The Feasibility of Valuing Woodlands' Contribution to Regulating Water Quality and Quantity

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Glossary

Atmospheric deposition – The transfer of substances in air to surfaces including soil, vegetation or surface water, by dry or wet processes.

Avoided damage costs – Avoided costs that would be assumed due to an extreme event such as flooding.

Baseline – Current conditions or a scenario depicting conditions if the woodland was not there.

Biophysical processes – Physical forces and cycling in the natural environment or in living organisms.

Catchment - The area of land bounded by watersheds or runoff draining into a river, basin or reservoir.

Coefficients – values associated with a specific (environmental) process that can be used to feed into or run appropriate models. A coefficient is usually a multiplicative factor in some term of an expression, is usually a number and does not involve any variables of the expression.

Denitrification – The conversion of nitrate into atmospheric nitrogen.

Ecosystem services - The services people obtain from ecosystems. These include provisioning services such as food and water; regulating services such as flood and disease control; cultural services such as spiritual, recreational, and cultural benefits; and supporting services such as nutrient cycling that maintain the conditions for life on Earth

Empirical data- Data acquired by means of observation or experimentation.

Erosion – The process of eroding or being eroded by wind, water or other natural agents.

Evapotranspiration – The process by which water is transferred from the land to the atmosphere by evaporation from the soil and other surfaces and by transpiration from plants.

Export coefficient – The weight of pollutant lost from each unit area per unit time.

Flow path – The route that water takes, either over the land surface or in groundwater, from its source to a sink (ultimately the sea). Governed by the topography of the land surface and any obstacles that impede the flow.

Geo-climatic region – A zonal classification based on land-use, soils and topography to infer the regional climate.

Half-life – (relating to pesticides or other chemical pollutants) An indicator of the level of persistence in the environment.

Hydraulic roughness – A measure of the amount of frictional resistance water experiences when passing over land.

Hydrological cycle –The journey water takes as it circulates from the land to the sky and back again - depicted in Figure 1.

Hypothetical market data – valuation of intangible or unquantifiable impacts from surveys of individuals' willingness to pay.

Infiltration – the downward entry of water into the soil. The velocity at which water enters the soil is the infiltration rate.

Leaching – The process by which a soluble chemical drains away from soil by the action of percolating water, especially rainwater.

Macro-modelling – Valuation of woodland for national accounting purposes.

Marginal values –The additional benefit of increasing the good or service by one unit.

Market price proxies – Costs observed directly from actual markets.

Micro-modelling – Quantification of marginal effects.

Parameterization - The process of populating a model with the data and coefficients needed to allow it to run and generate outputs.

Partition coefficient – (relating to pesticides or other chemical pollutants) An indicator showing the level of solubility.

Physical effects – Any consequences of a set of factors related to the material world.

Pollutants – In this study, relates to nutrients (nitrogen and phosphorous), sediment and pesticides.

Probabilistic models – Models that incorporate equations derived from statistical models of real data.

Process-based models – Models that describe the mechanism and processes in operation in a system.

Recharge – The hydrological process by which water moves downward from surface water to groundwater.

Replacement costs – Avoided capital and operating costs of an alternative provision.

Return period – An estimate of the likelihood of an event occurring, usually expressed as an expected frequency (e.g. 1 in 100 years).

Revealed preferences – Observations of consumers' market behaviour can reveal their preferences for non-market environmental goods.

Riparian – Relating to or situated on the banks of a river.

Sediment – Material that settles to the bottom of a liquid.

Spatial resolution – The level of detail to which a variable is represented across a landscape.

Stated preferences – Direct responses from a representative survey sample, used to obtain hypothetical market data.

Stock values – The average values across a catchment, county or country.

Surrogate market data – Costs obtained by observing consumer behaviour.

Topography – The shape and features of the land surface.

Total Economic Value – is the total value derived from people from an environmental good including market and non-market values.

Transpiration – The process of water movement through a plant and its evaporation from leaves, stems and flowers.

Value transfer – The process of searching, selecting and adjusting economic value evidence from the literature for use in valuation assessments.

Water quality - Physical, chemical, biological and organoleptic (taste-related) properties of water.

Willingness to pay/accept - The price that someone is willing to pay to acquire a good or service or the price someone is willing to accept in order to give up a good or service. Willingness to pay does not require an actual payment, it is a theoretical amount.

Acronyms and Abbreviations

ALC – Agricultural Land Classification (England and Wales)

CEH – Centre for Ecology and Hydrology

DEM – Digital Elevation Model

GB – Great Britain

GIS – Geographical Information System

JAC – June Agricultural Survey

LCA – Macaulay Land Capability for Agriculture System (Scotland)

LCM2007 – CEH Land Cover Map

LU – Land Use

SSSI – Site of Special Scientific Interest

TEV – Total Economic Value

UK – United Kingdom

WFD – European Water Framework Directive

WTP – Willingness to pay

1 Executive Summary

The purpose of this study is to provide an assessment of the feasibility of valuing the contribution of woodland to regulating water quality and quantity in Scotland, England and Wales. A valuation study would require the physical effects of woodland on the water environment to be quantified and subsequently linked to valuation data and methods. This report therefore evaluates models, methodologies and data sources that could quantify the physical effects and identifies a range of valuation methods for estimating an economic value for these effects.

The study considers possible approaches to estimating both the water-related value of existing woodland at a national scale and finer scale modelling in specific catchments to estimate marginal effects of planting new woodlands. It is suggested that national-scale modelling could be used to identify catchments where more detailed modelling might be beneficial (i.e. where additional woodland could provide optimal water ecosystem service (ES) benefits[1]).

A baseline scenario of zero woodland would be required to calculate the value of existing woodland. The total value of all land-uses for both the baseline and the existing scenarios would be calculated and the difference between the two would provide an estimate of the value of woodland. The baseline should therefore infer the land-use that would be most likely if the woodland were not there. It is recommended that this is done using national Land Classification Systems, which classify land by its potential productivity for agriculture.

A brief review of the processes that govern the physical effects that woodlands have on water and the main reasons for their variation is presented. In general, two types of effects would need to be modelled:

- Land-use replacement effects: the difference in pollutant losses or water use from a parcel of woodland compared to some other land use. Estimates of pollutant losses (nutrients, sediment, pesticides) or water use would be required for its key determinants, namely: by broad crop types, livestock types, climatic regions, woodland types and soil types at a minimum.
- Interception/ retention effects: the effects that woodland has on altering the quantity of pollutants or volume of water arising from upslope land that reach a waterbody. The percentage interception/ retention commonly varies by woodland strip width, woodland composition, soil type/ geology, flow velocity and flow volume and therefore estimated values for these variables would ideally be required.

Replacement effects are considered to be more important than interception/ retention effects for a national-scale analysis. Interception effects depend primarily on the upslope land use and could therefore be a key factor in the optimal placement of new woodland.

We reviewed existing models and methods that could be used to quantify the water ES provided by woodland. We categorised the models into three groupings:

- Pollutant models: that only estimate land-use replacement effects
- Ecosystem service models: which are designed to quantify or value multiple ES and take account of interception/ retention effects
- Hydrological models: which model hydrological processes in detail with potentially more accurate results for interception effects.

Potential sources of data required to run the models are identified and an assessment made as to the suitability of each source of data in terms of coverage, spatial resolution, temporal resolution, accuracy, cost and accessibility. Recommendations are made as to the most suitable models and datasets for modelling and valuing both existing woodland and woodland creation.

Relevant economic valuation methods are identified in order to consider the ways that the different models and methods will be able to link to them to produce economic results. It is noted that valuation requires a quantified measure of change in ES against the baseline scenario. Less accurate quantification (e.g. categorical variables) can be used, but produce more uncertain valuations. We assume it would not be feasible to carry out primary valuation work to assess national impacts due to the likely costs involved. Therefore, any modelling will necessarily rely on using ‘value transfer’ to apply existing economic valuation evidence to the changes in water ecosystem services.

[1] Recognising that optimal arrangement requires accounting for all ecosystem services from woodland.

Understanding of the application of economic analysis methods is gained from a review of some existing studies valuing the influence of woodlands on ES affecting water. Although valuations can be made of the individual processes through which woodland impacts water ES, a grouping of the biophysical processes is suggested. This makes the economic valuation more feasible without hindering the ability to cover comprehensively the ecosystem services provided by woodlands. This identifies three final ecosystem services (concentration of contaminants in surface and ground waters; quantity of water in surface and ground water; and volume of flows entering surface waters during extreme events), which in turn support four impacts to be valued:

(i) reduction in costs of public water supply;
(ii) alteration of quality of water / wetland environments;
(iii) reduction in flood risk / damage; and
(iv) reduction in service interruptions during drought.

Analysis of each of these benefits shows that as well as identifying the best models for quantifying ecosystem services changes, effort is needed to link these changes to benefits to society. For alteration of quality of water/ wetland environments, the determinants of value (e.g. proximate population, existing quality of water body) are well known, but the available economic evidence is mainly derived through studies by water companies applying Stated Preference techniques. The extent of publication of water company valuation data will influence the richness of this evidence base available for the analysis.

For the other benefits, converting changes in ecosystem services (e.g. improvements in quality of water for public supply) into benefits (e.g. reduction in treatment costs), can only be done using available literature and/or if stated preference data from water utilities are published. It also requires understanding the systems through which the benefits of ecosystem services are realised (e.g. water treatment infrastructure).

Four options are proposed for taking this work forward, the first three proposing methodologies for estimating the national value of woodland and the fourth proposing a method to optimise the placement of additional woodland within target catchments. An estimated cost range is presented for each option.

Option 1: Use the ADAS diffuse pollution model “APT” on a 1x1km grid to obtain an estimate of the land-use replacement effect of woodland on water at a national scale. This option would require some adaptation of the model to better represent the effects of woodland and to enable it to be run for Scotland. £50-70K.

Advantages: simplest and lowest cost option for national valuation; model used for a number of policy purposes in GB

Disadvantages: does not account for interception/ retention effects

Option 2: Use the ES model “InVEST” on a 1x1km grid to estimate the water ecosystem service provision of woodland on a national scale, which would account for both replacement and interception/ retention effects. This option would require verification of model for use in the UK. £60-80K.

Advantages: model designed for purpose of valuing ecosystem services; offers scope for integration of other services in the future

Disadvantages: ecosystem service models relatively new and not been extensively used in UK; would likely be more expensive than option 1.

Option 3: Create typologies for catchments and model impacts of a range of woodland configurations for a representative catchment for each typology using finer scale input data and a more detailed hydrological model. Conduct detailed economic modelling in each representative catchment in collaboration with Environment Agency & OFWAT/ water companies. Scale up results to GB based on actual woodland configurations. £170-370K.

Advantages: captures finer scale effects of woodland in a national valuation (including flooding) whilst keeping costs lower by using catchment typologies rather than modelling all catchments

Disadvantages: more complex and expensive option

Option 4: Use methods from option 3 or a spatially detailed ecosystem service model such as “LUCI” to determine the optimal placement of additional woodland depending on the catchment typology. Economic modelling could demonstrate where additional woodland cover is most cost-effective in terms of impacts on water regulation services. £130-140K for first catchment (subsequent catchments would be less).

2 Introduction

The Forestry Commission (FC) commissioned a study to assess the feasibility of valuing the contribution of woodlands to regulating water quality and quantity in Scotland, England and Wales. The main driver for this research is the need to demonstrate the value to society that woodland brings in terms of improving the quality and quantity of water and thereby reducing flood risk and reducing the cost of cleaning water so that it is potable, as well as benefiting biodiversity, landscape and those seeking recreational opportunities. Economic valuation of such non-market benefits could provide an additional reason to prioritise woodland planting by helping to demonstrate its considerable water-related value but are not assessed in this study. There are also policy drivers for the protection of water resources, such as the European Water Framework Directive (WFD).

The effects of woodland on the water environment are very much dependent on the location of the woodland and its attributes (e.g. type, size). It is recognised that planting 'the right trees in the right place' can provide considerable benefits to the quality and quantity of water. The UK Forestry Standard (Forestry Commission 2011) provides guidelines on the suitable siting and type of new planting or restocking to maximise benefits to the water environment and minimise any adverse impacts. Woodland in the 'wrong place' can have a detrimental effect on water quality and quantity in a catchment. It is therefore important to consider the spatial nature of the impacts that woodland has on water.

This study is multidisciplinary in nature, with economic, scientific and GIS aspects. It builds on reviews by Forest Research/ ADAS (Nisbet, Silgram, et al. 2011) for the scientific and GIS components and eftec (eftec 2011) for the economic valuation component. There is an increasing body of scientific evidence on the physical effects of woodland on the water environment. However, the data and methods required to quantify these effects at a national scale, taking into consideration the placement of woodland in the landscape, and subsequently link them to valuation data and methods is less well researched.

A preliminary assessment of the value of water regulation effects of forests in GB was provided by the Social and Environmental Benefits of Forest research study (Willis, et al. 2003), although no strong conclusions were drawn. The report estimated the opportunity costs of trees in terms of the effects they can have on reducing water available for public supply. These costs may have since increased due to increased population, water use and climate change. The report also discussed the effects of forests on water quality, but did not quantify the value of the impacts. Since the introduction of the WFD in 2003 a considerable amount of research has been undertaken on means of improving water quality and regulating water quantity. Currently available models, data and methods may provide a means of valuing this ecosystem services provided by woodland.

The overall aim of this study is to assess the feasibility of valuing the contribution that woodland makes to water quality and quantity by evaluating data sources and models and proposing methods to estimate the value of the resultant water-related ecosystem services.

Specific objectives are to:

1. Provide a qualitative evaluation of data sources, models and methodologies that could establish and quantify the physical effects of woodland on the water environment in Scotland, England and Wales

2. Identify any critical data gaps and options for dealing with them.

3. Identify a range of valuation methods, using the data and models identified, for estimating a value for the water quality and quantity benefits and disbenefits provided by woodlands in Scotland, England and Wales.

4. Identify how the proposals can be used to account for the spatial and context-specific nature of rivers and catchments, including the type and size of woodland and its proximity to river catchments, and if the proposals would benefit from incorporating GIS analysis.

The main focus of this study is on existing woodland cover because the methodologies that are typically used for the optimal placement of new woodland to maximise water-related benefits are very different to those that would be used for quantifying benefits of existing configurations. This study does, however, aim to investigate methods that will develop an understanding of where woodland has highest value in terms of its location in relation to the local pressures. This understanding will then help to inform where additional woodland will have highest value.

This study focuses on rural woodlands. Urban trees are not within the scope of this study. There is a separate body of research and modelling methods to value the ecosystem service benefits provided by trees in the urban environment including reduction in storm water runoff and improvement in water quality. The i-Tree software[2] developed by the US Department of Agriculture Forest Service provides a means of quantifying the structure of the urban forest and the environmental services they provide. I-Tree Hydro is designed to simulate the effects of changes in urban tree and impervious surface characteristics within a catchment on stream flow and water quality. It consists of a module designed to simulate hourly changes in stream flow due to urban land-cover characteristics and a water quality module that simulates changes in water quality. I-Tree has been applied to UK cities, for example Torbay (Rogers, et al. 2011) and Edinburgh (Hutchings, Lawrence and Brunt 2012). The model is still being developed for use in the UK, and currently only a limited number of ecosystem services can be quantified.

[2] http://www.itreetools.org/index.php

3 Defining the baseline

For any potential valuation study, a baseline will be required against which to quantify the value of existing or new woodland. This would be achieved by estimating the difference between the value of the land in the baseline and the value of the land under the alternative scenario, which would include the woodland that we wish to value.

The purpose of a valuation study could be to influence national policy (i.e. value existing woodland) or help design cost-effective policy on changes in woodland cover. These purposes would result in different baselines. In order to value existing woodland, the baseline should infer the land-use that would be most likely if the woodland were not there and the alternative scenario would be the current land-use. In order to value new woodland, the baseline would be the existing land-use and the alternative scenario would replace some currently non-wooded land with woodland.

A key issue to consider is the presence and displacement of agricultural activities. It is necessary to assume that in the absence of woodlands the land would be used for agricultural activities if economically and environmentally viable, or some other land cover where it is not. When comparing the value of water-related benefits of woodland to baseline agricultural use, the assessment needs to take into account whether there would be a net loss of agricultural activities or simply a displacement of them (and their effects) elsewhere. The net effect on society is unclear, and it can be either a net cost or net benefit depending on the choice of baseline.

We suggest that a valuation study of *existing woodland* assumes that there is no displacement of agricultural activity from the baseline. We consider this a reasonable approach as displacement that would have occurred due to the past planting of current woodland would automatically be included in the current scenario i.e. other land use change in the catchment that occurred due to the past planting of woodland would be captured in current land-use data.

If valuing woodland creation, when the impacts of agricultural activity are potentially displaced rather than avoided, the impacts of the displaced activity will vary depending on scale. At a local level, a small area of new woodland may displace agricultural activity by the farmer to another site. The proximity to water and intensity of activity at this other site will determine the impacts on the water environment. For example, if this site is grassland conversion to arable and is closer to a water body than the new woodland block, the impacts on the water environment are likely to increase. At local and larger scales, displacement may happen in a more diffuse manner, through a slight increase in intensity of farming activity across a wide area.

A key impact to assess in a detailed model for optimisation of new woodland planting is therefore the effects of displacing agricultural activity from land where it has greatest impact on the water environment (e.g. on land adjacent to water bodies and/or with greatest slope), to other land where its impacts on the water environment are lower (i.e. reflect typical locations and impacts for agricultural land).

For the main focus of this study (national valuation of existing woodland), the baseline should infer the land-use that would be most likely if the woodland were not there (i.e. it is assumed that the land is ‘optimally’ managed in its next-best use). We propose using the Agricultural Land Classification (ALC) system in England and Wales and the Macaulay Land Capability for Agriculture (LCA) system in Scotland. Both of these classification systems are analogous and make an assessment of the potential agricultural productivity of the land and the range of crops that could be grown based upon climate (e.g. rainfall), soil type (some soils are more productive than others) and topography (the hilliness of the land). They can therefore provide an indication of the likely land-use in the absence of woodland.

The LCA is a seven class system with Class 1 representing land with the highest potential flexibility of use and Class 7 having very limited agricultural value. Four of the classes are further subdivided into divisions. The classes and divisions can be simplified into four categories that are broadly indicative of the land’s agricultural capability (Table 1).

The ALC is a five class system with Grade 1 land being of excellent quality for agricultural production and Grade 5 land of very poor quality for agricultural production. Grade 3 land is further divided into two sub-grades (Table 1). The limiting factors considered include climate, site (e.g. topography) and soil.

Table 1. The Scotland (LCA) and England & Wales (ALC) land classification systems

LCA Class	Description	ALC Class	Description
Arable agriculture (classes 1 – 3.1)	Land capable of production of a wide range of crops. Climate is favourable, slopes are no greater than 7 degrees and the soils are at least 45cm deep and imperfectly drained at worst.	Grade 1	Excellent quality agricultural land. Land with no or very minor limitations to agricultural use. A very wide range of crops can be grown and commonly includes fruit and vegetables.
Mixed agriculture (classes 3.2 – 4.2)	Land capable of production of a moderate range of crops including cereals, forage crops and grass. The climate is less favourable than on prime land, slopes up to 15 degrees are included and many soils exhibit drainage limitations.	Grade 2	Very good quality agricultural land. Land with minor limitations that effect crop yield, cultivations or harvesting. A wide range of crops can be grown but on some land there may be reduced flexibility.
Improved grassland (classes 5.1 – 5.3)	Land with the potential for use as improved grassland. Limitations to capability include climate, slope and soil wetness.	Grade 3a	Good quality agricultural land. Land capable of consistently producing moderate to high yields of a narrow range of arable crops, especially cereals, or moderate yields of a wide range of crops.
Rough grazing (classes 6.1 – 7)	Land with very severe limitations that prevent sward improvement by mechanical means. The land is either steep, very poorly drained, has very acid or shallow soils, occurs in wet cool or cold climate zones or has a combination of these limitations.	Grade 3b	Moderate quality agricultural land. Land capable of producing moderate yields of a narrow range of crops, principally cereals and grass, or lower yields of a wider range of crops or high yields of grass.
		Grade 4	Poor quality agricultural land. Land with severe limitations that significantly restrict the range of crops and/or yield. Mainly suited to grass with occasional arable crops.
		Grade 5	Very poor quality agricultural land. Land with severe limitations that restrict use to permanent pasture or rough grazing.

These classification systems have well established methods and only consider physical factors that determine land quality rather than existing land-use. This is desirable for determining a baseline as existing land-use should not be a consideration. Land class data is useful for determining an alternative land-use to woodland but difficulties would arise in making the choice of baseline land-use for intermediate grades that could be used for either arable crops or grass. To guide the choice of land-use for intermediate grades in the LCA and ALC, the authors propose that the non-woodland terrestrial land-use classifications in the CEH's 2007 Land Cover Map (LCM2007) of (i) arable; (ii) improved grassland; (iii) semi-natural grassland and (iv) mountain, heath & bog are used to estimate the non-woodland land-use split within each Class or Grade at the scale of the Water Framework Directive (WFD) management catchment. A catchment is the area from which rainfall flows into a river, lake or other water-body.

An assumption should also be made for the likely crop type on arable land, since this will have a substantial impact on the pollutant loadings and erosion risk. Defra and Scottish Government June Agricultural Survey (JAC) data could be used at a county or other administrative area scale (or datasets on a regular grid derived from JAC created by ADAS or EDINA) to estimate the percentage splits of crop types within a local area or catchment.

3.1 Conclusions

For any potential valuation study, a baseline has to be defined. For the creation of new woodland, the baseline is the existing land-use. For a national valuation of existing woodland, this baseline should consider the likely alternative land-use for each parcel of woodland. We have considered the use of agricultural land classification systems and other land-use data to infer alternative land-use. We have also considered the potential economic impacts of the choice of baseline and any likely displacement effects. We recommend the use of land classification systems in conjunction with land-use data for creation of the baseline, and that an assumption is made that displacement of agricultural land does not occur from baseline to current scenario.

4 Biophysical processes determining the impacts of woodland on the water environment and factors that influence variability

4.1 Introduction

Due to the many factors that govern the effects that woodland has on water, and the need for adequate data for models to reflect these, this section presents a brief description of the processes involved and the main reasons for their variability across a landscape. More detail on the evidence for these differences is provided in Appendix 1. The availability of spatial data to represent the spatial variability in important things such as climate, soil type, topography, geology and land-use is reviewed in Section 7. This Section considers the coefficients that might be required (i.e. in the form of look-up tables that can be linked to spatial variables) to parameterise a model and whether or not such coefficients are available in the published literature. This review focused on the literature cited in the Woodland for Water project (Nisbet, Silgram, et al. 2011) and closely related studies.

The effects of woodland on water quality and quantity in a catchment can be split into two broad groupings, each of which has a fundamentally different modelling requirement. The first group deals with replacing agriculture (or another alternative land-use) with woodland. The second deals with the more complex effects of woodland intercepting and/or retaining the polluting activity from up-slope land.

1. **Effects of replacing other land uses.** When considering the difference in loads of a pollutant (fertiliser or pesticide) or water use/ infiltration for woodland compared to another more intensively managed land-use, we need to quantify the reduction in the loss of this pollutant from the land parcel. In this case, the location of woodland in relation to the surrounding landscape is not important, although other spatial variables such as soil type, geology and climate are very important. Models that simulate the movement of water and dissolved pollutants down through the soil are usually sufficient for this purpose. These types of models take no account of the subsequent flow path of the water and any interception that occurs before it reaches a water course. Sometimes such models are used to provide results at the catchment scale by simply summing the field or grid-scale results; however this does not give accurate results when we wish to also model the interception effects of woodland within a catchment (see (2)).

2. **Effects of interception and retention.** Interception in this context is the function woodland has in interrupting water flow (and thus the flow of nutrients) from upslope land and the capture of pollution from the atmosphere. Retention is the amount of pollutant or water that is prevented from continuing on the path it would otherwise have taken.

   In order to quantify the effects that woodland has on water (and diffuse pollutant) flow in a catchment, we need to consider the exact positioning of the woodland in the landscape as this determines how much water is intercepted. Other spatial variables such as soil type, geology and climate are also important. Models therefore need to route the flow of water from upslope to downslope in the catchment. If these routing models are accurate enough, woodland located where it will have greater benefit for ecosystem services (i.e. in the flow-path) will be valued more highly than that in locations where it will have less impact. Models for quantifying dissolved pollutant loads delivered to a watercourse also require linkage to the types of models described in (1) that estimate a pollutant concentration in the flowing water based on the up-slope land-use and other variables.

   Routing models are also required to model the effects of woodland parcels on sediment movement (and attached pollutants) across a landscape. The exact positioning of the woodland in the landscape determines how effective it is for intercepting and retaining sediment. Modelling requirements are thus similar to water flow, but the movement of sediment and attached pollutants across the landscape and the processes involved in interception by vegetation are different to that of water and dissolved nutrients and therefore need to be modelled differently.

   When considering the effects of reduced/increased pollutant reaching surface water bodies via the ‘scavenging’ effect of woodland on atmospheric pollution (e.g. acidic sulphur & nitrogen), the exact positioning of woodland in relation to source and water body is very important in terms of whether the effect is beneficial or detrimental to water quality.

The processes that will be considered under each group are as follows.

1 Effects of replacement of baseline land-use (LU) with woodland

a. Reduction in pollutants lost from a land parcel by woodland compared to baseline LU.
b. Increase in water use and soil infiltration by woodland compared to baseline LU.
c. Increase in surface water acidification by woodland compared to baseline LU due to increased capture of atmospheric pollution.

2 Effects of interception and retention by woodland

d. Reduction in soluble pollutant concentrations in water bodies due to interception by woodland.
e. Reduction in sediment and attached pollutant concentrations in water bodies due to retention by woodland.
f. Reduction in flooding due to interception/ retention by woodland.

The effectiveness of replacement and interception/ retention by woodland will depend on many factors, including the pollutant and the quantity applied to upslope land, characteristics of the woodland, hydrogeology, climate, topography and soil. The ranges given in Table 2 are therefore necessarily broad, but give an indication of the potential effectiveness of woodland replacement and interception/ retention on the reduction in delivery of various pollutants to water bodies. It is worth noting that the ranges for interception/ retention effects are larger than ranges for replacement effects due to the greater complexity and variability in the processes governing these.

Table 2. Ranges derived from (Nisbet, Silgram, et al. 2011) for the potential effectiveness of woodland on reducing the delivery of agricultural pollutants to water

	Nitrate	Phosphate	Sediment	Pesticides	Ammonia
Replacement	70-90%	90-100%	90-100%	90-100%	70-90%
Interception/ retention	50-90%	70-100%	50-100%	60-100%	50-90%

The processes listed above are briefly described in the remainder of this Section, with a summary of the main causes of their variability and the availability of coefficients to represent this variability in a modelling context. Many of these processes are driven by catchment hydrology. Figure 1 gives a simple schematic representation of the hydrological cycle and the influence that woodland can have on this cycle.

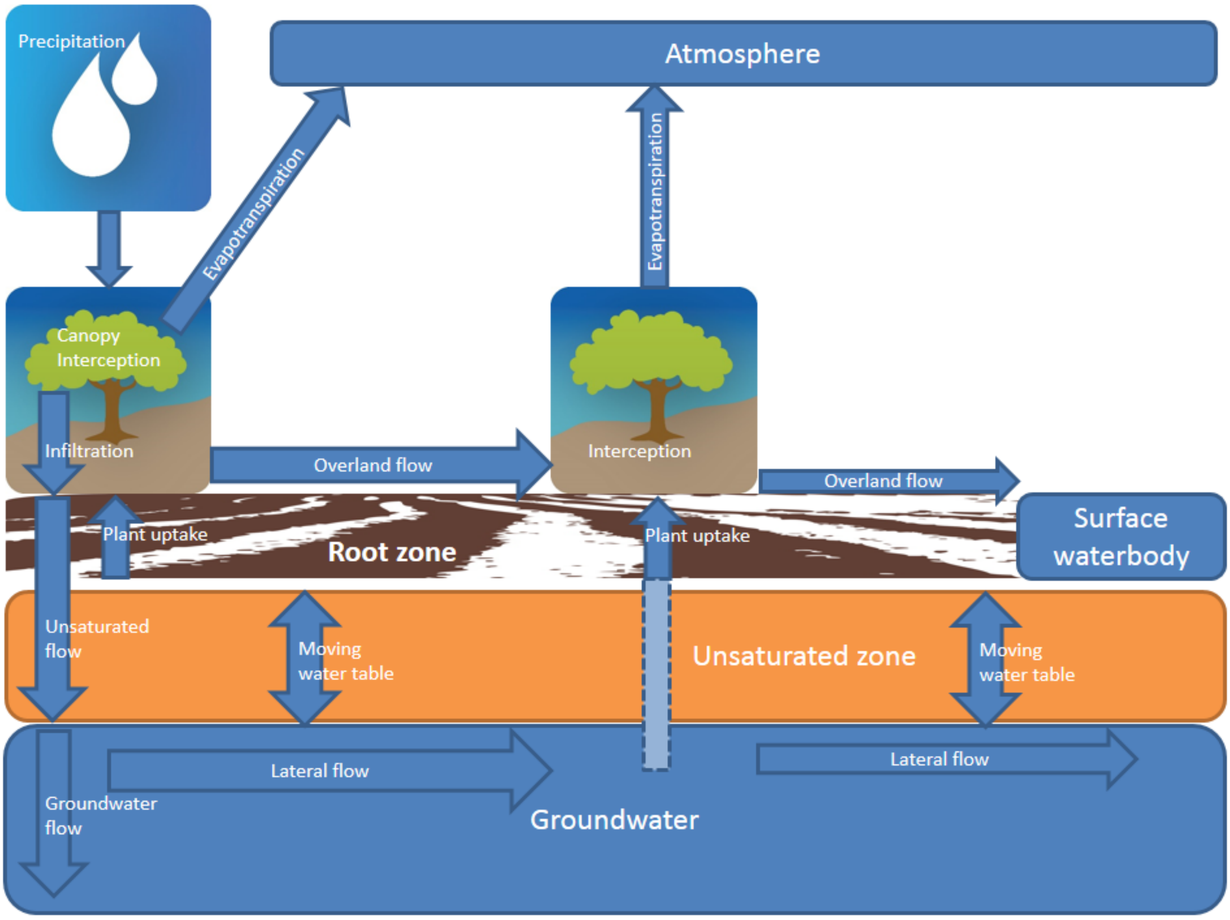


Figure 1. Simplified representation of the hydrological cycle and the influencing effects of woodland

4.2 Results

4.2.1 Reduction in pollutants lost from a land parcel by woodland compared to baseline LU

4.2.1.1 Reduction in nitrate leaching

The main source of nitrate pollution in surface and ground waters in Great Britain is managed agriculture. Fertilisers are applied in large amounts to agricultural land and approximately the same amount of nitrogen that is applied is removed via leaching (loss from soil when dissolved in water) and harvesting. Leaching to ground water and stream water is high because the soils are often saturated with nitrogen and vegetation cover is low during the wetter winter season. Leaching of nitrate from woodland is typically much lower than from arable land-uses due to the considerably lower inputs and the year-round vegetation cover increasing uptake. Inputs to woodland originate largely from atmospheric deposition of nitrogen compounds. The main variables that have been found to influence the nitrate leaching rate (and thus should have different coefficients) are listed in Table 3.

Table 3. Variables that will alter the nitrogen leaching rate and the availability of coefficients to represent these

Ideally require different N leaching coefficients for:	Available in literature?
Broad crop types (as opposed to just arable land)	Yes
Grazing livestock type	Yes
Geo-climatic region	Yes
Different N deposition rates	Yes
Deciduous vs. coniferous woodland	Yes
Different stand ages of woodland	Yes
Soil type/ geology	Yes
Recently clear-felled woodland	Possibly – could be estimated from clearfelling studies
Type of weed control for prepared woodland planting sites	No – but may be of limited importance

4.2.1.2 Reduction in erosion and phosphate loss

Well managed woodland usually has lower sediment losses compared to other land-uses such as pasture and arable. Woodland can reduce erosion by providing physical shelter from the wind, reducing water run-off, aiding infiltration of water into the soil and improving soil strength and stability (Nisbet, Orr and Broadmeadow 2004). Riparian woodland can also protect river banks from erosion. Sediment reaching water courses can damage species and habitats as well as contributing to flood risk. Eroded sediment can also be an important source of phosphate, which contributes to eutrophication of surface water. Reduction in erosion therefore also has the benefit of a reduction in phosphate export. Table 4 lists the main variables influencing sediment/ P loss and the availability of relevant coefficients from the literature.

Table 4. Variables that will alter the sediment/ P loss rate and the availability of coefficients to represent these

Ideally require different sediment/ P loss coefficients for:	Available in literature?
Broad crop types (as opposed to just arable land)	Yes
Grazing livestock type	Yes
Geo-climatic region	Yes
Soil type/ geology	Yes
Channel banks	Possibly
Recently clear-felled woodland	Possibly – should be low with good practice

4.2.1.3 Reduction in pesticide loss

Woodland usually has much lower inputs of pesticides than other managed land-uses, therefore the losses of pesticides to water will usually be lower. Table 5 lists the main variables influencing pesticide loss and the availability of relevant coefficients from the literature.

Table 5. Variables that will alter the pesticide loss rate and the availability of coefficients to represent these

Ideally require different coefficients for:	Available in literature?
Broad crop types (as opposed to just agricultural land)	Yes
Geo-climatic region	Yes
Soil type/ geology	Yes
Pesticide properties (partition coefficient, half-life)	Yes

4.2.2 Increase in water use and soil infiltration by woodland compared to baseline LU

Water recharge is the sum of surface run-off, lateral drainage and leaching to groundwater (Figure 1). It depends on the balance between rainfall, evapotranspiration and soil water storage capacity. Evapotranspiration comprises evaporation of rainfall from the plant canopy (interception), transpiration of the vegetation and soil evapotranspiration. The evapotranspiration rate of woodland is generally higher than for many other vegetation types (Calder, Reid, et al. 2002). Forest and woodland soils can also store more rainfall. Studies have shown that rates of water infiltration into soil can be up to 60 times higher in woodland compared to pasture (Bird, et al. 2003).

Table 6 shows the main variables influencing the evapotranspiration and infiltration rates and the availability of relevant coefficients from the literature.

Table 6. Variables that will alter the evapotranspiration and infiltration coefficients and their availability in the literature

Ideally require different evapotranspiration/ infiltration coefficients for:	Available in literature?	
	Evapotranspiration	Infiltration
Broad crop types (as opposed to just agricultural land)	Yes	Possibly
Coniferous vs deciduous woodland	Yes	NA
Soil type/ geology	Possibly	Yes
Climate	Possibly	Possibly

4.2.3 Increase in surface water acidification by woodland compared to baseline LU due to increased capture of atmospheric pollution.

Forests can increase the rate of acid deposition and thus increase surface water acidification. This is mainly due to the rough canopies increasing the surface area by which to capture atmospheric sulphur and nitrogen, but also due to the foliage roughness decreasing deposition velocity. Acidification of surface waters can decrease their biological and chemical quality. Emission control policies appear to be resulting in the recovery of acidified waters and thus the contribution of forestry to acidification may also be reducing. The longer-term effects of N deposition are less certain due to the possibility of nitrate loss under certain circumstances.

