socially optimal level (see Fig. 4). Developed floodplains are assumed to generate a constant stream of benefits into the future and to be associated with a constant stream of costs (in the form of flood risks). Increasing the discount rate lowers the present value of the net benefits of floodplain development at the optimal level. At the same time it increases the relative weight given to the net costs incurred during the convergence period. As a result, an increase in the discount rate will reduce the socially optimal level of floodplain

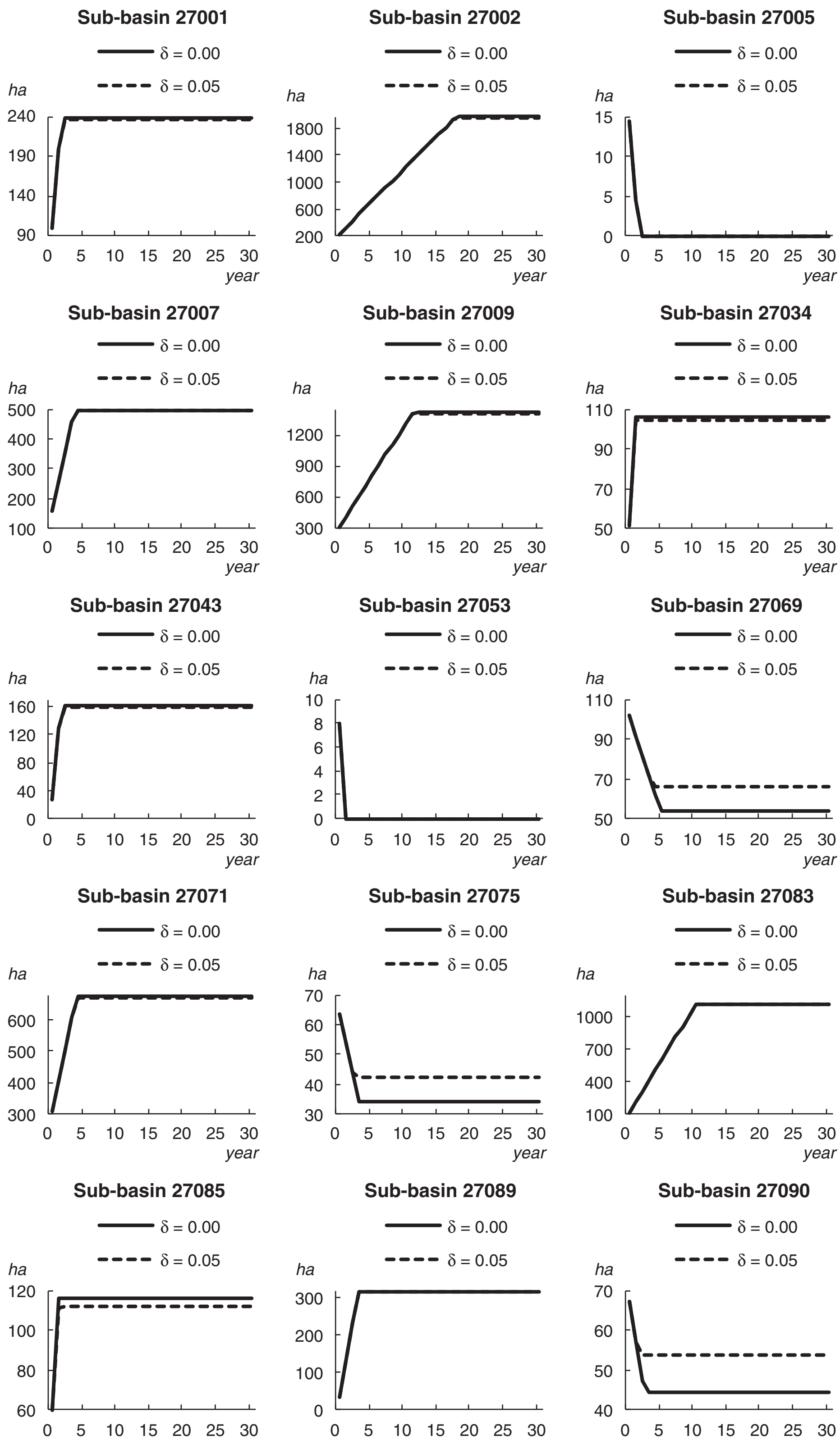

Fig. 4. Sensitivity of the area of developed floodplains to the discount rate.

development if the initial level of floodplain development is too low, and will increase the socially optimal level if the initial level is too high.