Table 7 lists the main factors affecting acid deposition rates to woodland and the availability of relevant coefficients from the literature.

Table 7. Variables that will alter acid deposition rates to woodland and their availability in the literature

Ideally require different acid deposition rates for:	Available in literature?
Upland vs. Lowland woodland	Yes
Deciduous vs. coniferous woodland	Yes
Size and structure of woodland	Possibly, although difficult to apply in modelling.

4.2.4 Reduction in soluble pollutant concentrations in water bodies due to interception by woodland.

Dissolved inorganic nitrogen (mainly nitrate) and soluble pesticides are transported via both surface and sub-surface routes. Woody vegetation on buffer strips can be effective in removing soluble pollutants from surface runoff by aiding infiltration into the soil. Table 8 lists the main factors affecting the soluble pollutant trapping efficiency of woodland and the availability of relevant coefficients in the literature.

Table 8. Variables that will alter interception efficiency of woodland buffers for soluble nutrients

Ideally require different coefficients for soluble pollutant trapping efficiency by:	Available in literature?
Buffer strip width	Possibly
Buffer strip composition (vegetation age and type)	Possibly
Flow velocity & volume[1]	Possibly (threshold value)
Soil type/ geology	Yes (infiltration rate)

[1] Slope, topography and artificial drainage upslope of the buffer strip and rainfall intensity will influence the flow velocity and volume, but these will be spatial variables used as input to models rather than coefficients.

4.2.5 Reduction in sediment and attached pollutant concentrations in water bodies due to retention by woodland.

Riparian buffer strips help remove suspended sediments and attached pollutants from surface runoff by the effect that the vegetation and organic litter on the soil surface have on reducing the velocity of flow and thus enabling the sediment to settle out. Suspended fine soil particles with bound pollutants also enter the soil profile. Table 9 lists the main factors affecting the sediment retention efficiency of woodland and the availability of relevant coefficients in the literature.

Table 9. Variables that will alter sediment and attached pollutant retention efficiency of woodland buffers

Ideally require different coefficients for sediment retention efficiency by:	Available in literature?
Buffer strip width	Possibly
Particle size of sediment	Possibly
Flow velocity & volume[1]	Possibly (threshold value)

[1] Slope, topography and artificial drainage upslope of the buffer strip and rainfall intensity will influence the flow velocity and volume, but these will be spatial variables used as input to models rather than coefficients.

4.2.6 Reduction in flooding due to interception/ retention by woodland.

In addition to increased water use, woodland has the ability to slow flow due to increased hydraulic roughness of the ground surface and retain water by facilitating the infiltration of surface water into the soil. This can help reduce peak flows and thus flooding risk. The main factors affecting hydraulic roughness (and thus reduction in flow velocity) and retention efficiency of floodplain and riparian woodland are shown in Table 10 along with the availability of coefficients from the literature.

Table 10. Variables that will alter flood water velocity reduction and retention efficiency of woodland buffers

Ideally require different coefficients for hydraulic roughness and flood water retention efficiency by:	Available in literature?	
	Hydraulic roughness	Retention efficiency
Woodland type	Not yet	NA
Woodland structure	Not yet	NA
Buffer strip width	NA	Possibly
Buffer strip composition	NA	Possibly
Soil type/ geology	NA	Yes
Flow velocity & volume[1]	NA	Possibly (threshold value)

[1] Slope, topography and artificial drainage upslope of the buffer strip and rainfall intensity will influence the flow velocity and volume, but these will be spatial variables used as input to models rather than coefficients.

4.3 Conclusions

This feasibility study has included a brief review of the main water-related processes that can be modified by woodland, with the aim of determining the key variables that influence the magnitude of these effects for each process.

In general, for modelling replacement effects, pollutant loss or water use coefficients would be required by broad crop types, livestock types, geoclimatic regions, woodland types (deciduous vs. coniferous) and ages and soil types. For modelling interception/ retention effects, the commonly required coefficients would vary by woodland strip width, strip composition, flow velocity and soil type/ geology.

Many of the coefficients that would have the greatest influence on the outputs are available in the published literature. Others may be available, but a more comprehensive review would be required to identify them and or/ expert judgement used. Care should be taken when using coefficients that they are applicable to the situation in the UK, since woodland management practices and environmental factors can be very different in other countries.

The interactions between different influencing variables are also important in many situations, for example a nitrate leaching coefficient for a particular crop type will vary by soil type and the efficiency of a buffer strip of a certain width will vary depending on the flow velocity and volume.

5 Economic approach for valuing woodlands' environmental goods

This Section considers the economic methods available to value the impacts of woodland cover on water ecosystem services, and how they have been applied in relevant published studies. The objectives of a valuation study would be to apply valuation evidence to the impacts of woodland on water across the UK. For this, we review the economic valuation methodologies commonly used for these purposes and we conclude that there exist suitable generic national values for changes in water ecosystem services.

5.1 Economic valuation methodologies

This Section identifies the economic methods that are available to value the ecosystem service processes provided by woodlands in relation to the water environment. All the processes identified in the previous Section use widely different physical units as a measure and hence a benefit of valuation is that a common numeraire of money is used.

The preference is for economic value data to be obtained from market sources. However, there are few, if any, markets for the impacts of woodland on water ecosystem services, at least in the UK. Therefore, other valuation techniques are likely to be required. These other valuations method can be based on (i) market price proxies, (ii) surrogate market data or (iii) hypothetical market data. The method choice will depend on whether these biophysical processes can be linked to a market transaction that reflects their economic value or if this has to be elicited by estimates of individuals' preferences. Detailed definitions are provided below:

- **Market price proxies** consider the costs that arise in relation to the provision of environmental goods and services that may be observed directly from actual markets. These costs can take the form of replacement costs (e.g. avoided capital and operating costs of an alternative provision) as well as avoided damage costs (e.g. costs that would be assumed due to an extreme event such as flooding). Hence, market proxy approaches can only be used for environmental goods and services that are marketed, or have clear market-based substitutes. An example of the latter is that some of the biophysical processes provided by forests can be valued on the basis of the cost of constructing equally effective human-made (or 'grey') infrastructures.

- **Surrogate market data** is obtained by observing consumer behaviour (known as revealed preferences) in relation to a traded good in order to infer the value of a good or service that is not traded. An example is hedonic property pricing, which is based on the notion that the price at which a property is sold is determined in part by the environmental characteristics of the surrounding location, including disamenities such as being in a flood-prone area. The difference between the prices of otherwise similar houses therefore imply a value for those characteristics. Such differences can also be reflected in the costs of insurance. Another typical approach is the avertive behaviour method, which uses the cost incurred by individuals for alternatives to the environmental good, such as water filters in cases of bad water quality. Another potential approach in this category would be the travel cost method, which uses the cost incurred by individuals in travelling to and gaining access to a site as a proxy for the value of that site. In practice it would probably be difficult to separate out the impacts of the presence of trees from other impacts on water quality. A caveat for these methods is that they can only value the environmental characteristics that are perceivable by the individuals.

- **Hypothetical market data** is used to value intangible or unquantifiable impacts by means of direct responses (known as stated preferences) from a representative sample on questions concerning what they are willing to pay (WTP), or willing to accept, for a specified environmental change. The data collected through surveys, which are used to estimate WTP, consists of attitudes, behaviours and preferences, i.e. trade-offs respondents make between an improved ecosystem services provision and outcomes, and money. The method is particularly flexible in the sense that it facilitates the valuation of environmental goods including the changes that are yet to be experienced (such as a deterioration of water quality or an increased risk of flooding), but is contingent on respondents' understanding of changes.

Given the choice of economic valuation methods potentially suitable for valuing environmental goods, the choice on which best fits can be based on a hierarchy as suggested in (UKWIR 2010):

- If market price data exist and are relevant for the given analysis (i.e. fully reflect the value for a change in provision of a good or service for its users), such data should be preferred as they can be verified. However, they may need to be adjusted to reflect the influence of transfers such as subsidies;

- If market price data do not exist, then suitable revealed preference data are preferred as they show how people's actual behaviour reflects their preferences;

- If neither market nor revealed preference data exist or are not appropriate (i.e. the baseline scenario might not exist in order to be compared), stated preference data should be used.

The choice of valuation techniques for an impact from woodland on the water environment may not be limited to a single method. There could be cases where an ecosystem service provided by woodlands has impacts that are reflected in different goods and services that may be valued through different valuation techniques. For instance, the benefit of avoiding pollutants entering water can include avoided investment in alternative 'grey' infrastructure (a market value) to treat water for public supply, as well as increased wellbeing from enhanced water-based recreational opportunities (a non-market value). Care is needed if this is the case, in order to avoid double-counting of benefits.

This Section identifies a choice of valuation techniques, but none will provide catchment-specific values for all the impacts of woodland on water being considered. Therefore, we suggest that any modelling should rely on using 'value transfer' to apply existing economic valuation evidence to each particular catchment. Value transfer is a process of searching, selecting and where relevant adjusting economic value (cost and benefit estimates) evidence from the literature for use in valuation assessments (eftec 2010).

Value transfer is considered a more efficient approach than carrying out primary valuation work across all areas impacted on a catchment basis. To get more specific catchment level values (i.e. a catchment by catchment survey of people's values for changes in ecosystem services) is not considered feasible due to the costs of the very large survey samples required. An alternative approach would be a national valuation survey with sufficient sampling to breakdown results according to different catchment characteristics, enabling meta-analysis of values to derive specific values for each catchment. This would also be very expensive (see Section 9).

5.2 Applied methodologies for valuing the benefits of woodlands

A methodological review of economic literature on the water ecosystem services benefits from woodlands was undertaken. This identified studies using the research team and steering groups' existing knowledge and participation in previous projects. This review was undertaken to give an insight on how the valuation methods in 5.1 have been used to value the impacts of the biophysical processes described in Section 4. The review took into account not only the economic valuation approach used, but also the modelling and measurement methods for the biophysical processes considered, if appropriate.

The following summarises the valuation methods found in the literature review against the biophysical processes identified in Section 4.

a. Reduction in pollutant loss from woodland compared to baseline LU (i.e. improvement in water quality):

- Revealed preferences (avertive behaviour): this relates to the value of the expense of bottled water/ water filters that households would save if less pollutants were present in water. However, it would be difficult to separate the motivation for this expenditure that relates to pollutants and other factors influencing consumers trust in raw water quality and in treated water (from public water supplies). Further primary research could help to better differentiate these links between additional expenses incurred due to presence of pollutants and other causes such as trust on the water service.

- Replacement cost: estimation of the reduced need for capital and operating costs of "end of pipe infrastructure" (water filtration equipment, new water treatment plants, etc.) to bring water supply to a particular level of quality.
- Stated preferences: WTP to bring (part of) a water body to a certain level of improved quality (many studies use 'good ecological status' as defined under the Water Framework Directive) (e.g. £ / household / km of river/ year).
- NB: these two methods (replacement cost and stated preferences) may be considered as valuing two different environmental goods and hence they are potentially additive; further discussion is provided in Section 5.3.

b. Increase in water use by woodland compared to baseline LU (i.e. regulation of water flows and increase / decrease of water supply):

- Avoided damage cost: in case the water body provides a commercial service that is dependent on a minimum flow (e.g. navigable canals; or hydropower plants), the reduction / increase of water availability can be used for modelling how the activity would be affected (e.g. changes in traffic, changes in energy production) and a market value can be assigned.
- Stated preferences: a WTP value can be obtained for (i) avoidance of water use restrictions; (ii) bringing the river to good ecological status (link to the low flows element in the economic valuation of Water Framework Directive target of good ecological status); and/or (iii) improved conservation or improvement in the condition of Sites of Special Scientific Interest (SSSIs).

c. Increase in surface water acidification compared to baseline LU due to increased capture of atmospheric pollution:

- Avoided damage cost: evaluating potential effects on recreational fish, effects on corrosion of water pipes (valued as investing costs avoided), and on human health risks.
- Stated preference: identifying WTP to avoid fish and health impacts identified above
- Replacement cost: cost that should be assumed in liming each hectare of forest affected by acidification (e.g. below pH 5) to bring it back to desirable levels.

d. Reduction in soluble pollutant concentrations in water bodies due to interception by woodland (i.e. improvement of water quality):

- Replacement cost: estimation of the reduced need for capital and operating costs of "end of pipe infrastructure" (water filtration equipment, new water treatment plants, etc.) to bring water supply to a particular level of quality. If focusing explicitly on retention of nitrogen and phosphorus by forest cover, valuation of each kg absorbed as the avoided cost in investing in treatment facilities is also done.
- Stated preferences: WTP to bring (part of) a water body to a certain level of improved quality (many studies use 'good ecological status' as defined under the Water Framework Directive) (e.g. £ / household / km of river/ year).
- NB: these two methods (replacement cost and stated preferences) may be considered as valuing two different environmental goods and hence they are potentially additive; further discussion is provided in Section 5.3.

e. Reduction in sediment concentrations in water bodies due to retention by woodland:

- Replacement cost: downstream dredging costs that should be assumed due to sediments delivered (m3/ha/year). In UK, this is most likely to translate into reduced costs of dredging silt to keep commercial water ways open (e.g. harbours, marinas), or maintain dams for water storage and/or hydropower generation.
- Stated preferences: WTP to avoid discoloured tap water.

f. Reduction in flooding due to interception / retention by woodland:

- Avoided damage costs: the costs of flooding can be estimated by using past events or by modelling the property affected and estimating their market value (market prices, input-output

modelling, etc.); the avoided cost is measured by estimating the change in the risk or probability of flooding, and applying this to expected damages. It can also potentially be measured through differences in insurance costs.
- Replacement costs: reduced replacement or construction costs for flood water management infrastructure due to reduced risk of flooding.
- Revealed preferences (hedonic prices): comparing the market value of household properties in a flood-prone (lower values) and a flood-protected area (higher values).
- Stated preferences: WTP to avoid flood events or reduce its frequency/severity (£ / household / property affected).

The overall conclusions from this review are that:

- All valuation techniques can be applied in most of the biophysical processes identified, although it is rare to find revealed preferences (only applied in reductions of flood runoffs and reduction of nutrient concentrations); there is a large reliance on cost-based approaches (especially replacement costs) as they appear to be the most straight-forward to calculate.

- Most of the literature reviewed covers areas beyond GB (mainly Europe and North America), but practically all methods can be applied to GB woodlands.

- Apart from the valuation of single-processes (absorption of phosphorus and nitrogen; flood runoff regulation etc.), the literature review also identified economic evidence from single valuation methods that can be applied to carry out a "collective" valuation of the impacts of all the processes in a bundle, including some non-water ecosystem services.

The economic methodologies reviewed above are applied in practice for single biophysical processes. However, the review above simplifies the fact that it isn't possible to link all the evidence from the valuation literature to a set of processes neatly defined with a single set of terminologies. Different terms are used in different studies. For the objective of this project, to provide a comprehensive valuation framework for the water ecosystem services provided by woodland cover, the processes can be grouped. The processes reviewed above generally relate to three types of final ecosystem services:

- Concentrations of contaminants in surface and ground waters;
- Quantity of water in surface and ground waters; and
- Volume of flows entering surface waters during extreme events (flood and drought).

5.3 Categorisation of environmental goods to be valued

In line with the UKNEA framework, the final ES identified in Section 5.2 should be valued in relation to the benefits they provide to people. We recommend that a valuation of GB woodland's water ecosystem services should focus on the following four benefits of value to people:

- Reduction in costs of public water supply;
- Alteration of quality of water / wetland environment;
- Reduction in flood risk / damage; and
- Reduction in service interruptions during drought.

This considers the processes related to water quality status, covering the release of pollutants and sediments from different sources; and the processes related to extreme events, covering protection in flood events and service interruptions during water scarcity periods. They are further described below:

- **Reduction in costs of public water supply:** the presence of forest cover in a water catchment alters the concentration of contaminants in surface and ground waters (nutrients, pesticides, sediments, etc.) and this is expected to have an impact on water treatment processes for water supply. Hence it could avoid incurring costs for extra treatment required for poor raw water quality.

- **Change in quality of water / wetland environments:** some of the processes that affect water quality can be assessed collectively via changes in individuals' wellbeing for alterations in the general quality status of the water catchment, i.e. recreational benefits, non-use value, cultural and heritage benefits, etc. As seen in the previous discussions, these changes correspond to a non-market valuation approach, suitable for stated preference studies. Note, however, that this environmental good could entail some double-counting with regards to the previous good, in the sense that the perceived quality of public water supply would be embedded in stated preference responses for the quality of water in the natural environment; care is needed in assessing the nature of the studies used to assess this risk.

- **Reduction in flood risk / damage:** forest cover alters the volume of flows entering surface waters, and water runoff, during extreme events such as intense precipitation. As a result, woodland can reduce flood risks. As seen in the previous discussion, different approaches to valuation can be applied depending on the nature of the underlying data – either via avoided damages or non-market valuation.

- **Reduction in service interruptions during drought:** water flows in the catchment are affected by the land use; forest cover would have a mixed effect on water flows, depending on a number of factors. Woodland can reduce water volumes entering rivers, hence reducing water flows, but can also increase infiltration to groundwater, potentially helping maintain groundwater fed river flows and or resources abstracted during low rainfall periods. Impacts on water availability can have many impacts on water users, including to households, businesses, hydropower generation and agricultural production. These impacts imply market costs (e.g. cost of hydropower foregone or industrial activity stopped due to water shortages) or non-market costs (e.g. wellbeing affected due to supply interruptions / hosepipe bans).

Each of these environmental goods can be valued using different approaches, depending on the feasible combination of economic values available and the physical outputs provided by the modelling tools. The categorisation presented here is used in Section 6 to evaluate the potential translation of model outputs into monetary values for each of the environmental goods.

The links from the three final ES to these benefits are shown in

Table 11. Figure 2 depicts the pathways by which the individual biophysical processes in Section 4 have been translated into benefits to society. The diagram starts by listing the biophysical processes that are affected by the presence of woodland, grouped into interception/ retention effects and replacement effects. These individual processes are further grouped into three broad ES relating to the quality and quantity of water. Finally, the practical economic valuation of these three ES is done by linking them to four benefits delivered to society for which people can assign a value. It is noted that some of the benefits described can be considered as stocks of natural capital (e.g. the quality of wetland environments), but in this instance they are valued in terms of the flows of benefits they produce (e.g. the annual existence value of having healthy wetlands for recreation).

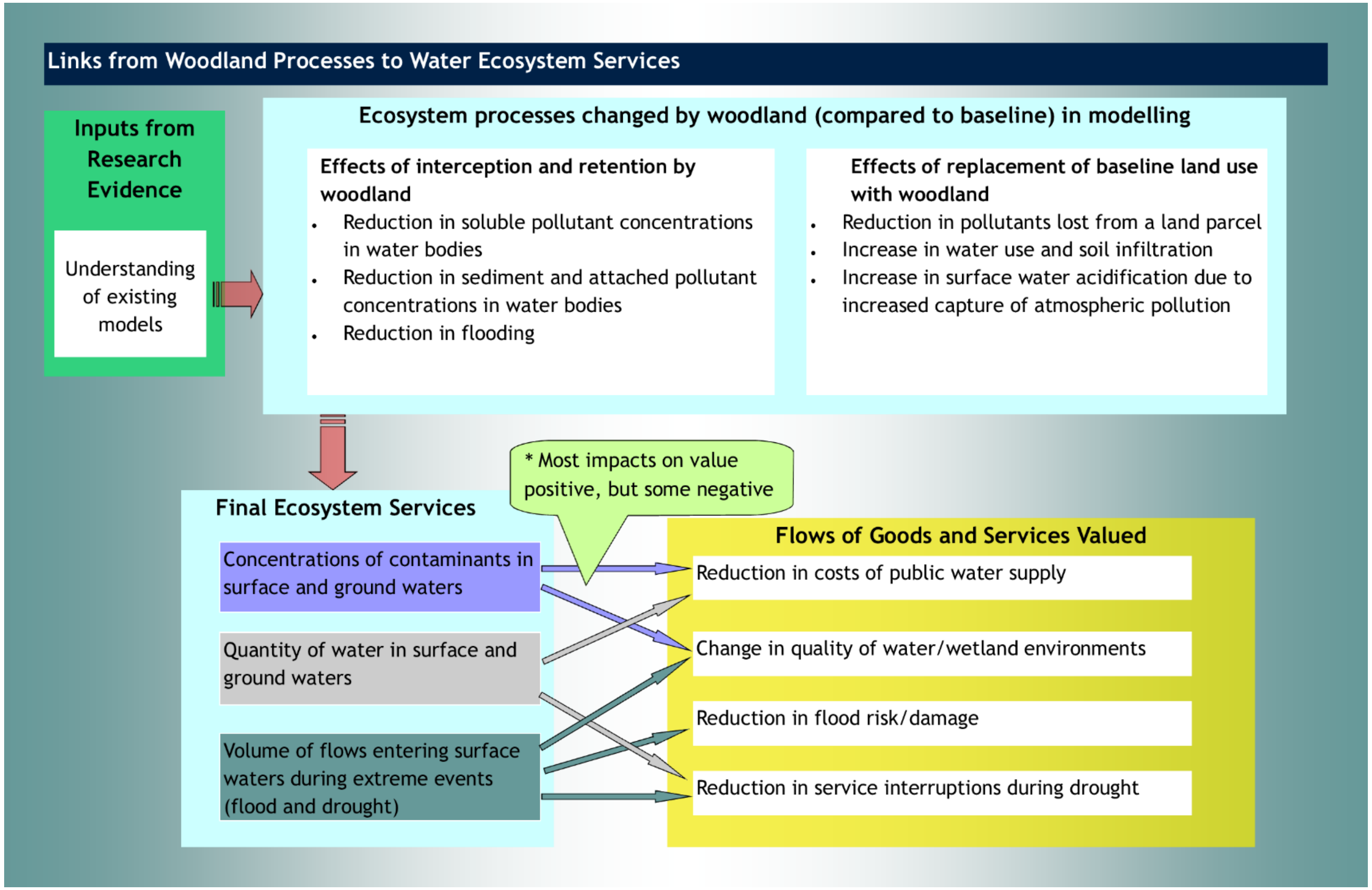
As shown in Figure 2, most of the links from the final ecosystem services to the benefits are positive, but some can be negative.

These valuation approaches for these benefits are discussed further in Section 8, where a practical link is made between the biophysical outputs from the modelling tools and the feasible options to estimate their economic value.

Table 11. Links from three final water ES from woodlands to four benefits valued.

Final ES influenced by woodland	Benefits			
	Reduction in costs of public water supply	Alteration of quality of water / wetland environment	Reduction in flood risk / damage	Reduction in service interruptions during drought
Concentrations of contaminants in surface and ground waters	**Yes**	**Yes**	No	No
Quantity of water in surface and ground waters	**Yes**	No	No	**Yes**
Volume of flows entering surface waters during extreme events (flood and drought)	No	**Yes**	**Yes**	**Yes**

Figure 2. Linking Woodland Processes to Water Ecosystem Services



6 Models and methods

6.1 Introduction

As discussed in Section 3, quantifying the contribution of woodland to water quality and quantity requires a baseline against which to compare the relative effect of woodland vs. non-woodland. Given that there is no way of attributing measured quantities (e.g. stream monitoring data) to the effect of woodland in the catchment without knowing what these measured quantities would have been in the absence of the woodland, we need to use models to carry out scenario analysis. In other words, we need to run a model at least twice; once with the current land-use and once with the baseline land-use. Comparison of the model outputs would then, in simple terms, enable a quantification of the contribution of woodland to the outcome.

Models and methods that quantify the hydrological processes of interest to this project are numerous and highly variable in terms of their methodologies and complexity. The review in this Section focuses on those that are widely cited in the literature and that were considered potentially capable of quantifying the impact that woodland may have on these processes (i.e. the ecosystem function of woodland). The models and methods considered here range from relatively simple export coefficient models to complex hydrological models.

Different models may need to be considered for carrying out a national-scale valuation of existing woodland and for carrying out a marginal valuation of woodland in a specific catchment and a specific location. For the former, it may be sufficient to use coarser scale, simpler modelling, which we will term 'macro-modelling'. For the latter, finer scale modelling ('micro-modelling') would be needed to capture the interception effects of narrower strips of woodland and would normally need to be applied on a per catchment basis.

The models are evaluated in terms of their ability to characterise the ecosystem processes changed by woodland environment, and quantify changes in final ES. Depending on the valuation methods adopted (with different and multiple options being available for the different flows of goods and services valued – see Section 5), further analysis may be required to link the final ES changes to the changes in flows of goods and services (see Section 8).

We also consider for each potentially useful model whether it would be most appropriate to use average values (e.g. average reduction in nutrient concentrations in surface water due to woodland nationally) or use thresholds (e.g. water quality thresholds for a water body based upon WFD guidance).

The review is based around the following considerations as to the suitability of each model and method, focusing on macro-modelling but also considering potential uses for micro-modelling;

- Methodological approaches
- Spatial scale
- Temporal representation
- Applicability to UK
- Data requirements
- Parameterisation
- Model outputs
- Optimisation and Uncertainty
- Accessibility
- Ease of translation of physical results to monetary valuations
- Summary of advantages and disadvantages
- Suitability for this specific application

The model characteristics that were considered under each heading are described in detail in Appendix 2.

Whilst we have taken care to thoroughly assess the information available on each of the models based on a review of information contained in user manuals, published model applications and other reference materials, the review did not include testing of any of these models. Some models are better documented than others and this may be reflected in the detail of information we have provided. We therefore make no guarantees as to the accuracy or completeness of the information provided in this report.

6.2 Model Evaluation

A full evaluation of each of the 18 models considered is provided in Annex 2. In this section, we give a brief overview of each of the models that were assessed as suitable or potentially suitable for a national valuation study and consideration of the ease of translation of physical outputs into monetary valuation (which is the link between the two disciplines and thus of high importance). Four models were considered potentially suitable for both macro- and micro-modelling. Seven were considered potentially suitable for macro-modelling only and two for micro-modelling only. Five were considered unsuitable. These results are summarised further in Table 14.

6.2.1 Process-based pollutant loss models

These types of models are widely used to estimate diffuse pollution loads delivered annually to water bodies by summing the loads exported from a variety of land uses. Export coefficients for different land uses and locations can be derived from scientific literature. They do not explicitly model the routing of flow over the land and therefore cannot account for interception/ retention effects of woodland. Three examples of widely used ADAS pollutant loss models are given here.

6.2.1.1 NEAP-N (Lord and Anthony 2000)

NEAP-N is an export coefficient model that has been developed over the last two decades by ADAS to predict the concentration of nitrate in water draining from agricultural land to surface and groundwater. The model takes into account climate, soil type, animal number and type, crop type and agricultural practice. It has been validated against detailed monitoring on a variety of commercial farms across England and Wales, as well as Environment Agency catchment monitoring data. The predictions from the model are on a 1km grid and represent the input concentration of nitrate from agriculture to surface water and groundwater. NeapN underpins Defra and Welsh Government nitrate policy and is a key component of the Environment Agency method for defining Nitrate Vulnerable Zones. It has also been parameterised for Scotland.

- This model is assessed as **suitable** for macro-modelling of the **replacement** effects of woodland, but may need some refinements as woodland is currently represented in a relatively simplistic way.
- The model is **unsuitable** for micro-modelling as it cannot quantify interception/ retention effects.

6.2.1.2 PSYCHIC (Davison, et al. 2008)

PSYCHIC models phosphorus (P) and suspended sediment (SS) losses in land runoff and subsequent delivery to watercourses via underdrainage and surface pathways. At catchment scale, the model uses easily available national scale datasets to infer all necessary input data. The model is sensitive to a number of crop and animal husbandry decisions, as well as to environmental factors such as soil type and field slope angle. The catchment scale model runs on a 1km grid.

- This model is assessed as **suitable** for macro-modelling of the **replacement** effects of woodland, but may need some refinements as woodland is currently represented in a relatively simplistic way.
- The model is **unsuitable** for micro-modelling as it cannot quantify interception/ retention effects.

6.2.1.3 APT – Agricultural Pollutant Transfer framework

This ADAS model framework was developed for national scale modelling for policy support. It builds on PSYCHIC and NEAP-N to provide estimates of multiple pollutant losses, which benefit from shared input data and common hydrological and crop growth models. Outputs to 1km grid.

- This model is assessed as **suitable** for macro-modelling of the **replacement** effects of woodland, but would need parameterisation for Scotland and may need some refinements to how woodland is represented.
- The model is **unsuitable** for micro-modelling as it cannot quantify interception/ retention effects.

These three models would cover the processes that allow valuation of the following three environmental goods:

Costs of public water supply. The avoidance of replacement investments in water treatment facilities can be linked to the model outputs by comparing the concentration indicators of several pollutants in the two scenarios modelled (current forest cover vs no forest cover). In addition, water temperature would provide an additional valuation of avoidance damage in case it is considered to affect water treatment process.

Quality of water / wetland environments. The indicators on water quality are usually used to evaluate whether a good ecological status of the water body (in terms of WFD compliance) is achieved or not. Value transfer of non-market values for this can be applied in this case (WTP for a km of river in good status).

Reduction in service interruptions during drought. Surface runoff and other water flow indicators can be used to value potential water use restrictions. These restrictions (potentially measured in m^3 of water deficit or probability of water shortages) can be measured by market effects or WTP to avoid the restrictions. However, it is not possible to directly link the physical indicators with scenarios of water availability shortages without a further iteration with water management models.

6.2.2 Ecosystem Service models

6.2.2.1 InVEST – the Natural Capital Project (Tallis, et al. 2013)

InVEST is a toolset of integrated models for quantifying, mapping and valuing the benefits provided by ecosystems. The models estimate the amount and value of environmental services provided by the current landscape or for alternative scenarios. The spatial resolution of the modelling is flexible and dependent upon the spatial scale of the input data. The models within InVEST are tiered, with lower tiers being simpler models with simpler data requirements. There are three modelled processes in InVEST that are of interest to this project. These are “Reservoir Hydropower Production”; “Water Purification: Nutrient Retention” and “Sediment Retention Model: Avoided Dredging and Water Quality Regulation”.

The three water-related processes modelled by INVEST can be used to cover the valuation of some of the environmental goods considered. These are specifically as follows:

Costs of public water supply. The outputs on *nutrient retention* (kg of nutrient retained by each sub-catchment) can be converted in monetary values by valuing each kg prevented from entering water bodies as the avoided cost in investing in water treatment facilities (usually provided in £ per kg of nutrients). A threshold would be need if considering avoidance of lumpy investments (i.e. large expenditures triggered by a certain threshold). In addition, the outputs for *sediment retention* can complement the previous valuation as a value can be set based on replacement costs for dredging of navigable waters and sediment removal in drinking water. Again a threshold can be established on the minimum amount of tonnes that need to be retained to avoid incurring costs for dredging operations or more treatment). Value transfer of stated preference values could also be applied if it is considered that sediment retention could have an impact in terms of coloured tap water (WTP to avoid this effect).

Quality of water / wetland environments. Value transfer of stated preference values can be combined with the overall *nutrient retention* if the amount of nutrients absorbed is linked to impacts on good ecological status of the sub-catchment. This aspect should account for potential double-counting if considered in addition to the previous aspect.

Reduction in service interruptions during drought. The model provides estimates on whether variations in flow would imply renewable energy generation foregone. This valuation can be done through the avoided damage in terms of the value of the energy not produced. The associated increase in conventional energy emissions can be valued through social cost of additional GHG emissions.

The models currently available in InVEST cover surface water quality regulation and sediment regulation. Whilst the hydropower production model estimates water yield and scarcity for a catchment, it doesn’t cover regulation of extreme events such as flood and drought due to the annual time-step.

- Tier 1 models are assessed as **suitable** for macro-modelling due to their simplicity and flexibility in spatial scale and thus representation of land-cover mosaics.
- Tier 2 models (when available) are **potentially suitable** for micro-modelling.

6.2.2.2 Polyscape/ LUCI (Jackson, et al. 2013)

LUCI (Land Utilisation & Capability Indicator) is an extension of the Polyscape framework that is being jointly developed by the University of Wellington (New Zealand) and the Centre for Ecology & Hydrology. It works at a scale of 5-15m grid cells and is therefore suitable for modelling the effects of small land parcels such as riparian woodland. It currently includes modules for flood risk, erosion, sediment delivery and water quality (under development).

The tool would cover the processes that lead to a reduction in flood risk / damage. However, it does not provide a quantitative assessment of the changes in flood runoff for different forest cover scenarios, but instead just recommends the areas that should be planted in order to intercept sediments or reduce flood vulnerability. Some 'rule of thumb' would be required in order to determine the extent to which the current forest cover decreases the probability of flooding events or reduces their severity as opposed to a baseline scenario of no forest cover, so this approach is less suitable.

Revealed preferences such as the difference in market value of household properties in a flood-prone area (lower values) and a flood-protected area (higher values) could be used as these methods can be based on qualitative assessment of flood risk, and do not need quantified inputs, i.e. they do not require any link with a modelled physical quantified data output. However, these could be problematic to generate.

- Its methods and spatial representation of processes seem sound, therefore it is assessed as **potentially suitable** for national valuation, but there may be difficulties in translating outputs to monetary values.
- It is assessed as **suitable** for prioritising woodland location in risky catchments. Calculations could be made of the area of mitigated land for each woodland parcel based on the outputs, which could then be used to characterise the woodland in terms of the magnitude of its mitigating effect.

6.2.2.3 ARIES – Artificial Intelligence for Ecosystem Services (Bagstad, et al. 2011)

ARIES uses probabilistic models to map the locations and quantity of the potential provision of ecosystem services (sources), their human beneficiaries (users), and any biophysical features that can interrupt service flows (sinks). The service flows across the landscape are then mapped. ARIES has models for flood regulation, sediment regulation and water supply. Due to the use of annual averages, extreme events cannot be modelled.

The outputs provided are semi-qualitative and this complicates and reduces the accuracy of their potential translation into economic terms. No economic valuation is provided in model framework.

- Assessed as **potentially suitable** for national valuation, however the translation of the outputs to monetary values may be problematic.
- Assessed as **not suitable** for valuing marginal effects due to the probabilistic approach.

6.2.2.4 TIM – The Integrated Model (Bateman and Day 2013)

The Integrated Model (TIM) was very recently developed by the Centre for Social and Economic Research on the Global Environment (CSERGE) for a follow-on project for the UK National Ecosystem Assessment (Bateman and Day 2013). It incorporates biophysical modules with economic valuation. TIM incorporates several component models for agricultural and timber production, GHG flows, recreation, water quality (nutrients) and biodiversity. The main purpose of TIM is for the evaluation of land-use options that deliver the best value for money for the individual user and for society as a whole.

The biophysical outputs can be linked to the environmental goods valued, in two ways:

Costs of public water supply. The indicator of annual nutrient (nitrates and phosphates) loss per hectare can be converted in monetary values by valuing each unit (kg/ha) as the avoided cost in investing in water treatment facilities (usually provided in £ per kg of nutrients).

Quality of water / wetland environments. The nutrients categories in each WFD river water body can be linked to the attainment of a good ecological status. This scenario has a non-market value as estimated by the NWEBS survey or the customer valuation studies done by water companies for OFWAT.