4. Economic instruments for optimally managing floodplain development

In this section, we evaluate possible policies for approaching the optimal floodplain management using the calibrated model. These extend well beyond the zoning restrictions and hard engineering traditionally used in floodplain management in the UK (Parker, 1995). We suppose that policy-makers are either (local) governments or governmental agencies, and that their objective is to maximize the social utility of the net benefits of floodplain development by applying a selected set of instruments. The instruments tested include: (a) a Pigouvian tax equivalent to the differential land use taxes applied in Germany, (b) payments to landholders for the preservation of floodplain functions, (c) the direct control of floodplain development through zoning, and (d) two types of marketable permits. Fig. 5 shows the impact of each instrument on our measure of wellbeing relative to the socially optimal path. The smaller the difference between the paths under the instrument and the socially optimal path is, the more efficient the instrument is. Table 3 reports the size of floodplain development at the terminal time under each instrument relative to the optimal size of floodplain development.

Consider, first, the two economic instruments (a) and (b). Pigouvian taxes are among the most common economic instruments used for internalizing environmental externalities. We impose a unit tax on floodplain development (per ha per year) equal to the marginal external costs of floodplain development. Specifically we define the function $\pi^i(y^i, X_t^i, D_t^i, R_t)$ in Eq. (3) to have the form

$$\pi^i\left(y^i, X_t^i, D_t^i, R_t\right) = r\left(1-\tau^i\right)X_t^i - \pi^i\left({y_t}^i\right) - \pi^i\left(D_t^i, R_t\right) \quad (13)$$

implying that the marginal impact of floodplain development on private profit is $\frac{d\pi^i}{d{X_t}^i} = r\left(1-{\tau_t}^i\right)$, r being the rate of return on X_t^i and τ_t^i being a flood risk tax. We also let the social problem in Eq. (7) have the form

$$\max_{y_t^i} E\left\{\sum_{t=0}^{T-1}\sum_{i=1}^{n}\rho^t\left[r\left(1-\tau^i\right)X_t^i - \pi^i\left({y_t}^i\right) - \pi^i\left({D_t}^i, R_t\right)\right] + \rho^T\left(\pi^i\left(X_T^i\right)\right)\right\}. \quad (14)$$

Setting the tax rate at ${\tau_t}^i = \frac{1}{r}\sum_j \frac{d\pi^j}{dD_t^j}\frac{dD_t^j}{d{X_t}^i}$, it can be shown that the conditions for the private and social optimization of this problem coincide. We accordingly expect the tax rate to differ between subbasins with differences in the marginal external cost of floodplain development. We also expect the use of the tax to lead to the socially optimal level of conversion. Applying a tax at this rate in the calibrated model leads to an outcome that is very close to the social optimum.

The second instrument, payments for floodplain services, is expected to have a similar effect to that of the Pigouvian tax. Payments to landowners for the maintenance of natural floodplains (per ha per year) are set equal to the marginal damage avoided.

Table 3
Area of developed floodplains at the terminal time under each instrument. unit: ha.

Sub-basin	Social optimum (= direct control)	Pigouvian tax and payments for floodplain services	Marketable permits for floodplain development	Marketable permits for developed floodplains	Private optimum
27001	236.86	236.74	239.19	236.86	255.78
27002	1956.54	1955.08	1987.28	1956.54	2138.59
27005	0.00	0.00	14.39	0.00	50.63
27007	493.14	493.19	503.39	493.14	1078.11
27009	1409.60	1409.29	1426.77	1409.60	1503.81
27034	104.40	104.39	108.48	104.40	448.22
27043	159.73	159.71	161.96	159.73	239.95
27053	0.00	0.00	7.97	0.00	347.13
27069	65.63	65.90	101.62	65.63	283.34
27071	670.22	670.05	685.15	670.22	1569.56
27075	42.10	42.26	63.81	42.10	185.21
27083	1115.21	1112.70	1116.83	1115.21	1119.67
27085	111.81	111.79	119.85	111.81	889.81
27089	315.81	315.62	318.88	315.81	341.42
27090	53.84	54.17	67.09	53.84	235.20
Welfare rank	1	2	3	4	5

For marketable permits, targets are required to be met within 30 years.

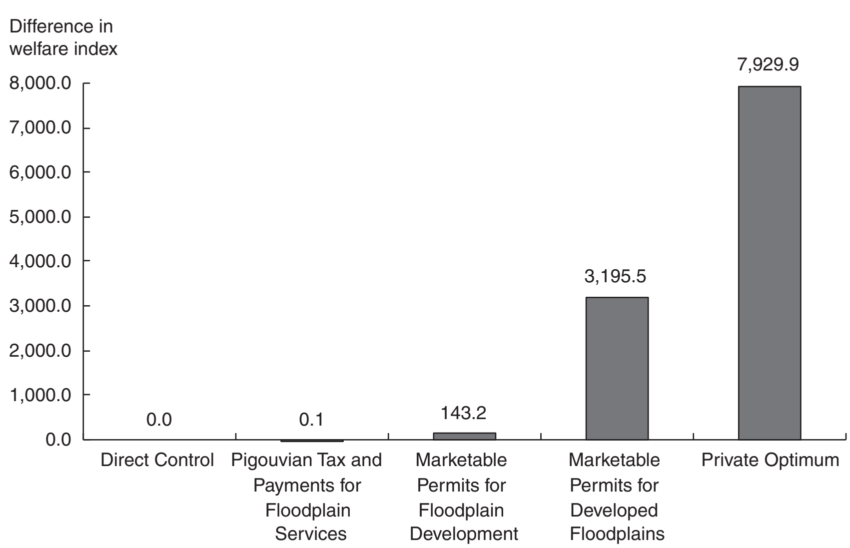

Fig. 5. The gap between the social optimum and the outcome under different instruments (no instrument in the case of the private optimum) under certainty. Note: If the difference in welfare index is nil, it implies that the policy instrument accomplishes the social optimum. The smaller the difference is, the better the policy instrument is. For marketable permits, targets are required to be met within 30 years.