- Assessed as **potentially suitable** for national valuation of woodlands' contribution to water quality with respect to nutrients, particularly if assessing against attainment of good ecological status in WFD.
- Assessed as **not suitable** for micro-modelling due to relatively coarse scale of modelling and thus inability to accurately model interception effects at a parcel scale.

6.2.3 Catchment-scale hydrological models

6.2.3.1 SWAT (Arnold and Fohrer 2005)

SWAT is the Soil and Water Assessment Tool, a catchment scale model developed for the USDA Agricultural Research Service. It was developed to predict the impact of land management practices on water, sediment and agricultural chemical yields in large complex catchments with varying soils, land use and management conditions over long periods of time. It is designed to study long-term impacts rather than, for example, single-event flood routing.

Based on the outputs provided, some indicators can be used to value some of the environmental goods considered in the project, as follows:

Reduction in flood risk / damage. Surface runoff and other water flow indicators can be used to value flood risk protection. However, it is not possible to directly link the physical indicators with scenarios of avoided floods. A rule on the risk avoided would need to be applied in order to use market price proxies or stated preference techniques. This approach is not ideal, but potentially feasible.

Reduction in service interruptions during drought. Surface runoff and other water flow indicators can be used to value potential water use restrictions. These restrictions (potentially measured in m^3 of water deficit or probability of water shortages) can be measured by market effects or WTP to avoid the restrictions. However, it is not possible to directly link the physical indicators with scenarios of water availability shortages without a further iteration with water management models.

Costs of public water supply. Organic N and P loading retained can be linked to the cost of water treatment that would arise in the absence of forest cover (measured as £/kg). Sediment yield indicator can also be used to set a value based on replacement costs (dredging costs). In this latter case, a threshold needs to be established on the minimum amount of tonnes/ha that need to be retained as to avoid downstream dredging. Non-market valuation can also be applied if it is considered that an absence of sediment retention could have an impact in terms of coloured tap water (WTP to avoid this effect).

- Assessed as **potentially suitable** for use for macro-modelling, perhaps for specific catchments, due to its incorporation of all of the water related ecosystem services under consideration.
- Assessed as **not suitable** for micro-modelling because of limitations of the flow routing.

6.2.3.2 RHESSys (Tague and Band 2004)

RHESSys is a GIS-based modelling framework that integrates water and chemical cycling and transport over spatially variable terrain.

The outputs of the model could be combined with economic valuation techniques in order to cover the valuation of the four environmental goods considered in the economic assessment:

Reduction in flood risk / damage. Surface runoff and other water flow indicators can be used to value flood risk protection. However, it is not possible to directly link the physical indicators with scenarios of avoided floods. A rule on the risk avoided would need to be applied in order to use market price proxies or stated preference techniques.

Reduction in service interruptions during drought. Surface runoff and other water flow indicators can be used to value potential water use restrictions. These restrictions (potentially measured in m^3 of water deficit or probability of water shortages) can be measured by market effects or WTP to avoid the restrictions. However, it is not possible to directly link the physical indicators with scenarios of water availability shortages without a further iteration with water management models.

Costs of public water supply. The reduced concentration of nitrate in stream as a result of forest cover could be converted to monetary values based on the avoided cost in investing in water treatment facilities. A threshold would be needed if considering avoidance of investment in whole treatment facilities.

Quality of water / wetland environments. Value transfer of non-market valuation can be applied if the overall indicators of water quality can be linked to a change in the water framework directive quality status. This aspect should account for potential double-counting if considered in addition to the previous aspect.

- Assessed as **potentially suitable** for macro- and micro-modelling due to it being one of the few models reviewed that simulates forest growth and can incorporate overland flow on impervious surfaces. Does not model pesticide, sediment and P loss and movement.

6.2.3.3 CAS-HYDRO (Conlan, et al. 2005)

CAS-Hydro is a catchment hydrological and water quality model developed in the UK, funded by UKWIR. It is able to simulate the movement of water and nutrients through the terrestrial and aquatic environments.

The tool would cover the processes that allow valuation of the following two environmental goods:

Costs of public water supply. The avoidance of replacement investments in water treatment facilities can be linked to the model outputs by comparing the concentration indicators of several pollutants in the two scenarios modelled (current forest cover vs no forest cover). In addition, water temperature would provide an additional valuation of avoidance damage in case it is considered to affect water treatment process.

Quality of water / wetland environments. The indicators on water quality are usually used to evaluate whether a good ecological status of the water body (in terms of WFD compliance) is achieved or not. Value transfer of non-market values for this can be applied in this case (WTP for a km of river in good status).

- Assessed as **potentially suitable** for macro-modelling if used at a catchment scale and then extrapolated to GB as computationally intensive.
- Assessed as **potentially suitable** for micro-scale modelling of a few catchments. Does not model sediment loss and transfer.

6.2.4 Atmospheric Deposition Models

The dispersion of pollutants would impact on, and therefore be valued as part of the same environmental change, through the same methods as the water quality variables. Model outputs could potentially be used as input to other models to avoid double counting.

6.2.4.1 FRAME (Dore 2009)

The FRAME (Fine Resolution Atmospheric Multi-pollutant Exchange model) atmospheric transport model can be applied to estimate the concentration and deposition of sulphur and nitrogen compounds at resolutions of 1km and 5km over the UK. FRAME has been the model used for UK policy on acidification for the last decade. It is also the finest spatial resolution of the reviewed national atmospheric deposition models and 5km outputs are available to download from the Defra website[3].

- Considered **potentially suitable** for the macro-modelling of N deposition to woodland and subsequently N leaching.
- Assessed as **not suitable** for micro-modelling due to relatively coarse spatial resolution.

6.2.5 Local scale models

Local scale models are assessed in Appendix 2 due to their suitability for only micro-modelling.

6.3 Conclusions

The reviewed process-based pollutant loss models are based on the quantification of processes and model nutrient leaching based on land-use, soil type and climate, but do not model the routing of water flow from source to stream (although PSYCHIC and APT use surrogates for likelihood of flow entering

[3] http://pollutantdeposition.defra.gov.uk/data

water bodies). They can therefore provide an estimate of the replacement effects of woodland but cannot explicitly model the interception effects. Whilst the reviewed models are designed to estimate nutrient pollution, they also provide an estimate of water loss from a grid cell and thus provide data to estimate drought (and possibly flood) risk.

Ecosystem service models are designed to model processes in the context of the services they provide. The reviewed ecosystem service models also have a representation of flow routing from source to sink and therefore can model interception effects. The reviewed ES models vary in the ease of translation of biophysical outputs to monetary values.

Detailed hydrological models are more complex as they attempt to represent the physical processes as accurately as possible given the local combination of land-use, climate, soil, geology and terrain. Some model all water flow pathways (surface and sub-surface), whilst others focus on surface water pathways, which are simpler to model.

Models based on the scientific quantification of processes (rather than statistical probability) are the most suitable for simulating the hydrological effects of *changes* in land-use because the parameters and equations relate directly to known physical processes within the catchment that can, in theory, also reflect change. The importance of representing the spatial distribution of woodland has also been highlighted for modelling its interception/ retention function; therefore models also need to support input land-use data at a sufficiently fine scale (e.g. able to capture strips of woodland along field edges or in riparian zones).

Woodland within a catchment may not only influence the magnitude of a process, but also the timing, which is particularly relevant for management of extreme events. Models of flooding therefore need to be capable of modelling specific sized events, or incorporate a daily time-series of weather data.

Calibration of any model for a catchment, or at least a region for the present-day scenario will be required, particularly since many of the models have not yet been tested in the UK. This usually involves the comparison of the model’s outputs against stream measurements. Following calibration and obtaining model results for the present-day scenario, the model’s parameters would then need to be changed to reflect the difference in land-use in the baseline scenario. Obviously, the baseline scenario parameters cannot be calibrated in the same way, but should reflect best estimates for the alternative land-covers in the catchment or region being modelled.

Table 12 gives an overview of the reviewed models and their assessed suitability against each of the water-related ecosystem services delivered by woodland.

Table 12. Reviewed models and their suitability for modelling each of the listed ecosystem services. Green cells show combinations that are potentially suitable for macro and micro-modelling, orange cells show combinations that are potentially suitable for macro-modelling only, yellow cells are those potentially suitable for micro-modelling only and red cells show combinations that are considered unsuitable for either. A key feature of each model that influenced the assessment is also shown in the table.

Model	Nutrient regulation (N)	Nutrient regulation (P)	Sediment regulation	Pesticide regulation	Flood regulation	Drought regulation	Surface water acidification regulation
NEAP-N	Simple & parameterised for GB					Simple & parameterised for GB	
PSYCHIC		Simple & parameterised for GB	Simple & parameterised for GB			Simple & parameterised for GB	
APT	Integrated pollutant framework	Integrated pollutant framework	Integrated pollutant framework			Integrated pollutant framework	
InVEST	Simple & flexible	Simple & flexible	Simple & flexible	Simple & flexible		Simple & flexible	
LUCI/ Polyscape			Good spatial representation		Good spatial representation		
ARIES			Maps service flows		Maps service flows		
MIMES	Not enough information						
Co$ting Nature	Bundled services						
TIM	New UK ecosystem services model	New UK ecosystem services model					
SWAT	Covers most services	Covers most services	Covers most services	Covers most services	Covers most services	Covers most services	
PRMS			Complex to parameterise & more difficult to value outputs		Complex to parameterise & more difficult to value outputs	Complex to parameterise & more difficult to value outputs	

Model	Nutrient regulation (N)	Nutrient regulation (P)	Sediment regulation	Pesticide regulation	Flood regulation	Drought regulation	Surface water acidification regulation
MIKE-SHE	Accurate modelling of entire hydrological cycle	Accurate modelling of entire hydrological cycle	Accurate modelling of entire hydrological cycle		Accurate modelling of entire hydrological cycle	Accurate modelling of entire hydrological cycle	
RHESSys	Simulates forest growth				Simulates forest growth	Simulates forest growth	
CAS-HYDRO	Developed for UK catchments	Developed for UK catchments			Developed for UK catchments	Developed for UK catchments	
SHETRAN	Full modelling of entire hydrological cycle	Full modelling of entire hydrological cycle	Full modelling of entire hydrological cycle		Full modelling of entire hydrological cycle	Full modelling of entire hydrological cycle	
FRAME							Finest spatial resolution of national deposition models
HARM							Coarser scale
EMEP4UK							Coarser scale

7 Spatial data

7.1 Introduction

Models that estimate the magnitude of pollution and runoff at source (i.e. for comparison of the source value of woodland compared to baseline), data on rainfall and soil type are required, which are unlikely to be available at sub-field or even field scale nationally. Models that route flow from a source downslope to a water course require a Digital Terrain Model, which are available at relatively fine spatial resolution. For realistic modelling of the interception of flow by sinks such as parcels of woodland using a high resolution DTM, data on the precise location of the woodland parcels are required. Many of the models considered require data in a gridded format as this improves processing efficiency. Grid cell size should be the same between each integrated model component, even if the data underlying the grid are at a coarser resolution.

7.2 Methods

Potential sources of spatial data and associated attribute data for Great Britain for potential model parameterisation were reviewed and evaluated according to their currency, spatial resolution, geographical coverage, frequency of update, format, cost and attributes. In general, datasets should have full GB coverage, or national datasets are similar enough to enable integration; they should be in vector or raster GIS format (for spatial data) and they should have a reasonable purchase cost. Datasets were categorised by theme, based on the general requirements for many of the models reviewed as potentially suitable. These themes were;

1. **Land use/ land cover**
   Land-use/ land-cover data are required to represent the current distribution of different vegetation types in the landscape and thus the spatial variation in risks and mitigating functions. The specific requirements for land-use or land-cover datasets are that;
   a) they are relatively recent (i.e. within the last few years), since land-use in particular changes over time;
   b) their spatial resolution is sufficiently fine to enable the representation of areas of woodland that might have an interception function, such as riparian woodland (if modelling interception effects);
   c) their frequency of update is sufficiently regular to capture the changing landscape;
   d) they should have sufficient breakdown of land-use/ cover types to which to apply different coefficients (for leaching, interception etc.)

2. **Soil**
   Soils data are required to characterise the spatial variation in soil properties and thus the hydrological responses in the catchment. Their spatial resolution should be sufficiently fine (although this is limited for national data) and they should have the necessary attributes for the parameterisation of models.

3. **Geology**
   Geology data are required to characterise the spatial variation in bedrock and aquifers and thus the interactions between surface and groundwater. Their spatial resolution should be sufficiently fine (although this is limited for national data) and they should have the necessary attributes for the parameterisation of models.

4. **Topography**
   Digital elevation models are required to represent the topographical variation in the surface of the landscape to enable flow routing. Their spatial resolution should be sufficiently fine to be able to model surface flow routes with reasonable accuracy *or* to provide an estimate of slope for land parcels or grid cells if not modelling flow routes.

5. **Catchments**
   Catchment boundaries are required to delineate surface water catchments, which are usually required as model inputs. They should be hydrologically accurate.

6. **Point sources of pollutants**
   Point sources of pollutants are required as input to some models. They should be reasonably current and provide quantitative estimates of pollutant export.

7. **Climate**
   Climate data are required for most models and will either be used directly to drive the hydrological component or used to parameterise a weather simulator. They should have the necessary parameters (usually rainfall and temperature at a minimum) and be on a suitable timestep for the model and at a reasonable spatial resolution.

8. **Crop management**
   Crop management data in terms of fertiliser practice and pesticide usage are needed to parameterise some models. These data should be as recent as possible and be applicable to broad crop types.

9. **River flows**
   Measured flows in catchments are often needed for model calibration. Measurement units should match the output units of the model.

10. **Catchment water quality**
    Water quality data for catchments are often needed for model calibration. Measurement units should match the output units of the model.

11. **Stream network**
    A stream network can be provided as input to many models, although for models that incorporate a DEM, a stream network can be generated from the elevation data. The network should be as accurate as possible and represent streams as well as main rivers.

12. **Floodplain extents**
    Some models require floodplain extents as input.

13. **Springs and wells**
    Some models require the locations of springs and wells as input.

Each dataset identified was given a classification based on this evaluation. Datasets classified as **suitable** meet all the requirements outlined above. Datasets classified as **potentially suitable** have some scope for use in the absence of better alternatives, but have some limitations. Datasets classified as **unsuitable** do not meet the requirements outlined above.

7.3 Results

Detailed results are shown in Appendix 2. A summary of the findings is given by theme below.

7.3.1 Land use/ land cover

The National Forest Inventory (Forestry Commission) was considered **suitable** for the accurate placement of woodland parcels in the landscape and differentiation between woodland types. The current spatial database has a minimum spatial resolution of 0.5ha and 20m width. Smaller patches of woodland and narrow woodland strips will therefore not be captured, which may be a problem given the recommended 12m width of riparian buffer strips on cultivated land to protect soil and water under Entry Level Stewardship. A version of the inventory at a more detailed spatial resolution to capture these smaller woodland parcels is planned for the near future.

The Centre for Ecology and Hydrology's Land Cover Map (LCM) 2007 was considered a **suitable** dataset for the accurate placement of other land-cover parcels in the landscape, although there is a considerable cost associated with the licencing of this dataset. The arable land category is not disaggregated into land-use types, which would limit the application of crop-specific loss coefficients. If the cost of LCM2007 data is prohibitive, the CORINE Land Cover data produced by the European Environment Agency is **potentially suitable**. More detailed disaggregated Defra June Agricultural Survey (JAS) data (EDINA or ADAS) are **suitable** for estimating crop splits for arable areas if required or for coarser-scale modelling.

7.3.2 Soil

The National Soil Resources Institute (LandIS) NATMAP 1000 dataset is a 1km gridded version of the National Soil Map and is considered **suitable** for the representation of the spatial variation in soil types for England and Wales for modelling purposes. The equivalent **suitable** dataset for Scotland is the 1 x 1km soils map for Scotland (James Hutton Institute). NSRI Soil Series Properties are tabular data that can be used in conjunction with the NATMAP spatial dataset. These tables are considered **suitable** for the provision of coefficients for modelling that can be linked to mapped soils data. The 1km soils data for Scotland includes attributes of the dominant soil series in the grid square. Data licencing costs of these soils datasets may be a limitation (depending on Government Agency agreements), however alternatives are available in the form of **potentially suitable** lower resolution (i.e. 5km) alternatives, or European Soils Data from the Joint Research Council.

7.3.3 Geology

The most **suitable** dataset for spatial geological information was considered to be the British Geological Survey's DiGMapGB-Plus dataset. This provides key characteristics of the geology of Great Britain and has been used in development of a BGS Ecosystem Services Model. The BGS' Boreholes Index would be suitable for determining the location of boreholes and their depth.

7.3.4 Topography

There are a number of digital terrain models (DTMs) that are **potentially suitable** for input into models. Those considered range from 5m to 50m spatial resolution, with the cost of the more detailed ones likely to be substantially more. A 5-15m resolution DTM, as recommended for LUCI/ Polyscape, would be considered sufficient to accurately model surface water flow. NEXTMap Britain (Intermap) is available at 10m resolution and is used by other Government Agencies. In addition to cost, there is the consideration of computing power required to run models on a fine spatial grid. Coarser resolution DTMs may be the only feasible option for modelling at the GB scale.

7.3.5 Catchments

Catchment boundaries are needed as input to many models. The WFD river waterbody catchments (Environment Agency/ SEPA) are recommended as **suitable** if these are available to the FC. **Potentially suitable** alternatives are CEH catchment boundaries or hydrometric areas (groupings of catchments) and the European Catchment Characterisation and Modelling (CCM) River and Catchment Database (Joint Research Council). Source Protection Zones are available from the EA for identification of high risk groundwater bodies.

7.3.6 Point Sources of Pollutants

Septic tanks and landfill sites are a source of non-agricultural nutrient pollution. Data on septic tank locations are potentially available from water companies and would be **suitable** if available. The EA and SEPA have a septic tank registration database, which would **be suitable** if location information were available. The EA hold data on historic and current landfill sites, but these only cover England and Wales and are therefore assessed as **potentially suitable**.

7.3.7 Climate

Long-term mean monthly weather surfaces from the Met. Office are likely to be **suitable** climate datasets for modelling purposes. These are available on a 5km grid for various time periods. 1km versions are also available, but these require licencing. MORECS station data (Met. Office) provide values for average annual potential evapotranspiration and daily weather parameters that would be **suitable** for modelling purposes. There are also soil temperature data if this information is required. Monthly rainfall grids (CEH) are **potentially suitable** for model calibration or for modelling a particular year. Met. Office meteorological station data are also **potentially suitable** for model calibration.

7.3.8 Crop Management

The British Survey of Fertiliser Practice (Defra/ Scottish Government) is an annual survey that is **suitable** to use in conjunction with land-use datasets to evaluate nutrient inputs to land for different crop types.

Similarly, the Pesticide Usage Survey (Defra/Fera) is **suitable** to use to estimate pesticide inputs to land for different crop types.

7.3.9 Flow Data

Some models require flow data as input. A **potentially suitable** option is the Peak River Flows gridded dataset produced by CEH. Other flow data are from sampling points that would be **potentially suitable** for model calibration at a catchment scale.

7.3.10 Catchment Water Quality

Water quality summaries at a catchment scale, especially reports and databases related to WFD assessments, would be **suitable** for the identification of sensitive catchments that could be priorities for modelling the effects of woodland on mitigating the particular pressures in these catchments. Water quality monitoring data could be **potentially suitable** for model calibration.

7.3.11 Stream Networks

The EA's Detailed River Network is **potentially suitable** if it is available to the Forestry Commission at a reduced rate. It is the most detailed dataset available for England and Wales. There are coarser scale GB alternatives available (from CEH and Ordnance Survey) that are also **potentially suitable**.

7.3.12 Dams and Flood Defences

The Environment Agency's flood map delineates flood defences and flood storage areas and is therefore considered **suitable**. There is a global Reservoir and Dam database that is **suitable** for locating dams and reservoirs, although better information should be available from water companies.

7.3.13 Floodplain Extents

The EA's flood maps show the areas across England and Wales that could be affected by flooding from rivers, the sea, reservoirs and surface water. It is considered **suitable** for mapping the floodplain. SEPA have equivalent maps for Scotland that would be **suitable**, although it is unclear whether or not the map data can be obtained in GIS format (rather than just viewed online). Liaison would be required with SEPA to determine if and how the maps could be used by the Forestry Commission.

7.3.14 Springs and Wells

There are two **potentially suitable** datasets from the BGS for locating wells and boreholes, but the data may be difficult to obtain. There may therefore be a data gap under this theme, although not a critical one.

7.4 Conclusions

For all of the themes, there is at least one dataset that is considered suitable or potentially suitable for use in modelling or calibration. One of the unknowns in many cases is cost. Pricing structures are often complicated or quotes are required, which may vary depending upon the organisation requesting the dataset and the use of the data. Data costs may therefore be prohibitive in some cases. Often there are freely available alternatives, albeit at coarser resolution or with reduced accuracy.

8 Valuation approaches

8.1 Discussion of available evidence

This Section combines the review of economic valuation approaches (Section 5) and the understanding of how existing modelling tools work (Section 6) with eftec's knowledge of the best available economic evidence that can be applied to value the change in the environmental goods provided by woodland. The discussion relates to the valuation of the goods and services identified in Figure 2 in Section 5. The valuation methods suggested here are selected as to be aligned with the ease of translating physical outputs of the most suitable tools in Section 6 into economic values. The discussion also covers some economic data sources suitable for using in the UK context for the purpose of this project.

8.1.1 Reduction in costs of public water supply treatment

Models that quantify the reduction in nutrients delivered to drinking water sources are suitable for the valuation of this environmental good. A cost of treating water for public supply can be associated with each nutrient (e.g. £ per kg of nitrogen or phosphorus). This could be determined using a generic value, based on the typical condition of water sources in the UK. Representative data available from the water industry on the costs of building and operating a water treatment plant in the UK could be used. However, it would be preferable to model individual catchments according to the quality (e.g. nutrient concentrations) of their water resources abstracted for public supply, and the current infrastructure operated to treat this. The reason is that costs are highly dependent on catchment circumstances – i.e. how close to WFD thresholds water bodies are, and what treatment capacity and operating life there is for existing infrastructure. In the absence of individual catchment information, the results would be excessively generalised.

At this scale, the costs avoided are not realistically £ per kg, but they represent a potential expense avoided, i.e. related to required investments in treatment facilities with a high (£10's millions) minimum cost. It cannot be consistently assumed in all cases that these investments will not be necessary in the future thanks to the presence of woodlands in the catchment. Therefore, an accurate way of determining whether or not such investments are actually avoided based on the situation in catchments needs to be established. Alternatively, a probabilistic assessment of that avoidance into the future could be suitable. The latter approach becomes more similar to the generic value decided above, but it should be based on data over an appropriate number of catchments (e.g. a water company supply area).

Several studies have considered the avoided investment in water treatment facilities due to the protection of woodlands in the upstream parts of water catchments (e.g. Seattle Public Utilities would have had to invest in a $200m water filtration plant if the surrounding woodlands had not been protected, among other examples reported in WRI, 2013).

8.1.2 Change of the quality of water / wetland environment

A different service to the previous one, although related, is the provision of good quality water and wetland environments. It has effects on people's wellbeing through different use and non-use values. For instance, improved water quality can be linked, for valuation purposes, to the determinants of Water Framework Directive (WFD) status. Many of the physical processes evaluated by the modelling tools are used collectively to determine whether a catchment complies with a good ecological status as set out in the WFD.

At a GB level, valuation of changes to the status of water bodies could be done by applying the average values for WFD good ecological status improvements used by the Environment Agency. These values are obtained from a stated preference study through the National Water Environment Benefit Survey (NWEBS) (NERA & Accent 2007)[4]. The benefits are expressed in £/km of river improved and differ depending on the status (e.g. from bad to poor, poor to moderate, etc.). The estimates reflect average total economic value

[4] Results further updated in 2013 and accessible at: https://www.gov.uk/government/publications/updating-the-national-water-environment-benefit-survey-values-summary-of-the-peer-review

of society for improvements in WFD status on a stretch of river, and they are provided individually per river catchment.

The WFD status in this stated preferences study is determined by six indicators: fish; other animals such as invertebrates; plant communities; clarity of water; condition of the river and flow of water; and safety of the water for recreational contact. It is not possible a priori to determine whether all categories or only some of them could be applicable to determine the value of the environmental good provided by forests on a specific catchment. The allocation of the values would depend on the extent of the quality improvement or deterioration and this has to be assessed on a case by case basis.

This approach could be used based on the probability that the presence of woodland cover in a catchment is sufficient to have contributed to a change in WFD status (e.g. from a denomination of "poor status" to "moderate status") for one or more of the indicators[5]. These assumptions will depend on the modelling tool to be used, although some models such as TIM already point towards the ecological status of the catchment unit evaluated.

The values from the NWEBS can be supported by a sensitivity analysis using the valuations done by the UK water companies as part of their 5-year price review process. Companies have to support their business plan with customer valuation surveys, where customers are asked for their WTP to improve a number of water, wastewater and environmental services. Most companies include river water quality or water flows as one of the attributes, which are valued in terms of £ per household/business per 1% of river length achieving at least a good ecological status. Although not all the studies are publicly available, some companies upload their results in their websites. A list of the available studies (consulted in March 2014) is as follows:

- Cambridge Water: http://www.cambridge-water.co.uk/home/customer-engagement#2
- South Staffs Water: http://www.south-staffs-water.co.uk/downloads/ccg/Final_Report_SSW_PR14_WTP_Study.pdf
- Southern Water http://www.southernwater.co.uk/pdf/about-us/publications/wrmp/SOR/A05_WillingnessToPay.pdf

Another approach would be to model that the presence of woodland enabled the avoidance of expenditure that would otherwise be legally required in order to achieve the WFD good status. This approach has some uncertainty due to the existence of exemptions (e.g. for disproportionate costs) in the directive.

Finally, there is evidence on value of water quality for recreation, from both revealed and stated preference studies. Unless already close to thresholds, a significant impact from woodland cover would be needed to change water quality sufficiently (e.g. to reduce risks of algal blooms) to impact on recreation. However, this evidence could be used as an alternative (or comparison) for the results of value transfer of stated preference data.

8.1.3 Reduction in flood risk / damage

Some modelling tools have been identified as suitable for evaluating the influence of woodland on runoff during high rainfall events. However, the valuation of this environmental good is complex due to the need to set links between changes in runoff from parts of a catchment to river flows and changes in levels or probabilities of flooding. A study by Defra on the "Slowing the flow" project (Defra 2011) provides a good theoretical basis, based on an avoided damage approach. However, the approach used in Defra's project relies on the availability of economic data on the costs of previous flooding events in the particular region.

In the absence of such values two approaches are possible:

1. If data is available, assumptions and/or values could be transferred from one or more similar neighbouring catchment(s). This transfer would increase the uncertainty of the valuation. However, this uncertainty can be minimised if there is sufficient availability of data of flood damage costs from different catchments to construct a meta-analysis for the UK. This gives a model using data from different studies that allows a value to be worked out based on a catchment's characteristics.

[5] It also assumes hence that all six indicators in the study have the same weight in generating benefits from a change in WFD status.

2. Economic valuation could be based on an assessment of the value of the assets at risk of flooding (e.g. by insured value of the assets), and the likely change in damage from a realistic estimate of the reduced risk to them as a result of the impacts of woodland (e.g. based on expected reduced height and/or duration of flood). Modelling these effects is also resource-intensive and needs to be done catchment by catchment.

An alternative approach would involve a value transfer from existing studies on hedonic pricing evaluation (i.e. lower value of real estate in a flood-prone area as compared to an area without flooding risks). There is no conclusive study in the UK that can be used and the most similar cases in terms of context, with many caveats and therefore very significant uncertainty, are studies carried out in the Netherlands. For instance, (Daniel 2009) finds that a higher flood occurrence decreased the value of houses by 9% in the flood-prone area.

8.1.4 Reduction in service interruptions during drought

As in the case of flood risk protection, some modelling tools provide estimations of the influence of woodlands on water flow levels but it is difficult to directly link these process outputs to an economic valuation approach. A link would be needed by which to determine whether the variations in water flows would reduce the time for which water bodies were unavailable for abstraction purposes during a drought[6]. The results could then be linked to evidence available on the value of water supply.

The value of water supply can be derived from WTP values. As in the case of the alteration of water quality, the customer valuation studies provided by water companies also evaluated the WTP for reducing the probability of water use restrictions or hosepipe bans. These values are provided in £ per household of a 1% reduction in the probability of restrictions during a year. More complex methods would include the impacts on turnover and profit for sectors that rely on the supply of water to function, such as the one developed by (Vivid Economics 2013).

8.2 Summary of the economic valuation feasibility

The evaluation of the economic approaches available (Section 5) concluded that a feasible valuation pathway is possible by categorising the biophysical processes from modelling tools into four general environmental goods that can be then translated into monetary terms. The valuation of each of these environmental goods has been assessed above. A summary table linking the goods valued with the suitable methods applied, the existing studies, applicability to the UK and coverage by the modelling tools is provided in Table 13 below.

[6] For instance, water management models fitted specifically for this purposes could be used in parallel to the modelling tools evaluated here. In a recent study by UKWIR (2014), hydro-economic modelling is used as to determine the value of each unit of water abstracted.

Table 13. Summary of environmental goods identified in the study and suitable valuation methodologies

Environmental good	Coverage by modelling tools	Suitable economic methods	Existing studies? (Including outside UK)	Applicability to the UK?
Reduction in costs of public water supply	Many of the models provide data output in the form of nutrients concentration in the river (usually in kg).	▪ Replacement costs	Studies have applied this method by combining a decrease in the pollutant's concentration (kg per ha, km or m^3) and a proxy for the value of each kg, based on the cost of treating the pollutants in a water filtration plant.	It is possible to apply this approach to the UK, but data on the change as a result of woodland presence in water treatment costs should be obtained, ideally by catchment as operational costs and age of infrastructure vary.
Change in quality of water / wetland environments	Many of the processes modelled by the tools can be used collectively to determine the overall quality status of the catchment. It requires, though, a further exercise of linking this to WFD status levels, and this depends on the model.	▪ Stated preferences	Studies covering this environmental good have used stated preference WTP values to achieve a certain quality standard. Usually values are provided in £ per household and per km of river or for the whole (sub)catchment.	Valuation evidence for the achievement of quality status as set in the WFD is available in the UK. The NWEBS study (NERA & Accent 2007) provides values (per catchment) of the WTP to achieve a moderate or good ecological status in rivers and it can be broken down in 6 different ecological indicators. This approach can be supported by WTP values reported by water companies for water quality improvements. Some of these studies can be publicly consulted as part of their price review process.
Reduction in flood risk / damage	A diversity of measurements of flood runoff affected by land cover is provided by some of the modelling tools. The link between a reduction of flood runoff and a lower probability of flooding or higher protection from damage is not direct and assumptions need to be made.	▪ Avoided damages ▪ Revealed preferences	The majority of studies valuing this environmental good have applied market price proxies, either in the form of replacement costs (infrastructure to protect for flooding) or avoided damage (based on information on previous flood events). Some other studies have assessed the lower value of houses in flood-prone areas based on hedonic pricing.	May be possible in some catchments with data on past flooding events, or by transfer of data from neighbouring catchments. Alternatively, a modelling of the assets at risk and their economic value could be applied (most resource-intensive option). There is no robust evidence for the UK on hedonic pricing valuation of flood risk. Values from existing studies in Netherlands could be transferred but with high uncertainty due to differences in flood risk.
Reduction in service interruptions during drought	A diversity of measurements of water flows affected by land cover is provided by some of the modelling tools. The link between an alteration of the water flows and an alteration of the probability to suffer a supply service interruption is not direct and assumptions need to be made.	▪ Stated preferences	A few studies covering this environmental good have used an approach based on avoided damage but they are very site-dependent.	The applicability of market price proxies is difficult in the case of the UK. WTP values based on water companies' customer valuation studies that are publicly available could be used. Most of these studies incorporate a service attribute defined as water use restrictions or hosepipe ban probability (in £ per household). More data-intensive methods can be used to value the effects of large-scale droughts.

9 Discussion

The aim of this study is to assess the feasibility of estimating an economic value for the contribution that woodlands make to water quality and quantity in Great Britain. This Section discusses the key issues from each of the preceding Sections in relation to designing such a study.

9.1 Scope of impacts considered

Woodland in the right location improves the quality of water in a catchment and mitigates the effects of flooding. Woodland therefore has an economic value due to its contribution to reduced water treatment costs, improvements in catchment water quality, avoided risk/damages due to flooding and reduction in service interruptions during drought. Woodland in areas susceptible to drought can have a negative value due to its effect on water recharge contributing to service interruption, as well as a positive value in helping to retain water in a catchment, maintaining flows in drought periods.

There are other ecosystem services provided by woodland that are outside the scope of this study but would nevertheless add to its value. These include carbon storage, benefits to biodiversity, improvement to landscape and increase in recreational opportunities. There are also other water-related benefits and dis-benefits provided by trees that are very difficult to model and/or value, therefore these have not been considered explicitly. These include reduction in faecal indicator organisms (FIO) in water bodies, the beneficial effects of riparian shading on lowering stream temperature and thus benefiting freshwater biodiversity, increase/ decrease in surface-water pollution due to increased local ammonia deposition, decrease in surface water pollution from pesticide spray-drift due to woodland shelterbelts, flood generation due to backing-up of flood water behind woodland barriers and alleviation of downstream flooding due to woody debris dams. These are very difficult functions to quantify, but should be considered as further potential benefits.

9.2 Baseline

For any valuation study, a baseline (counterfactual) is required against which to measure change. Section 3 suggests a baseline for national valuation of existing woodland guided by the land classification systems in use in Scotland and England & Wales. These classifications do not take account of the current land-use, rather they rate the quality of the land for agricultural use based on limitations such as climate, soil type and site-specific factors. Estimates of the proportions of current non-woodland land-uses within each grading and geographical area could then be used to assign alternative land-uses to parcels that are currently woodland. This approach is considered the most appropriate for the purpose of a national valuation study, but some assumptions do have to be made.

On some low grade land, woodland may be considered the only realistic option due to the limitations of that land (e.g. steeply sloping). In these cases it could be assumed in any modelling that the alternative would be rough pasture or some other natural land-cover.

Another assumption would need to be made regarding the displacement of agricultural activities. For national modelling the recommended assumption is that displacement does not occur, because the baseline involves the complete absence of woodland, and displacement on this scale is unrealistic. The baseline pressures on the woodland environment might therefore also be considered unrealistic, although perhaps only due to the policies and agri-environment schemes in place for environmental protection. The approach would be quite different if valuation of new woodland were to be attempted. In this case, the optimal location of new woodland would need to be determined and then the baseline would be the land-use that it was displacing. The effects of displacement could be taken into account in this case, although assumptions used would depend on the scale of new woodland being considered (both the amount of new woodland, and the area within which it was being created).