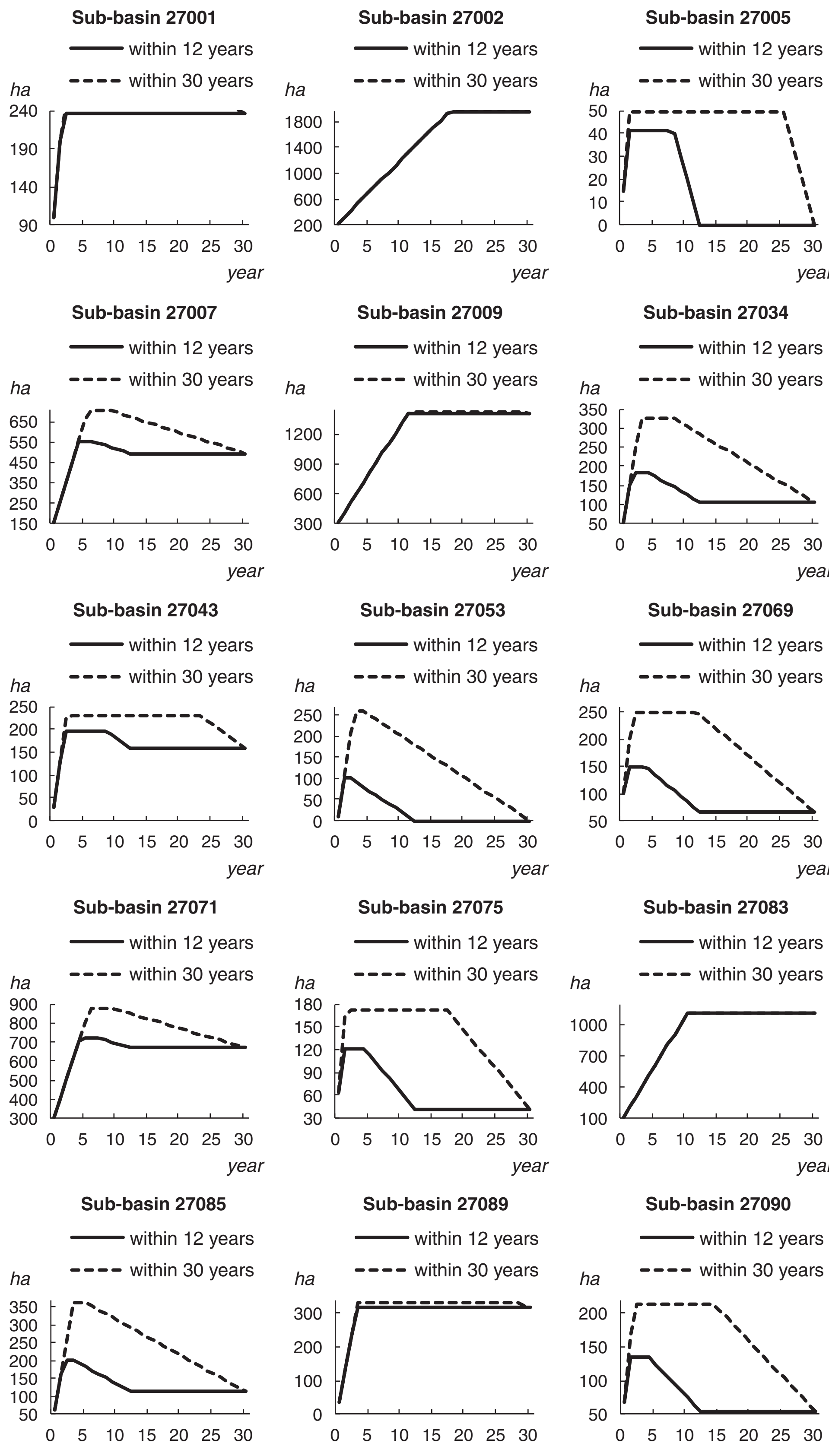

Fig. 6. Sensitivity of the area of developed floodplains under marketable permits to the floodplain authority's time horizon. Note: In sub-basin 27002, the target can be met within 18 years due to the constraints on the control variable.

This implies that the function $\pi^i(y^i, X_t^i, D_t^i, R_t)$ has the form

$$\pi^i\left(y^i, X_t^i, D_t^i, R_t\right) = rX_t^i + \sigma^i\left(X_t^i\right) - \pi^i\left(y_t{}^i\right) - \pi^i\left(D_t^i, R_t\right) \tag{15}$$

in which

$$\sigma^i(X_t) = \left(L_F^i - X^i\right) \sum_j \frac{d\pi^j}{dD_t{}^j} \frac{dD_t{}^j}{dX_t{}^i}. \tag{16}$$

Once again, it can be shown that the conditions for the private and social optimization of this problem coincide, and we do in fact find that the area of floodplain development at the terminal time under payments for floodplain services is almost the same as that under the tax policy. The reason that taxes and payments for floodplain services are convergent in this case is both the absence of uncertainty, and the fact that the income effects of the payments are weak. If the income effects of payments were sufficiently strong to outweigh the substitution effects of the associated change in relative prices, the outcome might be different.

Our third instrument is closest to traditional management, and directly controls the level of developed floodplains through zoning restrictions. That is, $\pi^i(y^i, X_t^i, D_t^i, R_t)$ has the form:

$$\pi^i\left(y^i, X_t^i, D_t^i, R_t\right) = rX_t^i - \pi^i\left(y_t^i\right) - \pi^i\left(D_t^i, R_t\right). \tag{17}$$

The floodplain authority might, for example, rezone a proportion of developed land in each year in order to restore floodplains in the sub-basins where the optimal level is smaller than the initial level. While it is notionally possible to force the system on to socially optimal path by this method, it is not generally possible to do so at least cost.

The last instrument we consider, marketable permits, is designed to address this problem. These instruments are potentially appropriate where the floodplain authority has established a target for floodplain development or floodplain restoration. Both variants of marketable permits considered are designed to ensure that floodplain targets are met at least cost. Marketable permits accordingly have two elements: (1) a floodplain target (cap) for each sub-basin or each class of sub-basins, and (2) the establishment of a market for permits within each sub-basin or sub-basin type. This is because the optimal size of developed floodplains is determined in each sub-basin, depending on the different external costs.

We consider two options for marketable permits. The first is a system of transferable development rights. In sub-basins where the optimal level of developed floodplains is larger than the initial level, tradable development rights are issued equivalent to the optimal level, and landowners are permitted to bid for those rights based on their expectations of the value of converted land. In sub-basins where initial floodplain development is greater than the optimal level, no permits are issued. Since this option does not allow for the reduction of floodplain development, the results diverge from the social optimum in sub-basins that are currently overdeveloped. The second option considered addresses this problem. Where the floodplain authority has a target for floodplain restoration, landowners are required to acquire permits for floodplain development in the market in the same sub-basin (or class of sub-basins) or to restore natural floodplains.

An important factor in the success of instruments of this kind is the time horizon over which they are implemented. We initially required that targets be met within 30 years. However, since landowners have no incentive to restore floodplains in early years, this led to inefficiency in some sub-basins due to the deferral of floodplain restoration costs. Reducing the time horizon for achievement of restoration targets in different sub-basins brought the system closer to the optimal path. The results are reported in Fig. 6.

5. Discussion

We compare the impact of this set of instruments on social welfare with and without 'uncertainty' about particular sets of model parameters, where uncertainty refers to undetected or unregistered change in the parameter values. Sensitivity analysis is crucial for assessing the robustness of safety margins to uncertainty (Bastola et al., 2011). This approach implies that policymakers' expectations either systematically overestimate or underestimate parameter values. It allows us to identify which instruments are most robust to error in parameter estimates. We consider two kinds of error. One is error in estimation of the hydrological variables of the model (which may be interpreted as an example of 'model error'). The other is error in the estimation of the benefits of developed floodplains (which may be interpreted as an example of measurement error).