9.3 Processes

The biophysical processes that are considered in Section 4 are those that can be influenced by woodland to result in changes to water quality or quantity. The influence of woodland is considered under two broad groups of effects – replacement and interception/ retention. The replacement effect of woodland will depend upon the baseline land-use (in addition to site-specific variables such as climate and soil type), whereas interception and retention effects will depend primarily upon the *upslope* land-use, which determines the pollutant load arriving at the woodland; and the topography, which determines the magnitude and velocity of water flow through the woodland. The characteristics of the woodland itself will also influence the magnitude of any effect.

Section 4 aimed to draw out the key influencing factors for each process and then determine whether or not coefficients to represent these are readily available. It was found that the most important factors governing the replacement effects are the baseline land-use (which have different pollutant export coefficients), geo-climatic region (because export coefficients vary by climate), soil type (determines how easily pollutants are leached or soils eroded) and woodland types and ages (influences pollutant leaching and water use).

The most important factors governing interception/ retention effects were the width and composition of the woodland strip (determines how much water flow/ pollutant is retained), the water flow velocity and channelling of flow (and thus how much water is intercepted) and the soil type (affects rate of infiltration). The most important coefficients that would be required to parameterise models are available in the literature or could be derived, although many of the studies cited are not from the UK. The environmental conditions and management practices in the UK can be very different to those in other countries, therefore coefficients from UK studies should be sourced wherever possible. This review is not exhaustive and therefore the findings should be considered indicative rather than conclusive.

9.4 Economic valuation methods

Regarding the economic valuation of these biophysical processes, Section 5 discusses the potential methodologies that can be applied. Valuation methods would rely on market price proxies, revealed preferences (surrogate market data) or stated preferences (hypothetical market data) given the few – if any – markets existing for the impacts of woodland on water. We suggest that valuation of environmental quality and service interruption impacts would have to rely on using ‘value transfer’ (i.e. the process of searching, selecting an economic value from the existing literature) to apply economic valuation evidence that is available from assessments in other catchments or from national scales. This proposal is based on the available WTP values for these impacts, which can be transferred to each catchment as opposed to having to carry out primary valuation to get more specific catchment level values.

To value reductions in flood risks and in the costs of public water supply, generic values could be developed and applied to different catchments. However, these would be highly uncertain, due to large variations in values in different circumstances (e.g. standards of flood protection, state of water treatment infrastructure) in different catchments. To develop more accurate values, catchment-specific modelling is required, which would only be feasible in partnership with relevant stakeholders (e.g. Environment Agency; Water Companies).

This section also highlights that all valuation techniques are applicable to most of the benefits from the biophysical processes considered. The valuation techniques most suitable for each benefit is identified in Table 13, which mostly use market price proxies such as replacement costs. Some economic evidence is available for a “collective” valuation of the processes in a bundle

9.5 Spatial models evaluation

Section 6 reviews spatial models and methods available for potential quantification of the physical effects that woodland has on the water environment, the outputs of which could subsequently be linked to the four categories of environmental goods and hence linked to valuation methods. The concepts of macro- and micro-modelling are introduced which, for the purpose of this study, make a distinction between national-scale modelling of the water-related value of existing woodland and catchment or sub-catchment scale modelling of woodland in specific locations to estimate marginal effects of planting new woodlands. Models fall under the groupings of process-based pollutant loss models, which only model replacement effects; ecosystem service models, which are designed to quantify or value multiple ecosystem services; and hydrological models, which usually attempt to model hydrological processes in detail with possibly (although not definitely) more accurate results.

9.5.1 Review of Available models

The reviewed process-based pollutant loss models have the benefits of being simple to parameterise and apply and thus offer a cheaper option for a national valuation study. The reviewed models were also developed in the UK and have been widely used for various policy purposes in England, Wales and Scotland. Limitations are that they are only capable of estimating the replacement effects of woodland as they do not incorporate the route that water takes to a river or stream. This may not be a critical issue for a national estimate of woodlands’ value. To date, woodland planting has not been targeted to provide water benefits and therefore its interception/ retention function at a national scale is not as important as its function as an alternative land-use to agriculture (T. Nisbet & V. Carter pers. comm.). Furthermore, riparian woodland is thought to constitute only a very small proportion of total woodland cover, particularly in lowland England where the majority of the diffuse pollution problems exist. These types of models are therefore considered sufficient for a rough estimate of the water-related value of woodland at a national scale (albeit an underestimate), with the exception of flood risk, which would need a more detailed modelling approach that incorporates the routing of water flow and daily weather data.

Ecosystem service models are attractive for any valuation study, since they offer smooth integration with models of other ecosystem services and their parameterisation is much more straightforward than the detailed hydrological models. They have also been specifically developed with monetary valuation in mind (even if they haven't gone that far yet). Although this project is focusing on water-related ecosystem services, it could be an advantage if the modelling could be later extended to add other ecosystem service components under the same model framework.

Of the integrated ecosystem service models, InVEST tier 1 models are thought to be the most suitable for macro-modelling of nutrient, sediment, pesticide and drought regulation and are relatively straightforward to parameterise, but to our knowledge these models have not been extensively tested in the UK and are fairly simple representations of the hydrological processes. Tier 2 models may be suitable for modelling flood regulation at a national scale due to their use of a daily time-step, or be useful for micro-modelling of individual catchments. ARIES or LUCI could potentially be used to model flood and sediment regulation (and possibly nutrient regulation in the future), but the outputs are not as readily translatable into monetary values. LUCI may be valuable for micro-modelling of processes in a limited number of catchments. TIM may have potential for macro-modelling of nutrient pollution, but its relatively coarse spatial resolution (2x2km) would not capture the finer-scale interception effects of woodland.

All of the reviewed hydrological models require significant parameterisation and calibration effort, but they offer more sophisticated modelling of hydrology. SWAT's ability to quantify all but the sediment regulation services makes it a possibility for macro-modelling; however, the increased complexity of the model has trade-offs in the form of simplified routing of flow. MIKE-SHE and SHETRAN have sophisticated flow routing and a high level of model complexity covering the entire hydrological cycle. However, MIKE-SHE has a high purchase cost and requires considerable expertise to parameterise and calibrate and would therefore not be suitable for application at a national scale. Advantages of SHETRAN are that it was developed in the UK and has a simpler version based on a graphical user interface that was developed to enable its use by non-experts in hydrology. RHESSys was one of the few hydrological routing models reviewed with particular representation of forest growth and impervious surfaces. However, to our knowledge it has not been tested in the UK.

CAS-HYDRO has potential for micro-modelling of all but sediment and pesticide regulation as it has been developed in the UK for the purpose of assessing the effects of climate and land-use change, but it is not freely available (except for the demo version) and would require parameterising/ calibration for each new catchment.

The list of hydrological models reviewed is by no means exhaustive (over 100 have been developed worldwide), but the examples included give a flavour of the range in their levels of complexity and usage. The increased complexity of full hydrological models over ecosystem service models does not guarantee an increased accuracy in the results. Therefore, the considerable effort required to parameterise and run such models might outweigh any benefits gained.

The effect of woodland on dry deposition (and subsequent increase or reduction in pollutants entering surface water) can be estimated using models such as FRAME. The resultant estimates could then be used as input to other models, with an export coefficient specific to the land-use.

9.5.2 Modelling Approaches

An alternative for macro-modelling of all (or most) of the relevant water-related services would be to develop a method of catchment characterisation that would enable more complex models to be applied to a few representative catchments and scaled up to a national level. This idea is explained further in the recommendations Section 9.9.

The availability of source code (the computer instructions that enable the model to run) is likely to be a key consideration for the choice of model(s) as there is then the scope to adapt these for this specific purpose.

The approach taken will be constrained by resources and will depend upon the objective (i.e. a rough estimate of national value, or a detailed spatial analysis to estimate marginal value for a particular locality). Some of the models are extremely complex, and intended for catchments rather than countries, whereas others are designed for valuation at a regional to national scale.

9.6 Data Availability

Section 7 reviews the GB spatial data available for potential model parameterisation. The accuracy of the outputs of any model is very much dependent on the accuracy and resolution of the input data. For example, realistic modelling of the interception of flow by woodland would require data on the precise location of the woodland and an accurate digital terrain model to represent the topography of the land. Many of the models considered require data in gridded format, with the cell size consistent for each input dataset. Whilst fine resolution spatial data is obviously optimal for accurate modelling of water flow and interception, there is a trade-off in the form of increased computing power required and the time that it would take to run the model at a national scale. It may therefore be necessary to use coarser-scale data for macro-modelling and fine-scale data for micro-modelling of specific catchments that could give an insight into the importance of woodland location and the difference in its effects between catchments with different pressures.

The availability of datasets was investigated by theme (e.g. land-use, soil type). For all themes, there was found to be at least one dataset that was considered suitable or potentially suitable for use in model parameterisation or calibration. Some datasets such as national soil maps and flood maps differ between GB countries. This can result in step-changes in results at the borders if the accuracy of the data or the method of derivation differs between datasets. There is not much that can be done to rectify this, other than to be aware of the possible reasons for any differences between country-level estimates. In some cases, the licensing cost of a dataset may restrict its use for a national scale analysis. Accurate pricing information has not been obtained for many of the datasets due to the cost being dependent on the user and the geographic extent of the data required. The Forestry Commission may have data sharing agreements in place with Government and its Agencies that would need to be taken into account when assessing the suitability of any particular dataset. Freely available alternatives to expensive datasets usually have a coarser resolution and/ or reduced accuracy.

9.7 Recommended economic valuation approaches

Although valuations can be made of the individual processes through which woodland impacts water ES, a grouping of the biophysical processes is suggested. This makes the economic valuation more feasible without hindering the ability to cover comprehensively the ecosystem services provided by woodlands. This identifies three final environmental goods (Table 13), which in turn support four impacts to be valued:

(i) reduction in costs of public water supply;
(ii) alteration of quality of water / wetland environments;
(iii) reduction in flood risk / damage; and
(iv) reduction in service interruptions during drought.

This is consistent with the classes of environmental goods used in similar studies. The valuation of each of these four benefits has been assessed. Each has suitable valuation methods available that can be linked to the outputs of the modelling tools and are applicable to the UK. Several have been used in existing studies. However, there are significant uncertainties in relating modelled outcomes to detailed changes in costs to society:

(i) Reduction in costs of public water supply: this is most likely to be valued through water treatment avoided costs. This could be done by estimating a generic UK value for the additional costs of water treatment when water quality deteriorates. Such a value could highlight the scale of this impact, but would be subject to considerable uncertainty, as costs will vary in each catchment depending on the capacity, type and age of existing treatment infrastructure. Therefore, a more detailed approach, taking into account these factors would be desirable as in practice capital costs avoided would be large and unevenly distributed (lumpy) rather than generic (although generic values would aim to average out their unevenness). However, detailed analysis would require more resources, and work in partnership with OFWAT and/or Water Companies would be necessary.

(ii) Alteration of quality of water / wetland environments: these can be valued by transferring stated preference evidence, such as the NWEBS values relating to WFD standards, and functions from wetland meta-analyses.

(iii) Reduction in flood risk / damage: this provides a complex challenge to relate modelled impacts of forest cover to actual flood risk, given the presence of different flood risk management infrastructure in different catchments.

(iv) Reduction in service interruptions during drought: this impact is valued in water company valuation evidence, although there may be questions over the availability of their data. As in (iii), there is a challenge to relate modelled impacts of forest cover to actual drought risk, given the presence of different water supply infrastructure in different catchments.

Each of these benefits show that as well as identifying the best models for quantifying ecosystem services changes, effort is needed to link these changes to benefits to society (i.e. people, or households and businesses). This cannot be done in detail only from published literature. It also requires understanding the systems through which the benefits of ecosystem services are realised (e.g. water treatment systems).

9.8 Uses of Valuation Outputs

The potential modelling approaches reviewed could generate valuation information that could be used in different ways:

- It could input to the UK's ongoing work to develop natural capital accounts. The results of any study could be added, ex post, to a UK woodland account. However, integration with the GIS analysis process used for the woodland account would be desirable. For example, this would allow the impacts of future changes in woodland cover on different ecosystem services to be captured more consistently in the accounts, enabling more confidence in any tradeoffs assessed.
- It would be possible to embark on an iterative process of firstly undertaking a simpler, lower cost national valuation model, with greater uncertainty of outputs, in order to steer resources towards more detailed modelling (both of ecosystem services and their values). This would help to rationalise the choice of the best combination of models laid out in Table 5 for detailed national modelling. It would also help understand how to best direct further valuation efforts by understanding the size of variation between values in different catchment. If the majority of values arise in a small number of catchments (e.g. those where diffuse pollution from land causes increases in water treatment costs), this provides a subset of impacts that should be modelled in more detail. It may also allow identification of micro modelling needs on specific catchments where there is potential for services to be significant locally (e.g. flood defence impacts within a specific catchment). From a simpler lower cost national valuation model, understanding could be gained of the drivers of variation in values to understand marginal valuation options better.
- Micro-modelling of catchment impacts would provide data to inform cost-effectiveness analysis of the marginal values of new woodland. However, this evidence would not be suitable for indicating the overall value of water ecosystem services from woodland, nor influencing policies to adjust woodland management on a regional or national scale. For example, modelling of a change in water run-off in a small part of a catchment does not automatically translate into a change is flood risk for downstream communities, as this also depends on wider catchment characteristics and flooding regime.

9.9 Recommendations

We propose four possible approaches to take this work forward. The first three options relate to a national valuation of existing woodlands and the fourth proposes an option for informing the optimal planting of new woodland. Broad estimates of costs of delivering these options (excluding data costs) are provided in Table 14.

Option 1. Use pollutant loss models and basic economic impacts modelling for a coarse national valuation

We recommend the use of the ADAS integrated pollutant loss model APT for macro-modelling of nitrate, phosphate and sediment regulation. An estimate of water balance for drought regulation could also be obtained from the model outputs, but the models are not suitable for estimating flood regulation benefits. Input data would be relatively coarse (1km grid) and are readily available (subject to licencing arrangements). The models would require a small degree of refinement to better represent the nutrient loss and water use coefficients of woodland. Advantages of this option are that the models are simple to use and have already been populated with data and parameters for England and Wales (and could be relatively easily extended to include Scotland). Disadvantages are that interception/ retention effects of woodland would not be valued and would therefore result in an underestimate of national value. Pesticide regulation and flood regulation could not be valued using this option.

Option 2. Use of the ecosystem service model InVEST and basic economic impacts modelling for a national valuation

We recommend the use of InVEST tier 1 models for macro-modelling of nutrient, sediment, pesticide and drought regulation. Input data could be relatively coarse (e.g. 1km grid) and parameters GB-specific (rather than for smaller regions). Advantages are that this ecosystem services model is that it is relatively easy to use, designed for the purpose of valuing ecosystem services and offers scope for integration of other services in the future. Disadvantages are that it would require more parameterisation effort than option 1 (since it has not been widely applied in the UK), tier 1 models are not suitable for the modelling of flood regulation (due to the annual time-step) and the relatively coarse analysis will not capture the local benefits of small patches or strips of woodland and therefore may underestimate the total water-related value of woodland.

Option 3. Create typologies for catchments with detailed biophysical and economic modelling of a representative catchment within each typology. Scale up to GB based on woodland configurations.

This option is a method of providing a more accurate alternative to the national valuations in options 1 and 2 and also including the flood regulation service. It is proposed that a hydrological model (e.g. Cas-Hydro) is used, but rather than applying such a model nationally (which these types of model are not designed for), small (e.g. WFD) catchments would be grouped into typologies based on their physical characteristics (rainfall, soil type and landscape structure). The model would be run for a single catchment in each typology with relatively fine scale input data (the scale of the smallest woodland parcels in the National Forest Inventory). A number of iterations would be run, changing the configuration of woodland each time. This could be a random process with ranges limited by those found within the typology. Each configuration would be quantified using a configuration index (CI). Several methods of deriving this index would be investigated. Outputs of model runs with different woodland configurations would be plotted against the CI. These results could be used to predict the percentage interception/ retention in other catchments of the same typology based on the actual configuration of woodland. National export coefficient models would provide an estimate of baseline pressures and the percentage interception/ retention applied to these.

There are two options to derive the estimates of the economic values from the biophysical model outputs within Option 3: either a detailed secondary valuation for a representative catchment within each typology OR a more accurate value transfer function. The detailed secondary valuation would comprise a valuation of one or two representative catchments within a typology. This would require cooperation of the Environment Agency for flood information and OFWAT/ Water Companies for data on water supply treatment. The other economic option to develop a value transfer function to give values for total impacts of woodland cover would be based on variables defining catchment types, plus others (e.g. human population). This could be supported by primary valuation work to fill evidence gaps (e.g. on local features of the water environment).

This option has the advantage of capturing the finer-scale effects of woodland in a catchment and providing a more accurate valuation, whilst keeping the costs reasonable by using catchment typologies rather than modelling all GB catchments individually. A disadvantage is the considerable development effort required compared to options 1 & 2.

Option 4. Use methods from option 3 *or* LUCI to determine the effects of different placements of additional woodland depending on the catchment typology

The value of a certain coverage and placement of *new* woodland will vary depending on the pressures in the catchment and the catchment typology. For an assessment of the value of new woodland creation, the interception function is likely to be significantly more important than woodland simply as an alternative land use. The interception benefit of new planting will be conditional on that planting taking place in optimum locations in the landscape (e.g. riparian zones, lower end of sloping fields) but care needs to be taken not to over-estimate the benefits as these are not always the areas that farmers are willing to plant.

This option would provide a means of determining the optimal placement of additional woodland for different catchment typologies. This could be achieved either by using detailed spatial ecosystem service models such as LUCI, or similar methods to those proposed in option 3. Economic modelling could demonstrate where, for a targeted catchment, additional woodland cover is most cost-effective in terms of impacts on water regulation services. These results could be transferred, with caveats, to similar catchments but would be harder to aggregate to national level due to the marginal value of additional woodland being potentially highly dependent on the amount and location of existing woodland cover in catchments. This would also require cooperation of the Environment Agency for flood information and OFWAT/ Water Companies for data on water supply treatment. Alternatively, the value transfer could be supported by primary valuation work to fill evidence gaps (e.g. on local features of the water environment).

The economic options presented take into account the existing valuation evidence (e.g. NWEBS discussed in Section 8.1), and therefore do not present an option for repeating such values. To generate more detailed valuation evidence (e.g. to support a more detailed value function than that in NWEBS) would require considerable survey effort, and hence is expected to have very high costs (of the order of £300,000 or more). These high costs are assumed to make such approaches infeasible for the Forestry Commission alone, but should be borne in mind in discussion with other bodies with interests in primary environmental economics research.

Table 14. Estimated Costs of modelling Options

	Option 1: Coarse scale replacement only (GB)	Option 2: Coarse scale replacement + interception (GB)	Option 3: Catchment typologies & finer scale hydrological model (GB)		Option 4: Optimal additional woodland placement
Biophysical: Pollutant/ drought/ flood regulation	£30-50K[7]	£40-60K[7]	£150-250K		£20-30K (per catchment)
Economics	Basic national	Basic national	Option 3A: Detailed secondary valuation for 1 catchment of each of 6 typologies[8]	Option 3B: Transfer function for catchment typologies to give detailed national value	Transfer function for value of additional impacts of woodland cover, given existing extent[9]
Flood	*NA*	*NA*	*£30k*	*£30k*	*£25k*
Water supply treatment	*£10k*	*£10k*	*£30k*	*£30k*	*£25k*
Water environment	*£10k*	*£10k*	*£20k[10]*	*£30k*	*£25k*
All modelled services[11]	£20k	£20k	£70 – 80k	£80 – 90k	£70k
				Plus detailed secondary valuation for 2 catchments: £140k	Plus detailed secondary valuation for 2 catchments: £140k
TOTAL	**£50-70k**	**£60-80k**	**£220 – 330k**	**£370-480k**	**£130-140K[12]**

[7] Not including flood regulation
[8] One valuation of each of 6 catchments (representing the typologies). This could be done once, which would provide useful information, but would be better to do 2 catchments for each typology, which is required to support development of a transfer function.
[9] Would be most logical as an extension to option 3A. Minimum cost of £100k to have work covering different catchments.
[10] Slightly lower costs due to more limited valuation evidence base.
[11] Assumes some economies of scale.
[12] For initial 'test' catchment. Costs for subsequent catchments would be very much lower, since the majority of the costs are to develop the transfer function.

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Appendix 1 – Additional detail on biophysical processes and factors that influence variability

Effects of replacement

Reduction in pollutants lost from a land parcel by woodland compared to baseline LU

Reduction in nitrate leaching

Nitrogen inputs

Mean annual nitrate leaching can be simply calculated as the sum of nutrient loads exported from each nutrient source in the catchment (Johnes 1996). Nutrient loads are determined by the type of land-use and crop (and typical fertiliser inputs), type of livestock (and typical manure output), sources of nitrate pollution from the human population (e.g. septic tanks) and nitrate inputs from atmospheric deposition (when nitrogen compounds in the atmosphere settle out on the land or are dissolved in rainfall). Export coefficients by geo-climatic region type for Great Britain are available from the literature.

Geo-climatic region

Export coefficients vary by soil type and climate. The UK can be divided into regions with similar soils, climate and farming practice for modelling purposes. For agricultural crops and livestock, the UK NEAP-N nitrate leaching model (Anthony, Quinn and Lord 1996) considers a single maximum potential nitrogen loss coefficient for each crop/ livestock type, which is modified by soil type and hydrologically effective rainfall. These values are derived from (Lord 1992) under the assumption that UK arable crops are being fertilised in accordance with Defra guidelines. Grazing livestock manure nitrogen loading values by geoclimatic region are derived from research underpinning the N-CYCLE model developed by IGER in the UK (Scholefield, et al. 1991).

Atmospheric deposition

For woodland, the majority of nitrogen inputs are from atmospheric wet and dry deposition of nitrogen compounds (Silgram, et al. 2004). Export coefficients will therefore vary depending upon the level of deposition in the locality. An annual figure for nitrogen loss of 13 kg N ha^{-1} has been adopted by (Johnes 1996) for modelling nitrate losses in northern temperate systems. In the NEAP-N model, a loss coefficient of 5 kg N ha^{-1} is used. European data has shown that leaching of nitrate from woodland soils starts to increase where the atmospheric deposition rate exceeds 10kg N ha^{-1} yr^{-1} (Kristensen, et al. 2004). Notably higher nitrate leaching losses were found where atmospheric deposition exceeds around 20kg N ha^{-1} yr^{-1} (Silgram, et al. 2004).

Woodland age

There is evidence that stand age influences nitrate leaching. Afforestation of former arable land has been found to result in a fairly rapid reduction of nitrate leaching within five years of planting when the demand for nitrogen is high and addition of fertiliser has ceased (Hansen and Vesterdal 2004). After canopy closure the demand for nitrogen decreases and nitrogen deposition increases, which may cause nitrate leaching to increase again. The long-term nitrogen leaching from woodland is nevertheless expected to be considerably lower than from fertilised arable soils.

Soil type

All other things being equal, nitrate leaching under woodland will be higher from nutrient-rich clay soils than from nutrient-poor sandy soils, since clay soils already have enough nitrogen for a forest to grow, therefore uptake of excess nitrogen will be lower. However, it is expected that arable land on clay soils would have received lower inputs of artificial fertiliser than sandy soils, therefore the effects may balance out.

Woodland type

In water-stressed areas, nitrate leaching can be greater under coniferous compared to deciduous woodland due to a lower rate of recharge (higher evapotranspiration) from coniferous woodland causing the nitrate in the leachate to be more concentrated (Calder, Reid, et al. 2002).

Weed control

Storage and leaching of nitrogen from forest can be dependent upon the management practices applied throughout the rotation. Weed control prior to planting varies from ploughing and other mechanical removal to the use of herbicides, mulching and competitive removal. The most intensive mechanical disturbances to the soil increase nitrate leaching losses (Gundersen, Friis and Hansen 2001); (Hansen and Vesterdal 2004), although evidence from upland forestry in the UK shows that cultivation has little effect on nitrate leaching to water (T. Nisbet pers. comm.).

Clear-felling

There can also be a marked effect on N leaching following clear-felling due to the disruption of plant uptake and the increased rates of mineralisation and nitrification, although this is influenced by soil type. Lower evapotranspiration also causes increased run-off and leachate. Concentration of nitrate in soil and stream water usually peaks in the first three years following clear-felling (Hansen and Vesterdal 2004). Concentrations usually return to pre-cutting levels after about 2-5 years.

Reduction in erosion and phosphate loss

Land-use

Risk of erosion from a land parcel is dependent upon the land-use and crop type (Collins and Walling 2007). In a study of the River Frome catchment in Southwest England, relative contributions to fine sediment in the river bed ranged from 1-6% from woodland, 10-42% from pasture, 44-81% from arable land and 7-21% from channel banks and subsurface sources (Collins and Walling 2007). Model-derived sediment and P export coefficients for agricultural land and rough grazing are available in the literature by climatic and soil zone. Sediment and P losses from woodland are usually assumed to be negligible (background levels).

Physical factors

Soil type, slope gradient, exposure to wind, frost and water, and land management also influence vulnerability to erosion.

Harvesting

Forestry can contribute to an increased risk of erosion during and following harvesting operations (Marks and Leeks 1998). This depends on the nature of the practice; losses should be low with good practice according to the UK Forestry Standard and Guidelines. In experimental catchments in Plynlimon in Wales suspended sediment yields increased by 83% in a catchment subject to timber harvesting. In comparison, sediment yields increased by 44% in an adjacent catchment that only had a small amount of harvesting in its headwaters (Marks and Leeks 1998). Timber harvesting in the riparian zone also resulted in a significant increase in erosion rates of adjacent channel banks. This was thought to be due to a reduction in winter temperatures due to removal of the insulating canopy.

Reduction in pesticide loss

Pesticide use in woodland is very low and declining. Usage is mainly for weed control in the few years after planting using broad-spectrum herbicides such as glyphosate. Sometimes insecticides such as cypermethrin are used as spot treatments. The risks associated with these applications are considered negligible compared to those from managed agriculture.

As well as considering the applied load of pesticide to the woodland or crop, we also need to consider the potential of a particular pesticide to contaminate the environment, which is determined primarily by its partition coefficient and half-life. A pesticide with a small partition coefficient (high solubility) and a long half-life (persistence) poses a considerable threat to groundwater through leaching. A pesticide with a high partition coefficient and long half-life is more likely to remain on or near the soil surface and thus be carried to a surface water body attached to sediment.

Quantitative prediction of pesticide loss via runoff and leaching requires models that use site-specific soil, crop and climatological information along with these pesticide-specific coefficients.

Increase in water use by woodland compared to baseline LU

Land-use

The evapotranspiration rate (both the interception and transpiration) of woodland is higher than for many other vegetation types (Table 15). The difference does, however, depend on the soil type and geology; water use from broadleaves can be less than grassland on chalk (Nisbet 2005). Estimates of recharge of the Sherwood Sandstone aquifer in the Midlands of England using the GIS-based HYLUC (HYdrological Land Use Change) soil water model predicted annual recharge rates of 201mm for grassland, 189mm for heathland, 136mm for oak woodland, and 48-63mm for Corsican pine woodland for a relatively wet period (Calder, Reid, et al. 2002). Expressed as a percentage of rainfall, these estimates are 25% for grass, 23% for heath, 17% for oak woodland and 6-8% for pine woodland.

Table 15. Reported annual evapotranspiration for various land cover types

Land cover/ land use	Evapotranspiration (mm)	Source
Woodland	603-684	(Ryszkowski 2007)
Sugar beet	442-478	(Ryszkowski 2007)
Winter wheat	427-483	(Ryszkowski 2007)
Pasture	352-447	(Ryszkowski 2007)
Bare soil	269-400	(Ryszkowski 2007)
Water body	439-638	(Ryszkowski 2007)
Conifers	560-800	(Nisbet, Water use by trees 2005)
Broadleaves	400-640	(Nisbet, Water use by trees 2005)
Grass	400-600	(Nisbet, Water use by trees 2005)
Heather	380-610	(Nisbet, Water use by trees 2005)
Bracken	600-800	(Nisbet, Water use by trees 2005)
Arable	380-420	(Nisbet, Water use by trees 2005)

Forest age

Water recharge under woodland also changes as a forest grows. Results from long-term monitoring studies indicate a rapid decline during the first 5-10 years after afforestation, followed by a much slower decline following canopy closure (Hansen and Vesterdal 2004). Coniferous species have higher evapotranspiration rates than deciduous species due to their higher leaf area. The amount of interception evaporation is largely determined by the density of the forest, with losses higher for dense forests.

Soil type

Water recharge varies from site to site due to the water storage capacity of the soil. Water recharge is usually higher from sandy soils compared to clay soils due to the greater water-holding capacity of clay soils. This effect can be counteracted by a lower level of transpiration of vegetation on clay soils when they are very wet. The lowest recharges are often found on intermediate texture soils where transpiration is not inhibited by drought or waterlogging (Hansen and Vesterdal 2004).

Climate

In general, the comparative influence of woodland compared to other land covers on water recharge will be dependent on the local climate. In dry areas, the actual evapotranspiration of trees will be less than their *potential* evapotranspiration and will therefore be more similar to that of other vegetated land covers. This will depend upon the rooting depth and access to groundwater. Under dry conditions, growth rate will also be lower resulting in lower rates of evapotranspiration. A disproportionate effect has, however, been found in the percentage reduction in water yield for the same percentage coverage of coniferous woodland in an upland catchment compared to a dry lowland catchment. Increased water use by woodland can therefore be a benefit in catchments prone to flooding (albeit limited in its effect for larger storm events), or a detriment in water-stressed catchments.

Increase in surface water acidification by woodland compared to baseline LU due to increased capture of atmospheric pollution.

Forest size & structure

The size and structure of a forest will affect the magnitude of the atmospheric deposition to it. Higher deposition has been observed at the forest edge in many studies (Hansen and Vesterdal 2004). A large contiguous area of woodland will therefore have an overall lower deposition rate than fragmented patches of woodland summing to the same area.

Woodland type

Atmospheric deposition to coniferous species is approximately two-fold higher than to deciduous species because conifers are green all year round and have a greater surface area to catch more deposition (Hansen and Vesterdal 2004). This is then expected to lead to greater leaching of nitrate and sulphate in older forests. The precise magnitude of the difference will depend upon the nature of the woodland, its location and the way it is managed.

N availability

Whilst elevated N deposition explains about half of the variation in N leaching, some of the remaining variability can be explained by differences in N availability. For coniferous forest, needle content of N >1.4% or forest floor C:N ratio of <25 were found to be thresholds for elevated leaching (Gundersen, Schmidt and Rauland-Rasmussen 2006). UK modelled estimates do not differentiate between conifer and broadleaved woodland as the differences are generally believed to be relatively small (T. Nisbet pers. comm.).

Baseline land-use

Depending on the baseline land-use, replacement by woodland may increase or decrease nitrate leaching. N deposition to woodland would be a small fraction of N inputs to arable land, whereas inputs to grassland are likely to be more similar. The largest detrimental effects to water quality would be where the baseline land-use would have been rough grazing or semi-natural grassland/ moorland.

Leaching coefficients

For translation of an N deposition rate to woodland to an expected concentration in groundwater, a leaching coefficient is required. In the NEAP-N model, the leaching coefficients include the effect of average deposition rates, but do not separate them out from other N inputs. In a study by (S. Anthony 2005), empirical data and assumptions used by a critical load exceedance model were used to establish a simple relationship between atmospheric N deposition to woodland and rough grazing and the soil nitrogen coefficient. The soil nitrogen leaching coefficient for woodland and rough grazing was predicted to be 35% of the balance of atmospheric N deposition, forestry off-take and soil-dependent immobilisation and denitrification. Coefficients for immobilisation and denitrification (kg N ha^{-1} yr^{-1}) are defined in N-Cycle by soil texture class and soil drainage class respectively. Calculations could therefore be made to estimate the N leaching coefficient for woodland if the N deposition were modelled. This could be estimated from measurements of nitrate concentrations in stream waters.

(Silgram, et al. 2004) suggest a loss coefficient of 6-8 kg N ha^{-1} for younger upland forest stands or upland areas where atmospheric deposition is <20 kg N ha^{-1} yr^{-1}. A higher value of around 15 kg N ha^{-1} is recommended for mature upland conifer stands or in upland coniferous woodland areas where dry deposition exceeds 15 kg N ha^{-1}. For lowland woodland, typical loss values of 4-8 kg N ha^{-1} are recommended. Higher values may be appropriate where atmospheric deposition is higher in local areas.

Effects of interception/ retention

Reduction in pollutant concentrations in water bodies due to retention by woodland.

The transport of nutrients and sediment from upstream sources to downstream water bodies is highly dependent on the pattern of land use and land cover in the catchment. Woodland can help to mitigate damage downstream by retaining a proportion of the nutrients, pesticides and sediment released and transported via surface and sub-surface flow. These proportions are determined by slope, vegetation type, volume of flow and the location of the vegetation in the catchment. Land with natural vegetation, such as woodland, will tend to be net sinks of nutrient, pesticide and sediment, whereas land under intensive agricultural production will tend to be net sources. The likelihood of a parcel of woodland retaining nutrients, pesticide and sediment increases the closer it is to source areas. Wooded areas on gentle slopes also tend to have higher levels of retention than those on steeper slopes.

The transport of nutrients and sediment is controlled primarily by hydrology. Organic and mineral phosphorous are mainly transported by overland flow in a particulate form bound to suspended sediment. The movement of sediment is therefore particularly important for the transport of phosphorous, and can also be an important pathway for organic nitrogen. The inorganic nitrogen (mainly nitrate) is transported in a dissolved form via surface and sub-surface routes. A major portion of nitrate flow in agricultural catchments is via sub-surface routes (Vought, et al. 1995).

A riparian buffer strip is specifically designed to remove nutrients, sediments, organic matter and other pollutants from surface runoff and shallow groundwater, thereby protecting water quality and enhancing the ecosystem of the water body. They are also used to create shade to lower the water temperature to improve the conditions for aquatic organisms, and to provide a source of detritus and woody debris for aquatic organisms and wildlife habitat (Schultz, et al. 2004).

Nitrate

A major portion of nitrate flow in agricultural catchments is via sub-surface routes (Vought, et al. 1995). For sub-surface dissolved nitrate, the denitrification process (converting nitrate to atmospheric nitrogen) is speeded up under the high soil moisture conditions of riparian woodland, which also increases the uptake of nitrate into the plants. Buffers will have very little effect on pollutants moving in deep groundwater or via artificial drains that bypass the buffer. Nitrate removal will be greatest for slow flow through a wide buffer of young, fast-growing woodland. The rate of removal is also determined by slope, vegetation type, volume of flow and the location of the vegetation in the catchment.

Sediment and phosphate

(Lee, Isenhart and Schultz 2003) found that sediment size has a dominant effect on the trapping efficiency of buffers. Fine clay sediments are less likely to be retained compared to coarser silt particles (Abu-Zreig 2001). Buffer strips work best for sediment retention when surface runoff is shallow and uniform within the buffer. If water becomes concentrated into channels, the efficacy of the strip is drastically reduced due to the increased velocity (Liu, Zhang and Zhang 2008).