First consider the robustness of the instruments to 'model error' about the relation between precipitation and flood risk. Suppose that the modeled risk of flooding is 20% below actual risk, and hence that the parameter values in the expected cost functions of flood risk are underestimated.[2] Error of this magnitude is consistent with current conditional projections of climate change in the UK. Taken over the range of scenarios used to project regional climate change, it is expected that winter precipitation will increase while summer precipitation will decrease by the 2080s, but that there will be little change in total precipitation (Hulme et al., 2002). Specifically, Hulme et al. find that: "Winter precipitation increases for all periods and scenarios, although these increases by the 2080s range from 5 to 15% for the Low Emissions scenario, to more than 30% for some regions for the Medium–High Emissions and High Emissions scenarios" (Hulme et al., 2002). The results of our sensitivity analysis are reported in Fig. 7. Private landowners are assumed to be aware of the change in the risk on their own lands in floodplains while policy-makers are not. In this case, direct control through zoning restrictions is seriously inefficient due to its inflexibility. However, zoning restrictions without marketable permits perform worse than zoning restrictions with marketable permits for floodplain development, because private landowners can adjust the timing of floodplain development under the system of marketable permits. They are more flexible than zoning along. Price-based policies such as taxes and payments for floodplain services are still relatively efficient, compared to other policies. This is because there is scope for private landowners to adjust their own decisions. As a result, price policies are more robust to this source of error than other policies.

Consider, next, the robustness of policies to uncertainty about the benefits of floodplain development. We suppose that the marginal benefits of floodplain development are 25% below the benefits expected by policymakers (i.e. policy makers are assumed to overestimate the benefits of developed floodplains by 25%) due to error in the benefit function of floodplain development.[3] The results are indicated in Fig. 8. As before, individual landowners are assumed to observe the change in the benefits of floodplain development and to change their decisions, but policy-makers are assumed to hold to the policies developed on the basis of their initial expectations. All policies are inefficient as compared with the social optimal path. However, instruments based on quantitative targets, such as zoning restrictions or marketable permits, impose higher social costs than alternative measures. This is, once again, because targets are inflexible. In fact marketable permits to support floodplain restoration targets impose higher costs on society than zoning restrictions alone. By

[2] We assume that the amount of precipitation increases by 20% in the hydrological model in the process of calibration. This provides the changes in the parameter values of the functions. In the model, we can interpret that an uncertain exogenous variable, R_t, changes.

[3] Using a simple linear function here, we change the amount of the marginal benefit by 25% for the sensitivity analysis.

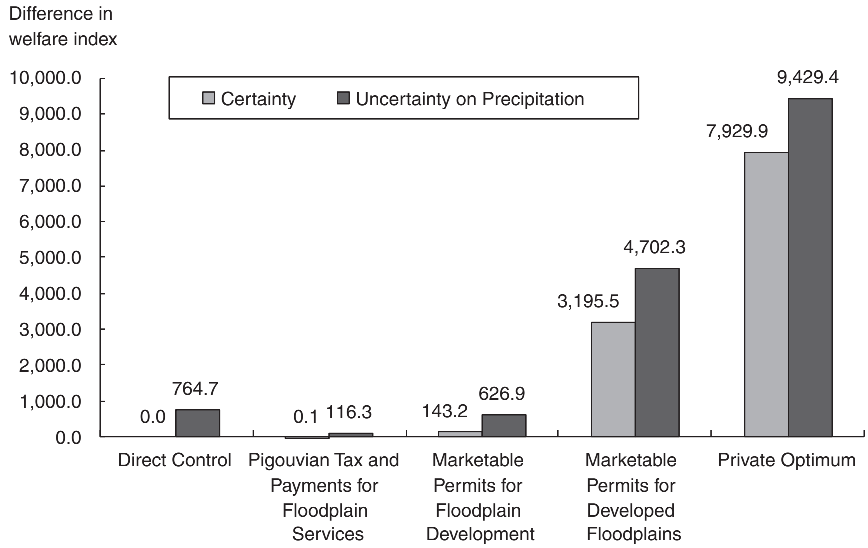

Fig. 7. Impact of uncertainty about precipitation on the gap between the social optimum and the outcome under different instruments (no instrument in the case of the private optimum). Note: If the difference in welfare index is nil, it implies that the policy instrument accomplishes the social optimum. The smaller the difference is, the better the policy instrument is. For marketable permits, targets are required to be met within 30 years.

contrast, price-based policies such as taxes and subsidies are still relatively efficient, due to the fact that private landowners retain flexibility to adjust their behavior.