The removal of sediment and bound phosphate usually occurs within the first few metres of a buffer strip (Vought, et al. 1995), with the exception of fine clay sediments, which are less likely to be retained compared to coarser silt particles (Abu-Zreig 2001) (Table 16). Buffer strips work best for sediment and phosphate when surface runoff is shallow and uniform within the buffer. If water becomes concentrated into channels, the efficacy of the strip is drastically reduced due to the increased velocity (Liu, Zhang and Zhang 2008). In very intensive agricultural areas, the topsoil may already be saturated with phosphorous and the buffering capacity of the soil will have reached its limits, meaning that any additional deposits will be leached to ground or surface waters. This may explain the difference between the phosphate and sediment retention capabilities in the USA study in Table 16.

A range of sediment trapping efficacies was found in a literature review by (Liu, Zhang and Zhang 2008). They carried out a meta-analysis, which showed that buffer strip width and slope were the two major factors affecting the efficacy of the buffer strips. Differences found in the removal efficiencies between different types of vegetation are not yet conclusive (Vought, et al. 1995), although a combination of woodland and grassland buffers has been found to enhance sediment removal (Lee, Isenhart and Schultz 2003).

A comparison between studies of nitrate and phosphate retention capacity by vegetated buffer strips of differing widths in Norway, Sweden and Germany gave the results shown in Table 16 (Vought, et al. 1995). The results from a study by (Lee, Isenhart and Schultz 2003) in the USA are shown for comparison, as are modelled values for sediment retention for different particle sizes from a study by (Abu-Zreig 2001). In general, removal efficiencies for sediment and phosphate are greater than for nitrate.

Table 16. Results of a few studies investigating the effects of buffer strip width and sediment particle size on trapping efficiency

Buffer strip width (m)	Nitrate (% retention)	Phosphate (% retention)	Sediment (% retention)	Country	Reference
7	62	58	95	USA	(Lee, Isenhart and Schultz 2003)
16	85	80	97	USA	(Lee, Isenhart and Schultz 2003)
5	40-50	65-85		Norway	(Vought, et al. 1995).
10	75	95		Norway	(Vought, et al. 1995).
5	10-15	40-45		Sweden	(Vought, et al. 1995).
10	25-30	65-70		Sweden	(Vought, et al. 1995).
15	40-45	85-90		Sweden	(Vought, et al. 1995).
10	50	70-80		Germany	(Vought, et al. 1995).
15			47 (clay)	Modelled	(Abu-Zreig 2001)
15			92 (silt)	Modelled	(Abu-Zreig 2001)

Pesticides

Wooded buffer strips can also reduce the amount of pesticide entering surface water bodies by reducing run-off volumes, through contact between dissolved pesticides and soil and vegetation in the buffer strip and/or by reducing flow velocities so that sediment particles with pesticide attached can settle out of the water (Sabbagh, et al. 2009). Buffer strips trap pesticides with high organic carbon sorption coefficients (K_{oc}) in a similar manner to which they trap sediment. Conversely, for pesticides with low K_{oc}, buffer strips trap them in a similar way to runoff. Pesticide trapping ability also depends on the physical characteristics of the woodland strip, such as location and soil type. Increasing width does not always improve trapping efficiency, particularly when there is concentrated flow (rather than sheet flow) through a strip. Efficiency ranges reported in the literature for the retention of strongly sorbed pesticides in vegetative filter strips are large (20-60%), which makes them virtually useless for modelling purposes (Reichenberger, et al. 2007).

Reduction in flooding due to interception/ retention by woodland

Infiltration can be up to 60 times higher within young native woodland shelterbelts compared to grazed pasture (Bird, et al. 2003). Forests and woodland have limited ability to mitigate flooding from large return period storm events because the increased soil infiltration only captures a small fraction of the total precipitation for large storms. Even so, peak flows could be reduced by between 13 and 48% by woodland shelterbelts on grazed pasture (Jackson, et al. 2008).

The greater hydraulic roughness of woodland compared to other land-uses can also reduce water velocity and thus increase water retention and soil infiltration. This can have the effect of delaying flood peak travel time. This is particularly relevant for floodplain and riparian woodland, with riparian woodland also contributing to the formation of large woody debris (LWD) dams within streams that can delay flood flows.

Appendix 2 – Detailed methodology and evaluation of models

Methodological approaches

Models range from complex, spatially explicit process-based models to simple probabilistic models derived from statistical relationships between variables. The process-based models make an attempt to describe the mechanisms and processes in operation in the landscape as accurately as possible based upon current knowledge. The probabilistic models incorporate a set of equations that are a result of fitting statistical models to data. Most models lie somewhere between these two extremes, for example process-based models that simplify the mechanisms involved. Model complexity is also considered in terms of the degree to which variables affecting hydrological response are represented.

Recently, a variety of tools that integrate individual process-based or probabilistic models with valuations within a decision-support framework have emerged to help perform assessments of ecosystem services and inform decision making. These tools range from simple spreadsheets to complex software packages and vary widely in their approaches. The majority of ecosystem service tools aim to quantify services at a landscape scale to support scenario analysis (Bagstad, et al. 2011). They tend to use simplified underlying biophysical models that are integrated in order to model processes across the landscape. Typically, these integrated models consist of a suite of pre-existing models originally designed to operate independently.

There are also a number of mapping tools under development in the UK (for examples see the Natural Environment Research Council's Biodiversity and Ecosystem Service Sustainability mapping gateway[13]) that layer GIS data to identify hotspots of service delivery and potential conflict areas. Whilst such tools are useful to encourage stakeholder engagement and identify areas of opportunity, they cannot quantify ecosystem functions in physical units and subsequently value them economically.

Spatial scale

Decisions about the spatial scale at which models should be run are usually the result of a trade-off between the scale at which outputs are required, the scale at which the process is best represented, the linkage between models representing processes at different scales and the constraints of data availability and computing power (van Delden, et al. 2011). In the case of valuing the contribution of woodland to water quality and quantity for national accounting, information is required at a national scale, but most of the hydrological processes involved need to be represented at a sub-field scale in order to incorporate interception effects.

Models can be categorised into three broad types; (i) lumped models that do not account for the spatial distribution of input data to represent heterogeneity in vegetation, soils etc.; (ii) semi-distributed models that divide a catchment into areas with common hydrological properties and (iii) distributed (or spatially explicit) models that account for the spatial variability of the input variables, typically using a regular grid.

Testing the same model at different spatial resolutions or with differing levels of complexity (for example in the degree of disaggregation of land-use classes) could inform decisions as to how best to represent the processes with the available data (van Delden, et al. 2011). It is likely that data availability will ultimately determine the scale at which a process is modelled.

Temporal representation

Whilst valuation of the contribution of woodland to regulating water quality and quantity need not necessarily be temporally explicit, many of the processes under consideration vary over time. For example, the magnitude of the beneficial effect that woodland has on alleviating flooding may vary with the size of the rainfall event and nutrients will be applied on crops at certain times of year, which may or may not coincide with rainfall events and subsequently runoff. These temporal aspects are largely driven by climate data. Many of the modelling approaches considered use annual averages of climate parameters and are known as static or steady-state models, whilst some take daily weather data or generate a synthetic weather series based upon long-term averages and are known as dynamic models.

[13] http://www.nerc-bess.net/ne-ess/

Another consideration is the time period over which the model should be run. Some models provide a snapshot in time, given the average values of the variables and parameters over a defined time period. Other models runs a simulation over a pre-determined and sometimes lengthy time period (which could be into the future), for example to capture a full forest rotation from planting to felling. Whilst it may be desirable to obtain simulations into the future for modelling the effects that new woodland planting may have, a snapshot in time may be sufficient for quantifying the effect of existing woodland. The assumption would need to be made that the current forested area is representative of the full forest rotation and that the variations in woodland maturity can be captured and parameterised sufficiently well.

Applicability to UK

The rural environment in the UK is very different from other parts of the world. A major difference is the greater variability in climatic and soil conditions given the relatively small land area. A second difference of relevance to water movement across the landscape is the predominance of artificial drainage in the form of tile drains and ditches, particularly in wetter arable areas with heavy soils. Models that have been developed and tested for other regions of the world that are dissimilar to the particular UK environment may therefore not be suitable for use in the UK without extensive calibration.

Data requirements

Data requirements of models vary extensively and the complexity of the requirements are usually in proportion to the complexity of the model. The availability and quality of data for input into models is a key consideration in the evaluation of the suitability of a model. Data will be available in different formats and will have varying quality, which will introduce uncertainty in the results. Ideally, we want to strike a balance between the complexity of the data requirements and the accuracy of the model outputs; however availability of data at the required resolution and geographic coverage is usually the main limiting factor. Here, we consider spatial data (e.g. describing spatial variation in land-use, soil type, climate) separately from coefficients (e.g. attributes of certain land-uses, soil types) for clarity.

Parameterisation

Model parameterisation is the process of populating the model with data and coefficients. Spatial data requirements are considered in the previous Section, whilst this Section of the review deals with coefficients, or static values that are needed to parameterise the model's equations. Coefficients that have more than one value depending on the land-use type or soil type for example, are usually stored in a lookup table that includes the land-use or soil code used in the spatial data. The parameterisation effort required for a model varies widely.

The availability of suitable coefficients is a key determinant of the thematic resolution of a spatial data layer. For example, if evapo-transpiration coefficients are not available for different ages of trees and these coefficients are required to run the model, then no benefit will be obtained from splitting the woodland land-cover into stands of different ages.

Model outputs

A robust assessment of ecosystem service delivery and subsequent valuation and how this changes for the current vs. baseline scenarios requires an accurate measure of the ecosystem functions at a suitable scale. The outputs of a model therefore need to be indicators of an ecosystem function, be quantifiable and reflect changes in land-use.

Optimisation and Uncertainty

Models vary in the extent to which they have been tested for performance against real measured data. Model testing has usually only been performed in a small number of catchments, particularly for newer models. If model optimisation has not been performed for UK catchments, there will usually be the need for the user to optimise the model parameters for the UK situation. Some models include optimisation routines in their structure, whilst others don't have this facility.

Some models, usually probabilistic models, provide measures of uncertainty around the estimates. This gives the user some idea of the confidence they can have in the results. Process-based models do not usually provide a measure of uncertainty, unless there are uncertainty estimates around the coefficients.

Accessibility

The accessibility of a particular model (to the Forestry Commission) also varies widely. Some models are open access, with source code and full documentation downloadable from a website. Others, particularly more complex models that have been developed by Universities and other academic institutions are not freely distributed and would need to be run by the developers. It is possible that Defra-funded or adopted models would be accessible to the Forestry Commission.

Another limitation to how accessible a model is for application to a UK-wide simulation is the computing power required and the run time. Some complex models need to be run on a suite of processors and take days to run one scenario, which may be prohibitive to their use for this purpose.

Ease of translation of physical results to monetary valuation

Since the overall purpose of this study is to investigate the feasibility of providing a monetary valuation of woodland's contribution to regulating water quality and quantity, a model will only be potentially suitable if the outputs can be translated into a monetary value in some way. The ease of translation into monetary terms varies across the different ecosystem service models:

- Some models have a valuation component embedded in the modelling process, which may or may not be suitable for the requirement of this project, but in most cases it would be possible to extract the physical information and apply alternative valuation methods and values to it;
- Some models produce modelled outputs that are quantified in physical terms (e.g. nutrient concentration in a water course);
- Some models only provide mapped outputs or bundled service indices that are unlikely to be suitable for input into a valuation model – except if the final outputs can be deconstructed in components or related disaggregated data.

The model evaluations assess the suitability of the economic outputs embedded in models, or the ease of combining the methodologies described in Section 6 with the model's physical outputs. The evaluation considers how the outputs can be representative of the 4 broad categories of environmental goods that can be feasibly monetised. The economic valuation of the benefits of woodlands on water will not be comprehensive (i.e. all the services are monetised) if the biophysical processes assessed do not completely cover the environmental goods to be valued.

Model Evaluation

NEAP-N
Methodological approaches The National Environment and Agricultural Pollution Nitrate (NEAP-N) model is a national scale tool for predicting annual average soil drainage, total nitrate load, and average and peak concentrations of nitrate in leachate from agricultural land. The model is part of the MAGPIE nitrate leaching decision support system which supports the development of government policy on the control of nitrate leaching. The predictions of nitrate leaching are sensitive to crop and animal type, soil type and climate. Extensions to the model predict nitrate losses from non-agricultural and urban land uses.
Spatial scale 1km grid
Temporal representation Annual
Applicability to the UK Has been applied extensively to develop catchment and national scale predictions of nitrate losses to support catchment characterisation and pollutant source apportionment for UK government policy development
Data requirements • Crop areas • Livestock numbers

- Climate
- Soil type
- Altitude

Parameterisation

- Soil parameters for soil type
- Fertiliser & manure loadings by land-use
- N export coefficients
- Drainage

Model outputs

- Total area of included land uses (arable, grass, rough grazing, woodland, open water) (ha)
- HER (hydrologically effective rainfall) (mm)
- Load of N leached (kg/ha) of the total included land uses
- Concentration of leached N (mg/l)

Optimisation and Uncertainty

Accessibility

Readily accessible for UK government research

Source code held by ADAS

Summary

Advantages

- UK model
- Used extensively in support of government policy
- Simple to parameterise and use

Disadvantages

- Does not model interception
- Relatively coarse scale
- Only models nitrate losses
- Simplistic treatment of woodland

PSYCHIC (Davison, et al. 2008)

Methodological approaches

PSYCHIC is a process-based model of phosphorus (P) and suspended sediment (SS) mobilisation in land runoff and subsequent delivery to watercourses. Modelled transfer pathways include release of desorbable soil P, detachment of SS and associated particulate P, incidental losses from manure and fertiliser applications, losses from hard standings, the transport of all the above to watercourses in underdrainage (where present) and via surface pathways, and losses of dissolved P from point sources. The model can operate at two spatial scales, although the scientific core is the same in both cases. At catchment scale, the model uses easily available national scale datasets to infer all necessary input data whilst at field scale, the user is required to supply all necessary data. The model is sensitive to a number of crop and animal husbandry decisions, as well as to environmental factors such as soil type and field slope angle.

Water balance and hydrological pathway components are modelled using the mean climate drainage model (MCDM), which calculates the water balance for seven representative UK land use types. It calculates monthly values of potential and actual evapotranspiration, soil moisture deficit and soil drainage. Sediment loss is modelled using a modified Morgan-Morgan-Finney method. P loss rate from manure and fertilisers is determined by rainfall intensity and cumulative rainfall since application. Solubilisation of P in soil is calculated as a function of soil Olsen P. P loss with eroded sediments is determined by soil total P and soil particle distribution in eroded material. Delivery is determined by landscape connectivity factors such as distance to water courses and presence of underdrainage.

Sediment loss is estimated using the Morgan-Morgan-Finney model, which predicts annual soil loss risk.

Spatial scale

$1 km^2$ or finer

Temporal representation

Monthly

Applicability to the UK

Has been applied extensively to develop catchment and national scale predictions of P and sediment losses to support catchment characterisation for UK government policy development

Data requirements

- Area of major crops & livestock numbers by type
- Dominant soil series
- Monthly climatic data (rain; rain days; wind speed; sun hours; max/min temperature)
- Index of proximity to surface water (drainage density)
- Mean slope per $1km^2$
- Number of people per $1km^2$

Parameterisation

- P applications by month as manures and excretal returns to land, by livestock type
- Soil series characteristics (% sand, silt & clay; HOST class; bulk density; organic carbon under grass & arable)
- Soil Olsen P by soil texture and land use

Model outputs

- Volume of surface and subsurface flow (including drainflow)
- Mobilisation of P (kg ha^{-1} yr^{-1}) in surface runoff & drainflow and total P transfer to watercourses from diffuse sources and combined diffuse and point sources
- Total P load (kg ha^{-1} yr^{-1})
- Suspended sediment load (kg ha^{-1} yr^{-1})
- Flow-weighted mean total P concentrations (mg/l)
- Flow-weighted mean suspended sediment concentrations (mg/l)

Optimisation and Uncertainty

PSYCHIC was evaluated in the Hampshire Avon and Herefordshire Wye catchments in the UK using empirical data (Stromqvist, et al. 2008). Statistical performance in relation to predicted exports of P and sediment reflected the potential shortcomings associated with using longer-term climate data for predicting shorter-term catchment response and the need to refine calculations of point source contributions and to incorporate additional processes such as channel bank erosion and in-stream geochemical processing. PSYCHIC is therefore best suited to characterising long-term catchment response.

Accessibility

Readily accessible for UK government research

Source code held by ADAS

Summary

Advantages

- UK model
- Used extensively in government research & policy development
- Fairly straightforward to parameterise and run

Disadvantages

- Does not explicitly model interception effects (catchment scale model)
- Only models P, sediment and water balance

• Simplistic treatment of woodland

APT (Zhang, et al. in press)
Methodological approaches The new ADAS Pollutant Transport (APT) model builds on and re-uses existing validated models for the estimation of nitrate, phosphate and sediment losses from agricultural land. The main change is that the nitrate module now uses the same hydrological data as the phosphorous and sediment modules. Diffuse agricultural pollution emissions (nitrogen, total phosphorus, sediment) were generated using the ADAS Agricultural Pollutant Transfer (APT) framework, which has been developed for national scale modelling for policy support. APT builds upon the existing, validated PSYCHIC model for phosphorus and sediment emissions and NIPPER model for nitrogen losses. By combining these two process-based models within a single framework it is possible to produce estimates of multiple pollutant losses which benefit from shared input data and common hydrological and crop growth sub-models. The APT framework predicts pollutant losses from agricultural land and woodland, including pollutant emissions delivered to watercourses. Land drainage as a pollution delivery pathway is represented, as well as surface runoff. The APT framework models crops as either part of a 3 year rotation, or (primarily for permanent grassland) as continuous cropping. The primary benefit of this is that it allows the predictions to include the effects of crop and manure management in previous years on the nitrogen cycle. APT runs covered a 20-year period (1991-2010) and annual average pollutant losses over this period per waterbody were calculated for inclusion in the SEPARATE screening tool. SEPARATE integrates information on pollutant emissions from multiple sources to provide apportionment.
Spatial scale The APT framework predicts losses at field scale, with a waterbody represented as a large number of fields which are then subject to landscape scale retention to estimate delivery of pollution from agricultural land to rivers. It can output at 1km^2 spatial resolution.
Temporal representation Daily time-step
Applicability to the UK Developed in the UK for the UK agricultural conditions.
Data requirements The APT framework requires three core types of data; daily weather information, physical attributes of the land, and crop and livestock management data. The daily weather data was interpolated for each waterbody from existing UK Meteorological Office records using an inverse distance weighting function in the IRRIGUIDE tool (Bailey and Spackman, 1996). A waterbody is represented by a small number of major soil types taken from the NSRI Natmap Soils Database. Other physical data required as input include slope and altitude, plus field boundary features (based on the countryside survey; Hornung, 1998) which are a key control on land-to-river connectivity. The crop areas are based upon the 2010 June Agricultural Census completed by farmers, which has been mapped to a 1 km grid.
Parameterisation Manure and excreta distribution and management are calculated using the Manures-GIS system (ADAS, 2008), which uses livestock numbers from the June Agricultural Census. Data on fertiliser application rates for different crop types were taken from the 2010 British Survey of Fertiliser Practice (BSFP; Thomas, 2011).

Model outputs

- Land area (ha)
- Total annual water flow (mm)
- Annual nitrate load (kg/ha)
- Annual dissolved Phosphorous load (kg/ha)
- Annual particulate P load (kg/ha)
- Annual sediment load (kg/ha)
- Monthly surface flow (mm)
- Monthly lateral flow (mm)
- Monthly seepage (mm)
- Monthly surface/ lateral/ seepage nitrate/ P/ sediment concentration (µg/L)
- Daily flows and pollutant loads

Optimisation and Uncertainty

The new nitrate modelling component has been validated at field scale, sub-catchment and catchment scales.

Accessibility

Readily accessible for UK government research

Source code held by ADAS

Feasible to use the model for national scale assessments

Summary

Advantages

- Developed and parameterised for England and Wales
- Uses daily weather data
- Estimates the volume of water (and thus pollutants) reaching water courses based on slope and boundary features
- Models multiple pollutant losses (N, P & sediment) under one framework

Disadvantages

- Not yet parameterised for Scotland
- Does not incorporate flow routing
- Fairly simple representation of woodland

InVEST – the Natural Capital Project (Tallis, et al. 2013)

Methodological approaches

Reservoir Hydropower Production

The two biophysical components of this model that are of interest are water yield and water scarcity. The tier 1 models do not consider surface-ground water interactions or the temporal dimension of water supply. The water yield model estimates the relative contributions of water from different parts of a landscape. This enables quantification of how changes in land-use affect the annual surface water yield from a catchment. The model runs off a gridded map by estimating the amount of water running of each grid cell. This is calculated as the precipitation minus the fraction that undergoes evapotranspiration. The model does not distinguish between surface, sub-surface and base flow but assumes that all water yielded from a grid cell reaches the catchment outlet via one of these routes. The water yield at the catchment or sub-catchment scale is quantified by summing and averaging the values over all grid cells.

The water scarcity model calculations are based on water yield and consumptive use, i.e. water that is not returned to the stream after use. Data are required on how much water is consumed per land-use land-cover type. The amount of water that reaches the catchment outlet is defined as the difference between the total water yield for the catchment and the total consumptive water use.

Water Purification: Nutrient Retention

This model estimates the contribution of vegetation to water purification by the removal of nutrient pollutants (N & P), but can also be used for other kinds of contaminants such as pesticides. The tier 1 model does not consider chemical or biological interactions other than filtration by vegetation and is less relevant for areas with tile drainage or ditching, strong surface-ground water interactions or dry regions with flashy rains. The model estimates the nutrient retention for each grid cell, then sums and averages nutrient export and retention per catchment or sub-catchment.

The annual average runoff from each grid cell is estimated using the water yield model. The quantity of pollutant exported from each grid cell is determined based on export coefficients – annual averages of pollutant fluxes per LULC type derived from field studies. Since these are averages, a hydrological sensitivity score (run-off index) is included that accounts for the differences in conditions between fields where the fluxes were measured and the conditions in the grid cells to which the model is being applied. Retention of the exported pollutant by each grid cell is determined by routing water down flow paths and allowing each grid cell to retain pollutant based on a coefficient for vegetation filtering for the LULC. Saturation of uptake is not accounted for. The model tracks how much pollutant reaches the stream by following the pollutant load of each grid cell all the way to the watercourse. The aggregated loading at catchment or sub-catchment scale can be compared to actual measurements or outputs from other models for calibration. Export coefficients and removal efficiencies can be adjusted until the modelled load matches the measured load.

Sediment Retention: Water Quality Regulation

This model estimates the capacity of each land parcel to retain sediment. Patterns of erosion and sediment movement are influenced by natural variation in soil properties, precipitation and slope. Vegetation holds soil in place and captures sediment moving overland and therefore changes in vegetation can alter the sediment retention capacity of land. The biophysical components of this tier 1 model calculates the annual average soil loss from each parcel, determines how much sediment may arrive at a point of interest and estimates the sediment retention ability of each parcel. The Universal Soil Loss Equation (USLE) is used at a grid cell level to estimate potential soil loss and sediment transport based on LULC patterns, topography, soil properties, rainfall and climate. The USLE accounts for the higher probability that soil particles will become detached and transported by run-off in areas of high rainfall intensity, and the higher probability of soil erosion where the soil has a high proportion of sand. The ability of vegetation to keep soil in place is estimated by subtracting erosion rates on that cell from what they would be on bare soil.

The USLE does not account for the capture of sediment that has eroded upslope of the vegetated land parcel. The InVEST model estimates this by routing all sediment that the USLE calculates will be lost from a grid cell downslope via a flow-path. How much of this sediment will be captured by downslope vegetation is estimated and the total exported sediment that reaches the stream determined. The total retained sediment is equal to the sum of the sediment removed by the grid cell itself and the sediment removed through routing filtration.

The USLE method is highly sensitive to the categorisation of LULC classes. Therefore, where there is variation across the landscape that affects a USLE parameter, the LULC classes should reflect that variation. In other words, where the attributes of the woodland have different sediment retention values they should be recorded in different LULC classes.

Tier 2 models

The tier 2 water models in InVEST (Mendoza, et al. 2012) simulate temporal variability in hydrology on a daily time-step. The water storage potential of the landscape takes into account the properties of the soil, the vegetation roots and the shallow aquifers in the catchment. The tier 2 models have a modular structure that enables users to add or replace different hydrology modules dependent on site-specific conditions, existing data and hydrologic understanding. The tier 2 approach uses the Precipitation Runoff Modelling System (PRMS) to estimate water supply. This is then an input to a water resources systems model that incorporates demand or use.

The tier 2 storm peak mitigation model (Ennaanay, et al. 2011) provides a probabilistic output for flood magnitude, which is affected by changes in the landscape mosaic, and quantifies incremental changes in risk associated with a specific flood volume. The extent of the flooded area is determined using the Hydrologic Engineering Centers River Analysis System software (HEC-RAS) and streamflow time-series from the PRMS model. Whilst the tier 1 model lumps all known land-cover related storage and infiltration functions into one number, the tier 2 approach is being designed to independently evaluate canopy interception, rooting effects, soil litter and other functions that mitigate runoff. Mitigation of storm peaks by vegetation will be reported relative to the landscape geomorphology and scale by the incorporation of hydraulic routing impacts. The incremental changes in risk with increasing storm intensities will be assessed given a change in landscape or climate.

The Tier 2 nutrient and sediment retention models (Conte, et al. 2012) capture the temporal dynamics of the rate of water flowing across the landscape, as opposed to the annual averages used in the Tier 1 models. The Agriculture Non-Point Source (AnnGNPS) model is used to estimate nutrient export and retention and the PRMS is used to predict the amount of sediment eroded and delivered to water bodies. Both run on a daily time-step. Whilst these models provide more realistic estimates, they are data intensive and require a detailed understanding of local hydrology. Unlike the tier 1 models, the tier 2 models allow management decisions made on sub-annual timeframes to be incorporated. The tier 2 nutrient retention model also recognises that nutrient pollutant export is highly dependent on dynamic hydrology and incorporates nutrient-specific characteristics that affect transport. The tier 2 sediment retention model calculates the retention on each hydrological response unit attributable to its land-cover class by running the PRMS model twice, once with bare soil and once with the land-cover.

In all of these ecosystem service models, one of the major constraints to using tier 2 is the effort and data required for calibration and optimisation. Model setup and interpretation require a relatively sophisticated knowledge of hydrology and will require extensive calibration, definition of modelling units, and an understanding of the driving processes.

Spatial scale

Flexible and dependent upon scale of input data. Calculations are performed at grid cell level, enabling representation of the spatial heterogeneity in the key driving factors. The theory behind the models, however, was developed at the sub-catchment to catchment scale. Results should not be interpreted at a finer scale than sub-catchment.

Temporal representation

Annual in Tier 1 models. Daily in Tier 2 models.

Applicability to the UK

Not yet been tested/ calibrated in the UK as far as we are aware

Data requirements

Reservoir Hydropower Production

- Elevation (m)
- Average annual precipitation (mm)
- Annual reference evapotranspiration (mm)
- Land-use and land-cover
- Seasonal distribution of precipitation
- Saturated hydraulic conductivity
- Consumptive water use (m^3 yr^{-1})

Nutrient retention

- Elevation (m)
- Average annual precipitation (mm)
- Annual reference evapotranspiration (mm)
- Soil depth (mm)
- Land-use and land-cover

Sediment retention

- Elevation (m)
- Soil erodibility
- Land-use and land-cover

Parameterisation

- Root restricting layer depth (mm)
- Plant available water content (fraction)
- Root depth for vegetation type (mm)

- Plant available water content (fraction)
- Root depth for vegetation type (mm)
- Evapotranspiration correction factor for vegetation type

- Rainfall erosivity index
- Cover management factor
- Support practice factor

• Evapotranspiration correction factor for vegetation type	• Nutrient loading for LULC class (g Ha^{-1} yr^{-1}) • Vegetation filtering value for LULC class (%) • Threshold flow accumulation value	• Sediment retention value for LULC class • Threshold flow accumulation value • Slope threshold for cultivation (%)

Model outputs

Reservoir Hydropower Production	*Nutrient retention*	*Sediment retention*
• Total water yield per sub-catchment/ catchment (m^3) • Mean water yield per sub-catchment/ catchment (mm) • Water yield volume per hectare per sub-catchment/ catchment (m^3/ ha) • Total realised water supply volume per sub-catchment/ catchment (m^3) • Mean realised water supply volume per hectare per sub-catchment/ catchment (m^3/ ha) • Calibrated water yield volume per sub-catchment/ catchment (m^3)	• Total amount of nutrient retained by each sub-catchment / catchment (kg) • Mean amount of nutrient retained by each sub-catchment/ catchment (kg/ha) • Mean amount of nutrient per sub-catchment/ catchment that is exported to the stream (kg/ha) • Total amount of nutrient per sub-catchment/ catchment that is exported to the stream (kg)	• Total amount of sediment exported to the stream per catchment (tonnes) • Total amount of sediment retained by the landscape in each catchment (tonnes)

Optimisation and Uncertainty

Results of sensitivity analysis in a catchment in China showed that, for both nitrogen and phosphorous, the model is more sensitive to changes in export coefficients that retention efficiency.

As a proxy for testing predicted outcomes relative to observed nutrient loading and sediment deposition, predicted outcomes have been compared to those of a well-respected model (SWAT) that has been calibrated to a specific region (Conte, et al. 2012). There was general agreement between the calibrated SWAT results and the InVEST model outputs in much of the test region. Differences between the two outputs are most apparent along river banks and mountain slopes, where the InVEST model predicts much higher phosphorous loadings than that of SWAT. This could be due to the assumption of homogeneous land-cover within the SWAT modelling units.

The biophysical component of the water supply model was also tested against outputs of SWAT in climatically diverse regions (Mendoza, et al. 2012). Performance was evaluated for annual water yield, and the water retention index was compared with SWAT's annual groundwater percolation outputs. The InVEST models could predict trends and rankings fairly well for annual water yield, but in terms of absolute values, higher results were overestimated and lower results underestimated compared to SWAT. Comparisons between water retention index and groundwater fluxes in SWAT revealed relatively low measures of agreement, however comparisons with measured stream baseflow reduction rate suggest that the index sufficiently describes the landscape's ability to regulate streamflow.

Steps are currently been taken to incorporate uncertainty estimation into the models.

Accessibility

Freely available to download and use, with comprehensive user guide. Older versions required ArcGIS but most recent version can be run independently.

Summary

Advantages

- Underlying models have been more extensively peer-reviewed than other similar tools
- Freely available with user guide
- Moderate data requirements
- Designed for a purpose aligned to this project
- Supports scenario analysis
- Models can be modified by user
- Spatial variations in land-cover can be well represented with sufficiently fine scale data
- Has valuation component and the processes can be valued in monetary terms

Disadvantages

- Does not allow for uncertainty estimation
- Static model – runs on annual average basis
- Appears not to account for possible scale dependence of underlying processes
- May not be accurate enough under certain conditions
- The USLE method predicts erosion for sheet wash only (i.e. not gully erosion)
- Sediment model results highly sensitive to categorisation of LULC
- Not tested in UK

Polyscape/ LUCI (Jackson, et al. 2013)

Methodological approaches

The flooding model is a detailed topographic routing of water accounting for storage and infiltration capacity as a function of soil and land use. The erosion model uses slope, curvature, contributing area, land use and soil type. The sediment delivery model uses the erosion model combined with detailed topographical routing. The water quality model uses export coefficients combined with water flow and sediment delivery models.

Flood Mitigation Tool

Information on the storage and permeability capacity of land parcels in the landscape is derived from soil and land-use data. The algorithm is based around flow accumulation, corrected by removing any flow that accumulates on grid cells that act as “sinks”. A more sophisticated version of the algorithm can be used to value land under different rainfall events (e.g. known return period events).

Erosion/ Sediment delivery risk Tool

The most severe forms of soil erosion occur in areas where overland flow is concentrated in natural depressions in the landscape, generating enough kinetic energy to detach and mobilise soil particles. The soil surface is lowered, resulting in further concentration of flow and ultimately the creation of erosion channels. Polyscape identifies areas of land that are vulnerable to this type of erosion using the Compound Topographic Index (CTI). This combines three important factors: overland flow magnitude, slope and overland flow concentration. The probability of soil erosion at a location is also dependent on soil and vegetation characteristics, which are represented in Polyscape via user-defined thresholds for each combination of region-soil type-land use variables.

The transfer of eroded sediment to rivers and streams depends on the hydrological connectivity between the origin and the watercourse. Areas of land vulnerable to severe erosion *and* at risk of being linked to a watercourse by uninterrupted overland flow are identified by combining the CTI with the flood mitigation tool.

Spatial scale

The models within Polyscape/ LUCI have been designed to be applicable at fine scales. The models are run at a recommended scale of 5-50m grid cells and therefore can account for the impacts of small land parcels such as riparian woodland.

Temporal representation

Steady state and annual. Sub-annual models in development.

Applicability to UK

Has been tested in the UK (Wales)

Data requirements

Inputs include commonly available national datasets such as elevation, slope, hydrography and land cover that can be modified to improve accuracy at high spatial resolution. Default look-up tables are provided that link to input datasets, but these can be modified by users if required.

- Stream network
- Digital Terrain Model (ideally 5x5m spatial resolution)
- Land-use data
- Soil data

Parameterisation

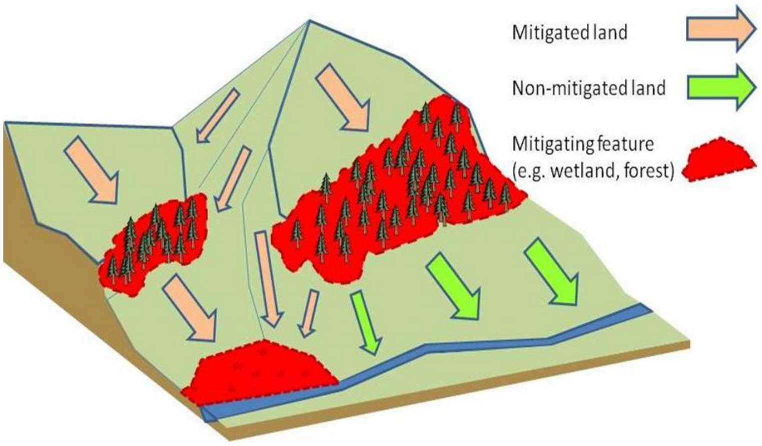
Default parameters are provided, but the user can modify them

Outputs

Outputs of Polyscape/ LUCI show parts of the landscape that currently provide ecosystem services and areas where management interventions could enhance or degrade services. All land uses or soil types that provide flood mitigation by acting as a sink for fast-moving overland or subsurface flow are treated as having high value. Areas whose flow is intercepted by these features are considered to be "mitigated". Mapped outputs show the study area divided into the following categories based on whether they are;

- High existing value
- Existing value
- Marginal
- Opportunity for change
- High opportunity for change

A quantitative summary of the percentage areas covered by (i) mitigating land; (ii) mitigated land and (iii) non-mitigated land is also provided.



Optimisation and Uncertainty

Some guidance on optimisation is given, but is largely considered through exploration of scenarios. Uncertainty estimates are not provided.