As a qualification to these results, note that the modeling approach adopted here is simplified both with respect to the complex interactions between sub-basins, and with respect to the costs of developing and implementing floodplain control policies (Mori, 2009). We do not, for example, take implementation costs of policies into consideration. Nor do we consider factors other than flood-risk when identifying optimal strategies. Nevertheless, the approach makes it possible to evaluate flood-risk relative to the gains of floodplain development or the costs of floodplain restoration. It also makes it possible to identify the degree to which these costs and benefits are factored into the decisions of both private landowners and the floodplain authority. Estimation of the gap between the payoff to society with and without attention to flood-risk also gives the social cost of the 'externality' visited by upstream developers on those downstream. With this information it is possible to develop flood-risk policies that confront developers with the full cost of their actions or, symmetrically, that reward those who protect the flood-mitigation functions of the floodplain. It is also possible to test the effectiveness of alternative policies.

The exclusion of implementation or transaction costs is potentially problematic. While we find that price polices such as taxes and payments for floodplain services are relatively effective, this may be compromised if there are significant transaction costs (e.g. implementation and administration costs). Similarly, the effectiveness of marketable permit systems depends on whether permits are fully tradable and markets are competitive, and this in turn depends on the size of market/sub-basins. In addition, each of the policy instruments discussed here has some implication for the distribution of income and assets. The principle behind tax or payment systems is that landowners should compensate society for the external costs of floodplain development, and should in turn be compensated by society for the external benefits of floodplain preservation or restoration. However, the income effects of such instruments are important both because they affect equity and because they can affect the way in which decision-makers respond to taxes or payments.

Finally, we note that a major benefit of the approach is that it provides a basis for constructing a system of payments/developing markets for floodplain services that has the potential to produce either an efficient level of protection (Wunder et al., 2008), or a cost effective way to meet floodplain targets. The basic principle of PES (payments for ecosystem services) schemes is that the people who provide ecosystem services should be compensated for the cost of doing so. Costs, in this case, include both the direct costs of service provision and the indirect opportunity costs of land uses that compromise service provision (Grieg-Gran and Bann, 2003). PES schemes are therefore markets in which the beneficiaries of ecosystem services (or their agents) purchase ecosystem services from landowners who otherwise would not provide the services (Ferraro and Simpson, 2002; Wunder, 2007). The five characteristics of PES schemes identified by these authors are: that they should be voluntary transactions; that they should involve a well-defined ecosystem service or a land use likely to secure that service; that the service be purchased by at least one buyer from at least one seller; and that payment be conditional on performance.

Watershed services have in fact been a popular subject for the development of PES schemes, in part because they can be implemented at relatively small scales. Because the services provided by landowners in the upper watershed are public goods, they will be under-supplied by the market. This makes the development of alternative mechanisms attractive. In fact, PES are just the most recent of many mechanisms designed to internalize environmental externalities and to enhance the supply of environmental public goods. The purchaser in such cases is generally either a governmental or non-governmental agency representing the group of consumers affected by the service. In order to be able to enhance efficiency in the supply of ecosystem services, they need to have information both on the potential efficiency gains to be had from changing levels of ecosystem service provision, and on the efficiency (or cost effectiveness) of the alternative instruments available. The modeling approach reported in this paper for the case of the floodplains has the capacity to contribute to both goals.

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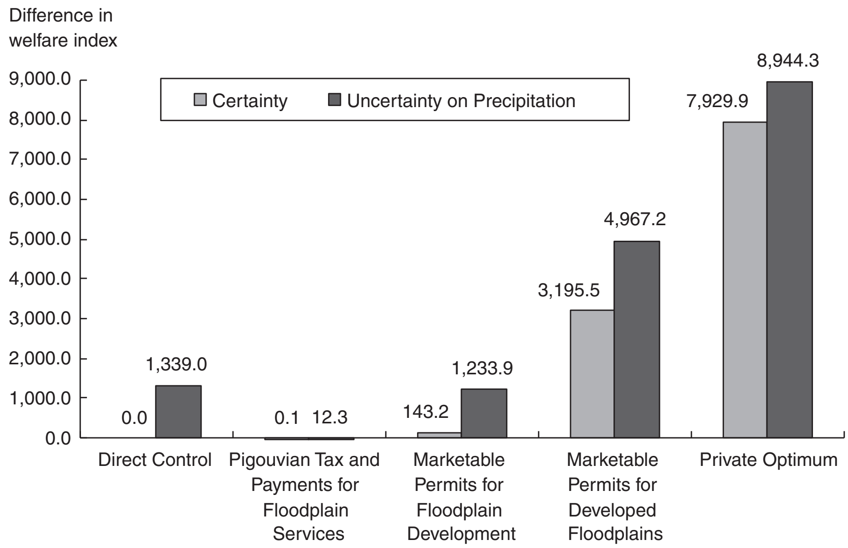