Accessibility

LUCI is an evolving tool, but a release version including the original Polyscape functionality is to be made available in the near future. It requires ESRI's ArcGIS 10.1 or above to run.

Advantages	**Disadvantages**
• Has been tested in the UK • Operates at a spatial resolution that is appropriate for modelling effects at field scale • Designed to work within the constraints of nationally available data • Algorithms can be modified by user or combined with other applications • Sediment delivery risk tool accounts for gully erosion • Computationally fast to run	• Limited guidance on use • Outputs may not be appropriate for valuation • Requires ArcGIS to run • Possibly overly simplistic representation of processes

ARIES – Artificial Intelligence for Ecosystem Services (Bagstad, et al. 2011)

Methodological approaches

ARIES uses probabilistic models to map ecosystem services provision, use and spatial dynamics. This means that conditional probability tables are used rather than fixed parameterisation of deterministic equations. Where peer-reviewed ecological process models can provide input data or values for the source, sink or use components, these can be incorporated into the chain instead of probabilistic models. The probabilistic models in ARIES may be more appropriate under conditions of data scarcity (K. S. Bagstad 2013). Artificial intelligence techniques are used to pair locally appropriate ecosystem service models with spatial data based on a set of encoded decision rules, quantifying ecosystem service flows and their uncertainty.

Flood Regulation

The flood models map sources of precipitation that can cause floods, and sinks that absorb, slow or increase infiltration of floodwater. Vegetation and soil data are incorporated with information on how well they absorb or attenuate flow. Sources of floodwater and sinks are spatially linked. The flow model routes water from its source locations through the catchment based on the topography and stream network. Once in a stream, it can overtop the banks depending on the amount of floodwater, floodplain width, and the presence of levees. The model operates on an annual time step. There are currently regional models for the USA (Orange County, California and Western Washington State). A generalised global model is planned for a future release of ARIES and will provide coarser resolution outputs.

Sediment Regulation

ARIES models sources of erosion and sinks where sediment deposition occurs. The sediment models can also quantify the erosion control benefits of vegetation. The source model uses an internal rule base to select the appropriate erosion model (i.e. Revised Universal Soil Loss Equation or regionally appropriate ad hoc erosion models where RUSLE is known to be inadequate). A generalised global sediment regulation model is planned for a future release of ARIES. Only sediment deposition in floodplains and reservoirs is considered in the sink model, as opposed to sediment carried and deposited by overland flow before reaching a stream. Sediment deposition is defined as a function of stream gradient, floodplain tree canopy cover and floodplain width – plus dams that cause deposition in reservoirs. The flow models describe the amount of sediment delivered or the amount carried in flowing water using a relatively simple hydrologic model. There are currently regional models for Dominican Republic, Madagascar and Western Washington.

Water Supply

In ARIES, water quantity is a function of topographically-based hydrologic simulation. Water supply models operate on an annual scale and currently only consider flows of surface water, although the infiltration of surface water into groundwater is modelled. A set of generalised models are used to represent sources of surface water (precipitation, snowmelt, springs, baseflow to rivers, inter-basin water transfers), sinks of surface water (evapotranspiration, infiltration), users of surface water and the flow of surface water across the landscape (using elevation data). There are currently regional models for Arizona and Northern Sonora, Mexico and Veracruz, Mexico. A generalised global model is planned for a future release of ARIES. Subsurface flows are considerably more complex that surface water flows. Future releases of ARIES will investigate the feasibility of linking groundwater models such as MODFLOW.

Spatial scale

Flexible.

Temporal representation

Currently only models annual runoff, sediment loss and water yield

Applicability to UK

Not yet been tested in UK

Data requirements

Flood Regulation

- Average annual precipitation
- Soil infiltration
- Actual evapotranspiration
- Average annual runoff
- Detention basins
- Dam storage
- Hydrologic soils group
- Impervious surface cover
- Mean days of precipitation per year
- Slope
- Successional stage
- Tree canopy cover
- Vegetation height
- Vegetation type
- Dams
- Elevation
- Floodplain extents
- Stream network
- Flood defences

Sediment Regulation

- Average annual precipitation
- Average annual runoff
- Average annual soil loss (RUSLE)
- Hydrologic soils group
- Slope
- Slope stability
- Soil texture
- Successional stage
- Tree canopy cover
- Vegetation type
- Floodplain tree canopy cover
- Floodplain width
- Reservoirs
- Stream gradient
- Dams
- Elevation
- Floodplain extents
- Stream network
- Flood defences
- RUSLE factors

Water Supply

- Average annual precipitation
- Soil infiltration
- Springs
- Actual evapotranspiration
- Annual maximum temperature
- Hydrologic soils group
- Hydrography
- Impervious surface cover
- Average annual runoff
- Slope
- Soil infiltration
- Springs
- Tree canopy cover
- Vegetation type
- Surface diversions
- Water extraction amounts and user types
- Well capacity
- Well depth
- Well locations
- Well user type
- Elevation
- Stream network

Parameterisation

Flood Regulation

Average annual soil infiltration is set as a function of impervious surface cover, slope and hydrologic soil group.

Sediment Regulation

Annual sediment loss is set as a function of runoff, vegetative maturity and soil erodibility.

Water Supply

Total surface water sink is set as the sum of evapotranspiration and deep soil infiltration.

Evapotranspiration is set as a function of percent tree canopy cover and vegetation type, with added influences for vegetation height and successional stage for one of the regional models.	Vegetative maturity is set as a function of vegetation type and percent tree canopy cover, with some case studies also incorporating successional stage. Runoff is set as a function of annual precipitation and tropical storm probability. Soil erodibility is set as a function of hydrologic soil group, soil texture and slope. Slope stability was added as an influence in W Washington.	Evapotranspiration is set as a function of vegetation type, percent tree canopy cover and annual maximum temperature. Deep infiltration is set as a function of hydrologic soil group, slope and percent impervious surface cover.
Model outputs		
Flood Regulation • Runoff: quantity of runoff produced by each portion of the landscape • Potential runoff mitigation: all areas capable of storing or impeding flood water • Potentially damaging flood flow: the flow route of floodwater in the absence of sinks • Actual flood flow: The flow route of floodwater in the presence of sinks • Utilised runoff mitigation: sinks that actively reduce floodwater • Absorbed flood flow: flood flows absorbed by sinks • Flood mitigated runoff: portion of total runoff that is stored, impeded or slowed by the action of sinks	***Sediment Regulation*** • Maximum sediment source: locations of areas capable of providing sediment to downstream areas • Maximum potential deposition: areas capable of accumulating waterborne sediment • Possible sediment flow: downstream movement of sediment when not accounting for sinks • Actual sediment flow: downstream movement of sediment that accounts for sediment sinks • Actual sediment source: areas that provide sediment downstream, accounting for flow pattern and sinks • Utilised deposition: areas that are actively performing a sediment trapping function	***Water Supply*** • Actual surface water flow • Used surface water supply: transitions that result in an initial source quantity • Actual surface water sink: locations where surface water transitions into groundwater or atmospheric water • Satisfied surface water demand: portion of demand for water satisfied by extraction
Uncertainty Uses probabilistic modelling to provide uncertainty estimates for ecosystem service flows		
Accessibility Web-based system, so readily accessible		
Advantages • Holistic approach to multiple ecosystem services • Web-based • Has measure of uncertainty	**Disadvantages** • Relies heavily on empirical approaches to extract relationships • Data intensive for new regions	

• Flexible framework	• Based on case studies in other parts of the world – currently no global model • Currently only models annual time steps • Currently lacking a groundwater model • Simplistic hydrological models

MIMES
Methodological approaches **Detailed physical models integrated with environmental, economic and social drivers. MIMES is a relatively new model that aims to be truly integrated and allows for modelling at various scales. MIMES is designed to account for temporal dynamics and feedback loops, incorporating existing ecological process models into ecosystem services modelling.** **There is currently not enough information to evaluate links with economic valuation.** • **It is currently assessed as not suitable as we don't know enough about it at this stage. Indications are that it is very complicated to use and may not be applicable for valuation of water resources in the UK.**
Spatial scale Flexible in theory, to date been applied at regional to global scale.
Temporal representation Flexible in theory, but data requirements currently limiting.
Applicability to UK Doesn't appear to have been tested in UK
Data requirements Input data include a wide range of spatial datasets
Parameterisation A large number of coefficients are required to parameterise the model's equations
Model outputs Outputs are spatially explicit time series of ecosystem service values.
Optimisation and Uncertainty
Accessibility MIMES is a public domain tool but is place-specific, requires a long lead time to develop, and/or requires contracting with universities or consultants. MIMES was developed using Simile, a commercial coding and software package.

Advantages	**Disadvantages**
• Full systems approach • Truly integrated model • Flexible spatial and temporal resolution	• Very data intensive • Difficult to parameterise • Developed using commercial software • Not very flexible

Co$ting Nature	
Methodological approaches **Co$ting Nature uses pre-loaded global datasets at 1km^2 or 1ha resolution to quantify water yield, carbon storage, nature-based tourism and natural hazard regulation for baseline conditions and climate or land-use change scenarios. It estimates and aggregates these values into a "bundled service index".** **The output in the form of a bundled ecosystem service index (i.e. no quantification of individual services or biophysical processes) implies that there is little scope for transferring an economic value for any of the individual environmental goods considered.** • **Assessed as not suitable for use in this project due to the inability to separate out different services.**	
Spatial scale Flexible, with global coverage at 1km^2 or 1ha	
Temporal representation Steady state	
Applicability to UK No information	
Data requirements None – data pre-loaded on web portal	
Parameterisation Default parameters provided, which can be adjusted by user if required	
Model outputs Bundled service index	
Optimisation & Uncertainty Scenario optimisation, but no measure of uncertainty	
Accessibility Readily accessible on web portal	
Advantages • Little or no effort required in terms of data gathering and parameterisation • Available for immediate widespread use • Simple to use	**Disadvantages** • Low flexibility • Does not support quantification of individual services • Not yet running scenarios for land-use change • Limited range of ecosystem services

TIM (Bateman and Day 2013)
Methodological approaches The water quality module covers the hydrological processes that link land-use to nutrient concentrations and ecological status in rivers. Nutrient export coefficient modelling is used to provide the inputs to and flow from catchments. Export coefficients values can vary widely between different geoclimatic regions, therefore five soil-climate classes were defined to represent units with broadly similar climate soil type, hydrogeology and farming practices. Environment Agency General Quality Assessment (GQA) measurements of nutrient concentrations in rivers are then used to construct statistical models that relate nutrient inputs on land to concentrations

in rivers. Highly significant relationships were found between land use and nutrient concentrations and subsequently ecological status of river bodies assessed by the WFD. Further statistical analyses revealed that changes in land use may have only marginal impacts on WFD classification due to the many factors determining ecological status.

The 2km grid cells covering GB are classified as either *land cells* or *river cells*. Land-use patterns in river cells can also impact on the quality of water in the river. The statistical model assumes that the nutrient concentration in any river cell results in part from nutrients that run off from the land and in part from other sources. Nutrients from land are calculated as a function of the nutrients exported from each land cell, using spatial data multiplied by the appropriate export coefficient. Not all the nutrient from the land will end up in a river. Nutrient decay processes are calculated as a function of the distance of the land cell to a river cell. The variability in the features of land and the path over which nutrients in run-off travel is captured through the inclusion of a land cell-specific scaling parameter. Most likely values of this parameter for each land cell were predicted using probability models constructed using data from the sampled river catchments. As would be expected, there are strong regional trends in this parameter, with higher levels of export in the hilly areas of Wales and Scotland.

Spatial scale

Medium catchment to national (2km grid square)

Temporal representation

Annual but could be sub-annual

Applicability to UK

Developed and tested in UK

Data requirements

Data is pre-loaded and available within the TIM software. These datasets provide information on determinants of nutrient inputs including measures of livestock, coverage of different land-use categories and population location data.

Parameterisation

Default parameters provided for the following;

- Annual fertiliser use and nutrient inputs from livestock
- Nutrient inputs from the human population
- Nutrient inputs from N fixation and atmospheric deposition
- Export coefficients per unit area of each land-use for soil-climate classes

Model outputs

- Annual nutrient loss (nitrates and phosphates) to surface water per hectare
- Nutrient concentration in rivers
- Phosphate and nitrate categories in each WFD river water body

Optimisation and Uncertainty

Statistical modelling approach means that it would be possible to obtain confidence estimates around predictions. A major source of uncertainty is the water quality data used to develop the equations, which are aggregated to annual means and are only from certain rivers in the modelled regions. There is also uncertainty in the parameters used to determine export from individual cells.

Accessibility

Not currently available as open source model, but the intention is to move towards an open-source system that would be shared freely.

Advantages	**Disadvantages**
• High flexibility with built-in optimisation procedure for land-use scenario exploration	• Does not accurately model the interception effects of woodland, since land-uses are assumed to be uniformly distributed across a $2km^2$ cell

• Pre-loaded with UK-specific data • Relates changes in land-use to the ecological status of water bodies as classified by WFD	• Major source of uncertainty is the water quality data, which are annual mean concentrations • Export coefficients were calibrated only for rivers used to derive the coefficients • Monetary valuations are not applied to changes in water quality

SWAT (Arnold and Fohrer 2005) (USDA)

Methodological approaches

Modelling occurs at a sub-catchment scale and is based around Hydrologic Response Units, which lump all similar soil and LU areas within a catchment into a single response unit. Simulation of the hydrology of a catchment is divided into (i) the land phase, which controls the amount of water, sediment, nutrient and pesticide loadings to the main water course in each sub-catchment and (ii) the water or routing phase, which is the movement of water and pollutants through the channel network to the outlet.

The model considers two soil layers (root zone and unsaturated zone), with conceptual shallow and deep aquifer stores and a single vegetation layer. The shallow aquifer can support return flow to streams and evapotranspiration from plants with deep roots. Evapotranspiration can be calculated using one of several options of varying complexity. Evapotranspiration values can also be input for a model run. Surface run-off is simulated using the SCS Curve Number or Green-Ampt methods. Streamflow routing is not explicit.

SWAT includes a plant growth calculation under optimal conditions by simulating the development of leaf area and conversion of light to biomass. Differences in growth between plant species are defined by parameters in a plant growth database.

Model features include;

- Watershed hydrology, sediment and water quality model
- Pesticide fate and transport simulation
- Channel erosion simulation
- Rural and agricultural management practices
- Simulates in-stream biological and nutrient processes, including changes in water temperature

In the water quality model, nitrogen and phosphorous are added to the soil by fertilisers, manures, N-fixation and atmospheric deposition. They are removed from the soil by plant uptake, leaching, volatilisation, de-nitrification and erosion. SWAT monitors pools of nutrients in different forms (mineral and organic). Organic nitrogen, mineral nitrogen and phosphorous transport are modelled differently. Unlike nitrogen, the solubility of phosphorous is limited and is only leached from the top 10mm of soil, with surface run-off being the main transport mechanism, along with P attached to soil particles that have been eroded.

Spatial scale

Grid size of tens of metres or HRU landscape units

Temporal representation

Daily time-step

Application to UK

Developed for US catchments but has been applied and validated in UK

Data requirements

- Land uses
- Soil
- Topography (DEM)
- Sub-catchments

- Point sources
- Climate data (daily temperature, precipitation, solar radiation, windspeed, relative humidity)
- Crop and management databases
- Flow data for calibration
- Long-term catchment quality data for calibration

Climatic variables can be observed records or generated during simulation independently for each sub-catchment from average monthly values.

Parameterisation

- Evapotranspiration (if not internally calculated)
- Leaf area index for vegetation
- Canopy height for vegetation
- Root depth for vegetation
- Stomatal conductances for vegetation
- Nitrogen uptake parameters for vegetation
- Deep aquifer percolation fraction for soil type
- Specific yield for soil type
- Groundwater delay time for soil type
- Recharge delay time for soil type
- Baseflow recession constant for soil type
- Soil hydrologic group
- Root depth for soil type
- Water capacity for soil type
- Hydraulic conductivity for soil type
- Percent sand/silt/clay for soil type
- Soil texture
- Width and depth of channel when filled to top of bank
- Channel length
- Side slope
- Manning's N

Model outputs

A number of output files are generated in every simulation. The standard output summary file provides catchment annual average, monthly or daily loadings from the HRUs to the streams. Average catchment values are the weighted sum of HRU loadings before any routing is simulated. The average annual values table provides a number of average annual parameter values for each HRU. Monthly averages for some of these variables are provided in the average monthly basin values table. Water balance and nutrient balances for the catchment are given in the average annual basin values tables and include the following (list not exhaustive);

- Average precipitation (mm)
- Snow fall (mm)
- Snow melt (mm)
- Water that changes directly to a gaseous state (mm)
- Surface runoff (mm)
- Lateral flow contribution to streamflow (mm)
- Drainage tile flow contribution to stream (mm)
- Groundwater contribution to stream (mm)
- Amount of water moving from shallow aquifer to plants/soil profile (mm)
- Deep aquifer recharge (mm)
- Total amount of water entering aquifers (mm)
- Water yield to streamflow from HRUs (mm)
- Water percolation at bottom of soil profile (mm)
- Actual evapotranspiration (mm)
- Potential evapotranspiration (mm)
- Average amount of tributary channel transmission losses (mm)

- Sediment yield from HRUs (metric tons/ha)
- Organic N loading to stream (kg N/ha)
- Organic P loading to stream (kg P/ha)
- Nitrate loading to stream in surface runoff (kg N/ha)
- Nitrate loading to stream in lateral flow (kg N/ha)
- Soluble P loading to stream (kg P/ha)
- Nitrate percolation past bottom of soil profile (kg N/ha)
- Average annual amount of P leached into second soil layer (kg P/ha)
- Plant uptake of N (kg N/ha)
- Average annual plant uptake of P (kg P/ha)
- Nitrate loading to groundwater (kg N/ha)

If pesticides were applied during the simulation, a pesticide table is also provided, which includes the amount of applied and decayed pesticide, the amount of dissolved and sorbed pesticide in surface runoff, the amount of pesticide leached from the soil profile and the amount of pesticide in lateral flow entering the stream.

Optimisation and Uncertainty

The calibration tool in the BASINS interface allows basic model calibration and sensitivity analysis. No tools were developed for uncertainty analysis.

Accessibility

Can be run on MS Windows operating system. The SWAT model software can be downloaded from http://swat.tamu.edu/software/swat-model/

The source code and documentation is also available.

Advantages

- High temporal resolution
- Accounts for seasonality
- Physically based
- Good documentation
- Inputs are facilitated by a GIS interface (BASINS)
- Detailed crop growth model
- Good land management modules
- Suitable for small to very large catchments
- Focus on water quantity and quality and representation of groundwater
- Studies indicate that SWAT can provide reasonable predictions of annual, monthly and daily streamflow from forested catchments
- Robust for simulating sediment and nutrient concentrations and loads

Disadvantages

- Data requirements complex – input file needed for every HRU
- Developed for US catchments
- Does not simulate individual storm events
- Can only model one pesticide at a time
- Cannot specify actual areas for fertiliser application
- Assumes one-dimensional well mixed streams and reservoirs
- HRU-based model that assumes homogeneous land-cover within each HRU – explicit representation of riparian buffer zones etc. not possible
- All HRUs directly linked to streams, rather than using the grid cell-based flow routing of other models

Precipitation-Runoff Modeling System (PRMS) (Leavesley, et al. 1983) (USGS)

Summary

The PRMS was developed to evaluate the impacts of various combinations of precipitation, climate and land-use on streamflow, sediment yields and catchment hydrology. The response of the catchment to normal and extreme precipitation can be simulated to evaluate changes in water balance, flow regimes, flood peaks and volumes, soil-water relationships, sediment yields and groundwater recharge.

The tool would cover the processes that lead to a reduction in flood risk / damage. However, the output in terms of runoff changes is not directly convertible into economic values (e.g. avoided damage costs of flooding). A rule is needed to relate changes in runoff with higher probability of flooding. Revealed preferences (different market value of properties in flood-prone and flood-protected areas) could be used in a simple way as in the case of LUCI/Polyscape.

- Assessed as not suitable for macro-modelling as the data requirements are demanding and the outputs are not as easily convertible into economic values compared to other options.
- Assessed as not suitable for micro-modelling due to simplified flow routing and lack of ability to account for the exact location of woodland parcels in the landscape.

Methodological approaches

A water balance and energy balance are computed daily for each HRU (see below). The sum of responses of all HRUs, weighted on a unit-area basis, produces the daily system response and streamflow from the catchment. The model runs from a series of process modules that are either physically based or have an empirical relationship with measured characteristics. PRMS simulates the hydrological processes within a catchment using a series of reservoirs that each has a capacity. Reservoirs can be the plant canopy, impervious surfaces, and soils. Water is collected and stored in these reservoirs for simulation of flow, evapotranspiration and sublimation. Flow to the drainage network is simulated by surface run-off, interflow and groundwater recharge.

PRMS also simulates sediment detachment using a revised form of the Universal Soil Loss Equation method. The detachment rate of sediment is dependent on rainfall intensity, geomorphology and run-off volumes. The movement of sediment in the stream channel is linked to energy in simulated flows. PRMS accounts for both sheetwash and streambank erosion.

The PRMS Basin Module computes shared catchment-wide variables, such as the area of each HRU that is pervious and impervious, the total area and the total area occupied by lake HRUs. The Cascade Module determines the order of the HRUs and ground-water reservoirs for routing flow. The Observed Data Module makes available the measured data for each specified time step.

Spatial scale

Hydrologic Response Unit – partitioning of catchment based on characteristics such as slope, aspect, vegetation, soil type, precipitation distribution. The definition of these units can be based on topology, a grid, or determined by combinations of characteristics.

Temporal representation

Will simulate mean daily to annual flows and stormflow hydrographs

Application to UK

Developed for US catchments but has been applied in UK

Data requirements

Input variables include descriptive data on the physiography, vegetation, soils and hydrologic characteristics of each HRU and the variation in climate over the catchment. The minimum requirements to run the daily-flow module are daily precipitation and maximum/ minimum daily air temperatures, which can be obtained from weather stations or simulations. Other time series data that can be provided are pan evaporation, streamflow, solar radiation, form of precipitation and rain day. To simulate hydrographs, rainfall depths for time intervals of 60 minutes or less are required. Programs are available to read and reformat non-U.S. data, which will need to be provided.

Parameterisation

Required parameters include;

- Seasonal cover density for vegetation
- Maximum interception storage depth for vegetation

- Winter cover density for predominant vegetation
- Hydraulic conductivity of soil transmission zone
- Effective value of the product of capillary drive and moisture deficit at field capacity and wilting point for the soil
- Specification of terrain and drainage network in each HRU

Model outputs

Model outputs vary depending on the options that the user has specified. As an example, the PRMS Water-Budget file provides summary tables of the water budget for a simulation by whatever time step the user has defined. Variables include;

- Precipitation (cm)
- Evapotranspiration (cm)
- Storage (cm)
- Potential runoff (cm)
- Observed runoff (cm)

Other model outputs include;

- Water balance
- Soil moisture
- Infiltration
- Water table
- Overland flow
- Subsurface flow
- Groundwater flow
- Sediment/ soil erosion
- Full hydrograph (using simplified channel routing)
- Annual yield (using simplified channel routing)
- Peak flow (using simplified channel routing)
- Low flow (using simplified channel routing)

Optimisation and Uncertainty

Parameter optimisation and sensitivity analysis capabilities are provided to fit selected model parameters and evaluate their effects on model outputs.

Accessibility

Version 3 of PRMS is a stand-alone program that can be run on a Linux or MS Windows platform. The software can be downloaded from http://wwwbrr.cr.usgs.gov/projects/SW_MoWS/PRMS.html

Advantages

- Modular design provides flexible framework for continued improvement
- Inclusion of streambank erosion component improves the model's ability to assign values to sediment retention on vegetated parcels

Disadvantages

- Complex model with demanding data requirements
- High level of expertise required to use
- Not designed for scenario exploration
- HRU-based model that does not account for the exact location of the woodland in the landscape
- Empirical watershed process representation – no explicit channel routing
- Does not include crop growth model

MIKE-SHE (Abbott, Bathurst, et al. 1986)

Summary

MIKE-SHE simulates the major processes in the hydrological cycle and includes models for evapotranspiration, overland flow, unsaturated flow, groundwater flow, channel flow and how these all interact. The full model is currently distributed by the Danish Hydrological Institute (DHI).

The outputs of the model could be combined with economic valuation techniques in order to value the following environmental goods:

Reduction in flood risk / damage. Surface runoff and other water flow indicators can be used to value flood risk protection. However, it is not possible to directly link the physical indicators with scenarios of avoided floods. A rule on the risk avoided would need to be applied in order to use market price proxies or stated preference techniques.

Reduction in service interruptions during drought. Surface runoff and other water flow indicators can be used to value potential water use restrictions. These restrictions (potentially measured in m^3 of water deficit or probability of water shortages) can be measured by market effects or WTP to avoid service interruptions. However, it is not possible to directly link the physical indicators with scenarios of water availability shortages without a further iteration with water management models.

The addition of water quality modules would facilitate the valuation of removal of nutrients concentration in water, i.e. by relating the amount of nutrients with the avoided water treatment cost.

- Assessed as unsuitable for macro-modelling due to the difficulty of parameterisation and required computing power.
- Assessed as potentially suitable for micro-modelling of flooding, drought and water quality due to it being one of the few models reviewed that fully models the entire hydrological cycle, including nutrient and sediment transport. Limitations are the purchase cost and the lack of source code.

Methodological approaches

The model is grid-based with multiple soil layers, a single vegetation layer and flexible time step. Canopy interception of precipitation and evapotranspiration are modelled. It includes three methods to simulate flow in the unsaturated zone, but each assumes that flow is vertical. A physical, three-dimensional saturated zone model is included.

Overland flow is simulated using either a simple, semi-distributed method for rainfall run-off modelling or a 2D diffusive wave approximation for detailed runoff and flood modelling. Channel flow can be simulated using a 1D hydrodynamics, including operation of hydraulic structures such as gates, pumps and weirs. For large networks, a much faster and less data-intensive flow routing method is available.

With the ‘Enterprise’ version, fully integrated soluble pollutant transport between surface water and subsurface can be simulated, including decay, sorption, precipitation and selective uptake. MIKE-SHE also has a soil erosion model, which is a version of the European Soil Erosion Model (EUROSEM). It predicts erosion and sedimentation patterns over a catchment, including simulations of detachment.

MIKE-SHE DAISY couples the DAISY model with MIKE-SHE. DAISY is an advanced soil-plant-atmosphere system model and simulates crop growth as well as water and nutrient dynamics in the root zone. It has mainly been used by researchers in Denmark to simulate water flow in the unsaturated zone, nitrate transport and transformation including plant uptake and advanced crop growth.

It is one of the few models that have been designed to fully integrate surface water and groundwater flow as well as soil vegetation atmosphere transfer processes.

Spatial scale

Flexible on uniform grid.

Temporal representation

Flexible – minutes to days. A time-series pre-processor is included for data management and input.

Applicability to the UK

Has been applied in the UK (e.g. for a lowland wet grassland).

Data requirements

- Precipitation
- Temperature
- Potential evapotranspiration
- Digital elevation model
- Soil type
- Geology
- Vegetation cover
- Diffuse pollution sources

Parameterisation

- Rain/ snow temperature thresholds
- Ground roughness
- Leaf area index for vegetation
- Field capacity for vegetation
- Wilting point for vegetation
- Interception value for vegetation
- Root zone depth for vegetation
- Hydraulic conductivity of soil
- Specific storage of soil
- Porosity of soil
- Anisotropy ratio of soil

Model outputs

- Full hydrograph
- Annual water yield
- Peak flow
- Low flow
- Evapotranspiration
- Water balance
- Soil moisture
- Infiltration
- Water table
- Overland flow
- Shallow sub-surface flow
- Groundwater flow
- Total catchment runoff
- Water quality
- Erosion and sedimentation

Optimisation and Uncertainty

Able to quantify uncertainties in predictions by carrying out sensitivity analyses for realistic ranges of the parameter values.

Accessibility

The model is complex and the software is expensive (approx. €16,000 in 2008). Computationally intensive. Requires ArcGIS to run and source code is not available.

http://www.crwr.utexas.edu/gis/gishyd98/dhi/mikeshe/Mshemain.htm

Advantages	**Disadvantages**
• Simulates complete hydrological cycle • Fully spatially explicit	• Simplified representation of woodland cover

• Models for water quality, erosion and sedimentation • Has been coupled with DAISY for crop growth model	• High purchase cost • Source code not available for adaptation • Not tested on steeply sloping terrain • High data requirements and set-up effort • Requires high level of expertise to use

Regional Hydro-Ecologic Simulation System (RHESSys) (Tague and Band 2004)
Methodological approaches A hierarchical approach is used to partition the landscape into hydrologically distinct units of similar soil and land use characteristics, hillslopes, climate zones and catchments. Multiple layers of vegetation can be included in the model. Water storage is conceptually divided into an unsaturated and saturated zone. Water intercepted by the canopy and transpiration are included, the latter calculated by physically based equations. At each time-step, net infiltration through canopy layers are added to the surface storage and infiltrated into the soil. Excess water that is not infiltrated becomes detention storage and subsequently overland flow. Drainage from the unsaturated to the saturated zone is limited by the field capacity of the unsaturated zone. Runoff is calculated using two approaches – a topographically defined wetness index TOPMODEL, and an explicit analytical routing model adapted from DHSVM (Distributed Hydrology-Soil Vegetation Model). Routing through open channels requires identifying the location of stream channels. RHESSys also allows for the simulation of road hydrology, including interception of runoff, precipitation and routing of road flow. Additional features include; • Spatial interpolation of climate variables is performed using the MTN-Clim model using topography and climate station information. • An eco-physiological model (BIOME-BGC) is included to estimate carbon, water and nitrogen fluxes from different canopy cover types. • Annual plant mortality rate can be simulated as a fixed percentage of current biomass. • Temporal event control to enable the user to define the timing and nature of disturbance events (e.g. felling)
Spatial scale Depends on DEM resolution and scale of application
Temporal representation Daily time step, with daily, monthly or yearly outputs
Applicability to UK No known application in the UK to date, but has been validated in some areas of Europe
Data requirements • Precipitation • Daily minimum and maximum temperature • Duration of rainfall (optional) • Shortwave and longwave radiation (optional) • Relative humidity (optional) • Wind speed (optional) • Topography (DEM) • Slope • Aspect

- Land-cover
- Vegetation
- Impervious areas
- Soil map
- Stream network (optional)
- Stream class
- Road network (optional)
- Road class
- Nitrogen deposition (optional)
- Water quality data for calibration
- Observed streamflow data for calibration

Parameterisation

Vegetation

- Fractional coverage
- Trunk space
- Height
- Leaf area index
- Albedo
- Aerodynamic attenuation
- Radiation attenuation
- Clumping factor
- Maximum release drip ration
- Stomatal resistance
- Moisture threshold
- Vapour pressure deficit
- Number of root zones
- Root zone depths
- Root fractions in each zone

Soil

- Lateral conductivity
- Porosity
- Surface albedo
- Vertical conductivity
- Maximum infiltration
- Pore size distribution
- Bubbling pressure
- Field capacity
- Wilting point
- Bulk density
- Thermal conductivity
- Thermal capacity

Land cover

- Irrigation
- N fertiliser input
- Septic nitrate load
- Septic water load

Model outputs

Outputs are available for spatial units from stratum to catchment and from time steps from daily to yearly. Outputs include:

- Full hydrograph
- Annual water yield (mm)
- Peak flow (mm)
- Low flow (mm)
- Evapotranspiration (mm)
- Water balance
- Soil moisture
- Infiltration
- Water table
- Overland flow
- Subsurface hillslope runoff
- Groundwater
- Road flow
- Watershed runoff
- Nitrate to stream (gN/m^2)
- Groundwater nitrate (mm)

Optimisation and Uncertainty

Four parameters are typically calibrated. Monte Carlo simulations are used to generate probability statistics.

Accessibility

Freely available from http://fiesta.bren.ucsb.edu/~rhessys/

Source code also available. Developed by the University of California.

Advantages

- Simulates forest growth
- Has a rudimentary groundwater component
- Models multiple vegetation layers
- Sophisticated method for calculation of evapotranspiration
- Can incorporate road network if required
- Can temporally control alteration of land cover details
- Has potential for ecological application in addition to hydrology

Disadvantages

- Has not been tested in UK
- Data requirements high
- High level of expertise required for use
- Considerable GIS and data processing required

CAS-HYDRO (Conlan, et al. 2005)

Methodological approaches

The model couples the hydrological process representation from the CAS-HYDRO model with a simple representation of the nitrogen cycle. To represent the spatial variability in these processes, the model is based on a fully distributed grid at a resolution of 100 metres. This is coupled with a river channel network model. The model is able to give detailed spatial and temporal predictions of the nitrogen and hydrological status of a catchment.

The processes are simulated in the terrestrial and aquatic environments. In the terrestrial environment, the uptake of water (and nitrogen) by vegetation, surface storage, infiltration, overland flow, through flow, percolation to groundwater and connection with streams are simulated, as well as the addition of nitrogen from deposition and fertiliser applications. The rates of each process are driven by soil moisture and temperature.

Spatial scale

100m grid

Temporal representation

Per-minute. The generation of a per-minute rainfall time-series is achieved through the use of a stochastic rainfall generator, which uses information on the characteristics of storms in the region.

Applicability to UK

Developed in the UK

Data requirements

- Daily rainfall
- Daily maximum and minimum temperature
- Location and characteristics of weirs
- Locations and characteristics of abstractions from rivers
- Digital Elevation Model (altitude data)
- Topographic form (map defining channel areas, hillslopes, ridges and plains)
- Flow direction
- Spatial pattern of soil classes
- Spatial pattern of land-cover classes

- Map of connections between landscape and river channel network
- Observed discharge values for calibration

Parameterisation

- Leaf Area Index of vegetation
- Rooting depth of vegetation
- Parameters relating to hydraulic geometry
- Discharge per unit width
- Nitrogen and oxygen parameters
- Soil depth per topographic form and soil type
- Soil saturation hydraulic conductivity in upper surface layer(m/s)
- Soil saturation hydraulic conductivity in main surface layer (m/s)
- Depth of upper soil layer
- Pore space in the soil (%)
- Interception depth (depth that water can be stored on vegetation canopy)
- Percentage of surface that is not directly covered by vegetation (%)
- Albedo – percentage of solar radiation in visible spectrum that is reflected by the surface
- Factor relating to overland flow velocity
- Percentage of cell with flow
- Irrigation
- P export coefficient (g/ha/yr) for land-cover type
- Optimal ammonification rate (g/s)
- Optimal nitrification rate (g/s)
- Optimal denitrification rate (g/s)
- C:N ratio of biomass
- Fertiliser application schedule for land-cover type
- Maximum vegetation height
- Vegetation growth rate (m/s)
- Growth temperature threshold
- First possible sowing date
- Last possible harvest date
- Harvest biomass
- Days at harvest biomass

Model outputs

Outputs provided for every 15 minutes of simulation:

- Time of output
- Rainfall intensity (mm/hr)
- Discharge (m^3/s)
- Nitrate concentration (mg/l)
- Ammonium concentration (mg/l)
- Total phosphorous concentration (mg/l)
- BOD concentration (mg/l)
- Dissolved oxygen concentration (mg/l)
- Dissolved oxygen saturation (%)
- Water temperature (°C)

Mass balances for hydrology and water quality broken down into landscapes and river channels e.g. total runoff to channel and percentage runoff.

Optimisation and Uncertainty

The model has undergone a multi-parameter sensitivity testing procedure to make sure that it performs within acceptable tolerances. It was found that the model can realistically simulate the hydrological behaviour of the River Derwent and Upper River Wharfe systems. Further parameterisation would be required to confidently simulate full catchment flows. The model has been parameterised and parameter uncertainty investigated. The model performance was tested by applying to a different catchment and time period with favourable results.

The assessment of water quality modules has been restricted due to limited validation data. It has not been possible to validate the phosphorous model.

Accessibility

Demo version available at coarser spatial scale

Advantages

- Designed to address questions related to the impacts of climate change and changes in land use/ management on flow extremes and water quality
- Designed to use a parameter set that can be determined for any catchment in the UK from published data

Disadvantages

- Data intensive and could be difficult to parameterise for new catchments
- Very detailed time-steps, therefore computationally intensive
- Not freely available software

SHETRAN-UK (Ewen, Parkin and O'Connell 2000)

Summary

SHETRAN is a river basin model that incorporates sediment and solute transport, fully coupled to water flow. It provides a system capable of being used for both river basin and groundwater modelling.

The outputs of the model could be combined with economic valuation techniques in order to value the following environmental goods:

Reduction in flood risk / damage. Surface runoff and other water flow indicators can be used to value flood risk protection. However, it is not possible to directly link the physical indicators with scenarios of avoided floods. A rule on the risk avoided would need to be applied in order to use market price proxies or stated preference techniques.

Reduction in service interruptions during drought. Surface runoff and other water flow indicators can be used to value potential water use restrictions. These restrictions (potentially measured in m^3 of water deficit or probability of water shortages) can be measured by market effects or WTP to avoid service interruptions. However, it is not possible to directly link the physical indicators with scenarios of water availability shortages without a further iteration with water management models.

The addition of water quality modules would facilitate the valuation of removal of nutrients concentration in water, i.e. by relating the amount of nutrients with the avoided water treatment cost.

- Assessed as not suitable for macro-modelling due to the difficulty of parameterisation/ use.
- Assessed as potentially suitable for the micro-modelling of flooding, drought and water quality due to it being one of the few models reviewed that fully models the entire hydrological cycle, including nutrient and sediment transport, and has been developed in the UK.

Methodological approaches

The components SHETRAN are Water Flow, Sediment Transport and Solute Transport.

The water flow component models canopy interception of rainfall, evapotranspiration, infiltration to subsurface, surface runoff (overland, overbank and in channels), snowpack development and snowmelt, storage and 3D flow in variably saturated sub-surface, aquifers, transfer between sub-surface and river water, ground-water discharge, well abstraction, river augmentation and abstraction and irrigation.

The sediment transport component models erosion, deposition and storage of sediment, overland flow, overbank transport, erosion of river beds and banks, deposition on river bed, down-channel transport, infiltration into river bed.

The solute transport component models 3D water flow, transport with sediments, dispersion, adsorption to soils, rocks and sediment, decay, atmospheric deposition, point and diffuse sources, erosion of contaminated soils, deposition of contaminated sediments, plant uptake and recycling, exchanges between river water and river bed.

The modelling structures are “stream links” and “columns”. River networks are networks of stream links and the rest of the basin modelled as a set of columns, each containing its own part of the ground surface and vegetation. There is lateral transport between cells in neighbouring columns as well as vertical transport.

A Graphical User Interface (GUI) has been developed that allows a catchment dataset to be set up quickly using minimum information. There is an algorithm for the automatic generation of river channel networks from a DEM and access to libraries of soil and vegetation parameters.

Spatial scale

Minimum 50x50m grid squares.

Temporal representation

Flexible.

Applicability to UK

Various case studies have been carried out in the UK, including land use change and flood risk in the forest of Bowland; wetland inundation on the River Derwent; soil moisture profiles in Clipstone forest and changes in forest hydrology in the Coalburn research catchment.

Data requirements

Water flow

- Precipitation and meteorological data for weather stations
- Soil/ rock types and depths
- Land-use/ vegetation
- Surface elevation
- River network (optional)
- Channel flow diversions
- Initial overland and channel flow depths
- Boundary flow rates

Sediment transport

- Sediment concentrations in waters

Solute transport

- Initial concentrations in surface and subsurface waters
- Concentrations in rainfall
- Dry deposition rates
- Concentrations in flows entering at boundaries

Parameterisation

Water flow

- Rates of borehole pumping etc.
- Initial hydraulic potentials for subsurface
- Canopy drainage parameters and storage capacities
- Ground cover fractions
- Canopy resistances
- Evapotranspiration
- Vegetation root density
- Porosity & specific storage of soil/ rocks
- Matric potential functions for soil/ rocks

Sediment transport

- Raindrop size distribution
- Drop sizes and fall distances for canopy drainage
- Proportion of canopy drainage falling as leaf drip
- Initial thickness of sediments and channel bed materials
- Sediment porosities and particle size distribution
- Erodibility coefficients

Solute transport

- Dispersion coefficients for soil/ rocks
- Adsorption distribution coefficients
- Mobile fractions for soil/ rocks
- Fractions of adsorption sites within mobile regions on soil/ rocks
- Exchange coefficients for mobile and immobile regions in soils/ rocks
- Decay constants
- Plant uptake constants

- Hydraulic conductivity for soil/ rocks

Model outputs

- Modelled discharge(m^3 s^{-1})
- Modelled runoff (mm)
- Modelled evapotranspiration (mm)
- Surface water depth (mm)
- Water table levels
- Soil moisture content
- Soil loss rate
- Sediment concentrations in waters
- Solute concentrations in waters and flows

Optimisation and Uncertainty

The model includes a calibration process based on measured data in the catchment.

Accessibility

The modelling system SHETRAN-UK was developed specifically for the UK and a limited version is free to download. A typical run-time for a 1year simulation is around 2 hrs.

Advantages

- Developed in the UK and has been successfully applied in UK catchments
- Models surface water and groundwater flow as well as sediment and solute transport
- Calibration against measured data
- The GUI can be used to set-up and run a simulation for water flow much more simply

Disadvantages

- Parameterisation effort is high – it usually takes at least a few weeks to create a preliminary dataset for a new basin
- Minimum 50x50m resolution

FRAME (Dore 2009)

Methodological approaches

Sulphur and nitrogen compounds (SO_2, NO_2, NH_3) can be removed from the atmosphere by dry deposition, or direct deposition to vegetation. The deposition rate of NH_3 is particularly sensitive to the type of vegetation, with high rates to forest and moorland.

The lateral dispersion in FRAME is modelled based on an air column moving along straight-line trajectories. Diffusion also occurs between 33 layers in the air column. Layer thicknesses vary from 1m at the bottom to 100m at the top. Separate trajectories are run at 1º resolution from all grid edge points. Wind frequency and wind speed roses are used to give appropriate weighting to directional deposition and concentration.

Emissions of ammonia are estimated for each 5km grid cell using the AENEID model that combines information on farm animal numbers with land cover information as well as fertiliser applications, crops and non-agricultural emissions. Emissions from sheep, fertiliser applications and non-agricultural sources are input to the lowest layer. Emissions from cattle, pigs and poultry are input to deeper layers depending on the relative time spent grazing and housed. For SO_2 and NO_x, the input layer is determined based on the emission source.

Dry deposition is calculated individually to five different land classes (arable, forest, moorland, grassland & urban). For ammonia, it is calculated at each grid square using a canopy resistance model.
Spatial scale 1km or 5km grid
Temporal representation Time-step for 5km version is 120 seconds and for 1km version is 20 seconds. Outputs provided on an annual average basis.
Applicability to UK 1km version has been developed specifically for UK application
Data requirements • Annual precipitation • Land use (moorland, forest, grassland, arable, urban, water) • Area and point source SO_2 emissions • Area and point source NO_x emissions • Area and point source NH_3 emissions
Parameterisation Parameter ranges for each parameter in the model are included in the model framework and are based on literature surveys, current practice and expert judgement. This includes a parameter for the canopy resistance for ammonia deposition, which is land-cover dependent, and parameters for the dry deposition velocities for the different species, which is land-cover and time dependent for ammonia. Land-uses for which dry deposition velocities are available in the literature are acid grassland, calcareous grassland, heathland, coniferous woodland and deciduous woodland. Other parameters are; • Chemical reaction rate constants • Wet scavenging coefficients (estimated as function of annual precipitation) • Background concentrations of chemical species • Wind speed (constant speed independent of location assumed; direction-dependent) • Frequency of winds from each wind direction sector (single wind rose) • Boundary layer height (allows for seasonal and diurnal variations) • Speciation of emitted sulphur dioxide and oxides of nitrogen
Model outputs • NO_x concentration per grid cell ($\mu g\ m^{-3}$) • NH_3 concentration per grid cell ($\mu g\ m^{-3}$) • SO_2 concentration per grid cell ($\mu g\ m^{-3}$) • Wet deposition of NO_x (kg N $ha^{-1}\ yr^{-1}$) • Wet deposition of NH_3 (kg N $ha^{-1}\ yr^{-1}$) • Wet deposition of SO_2 (kg S $ha^{-1}\ yr^{-1}$) • Dry deposition of NO_x to arable land, forest, grassland and urban (kg N $ha^{-1}\ yr^{-1}$) • Dry deposition of NH_3 to arable land, forest, grassland and urban (kg N $ha^{-1}\ yr^{-1}$) • Dry deposition of SO_2 to arable land, forest, grassland and urban (kg S $ha^{-1}\ yr^{-1}$)
Optimisation and Uncertainty A direct assessment of the accuracy of FRAME can be made by comparison with actual measurements from the UK national monitoring networks.
Accessibility The FRAME model code is written in High Performance FORTRAN 90 and executed in parallel on a Linux Beowulf cluster comprising of 60 dual processors, (i.e. 120 processors in total). Run time for a

simulation employing 100 processors is approximately 25 minutes. 5km outputs are available to download from Defra website. 1km version would need to be run by CEH.

Advantages	Disadvantages
• Fine spatial resolution (compared to other AQ models) • Fine near-surface vertical resolution • Good comparison with measures of actual concentrations and wet deposition • Low computational costs • Good methods for dry deposition processes with improved algorithms	• Simple modelling approach • Limited scope for further improvement of model • Underestimation of concentrations and deposition rates in remote areas and overestimation in source areas • Simple, uniform wind rose • Constant drizzle assumption for rainfall

HARM (Metcalfe, et al. 2001)

Summary

HARM uses a simple trajectory model approach to predict the concentrations and rates of deposition of gases and aerosols containing sulphur and nitrogen over north-west Europe.

- **Considered not suitable due to its coarse resolution compared with FRAME.**

Methodological approaches

The model is driven by spatial variations in the emission rates of sulphur dioxide, nitric oxide, ammonia and hydrogen chloride and in the wet scavenging coefficients and dry deposition velocities. The spatial variation in dry deposition velocity by land use type of sulphur dioxide, nitrogen dioxide and ammonia is represented in the model. In earlier versions, an assumption of instantaneous mixing was assumed, which meant that vertical and horizontal concentration gradients were ignored.

The model calculates long-term average concentrations and rates of deposition at each receptor point by averaging the results obtained for trajectories arriving at that point from each wind direction, weighted by the frequency of winds from that direction. The model ignores diurnal variation in the rates of chemical reactions.

Coupled chemistry attempts to represent the interactions between sulphur, oxidised and reduced nitrogen. The coupling with ammonia is significant in determining the transport distance and whether they are wet or dry deposited.

The initial 10km version of HARM had the problem of severe underestimation on dry deposition of ammonia. Version 11.5 incorporated local, grid-cell level dry deposition factors, representing a fraction of the ammonia emission from each grid square that is immediately re-deposited within that square. These factors were derived from the FRAME model. This brought the estimates of dry deposition of ammonia closer to those estimate using FRAME, but they are still substantially lower.

A new version HARM12.1 **(S. W. Metcalfe 2005)** incorporates vertical layering into three layers, with UK emissions from the different source categories put into the most appropriate layer. Dry deposition only occurs from the surface layer (<10m), whilst wet deposition occurs from all the layers. The pattern of dry deposition in version 12.1 more closely reflects that of emissions. In this version, dry deposition is driven using deposition velocities for each of nine land-cover types: acid grassland, calcareous grassland, heathland, coniferous woodland, deciduous woodland, freshwater, sea, urban, agricultural. Modelled deposition can be used to generate critical load exceedance maps for individual land use types, or combined to produce estimates for most of the Broad Habitat types.

Spatial scale

10 x 10km grid

Temporal representation

Average annual outputs.

Applicability to UK

Covers UK

Data requirements

- Emissions
- Land-cover data - % in each 10km grid square (supplied by CEH or derived from Bartholemews digital map data (sea and urban)
- Annual precipitation

Parameterisation

- Dry deposition velocity for each chemical species. Velocities for sulphur dioxide, nitrogen dioxide and ammonia are land-cover dependent in this model.
- Wet scavenging coefficients (assumed to occur only during wet periods with a coefficient proportional to rain rate)
- Background concentrations of chemical species
- Wind speed (constant speed independent of location assumed; independent of wind direction)
- Frequency of winds from each wind direction sector (single wind rose)
- Boundary layer height (non-variable)

Model outputs

- Wet deposition of NO_x (kg N ha^{-1} yr^{-1})
- Wet deposition of NH_3 (kg N ha^{-1} yr^{-1})
- Wet deposition of SO_2 (kg S ha^{-1} yr^{-1})
- Dry deposition of NO_x (kg N ha^{-1} yr^{-1})
- Dry deposition of NH_3 (kg N ha^{-1} yr^{-1})
- Dry deposition of SO_2 (kg S ha^{-1} yr^{-1})
- NO_x concentration per grid cell (µg m^{-3})
- NH_3 concentration per grid cell (µg m^{-3})
- SO_2 concentration per grid cell (µg m^{-3})

Optimisation and Uncertainty

HARM12.1 outputs were compared against measurements of concentrations of SO_2, NO_2 and NH_3 from rural sites. HARM is able to reproduce the broad spatial pattern of these gases but tends to overestimate SO_2 and underestimate NO_2 and NH_3. The overestimation of SO_2 may be due to mixing the gas to the ground level too quickly. The underestimation of N species is still an issue, which could potentially be improved by the addition of another vertical layer at 1m. HARM12.1 appears better than its predecessor at modelling deposition across the UK.

Variability in precipitation is a key variable that has probably been neglected. Assessment of sensitivity to precipitation is being undertaken for HARM.

Accessibility

61 minute run time for 10km version. Not publically accessible, but much of the development of HARM has been funded by UK Defra.

Advantages	**Disadvantages**
• Cost-effective – run times are short and model can be run on a PC	• Highly simplified climatology • Does not perform as well as some other models for estimating annual average concentrations of NO_2, NH_3, HNO_3, NH_4^+ and NSS SO_4 • Coarser horizontal and vertical resolution than FRAME

EMEP4UK (Vieno 2010)

Summary

EMEP4UK is a state-of-the-art grid model developed recently by CEH that simulates a number of atmospheric pollutants including nitrogen and sulphur deposition.

- **Assessed as not suitable given the coarse resolution compared with FRAME, although it may be an alternative in the future if a 1km resolution model is developed for the UK.**

Methodological approaches

The EMEP4UK model framework is a nested regional chemistry-transport model. The meteorological input is provided by the Weather Research Forecast (WRF) model rather than statistical meteorology. It is therefore better able to represent atmospheric chemical processes and provide a more reliable simulation of source-receptor relationships. The underlying chemistry-transport model is the EMEP Unified Model **(Simpson 2003)**, modified recently to enable application at scales ranging from 5x5km to global. Emissions input data are distributed temporally according to monthly and daily factors specific to each pollutant, emission sector and country. Simple day-night factors are also applied.

Both EMEP4UK and WRF use 20 vertical layers. Modelled pollutants are calculated at 3m above the plant canopy, including a factor for aerodynamic resistance. Sixteen basic land-use classes are used in the dry deposition model. Land-uses applicable to the UK are temperate coniferous forests; temporal deciduous forests; temperate crops; root crops; seminatural/moorland; grassland; wetlands; water; urban. Additional land-use classes are easily defined. In principal, the EMEP model can accept land-use data from any dataset covering the whole of the modelled area and providing sufficient resolution of vegetation categories.

Spatial scale

5 x 5km for UK

Temporal representation

Hourly, daily and monthly

Application to UK

Developed specifically for UK use

Data requirements

- Gridded annual national emissions data including NO_x, NH_3, SO_2 (from UK NAEI at 1x1km resolution) by source sector
- Land-use data giving fractional coverage of different vegetation types per grid cell.

Parameterisation

Default parameters in the model include the following;

- Meteorological parameters from Numerical Weather Prediction model
- Temporal emission factors for each pollutant and emission sector
- Height of vegetation by landcover type (m)
- Albedo by landcover type (%)
- Growing season of vegetation by landcover type
- Leaf-area index parameters by landcover type
- Landcover-specific parameters for stomatal conductance modelling

Model outputs

- Dry deposition to land-use class
- Wet deposition
- Gas concentrations

Optimisation and Uncertainty

The EMEP Unified model has been subject to continuous evaluation of its performance, all of which is in the public domain. For EMEPUK, only the nitrate in precipitation is noticeably underestimated in evaluation of the model performance.
Accessibility The EMEP4UK 5km resolution model needs to be run in-house at CEH and takes more than 6 days for a national simulation. The base model EMEP Unified model is available as open source code (http://www.emep.int/models.html).

Advantages	**Disadvantages**
• Sophisticated model, using up to date models and algorithms for meteorological and chemistry components • Uses UK emission data • Good model performance • EMEP Unified model (50x50km resolution) is open source	• Computationally intensive • Model system is not as well developed as some alternatives

VFSMOD (Sabbagh, et al. 2009)
Methodological approaches The FOCUS Landscape and Mitigation group (FOCUS, 2007) reviewed the evidence on the efficacy of vegetated filter strips on the reduction of pesticide transport in surface run-off. Whilst they found considerable variability in buffer efficacy under a range of conditions, they were able to recommend conservative factors for the reduction in water, sediment and pesticide load transferring across a strip. These factors vary with the size of the strip. At the time, there were no suitable modelling tools to simulate this reduction in load, but subsequently the VFSMOD (Vegetative Filter Strip MODel) was developed and validated in the USA (Sabbagh, et al. 2009). This is a physically-based field-scale model developed to route an incoming hydrograph and sedigraph from a field through a vegetated filter strip and calculate the resulting outflow, infiltration and sediment trapping. The model accounts for sediment type and concentration, vegetation type, slope and length of the filter strip. (Sabbagh, et al. 2009) subsequently developed an empirical model for estimation of trapping efficiency of pesticides by vegetated filter strips, which they parameterised using outputs from VFSMOD, specifically the percent reduction in water volume (infiltration) and the percent reduction in eroded sediment mass. A phase distribution parameter that represented the ratio of the mass of pesticide in the dissolved phase to the mass sorbed to sediment was also estimated. These parameters, plus the percent clay content of the soil, are used to estimate the pesticide trapping efficiency of the filter strip.

Other methods and models

The following methods and models have been considered but not assessed in full due to it being immediately apparent that they would not be suitable for national-scale valuation. They are included here for completeness and also for their potential for the quantification of marginal effects or the identification of opportunities for woodland planting.

SCIMAP (Lane, Reaney and Heathwaite 2009)

SCIMAP was designed to take a 'risk' based approach rather than precise prediction of diffuse pollution. SCIMAP focuses on the questions of: 'where is the most nutrient or sediment likely to be coming from?' and 'where should mitigation efforts be spatially targeted?' In this respect, it is perhaps more applicable to targeting planting of new woodlands to reduce flood and diffuse pollution risk, which is what the Eden Rivers Trust has used it for. SCIMAP uses data on land use, topography (ideally 5m DTM but maximum 10m) and rainfall to make map-based predictions of where risk is generated, connected and concentrated within the landscape. Predictions are generated at a 5m grid cell level and applied at whole landscapes for fine sediment, N and P.

Land Use and Ecosystem Services (LUES)

The LUES programme, run by Forest Research, aims to better understand and spatially map the link between woodlands and the ecosystem services they provide. The study has been applied in the South Downs National Park and covers the hydrological services of water supply and flood control.

Mapping Ecosystem Services

This Natural England project attempts to map key ecosystem services (including water supply and drinking water quality) in England on 200m grid squares based on the underlying habitat types and their ability to provide a particular service. It is still in early stage of development.

SCCAN

Under development by Natural Resources Wales since 2010, this project aims to deliver an ecosystem service mapping system to aid in decision making. SCCAN brings together data from a wide range of sources and at varying scales and converts them to a common grid structure. A rule-based approach is used to evaluate and set priorities by determining which data can be used to describe a service and how to apply weightings based on expert opinion. The aim is to provide the best mix of services to meet society's needs whilst being ecologically resilient.

Bayesian Belief Networks

Bayesian Belief Networks (BBN) are graphical probabilistic models, with the explanatory variables presented in the form of a network with a probability at each step. Advantages of this approach are that the expected relationships between a biophysical process and an ecosystem service can be expressed and variables that cannot be measured explicitly can be formally modelled. The networks can also be improved as new information becomes available. BBN are a relatively new approach to ecosystem service modelling originally used by (Haines-Young, et al. 2010) for assessment of the ecosystem services of UK uplands. A Natural England pilot study in three upland catchments (Bellamy, et al. 2011) subsequently recommended use of this framework for application across the whole of the UK uplands. (Haines-Young, et al. 2010) found that full calibration of BBN models was a lengthy process. They recommend that BBNs are initially used for scenario construction rather than as models intended to support specific operational decisions.

OVERFLOW

OVERFLOW is a simplified hydrological model developed by Durham University as part of the Rural Economy and Land Use (RELU) programme (Odoni and Lane 2010). It was designed as an exploratory tool to allow optimal identification of upstream interventions that might be used to reduce downstream flood risk. The model simplifies components of more process-based models, and justifies this simplification by restricting its application to particular events that occur in a known location. It is therefore not suitable for application at the national scale that the current project requires, however it is mentioned here as a potentially useful tool for optimising new woodland planting.

Opportunity Mapping for Woodland Creation

A mapping methodology was developed by Forest Research and ADAS (Broadmeadow, et al. 2009) for the Forestry Commission and Environment Agency to identify areas where woodland creation would be most beneficial for water management. The method works across a range of scales, from region or catchment down to the field scale. The approach taken relied on readily obtainable data with the best possible resolution and accuracy to characterise water pressures and identify opportunities where woodland creation could help tackle these. Water bodies currently failing to meet 'good' ecological or chemical status under the Water Framework Directive were identified, in addition to areas at risk of flooding. The probable causes of a water body failing to meet 'good' status were identified using risk maps and pressures. Potential pollutant sources and pathways within each catchment were identified using the best available data. Connectivity to watercourses or groundwater were then assessed in a simple way using detailed river networks, indicative flood maps and groundwater maps. Constraints to woodland creation were identified. This led to the identification of priority areas for woodland creation that could provide the greatest water and other ecosystem services. The method was applied in a case study catchment. This is not considered a suitable method for a national valuation study, but could be used to identify areas of a catchment where woodland is likely to be having the most beneficial effects.

Appendix 3 - Datasets

Land-use/ Land-cover

Dataset (ownership)	Description	Derived from	Time period data collected	Spatial resolution	Coverage	Frequency of update	Format	Cost	Attributes	Evaluation
National Forest Inventory (Forestry Commission)	For NFI the definition of woodland is:- A minimum area of 0.5 hectares under stands of trees with, or with the potential to achieve, tree crown cover of more than 20% of the ground. Areas of young trees, which have the potential to achieve a canopy cover of more than 20%, will also be interpreted as woodland and mapped. The minimum width for woodland is 20 m, although where woodlands are connected by a narrow neck of woodland less than 20 m wide, the break may be disregarded if less than 20 m in extent.	25 cm per pixel resolution orthorectified Ordnance Survey imagery (England and Scotland). 40 cm per pixel resolution orthorectified Ordnance Survey imagery (Wales)	2000-2009	Minimum 0.5 ha & 20m width	GB	Regular rolling programme utilising change detection software and new planting information	ESRI shapefile	Free	Woodland source (method of identification) Interpreted woodland type (Broadleaved; Conifer; Felled; Ground prepared for new planting; Mixed – predominantly broadleaved; Mixed – predominantly conifer; Young trees; Coppice; Coppice with standards; Shrub land; Uncertain; Cloud or shadow; Low density; Assumed woodland) Non-woodland (interpreted open areas)	Suitable for the accurate placement of woodland parcels in the landscape and differentiation between types of woodland

Dataset (ownership)	Description	Derived from	Time period data collected	Spatial resolution	Coverage	Frequency of update	Format	Cost	Attributes	Evaluation
Land Cover Map (LCM) 2007 (CEH)	Parcel-based classification of UK land cover based on UK BAP Broad Habitats. Woodland: vegetation dominated by trees > 5 m high when mature, which form a distinct canopy with a cover > 20%. Recently felled woodland included where there is a clear indication that it will return to woodland. Coniferous woodland - stands of native & non-native coniferous trees species where % cover >80% of total cover. BL woodland - stands of native & non-native broadleaved tree species, where % cover >20% of total cover.	Derived from satellite images and digital cartography. Objects come from generalised digital cartography, refined with image segments	Field validation 2006-2008 (mostly 2007). Satellite imagery 2005-2008 (target year 2007).	Minimum 0.5 ha. Min feature width 20 m	UK	Roughly every 10 years (previous LCM 2000, 1990)		Various. Non-commercial use free (academic, research, educational)	Soil type; Digital Elevation Model; Non-woodland (e.g. grassland, arable, urban etc.). Woodland type: Coniferous woodland split into conifer, larch, recent (<10yrs), evergreen, felled. Broadleaved woodland split into deciduous, recent (<10yrs), mixed, scrub.	**Suitable** for the accurate placement of woodland and other land-cover parcels in the landscape (vector version) and differentiation between types of woodland. Limitations are cost and no disaggregation of arable category.
		Vector data (polygons with metadata attached)					ESRI shapefile	£16k p.a. commercial. £12k p.a. public sector non-commercial.		
		Raster data 25 x 25 m raster with 1 x 1 km raster summary. OSGB 1936 (GB) and Ireland 1965 (Northern Ireland)					GeoTiff	£8k p.a. commercial. £6k p.a. public sector non-commercial. 1 km raster available via CEH Gateway.		

Dataset (ownership)	Description	Derived from	Time period data collected	Spatial resolution	Coverage	Frequency of update	Format	Cost	Attributes	Evaluation
National Inventory of Woodland and Trees (Forestry Commission)	(Superseded by NFI). 1990 to 2003.	1:25,000 OS/ AP. Polygon files	1990-2003	Minimum 2 ha	GB	Replaced by NFI	ESRI shapefile		Replaced by NFI	**Not suitable** – has been superseded
Native Woodland Survey of Scotland (Forestry Commission)	Woodland map of native and nearly native woodlands and PAWS sites in Scotland linked to dataset with type, extent and condition of woods. Native: >50% native sp. Nearly-native: >=40% and <=50% native sp. Open land: <20% canopy cover, surrounded by woodland/adjoining native woodland.	Used OS MasterMap features and recent colour ortho-rectified AP <= 3yrs old. 1:10,000 scale.	2004-2007	Minimum 0.5 ha	Scotland	Biannual.	ESRI shapefile	Free	Native woodland; nearly native woodland; open land; Woodland condition	**Potentially suitable** if information is required on native woodland and its condition, but geographic coverage limited to Scotland.
CORINE Land Cover data (EEA)	European coverage for CLC2006 inventory. Provides	UK component based on LCM2007 data	2000-2006	100m and 250m.	UK (EU wide)	Previous maps 1990, 2000	Raster datasets	Free for research purposes only.	Change in land cover, land cover types, forest and land cover change.	**Potentially suitable** if cost of LCM data is prohibitive, but

Dataset (ownership)	Description	Derived from	Time period data collected	Spatial resolution	Coverage	Frequency of update	Format	Cost	Attributes	Evaluation
	44 land cover classes.									spatial resolution poorer.
CORINE Land Cover 2006 vector data	Seamless vector data for CLC2006 updated.	UK component based on LCM2007 data	2000-2006	Minimum mappable unit 25 ha.	UK (EU wide)	Previous maps 1990, 2000	ESRI shapefile		Road/rail networks, mineral extraction sites, dump sites, green urban areas, arable land, forest (broadleaved, coniferous, mixed), watercourses, waterbodies	**Potentially suitable** if cost of LCM data is prohibitive, but spatial resolution poorer.
Countryside Survey 2007 (CEH)	Field survey component of LCM including soils, freshwater, habitats and landscape features. Reported at UK level and by individual country (E, S, W, NI). Over 590 1km squares in GB and 270 in NI.	Field survey of sample squares and subsequent extrapolation of some variables based on land-uses	2007	1 km grid	UK	Roughly every 10 years	Various. Includes linear/point features		Broad and Priority Habitats, vegetation type, soil samples.	**Not suitable** due to it only being a sample
Meridian 2 (OS)	Vector product, supplied as dataset covering GB, containing developed land-use areas, rivers and canals, roads,	Vector data. Complete cover of GB (2848 tiles) and 10 x 10 km DXF tiles. 1 m resolution.		Nominal scale of 1:50,000.	GB		DXF, MID/MIF or Shapefile	OS OpenData	Extent of non-agricultural land use. Applications: Flood areas analysis; Land management.	**Potentially suitable** for locating impervious areas, road networks and rivers.

Dataset (ownership)	Description	Derived from	Time period data collected	Spatial resolution	Coverage	Frequency of update	Format	Cost	Attributes	Evaluation
	railways and coastline.									
LUCAS (Land Use/ Cover Area Frame Statistical Survey) (EC/ Eurostat)	Europe-wide land use and cover surveys.	Micro data (land cover, land use and environmental parameters at single surveyed points on 2 km grid). Point and landscape photos; and statistical tables with aggregated results.	2006, 2009, 2012	2km grid	UK (EU wide)	3 yearly	Viewer: ArcGIS API for FLEX. Data also on Excel & Access	Available on LUCAS viewer free: http://ec.europa.eu/eurostat/statistical-atlas/gis/viewer/?myConfig=LUCAS-2012.xml	8 categories of land cover (artificial land; cropland; woodland; shrubland; grassland; bareland; water; wetlands). Woodland split into broadleaved and evergreen; coniferous; mixed woodland.	**Not suitable** due to it only being a sample
Agcensus (EDINA)	Grid square agricultural census data for England, Scotland and Wales.	Algorithms used to convert the Defra Agricultural Census data into grid square estimates.	1969-present	2km, 5km or 10km grid squares	GB	Approx. annual	ASCII	Subscription fee applies	Census items (arable crops and livestock) disaggregated to grid squares	**Potentially suitable** for disaggregation of crop types, although a statistical representation of location
1km^2 land use data (ADAS)	Land cover/ land uses datasets at 1km^2. Identification of non-agricultural	OS Vector data, ITE landcover and	1980, 1995, 2000,	1 km^2	GB	Approx. every 4-5 years	ESRI shapefile	Requires ADAS licence.	Identification of non-agricultural land use (urban land, water, woodland and	**Suitable** for disaggregation of crop types or coarser-scale

Dataset (ownership)	Description	Derived from	Time period data collected	Spatial resolution	Coverage	Frequency of update	Format	Cost	Attributes	Evaluation
	land use from OS Strategi data and Common Land database; agricultural land from Agric census/ LCM.	DEFRA census stats	2004, 2009, 2010						infrastructure layers and Common Land) and agricultural land use split by arable crops and livestock categories in Census.	modelling, although a statistical representation of location
NVC surveys - Woodland NVC (JNCC)	35,000 samples of vegetation (classification to vegetation type). Distribution maps and information on Woodland NVC types.	Survey data	1978-1999		GB		Excel with E/N	Free	Identification and characterisation of areas classified as woodland.	**Potentially suitable** for provision of more detailed information on species composition of older woodlands.

Soil

Dataset (ownership)	Description	Derived from	Time period data collected	Spatial resolution	Coverage	Frequency of update	Format	Cost	Attributes	Evaluation
NATMAP (NSRI – LandIS)	National Soil Map (England and Wales). Vector dataset with 300 mapped soil associations. Also NATMAP topsoil texture, subsoil texture, wetness, available water and carbon.	Soil surveys	1970s-80s	1:250,000	England & Wales	Never	ESRI shapefile	£500 per 1000 km^2	National Soil Map Units, soil associations, soil series, geological parent material, cropping/land use. Soil properties (clay content, susceptibility to runoff, soil depth, organic carbon etc.).	Potentially suitable for the delineation of boundaries between different soil associations. NATMAP1000 gives better thematic resolution of soil series.
NATMAP 1000 (NSRI – LandIS)	1km x 1km gridded-vector reclassification of NATMAP (dominant series per $1km^2$ or relative % of soil series per polygon). 297 soil series mapped.	NATMAP	1970s-80s	$1km^2$	England & Wales	Never	ESRI shapefile	£150 per 1000 km^2	Dominant soil series and % of soil association (map unit) in top 20 soil series	Suitable for the representation of the spatial variation in soil types. Best product available for England & Wales.
NATMAP 5000 (NSRI – LandIS)	5km x 5km gridded-vector reclassification of NATMAP (dominant series	NATMAP	1970s-80s	$5km^2$	England & Wales	Never	ESRI shapefile	£900 for E&W	Dominant soil series and % of soil association (map unit) in top 20 soil series	Potentially suitable for the representation of the spatial variation in soil types if the cost

Dataset (ownership)	Description	Derived from	Time period data collected	Spatial resolution	Coverage	Frequency of update	Format	Cost	Attributes	Evaluation
	per 25 km^2 or relative % of soil series per polygon). 297 soil series mapped.									of NATMAP 1000 is prohibitive.
Soilscapes (NSRI – LandIS)	Simplified soils dataset for England and Wales with 27 soil map units.	NATMAP	1970s-80s	1:250,000	England & Wales	Never	ESRI shapefile	£250 per 1000 km^2	Soil description; texture; drainage; fertility; land cover type; habitats.	**Not suitable** as descriptions are very general.
NATMAP HOST (NSRI – LandIS)	Hydrology of soils types. Classification is based on conceptual models of the processes that occur in the soil. 29 classes, based on eleven response models. Soils are assigned to classes on the basis of their physical properties, and with reference to	NATMAP	1970s-80s	1:250,000	England & Wales	Never	ESRI shapefile	£250 per 1000 km^2	To assess soils more prone to generating rapid runoff/ pathways along which water flows to streams. % of polygon in diff soil types, waterlogging, free draining, drained. Classified into 3 types (soil on permeable substrate with deep groundwater >2 m; soil on permeable substrate with shallow water table <2 m; soil with	**Potentially suitable** for the delineation of boundaries between different HOST classes.