Fig. 8. Impact of uncertainty about the benefits of developed floodplains on the gap between the social optimum and the outcome under different instruments (no instrument in the case of the private optimum). Note: If the difference in welfare index is nil, it implies that the policy instrument accomplishes the social optimum. The smaller the difference is, the better the policy instrument is. For marketable permits, targets are required to be met within 30 years.

Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.scitotenv.2012.04.076.

References

Alchian AA, Demsetz H. The property right paradigm. J Econ Hist 1973;33(1):16–27.
Arriagada R, Perrings C. Paying for international environmental public goods. AMBIO 2011;40(7):798–806.
Bastola S, Murphy C, Sweeney J. The sensitivity of fluvial flood risk in Irish catchments to the range of IPCC AR4 climate change scenarios. Sci Total Environ 2011;409:5403–15.
Bedient PB, Huber WC. Hydrology and floodplain analysis. 3rd ed. Upper Saddle River: Prentice Hall; 2002.
Black AR, Burns JC. Re-assessing the flood risk in Scotland. Sci Total Environ 2002;294:169–84.
Bromley DW. Environment and economy: property rights and public policy. Oxford: Blackwell; 1991.
Burby RJ. Flood insurance and floodplain management: the US experience. Global Environ Change Part B 2001;3(3–4):111–22.
Chang CT. Introduction of a tradable flood permit system. Environ Sci Policy 2008;11:329–35.
Chang CT, Leentvaar J. Risk trading in trans-boundary flood management: case study of the Dutch and German Rhine. J Flood Risk Manage 2008;1:133–41.
Coon WF. Estimation of roughness coefficients for natural stream channels with vegetated banks. Washington: U.S. Geological Survey Water-supply; 1998. Paper 2441 (WSP2441).
Crooks S, Turne RK, Pethick JS, Parry ML. Managing catchment-coastal floodplains: the need for an UK water and wetlands policy. University of East Anglia; 2001. CSERGE Working Paper, PA01-01.
De Martino G, De Paola F, Fontana N, Marini G, Ranucci A. Experimental assessment of level pool routing in preliminary design of floodplain storage. Sci Total Environ 2012;416:412-147.
de Moel H, Aerts JCJH. Effect of uncertainty in land use, damage models and inundation depth on flood damage estimates. Nat Hazard 2011;58:407–25.
Dister E, Gomer D, Obrdlik P, Petermann P, Schneider E. Water management and ecological perspectives of the Upper Rhine's floodplains. Regul Rivers: Res Manage 1990;5:1-15.
Edwards PJ, Abivardi C. Ecological engineering and sustainable development. In: Urbanska KM, Webb NR, Edwards PJ, editors. Restoration ecology and sustainable development. Cambridge: Cambridge University Press; 1997. p. 325–52.
Emerton L, Iyango L, Luwum P, Malinga A. The present economic value of Nakivubo urban wetland, Uganda. Nairobi: IUCN, the World Conservation Union; 1998.
Engel S, Pagiola S, Wunder S. Designing payments for environmental services in theory and practice: an overview of the issues. Ecol Econ 2008;65:663–74.
Environment Agency. The Humber flood risk management strategy. Leeds: Environment Agency; 2008.
Ferraro PJ, Simpson RD. The cost-effectiveness of conservation payments. Land Econ 2002;78:339–53.
Gren I-M, Groth K-H, Sylvén M. Economic values of Danube floodplains. J Environ Manage 1995;45:333–45.
Grieg-Gran M, Bann C. A closer look at payments and markets for environmental services. In: Gutman P, editor. From goodwill to payments for environmental services, a survey of financing options for sustainable natural resource management in developing countries. WWF Macroeconomics for Sustainable Development Programme Office; 2003.
Gustard A, Bullock A, Dixon JM. Low flow estimation in the United Kingdom. .. Report No. 108Wallingford: Institute of Hydrology; 1992.
Gutrich JJ, Hitzhusen FJ. Assessing the substitutability of mitigation wetlands for natural sites: estimating restoration lag costs of wetland mitigation. Ecol Econ 2004;48:409–24.
Hall JW, Sayers PB, Dawson RJ. National-scale assessment of current and future flood risk in England and Wales. Nat Hazard 2005;36:147–64.
Heimlich RE, Wiebe KD, Claassen R, Gadsby D, House RM. Wetlands and agriculture: private interests and public benefits. Agricultural Economic Report, No. 765. Resource Economics Division, Economic Research Service, U.S. Department of Agriculture; 1998.
Hey RD, Thorne CR. Stable channels with mobile gravel beds. J Hydraul Eng 1986;112:671–89.
Holway J, Burby RJ. The effects of floodplain development controls on residential land values. Land Econ 1990;66(3):259–71.
Hulme M, Jenkins GJ, Lu X, Turnpenny JR, Mitchell TD, Jones RG, et al. Climate change scenarios for the United Kingdom: The UKCIP02 Scientific Report: 120. Tyndall Centre for Climate Change Research. Norwich: University of East Anglia; 2002.
Kinzig AP, Perrings C, Chapin FS, Polasky S, Smith VK, Tilman D, et al. Paying for ecosystem services: promise and peril. Science 2011;334:603–4.
Knighton D. Fluvial forms and processes: a new perspective. London: Arnold; 1998.
Messner F, Pennning Rowsell EC, Meyer V, Tunstall SM, van der Veen A. Evaluating flood damages: guidance and recommendations on principles and practices. Wallingford: HR Wallingford; 2007.
Mitsch WJ, Gosselink JG. Wetlands. 3rd ed. John New York: Wiley & Sons; 2000.
Mori K. Modelling hydrological, ecological and economic interactions in river floodplains: a case study of the Ouse catchment (North Yorkshire, England). PhD thesis, The University of York; 2006.
Mori K. Can market-based policies accomplish the optimal floodplain management? A gap between static and dynamic models. J Environ Manage 2009;90(2):1191–4.
Mori K. Can we avoid overdevelopment of river floodplains by economic policies? A case study of the Ouse catchment (Yorkshire) in the UK. Land Use Policy 2010;27(3):976–82.
Munich Re. Weather catastrophes and climate change. Munich: Munchener Ruckversicherungs-Gesellschaft; 2005.
Ogawa H, Male JW. Simulating the flood mitigation role of wetlands. J Water Resour Plann Manage 1986;112(1):114–28.
Parker DJ. Floodplain development policy in England and Wales. Appl Geogr 1995;15(4):341–63.
Penning-Rowsell E, Johnson C, Tunstall S, Tapsell S, Morris J, Chatterton J, et al. The benefits of flood and coastal defence: techniques and data for 2003. Middlesex University: Flood Hazard Research Centre; 2003.
Penning-Rowsell E, Johnson C, Tunstall S, Tapsell S, Morris J, Chatterton J, et al. The benefits of flood and coastal risk management: a manual of assessment techniques. London: Middlesex University Press; 2005a.
Penning-Rowsell E, Johnson C, Tunstall S, Tapsell S, Morris J, Chatterton J, et al. The benefits of flood and coastal risk management: a handbook of assessment techniques. London: Middlesex University Press; 2005b.

Smith RL, Smith TM. Ecology and field biology. San Francisco: Benjamin Cummings; 2001.

te Linde AH, Aerts JCJH, Bakker AMR, Kwadijk JCJ. Simulating low-probability peak discharges for the Rhine basin using resampled climate modeling data. Water Resour Res 2010;46:W03512. http://dx.doi.org/10.1029/2009WR007707.

Thomas LE. ENG – hydrology – time of concentration. No. N4Hydrology Technical Note. United States Department of Agriculture, Soil Conservation Service; 1986.

Thonon I, Klok C. Impact of a changed inundation regime caused by climate change and floodplain rehabilitation on population viability of earthworms in a lower River Rhine floodplain. Sci Total Environ 2007;372:585–94.

Tockner K, Stanford JA. Riverine flood plains: present state and future trends. Environ Conserv 2002;29:308–30.

Turner K. Economics and wetland management. Ambio 1991;20(2):59–63.

USACE. Hydrologic Modeling System HEC-HMS. . User's Manual, Version 2.1.US Army Corps of Engineers; 2001.

van den Bergh JCJM, Barendregt A, Gilbert AJ. Spatial ecological-economic analysis for wetland management: modelling and scenario evaluation of land-use. Cambridge: Cambridge University Press; 2004.

Woodward RT, Wui Y-S. The economic value of wetland services: a meta-analysis. Ecol Econ 2001;37:257–70.

Wunder S. The efficiency of payments for environmental services in tropical conservation. Conserv Biol 2007;21(1):48–58.

Wunder S, Engel S, Pagiola S. Taking stock: a comparative analysis of payments for environmental services programs in developed and developing countries. Ecol Econ 2008;65:834–52.