Dataset (ownership)	Description	Derived from	Time period data collected	Spatial resolution	Coverage	Frequency of update	Format	Cost	Attributes	Evaluation
	the hydrogeology of the substrate.								impermeable layer <1 m from surface).	
NATMAP topsoil/ subsoil texture (NSRI – LandIS)	A new product providing a description of the range of texture classes.	Simplification of the NATMAP	1970s-80s	1:250,000	England & Wales	Never	ESRI shapefile	£250 per 1000 km^2	The dominant texture class in the polygon, plus the percentage of the polygon with each of the soil types in the Soil Texture Triangle.	**Potentially suitable** for the simple classification of the landscape into different soil textures.
NATMAP Wetness (NSRI – LandIS)	A new product providing a description of the range of soil wetness regimes.	Combination of the NATMAP and climate zone map	1970s-80s	1:250,000	England & Wales	Never	ESRI shapefile	£250 per 1000 km^2	The dominant wetness class in the polygon, plus the percentage of the polygon in each Wetness Class (I-IV)	**Potentially suitable** for the simple classification of the landscape into different soil wetness classes.
NATMAP available water (NSRI – LandIS)	A new product showing the average crop-adjusted available water capacity of the soils.	For each soil series represented on the National Soil Map the total and easily available water is calculated for each horizon from the HORIZONhydraulics dataset	1970s-80s	1:250,000	England & Wales	Never	ESRI shapefile	£250 per 1000 km^2 (discount of 90% if NATMAP and HORIZONhydraulics are ordered.	Water available to cereal crops; water available to grassland crops; water available to sugar beet; water available to maincrop potatoes	**Potentially suitable** for the assessment of drought, as the water available in the soil offsets the water balance between rainfall and evapotranspiration.

Dataset (ownership)	Description	Derived from	Time period data collected	Spatial resolution	Coverage	Frequency of update	Format	Cost	Attributes	Evaluation
		and totalled for the series following the crop rooting pattern models. To interpret this on a soil association basis the mean of the crop adjusted available waters for each component series was calculated, weighted by the proportion of each series in the soil association.								
National Soils Inventory (NSI Site)	Spatial, point data with 6127 points in a 5 km grid across England and Wales. Provides detailed information for each intersect of the grid.	Soil sampling	1980, mid-1990s	5km grid	England & Wales	Never	ESRI shapefile	£10 per point; £3500 for whole dataset	Land use, slope, slope form, influence of man on landscape, rock outcrops, altitude, aspect, erosion and deposition features, rock type.	**Potentially suitable** for the characterisation of erosion risk

Dataset (ownership)	Description	Derived from	Time period data collected	Spatial resolution	Coverage	Frequency of update	Format	Cost	Attributes	Evaluation
National Soils Inventory (NSI Profile)	Statistically representative of England and Wales.							£15 per point; £6250 for whole dataset	Detailed description of soil profile including soil texture, porosity, root nature, stone abundance, soil water state, mottle size/ colour. Repeated for each horizon of the soil.	**Not suitable** as lower cost, interpolated soil profile data are available
National Soils Inventory (NSI Topsoil)								1983 data: £30 per point; £12,300 for whole dataset. 1995 partial resurvey: poa	Includes pH reading of soil, soil OC, Aluminium/Arsenic/ Phosphorus etc. concentrations at each point.	**Potentially suitable** for model calibration (e.g. soil P)
National Soils Inventory (NSI Textures)								£15 per point; £6250 for whole dataset	Texture of topsoil - can be used to identify areas of topsoil heavily influenced by clay, silt or sand.	**Not suitable** as lower cost, interpolated texture data are available
National Soils Inventory								£24 per point; £9550 for	Includes depth from surface to various layers and provides	**Potentially suitable** for the

Dataset (ownership)	Description	Derived from	Time period data collected	Spatial resolution	Coverage	Frequency of update	Format	Cost	Attributes	Evaluation
(NSI Features)								whole dataset	info on amount of risk posed by erosion and flooding.	characterisation of erosion risk

Dataset (ownership)	Description	Derived from	Time period data collected	Spatial resolution	Coverage	Frequency of update	Format	Cost	Attributes	Evaluation
Soil Series Properties (NSRI- LandIS)	Tabular data that can be used in conjunction with any of the NATMAP products to assess or model the capability or vulnerability of land.	Laboratory measurement for a broad range of characteristics for each soil series.	N/A	N/A	N/A	N/A	Text files	Need to be leased with a NATMAP soil map dataset. Prices vary.	"Pesticides" includes information such as pesticide leaching and runoff classes; "Hydrology" provides extensive information on the water regime, moisture release and hydrology of each soil; "Fundamentals" provides very detailed descriptions of the texture and structure of each soil horizon; "Hydraulics" provides a range of hydraulic properties, e.g. water content, for each layer.	Suitable for the provision of coefficients for modelling that can be linked to mapped soils data.

Dataset (ownership)	Description	Derived from	Time period data collected	Spatial resolution	Coverage	Frequency of update	Format	Cost	Attributes	Evaluation
1:250,000 soils map for Scotland (James Hutton Institute)	The National Soil Map, published in 1982, represents the first complete soils coverage of Scotland.	Based on fieldwork using 1:50,000 scale maps and air photo interpretation and incorporates earlier soil surveys undertaken in the lowlands and foothills.	1978-1981	1:250,000	Scotland	Never	Raster or vector ArcGIS data or ASCII	£0.10-£0.48 per sq km per primary attribute, dependent on area required	Soil Map Unit (580); pH, soil texture, soil organic matter + others	**Potentially suitable** for the delineation of boundaries between different soil units.
1 x 1km Soils Data (James Hutton Institute)	1km x 1km gridded-vector reclassification of NSI (dominant series per 1km^2).	1:250,000 scale dataset	1978-1981	1km grid	Scotland	Never	Raster ArcGIS or text files	£5,400.00 per single attribute (or the first attribute) for the whole of Scotland. £ 900.00 per attribute for the second and subsequent attributes for the whole of Scotland.	Dominant soil series; soil drainage, topsoil and subsoil organic matter, topsoil and subsoil texture, topsoil and subsoil pH, available water capacity, bulk density. *Others available.*	**Suitable** for the representation of the spatial variation in soil types. Best product available for Scotland for modelling purposes.

Dataset (ownership)	Description	Derived from	Time period data collected	Spatial resolution	Coverage	Frequency of update	Format	Cost	Attributes	Evaluation
National Soils Inventory (NSI) (James Hutton Institute)	Point database collected on a 5km grid across Scotland. A range of site and soil characteristics are available for each grid point. Points on a 10km grid include details of soils chemical analyses with physical and chemical details relevant to individual soil horizons.	Soil survey		5km or 10km grid	Scotland	Never	Text files	£ 720.00 per primary attribute, per horizon. £ 180.00 per associated attribute, per horizon.	Grid ref; soil series; soil association. General: Altitude, slope, aspect, rockiness, boulderiness, vegetation, flushing, site drainage, soil drainage class, degree of erosion, parent material, major soil subgroup, phase, parent rock type, climatic region, land capability classification for agriculture. For each horizon: Horizon symbol, depth to base of horizon, colour, organic matter, texture, structure, moisture status, consistence, induration, cementation, nature of horizon boundary.	**Potentially suitable** for characterisation of erosion risk and other site-specific factors.

Dataset (ownership)	Description	Derived from	Time period data collected	Spatial resolution	Coverage	Frequency of update	Format	Cost	Attributes	Evaluation
European Soil database (JRC)	European Soil Database v2 Raster Library. Raster data files with cell sizes 1 x 1km for many soil parameters.			1 x 1 km raster	EU		ESRI GRID	Free after registration	Soil classification (WRB/ FAO); texture; parent material; land use; limitation to agricultural use; obstacle to roots; impermeable layer; soil water regime; water management system; altitude; slope; primary properties (surface texture class, OC content, elevation); chemical properties (mineralogy, cation exchange capacity, base saturation); mechanical properties (structure, packing density, volume of stones); hydrological properties (available water capacity, depth to impermeable layer); applications (land use class, soil	**Potentially suitable** for low-cost spatial representation of soil types and associated attributes
	European Soil Database v2 Raster Library. Raster data files with cell sizes 10 x 10km for many soil parameters.			10 x 10km raster			ESRI GRID			

Dataset (ownership)	Description	Derived from	Time period data collected	Spatial resolution	Coverage	Frequency of update	Format	Cost	Attributes	Evaluation
									erodibility class, soil crusting).	
	European Soil Database v2.0 Vector data (includes Soil Geographical DB of Eurasia; PedoTransfer Rules DB, Soil Profile Analytical Database of Europa and DB of Hydraulic Properties of European Soils)			1:1,000,000			Various		Total available water content; depth available to roots; clay content; silt content; sand content; organic carbon; bulk density; coarse fragments.	
	Derived data (ESDB, HWSD, SOTER)			1 x 1km raster			Idrisi raster format			

Geology

Dataset (ownership)	Description	Derived from	Time period data collected	Spatial resolution	Coverage	Frequency of update	Format	Cost	Attributes	Evaluation
Digital Geological Map of Great Britain (DiGMapGB-10) (BGS)	Detailed digital geological map data.	Paper maps		1:10,000	Partial GB	Never	ESRI, MapInfo line/polygon data	£1.50 per km^2 (& licence and data prep fee)	Bedrock geology, superficial deposits, mass movement, artificial ground, linear features e.g. faults	**Not suitable** due to partial GB coverage.
DiGMapGB-25 (BGS)	Semi-detailed digital geological map data.	Paper maps		1:25,000	Various locations in GB	Never	ESRI, MapInfo line/polygon data	£0.60 per km^2 (& licence and data prep fee)	Bedrock geology, superficial deposits, mass movement, artificial ground, linear features e.g. faults	**Not suitable** due to partial GB coverage.
DiGMapGB-50 (BGS)	The geological areas are labelled or attributed with a name and their composition (rock type or lithology). This information is arranged in 4 themes: bedrock geology; superficial deposits; mass movement; and	Paper maps		1:50,000	GB	Never	ESRI, MapInfo GIS grid data	20p per km^2 for commercial use. Subject to licence fee and data preparation fee.	Key characteristics of geology including texture, structure, colour, mineralogy, engineering parameters.	**Potentially suitable** for use if geology information is required.

Dataset (ownership)	Description	Derived from	Time period data collected	Spatial resolution	Coverage	Frequency of update	Format	Cost	Attributes	Evaluation
	artificial ground. Faults and other linear features are available in a separate theme.									
DiGMapGB-250 (BGS)	The geological areas are labelled or attributed with a name and their composition (rock type or lithology). This information is arranged in two themes: bedrock geology and faults.	Paper maps		1:250,000	GB	Never	GIS data (ESRI, MapInfo)	0.6p per km^2. Subject to licence fee and data preparation fee.	Bedrock geology, superficial deposits, mass movement, dykes, linear features e.g. faults	**Potentially suitable** for use if geology information is required.
DiGMapGB-625 (BGS)	Solid and drift geology and linear features. Separate polygon themes (bedrock and superficial deposits) can be downloaded.	Derived from 1:625,000 BGS maps of UK.		1:625,000	UK	Never	ESRI shapefile & MapInfo MID/MIF formats	Free	Bedrock geology, superficial deposits, mass movement, dykes, linear features e.g. faults	**Potentially suitable** for use if geology information is required. Freely available version, but poorer spatial resolution.
DiGMapGB-Plus (BGS)	The primary goal for the project is to provide key	DiGMapGB-50		1:50,000	GB	Never	ESRI & MapInfo	On application. Subject to	Data will be provided as a series of attributes that will	**Suitable** for use if geology information is required. May

Dataset (ownership)	Description	Derived from	Time period data collected	Spatial resolution	Coverage	Frequency of update	Format	Cost	Attributes	Evaluation
	characteristics of the geology of Great Britain, such as texture, structure, colour, mineralogy and engineering parameters in a way that is suitable for rapid deployment by non-geologists.							licence fee and data preparatio n fee.	be available to licence individually or as a personally selected a range of 'modules' to meet your own requirements. The data is normally supplied as a single GIS layer of 'surface-geology' compiled from the combined bedrock and superficial layers of DiGMapGB-50.	be more suitable than other DiGMap datasets. Areas of interest include for information on ecosystem services properties in development of a BGS Ecosystem Services Model.
Superficial Deposits Thickness Models (BGS)	Shows depth of bedrock surface.	Produced by analysing info from 600,000 borehole logs and uses extent of superficial deposits from DiGMapGB-50.		1:50,000	GB	Never	ESRI shapefil e & MapInfo MID/MI F formats	£0.15 per km^2 (& licence and data prep fee)	Evaluation of groundwater resources and possible water pollution; prediction of surface hazards and collapse of underlying rocks.	**Potentially suitable** for identification of areas with groundwater pollution problems.

Dataset (ownership)	Description	Derived from	Time period data collected	Spatial resolution	Coverage	Frequency of update	Format	Cost	Attributes	Evaluation
Soil Parent Material Model (BGS)	This model details the distribution of physiochemical properties of the parent materials, detailing over 30 rock and sediment characteristics.	DiGMapGB-50 dataset.		1:50,000	GB	Never	ESRI shapefile & MapInfo MID/MIF formats	£0.30 per km^2 (subject to licence fee and data prep fee)	Allows spatial mapping of UK soil properties and identification of soils and landscapes sensitive to erosion. Includes texture information, colour, structure, mineralogy, lithology, carbonate content and genetic origin.	**Potentially suitable** for identification of areas susceptible to erosion
Boreholes Index (BGS)	Single Onshore Boreholes Index (SOBI) contains over 1 million records of boreholes, shafts and wells from all forms of drilling and site investigation work held by the BGS.	Records produced from geologists/ surveyors observations of rock core extracted from the ground.	1790-present	N/A	GB	Annual	ESRI shapefile & MapInfo MID/MIF formats	Index level data free (Boreholes WMS layer).	Includes locality, lithological descriptions with depth and thickness and sometimes geophysical logs.	**Suitable** for location of boreholes and their depth.
Susceptibility to Groundwater	National hazard dataset for groundwater flooding.	Based on geological and			GB	Annual	ESRI shapefile (GIS	£0.30 per km^2 (subject to licence fee	Can be used to identify areas where geological conditions could enable	**Potentially suitable** for identification of areas

Dataset (ownership)	Description	Derived from	Time period data collected	Spatial resolution	Coverage	Frequency of update	Format	Cost	Attributes	Evaluation
Flooding (BGS)		hydrological information.					Polygon data)	and data prep fee)	groundwater flooding to occur and where groundwater may come close to the ground surface.	susceptible to groundwater flooding.

Topography

Dataset (ownership)	Description	Derived from	Time period data collected	Spatial resolution	Coverage	Frequency of update	Format	Cost	Attributes	Evaluation
EA 2m Composite LiDAR DTM (EA)	Accurate elevation data	Derived from surveys carried out by EA.	1996-2010	Resolution of 2 m (25 cm, 50 cm and 1 m also available).	50% of England and Wales.		Digital Terrain Model	Price on application	Elevation	**Not suitable** due to partial GB coverage.
Hydro1k (USGS)	HYDRO1k is a geographic database developed to provide comprehensive and consistent global coverage of topographically derived data sets,	Derived from the USGS' 30 arc-second digital elevation model of the world (GTOPO30).		1x1km	Global		Vector datasets in ARC/INFO GRID; raster data		Hydrologically correct DEM, derived flow directions, flow accumulations, slope, aspect, topographic (wetness) index. Derived streamlines and basins. Useful	**Not suitable** due to coarse spatial resolution.

Dataset (ownership)	Description	Derived from	Time period data collected	Spatial resolution	Coverage	Frequency of update	Format	Cost	Attributes	Evaluation
	including streams, drainage basins and ancillary layers. Provides a suite of geo-referenced data sets, both raster and vector, which will be of value for all users who need to organize, evaluate, or process hydrologic information on a continental scale.								for watershed analysis.	
Integrated Hydrological DTM (CEH)	50m grid interval DTM. Five separate gridded datasets. Consistent with CEH 1:50,000 Watercourse Network dataset.	Derived from 1:50,000 scale mapping.		50m (0.1m vertical resolution)	UK	N/A	ESRI shapefil e		Elevation, Outflow and Inflow drainage directions, Cumulative Catchment Area and Surface Type	**Potentially suitable** although relatively coarse resolution for modelling of flow.
OS Terrain 50 (OS)	Simplified DTM. Supplied as set of 50 m gridded DTM and 10 m	Derived from OS 1:50,000 mapping and vector data.		50m	GB		ESRI shapefil e; ASCII	Free (OS OpenData)	Simplified DTM for 3D visualisation of large landscape	**Potentially suitable** although relatively coarse

Dataset (ownership)	Description	Derived from	Time period data collected	Spatial resolution	Coverage	Frequency of update	Format	Cost	Attributes	Evaluation
	contours and spot heights (OS Terrain 50 grid and OS Terrain 50 contours).						GRID/ GML		areas. Slope, viewshed maps.	resolution for modelling of flow.
OS Terrain 5 (OS)	Height data created as a digital terrain model representing bare surface. Particular attention has been given to the modelling of significant landscape features such as roads, railways, quarries and lakes.	Derived from aerial imagery		5m	GB		ESRI shapefile; ASCII GRID/ GML	Price on application	Elevation	**Potentially suitable** dependent upon cost.
Bluesky DTM (Landmap)	Elevation data.	Photogramerically derived. 100 x 100 km^2 tiles.		5 m resolution (also available from 2 m to 25 m).	England & Wales		ASCII GRID		Elevation	**Potentially suitable** dependent upon cost, but does not cover Scotland.
NEXTMap (Intermap)	British DTM dataset. Data	IFSAR	2001-2003	DSM 5 m; DTM 5 m,	GB		ArcInfo Binary		Slope gradient; used to define slope	**Potentially suitable**

Dataset (ownership)	Description	Derived from	Time period data collected	Spatial resolution	Coverage	Frequency of update	Format	Cost	Attributes	Evaluation
	acquired by BGS and used for NERC-funded research only. OS/BNG tiles of 10 x 10 km.			10 m and 50 m resolution .			Grid & GeoTiff		classes in terms of sensitivity to erosion (steep >7°, moderate 3-7°, gentle 2-3°, level <2°), where 3° = critical angle at which rill erosion begins.	dependent upon cost

Catchments

Dataset (ownership)	Description	Derived from	Time period data collected	Spatial resolution	Coverage	Frequency of update	Format	Cost	Attributes	Evaluation
Catchment boundaries (CEH)	Boundaries available for all GB gauging stations within CEH's National River Flow Archive. Hydrometric area boundaries are also available. Boundaries can be derived for almost any point	Derived from CEH's Integrated Hydrological DTM		1:50,000 scale.	UK		ESRI shapefil e	Needs licence		**Potentially suitable** for delineation of catchments

Dataset (ownership)	Description	Derived from	Time period data collected	Spatial resolution	Coverage	Frequency of update	Format	Cost	Attributes	Evaluation
	on the UK river network.									
WFD river waterbody catchments (EA/SEPA)	Series of non-overlapping polygon catchments. Hydrologically correct boundaries for the WFD catchments.				GB		ESRI shapefile	Needs licence		**Suitable** for delineation of catchments if cost is not prohibitive
Hydrometric Areas (HA) (CEH)	Digital spatial boundary data licensed from CEH. Integral river catchments or groupings of catchments which have topographic similarity (97 on mainland GB, 8 on islands, 8 in NI)				UK					**Potentially suitable** for modelling at coarser scale than catchments
Catchment Characterisation and Modelling (CCM) River and	It includes a hierarchical set of river segments and catchments based on the Strahler	Modelling from 100m DEM		1:500,000	Europe		ESRI Shape	Reproduction for non-commercial purposes is authorised, provided the	Catchment boundaries and rivers	**Potentially suitable** for delineation of catchments if cost of WFD catchment

Dataset (ownership)	Description	Derived from	Time period data collected	Spatial resolution	Coverage	Frequency of update	Format	Cost	Attributes	Evaluation
Catchment Database (JRC)	order, a lake layer and structured hydrological feature codes based on the Pfafstetter system.							source is acknowledged.		dataset is prohibitive or the detail of these is considered too large.
Source Protection Zones (EA)	SPZs defined for 2000 groundwater sources (wells, boreholes and springs) used for public drinking water supply.				England & Wales	Quarterly	ESRI shapefile		Three main zones (inner, outer and total catchment) and a 4th zone of special interest. Zones show risk of contamination from any activities that could cause pollution.	**Potentially suitable** for identification of high risk groundwater bodies.

Point sources of pollutants

Dataset (ownership)	Description	Derived from	Time period data collected	Spatial resolution	Coverage	Frequency of update	Format	Cost	Attributes	Evaluation
Landfill sites data (EA)	Point source data for historic landfill sites (not current sites).	EA records	1948-2010	1:10,000	England & Wales	Regular	ESRI shapefile	Free for non-commercial use	Defines location of and provides specific attributes for known historic (closed)	**Potentially suitable** but only has E&W coverage.

Dataset (ownership)	Description	Derived from	Time period data collected	Spatial resolution	Coverage	Frequency of update	Format	Cost	Attributes	Evaluation
									landfill sites, including what was deposited.	
Permitted Waste Sites - Authorised landfill site boundaries (EA)	Polygon dataset containing boundaries of landfill sites that are currently authorised by the EA.	EA records			England & Wales	Quarterly	ESRI shapefile	Free for non-commercial use		Potentially suitable but only has E&W coverage.
Septic tank registration (EA, SEPA)	Under Controlled Activity Regulations (CAR) 2005, septic tanks are now required to be registered with SEPA (in Scotland) and EA (in England and Wales). Does not cover tanks constructed prior to planning consent. Septic tanks and other sewage treatments are responsible for some of the	EA and SEPA records			GB				Assess overall risk of small sewage discharges causing pollution problems. Investigate catchments at a local level.	Suitable for use if available alongside location information.

Dataset (ownership)	Description	Derived from	Time period data collected	Spatial resolution	Coverage	Frequency of update	Format	Cost	Attributes	Evaluation
	phosphorus in surface waters.									
Data on septic tank locations (Water Companies)	Information on locations of septic tanks.	Derived from address points 30 + from sewer network.			UK					Suitable for use if available.

Climate

Dataset (ownership)	Description	Derived from	Time period data collected	Spatial resolution	Coverage	Frequency of update	Format	Cost	Attributes	Evaluation
1km monthly rainfall grids (CEH)	UK monthly rainfall grids	Created through a process of interpolating daily and monthly Met Office raingauge observations	1961-present	1km	UK	Monthly	ESRI shapefile		Monthly rainfall (mm)	Potentially suitable for model calibration or modelling a particular year
Regional climate values of rainfall by year (Met Office)	Rainfall data	Station data			UK	Monthly		Open Government Licence	Monthly rainfall (mm)	Potentially suitable for model calibration

Dataset (ownership)	Description	Derived from	Time period data collected	Spatial resolution	Coverage	Frequency of update	Format	Cost	Attributes	Evaluation
Historical monthly data for met stations (Met Office)	Historical monthly data for met stations	Station data			UK	Monthly		Open Government Licence	Includes max temp, min temp, days of air frost, total rainfall, total sunshine duration	**Potentially suitable** for model calibration
MORECS (Met Office)	Daily weather data giving real-time assessments of rainfall, evaporation and soil moisture	Station data	1970s-present	Interpolated by the IRRIGUIDE model to catchments	UK	Daily	Txt file		Mean daily max/ min temperature, rainfall, sunshine, windspeed	**Suitable** for modelling purposes
Mean monthly weather surfaces (Met Office)	Long-term average weather data.		1914-2006	5 x 5 km	UK		txt files; can be loaded as a grid into ArcGIS	Free for research purposes.	Frost, rainfall, snow cover, max/min/mean temperatures, vapour pressure, cloud cover, wind speed, precipitation, sunshine duration	**Suitable** for modelling purposes
Mean monthly weather surfaces (Met Office)	Long-term average weather data.		1971-2000	1 x 1 km	UK		txt files; can be loaded as a grid into ArcGIS	Licence required.	Frost, rainfall, snow cover, max/min/mean temperatures, vapour pressure, cloud cover, wind speed, precipitation, sunshine duration	**Potentially suitable** for modelling purposes if cost is not prohibitive

Dataset (ownership)	Description	Derived from	Time period data collected	Spatial resolution	Coverage	Frequency of update	Format	Cost	Attributes	Evaluation
MORECS Averages (Met Office)	Average Annual Potential Evapotranspiration (grass)	Derived from daily MORECS data	1961-1990	40 x 40 km	UK		ESRI shapefile	Free for govt-funded research	Potential evapotranspiration	Suitable for modelling purposes
Soil Temp (Met Office)	Soil temperatures		1961-1990		UK			Licence from Met Office required (>£1000)	Soil temperature	Potentially suitable for modelling purposes if soil temperature information is required.

Crop management

Dataset (ownership)	Description	Derived from	Time period data collected	Spatial resolution	Coverage	Frequency of update	Format	Cost	Attributes	Evaluation
British Survey of Fertiliser practice (Defra/ SG)	Survey of fertiliser practice - annual survey based on selection of a sample of farms from GB. Purpose is to estimate application rates of N, phosphate and potash for	Survey		N/A	GB	Annual	Excel	Free	Use in conjunction with land use datasets to evaluate inputs to land for different crop types.	Suitable for estimation of loading parameters

Dataset (ownership)	Description	Derived from	Time period data collected	Spatial resolution	Coverage	Frequency of update	Format	Cost	Attributes	Evaluation
	agric crops and grassland. Dataset gives annual statistics on fertiliser use on major crops and grass on mainland Britain.									
Pesticide Usage survey (Defra/ FERA)	Data on inputs of pesticides by crop type	Survey	1965-present	N/A	GB	Every four years?	Database	Free	Use in conjunction with land use datasets to evaluate inputs to land for different crop types.	Suitable for estimation of loading parameters

Flow data

Dataset (ownership)	Description	Derived from	Time period data collected	Spatial resolution	Coverage	Frequency of update	Format	Cost	Attributes	Evaluation
Peak River Flows (Q(T) Grids) (CEH)	Flood peak river flows estimated for a range of return periods at 50 m intervals along the UK river network. Used in conjunction with	Sampling		50m	UK		ESRI shapefile		Peak flows	Potentially suitable for modelling purposes

Dataset (ownership)	Description	Derived from	Time period data collected	Spatial resolution	Coverage	Frequency of update	Format	Cost	Attributes	Evaluation
	DTMs to produce flood risk maps.									
BIBER River Flow data (EA)	Points sources	Sampling 7796 points with ADCP measurement.		N/A	E&W				Flows	**Potentially suitable** for model calibration at catchment scale
UK National River Flow Archive (CEH + collab)	River flow data from UK river catchments, daily flow data	Sampling from 1450 gauging stations.		N/A	UK		Time series as csv	Free	Time series of river flows; hydrometric characteristics of river flow gauging stations; spatial catchment information (boundary, area, topography, geology, land use); time series/ statistics of areal rainfall for catchments (monthly series and derived stats).	**Potentially suitable** for model calibration at catchment scale
Daily mean river flow data (WISKI) (EA)	Mean daily river flow for a range of catchments in England and Wales	Sampling (196 sampling sites)			E&W					**Potentially suitable** for model calibration at catchment scale

Dataset (ownership)	Description	Derived from	Time period data collected	Spatial resolution	Coverage	Frequency of update	Format	Cost	Attributes	Evaluation
Daily mean river flow data (SEPA)	Mean daily river flow	Sampling			Scotland					Potentially suitable for model calibration at catchment scale

Catchment water quality

Dataset (ownership)	Description	Derived from	Time period data collected	Spatial resolution	Coverage	Frequency of update	Format	Cost	Attributes	Evaluation
Reason for failure datasets (EA/SEPA)	Targeting of waterbodies failing to reach good ecological status due to diffuse pollution from agriculture/ land management.	WFD assessments	2003-	WFD waterbody	UK		Database	Unpublished dataset (to be released as EA open data)	Identifies cause of less than 'Good' classifications (activity, source, sector) with defined set of reasons for failure.	Suitable for identification of sensitive catchments
WFD status reports (EA/SEPA)	Good Ecological Status assessments. Part of the WFD monitoring programme. Risk-	WFD assessments	2003-	WFD catchment	UK		Reports	Open Government Licence		Suitable for identification of sensitive catchments

Dataset (ownership)	Description	Derived from	Time period data collected	Spatial resolution	Coverage	Frequency of update	Format	Cost	Attributes	Evaluation
	based monitoring focusing on areas where there is likely to be a problem.									
WFD monitoring data (EA/SEPA)	Datasets consist of points representing monitoring locations used in WFD cycle 1 2009 baseline year. Part of the WFD monitoring programme.	Monitoring points	2009	N/A	UK			Unpublishe d		**Potentially suitable** for identification of problem catchments/ model calibration if available.
Harmonised Monitoring Scheme (HMS) (EA)	Water quality data for UK. Shows annual averages of site means for each landscape type.	Sampling network of 230 sites at tidal limits of major rivers or at points of confluence of significant tributaries.	1974-date	N/A	UK		Database	Open Governmen t Licence	Oxygen and ammonia, nutrients, metals and pesticides	**Suitable** for model calibration
General Quality Assessment (EA/SEPA)	Nitrate and phosphate levels in river water. Part of the		1990, 1995 & 2000-2009	N/A	UK		Database			**Potentially suitable** for model

Dataset (ownership)	Description	Derived from	Time period data collected	Spatial resolution	Coverage	Frequency of update	Format	Cost	Attributes	Evaluation
	Observatory monitoring framework. Data collected over 3 years used to determine average nutrient concentrations.									calibration if available
Diffuse Pollution risk characteristic (EA/SEPA)	Baseline study per WFD catchment of the 2004 risk of diffuse pollution impacts. Assessment of the risk of not achieving good ecological status, by pollution type.	WFD Risk Assessments	2004	WFD catchment	UK	Updated in December 2013	Reports	Free for govt research but needs licence.	Pollution types included: point source e.g. authorised discharges (sewage works etc.); diffuse (nutrients, sediment, pesticides, acidification, mines and minewater, urban pressures); abstraction and flow regulation; and morphology (flood defences, dredging).	**Suitable** for identification of sensitive catchments
Sensitive Areas maps - Nitrates Rivers (EA)	Extent of Urban Wastewater Treatment Directive sensitive areas (nitrate).				England & Wales		ESRI shapefile	Open Govt Licence	Shows rivers currently designated as UWWTD nitrate sensitive areas.	**Potentially suitable** for identification of sensitive catchments, but only E&W

Dataset (ownership)	Description	Derived from	Time period data collected	Spatial resolution	Coverage	Frequency of update	Format	Cost	Attributes	Evaluation
Sensitive Areas maps - Eutrophic Rivers (EA)	Extent of Urban Wastewater Treatment Directive sensitive areas (eutrophic).				England & Wales		ESRI shapefile	Open Govt Licence	Shows rivers currently designated as UWWTD eutrophic sensitive areas.	**Potentially suitable** for identification of sensitive catchments, but only E&W

Stream network

Dataset (ownership)	Description	Derived from	Time period data collected	Spatial resolution	Coverage	Frequency of update	Format	Cost	Attributes	Evaluation
Detailed River Network (WFD) (EA)	Large-scale digital centreline. Captures from water features theme of OS MasterMap topographic layer. Includes Detailed River Network Lines, Nodes and Offline Drainage.	OS MasterMap	2008-2012	1:1,250, 1:2,500 or 1:10,000	E&W	Quarterly or Annually	ESRI shapefile	Up to £15,000 dependent on user	Details name and type of river, direction of flow, source points, sink points, tributary junctions etc. Can be used to carry out accurate network analysis.	**Potentially suitable** for use if available to FC at reduced rate. Most detailed dataset available for E&W.
1:50,000 Watercourse Network (CEH)	Continuous centreline network of rivers,	OS data	1970s-late 1990s	1:50,000 scale.	GB		ESRI shapefile	Requires licence	Consists of four components (rivers, canals, surface pipes	**Potentially suitable** for use if available to FC.

Dataset (ownership)	Description	Derived from	Time period data collected	Spatial resolution	Coverage	Frequency of update	Format	Cost	Attributes	Evaluation
	canals and field drains for GB.								and miscellaneous channels)	
Statutory (sealed) Main Rivers (EA)	Watercourses shown on the statutory main river maps held by the EA and Defra and NRW/WAG.				E&W		ESRI shapefile	Requires licence		**Not suitable** due to it only detailing main rivers.
Stream density connectivity (CEH/EA)	Datasets describing connectivity and stream density on a 1 km basis.				E&W		ESRI shapefile	Requires licence	Average and medium distance to stream, connectivity ratio for each 1 km cell.	**Potentially suitable** for use in simpler models
GB Rivers (OS)	River network of GB	Extracted from Ordnance Survey Strategi Data	2010-		GB		ESRI shapefile	OS OpenData	Rivers are classified as either, main river, secondary river or minor river.	**Potentially suitable** for use if more detailed representations not available.
Catchment Characterisation and Modelling (CCM) River and Catchment Database (JRC)	It includes a hierarchical set of river segments and catchments based on the Strahler order, a lake layer and structured hydrological	Modelling from 100m DEM		1:500,000	Europe		ESRI Shape	Reproduction for non-commercial purposes is authorised, provided the source is acknowledged.	Catchment boundaries and rivers	**Potentially suitable** for use if more detailed representations not available.

Dataset (ownership)	Description	Derived from	Time period data collected	Spatial resolution	Coverage	Frequency of update	Format	Cost	Attributes	Evaluation
	feature codes based on the Pfafstetter system.									

Dams & flood defences

Dataset (ownership)	Description	Derived from	Time period data collected	Spatial resolution	Coverage	Frequency of update	Format	Cost	Attributes	Evaluation
Flood map (EA)	Flood Defences shows those defences constructed during the last five years with a standard of protection equal to or better than 1% (1 in 100) for rivers and 0.5% (1 in 200) from the sea. Flood Storage Areas shows those areas that act as a balancing reservoir, storage basin or				E&W		ESRI shapefil e		Delineates flood defences and flood storage areas	Suitable for locating flood defences and storage areas

Dataset (ownership)	Description	Derived from	Time period data collected	Spatial resolution	Coverage	Frequency of update	Format	Cost	Attributes	Evaluation
	balancing pond. Their purpose is to attenuate an incoming flood peak to a flow level that can be accepted by the downstream channel.									
Global Reservoir and Dam database (GRanD) (Global Water System Project)	Mainly capacity of > 0.1 km^3. Contains 6,862 records of reservoirs and associated dams.	Dams geospatially referenced and assigned to polygons depicting reservoir outlines at high spatial resolution.		Various (point coordinates, reservoir polygons). Most polygons 30 m pixel resolution.	Global		ESRI shapefile	Free for non-commercial use	Reservoir/dam name, river name, basin, height/ length of dam, area of reservoir polygon, storage capacity, depth etc.	**Suitable** for locating dams and reservoirs

Floodplain extents

Dataset (ownership)	Description	Derived from	Time period data collected	Spatial resolution	Coverage	Frequency of update	Format	Cost	Attributes	Evaluation
Flood Hazard maps (EA)	The Flood Maps shows the areas across England and Wales that could be affected by flooding from rivers and the sea, from reservoirs and from surface water. The maps include the predicted extent, depth and velocity of flood waters.	National Flood Risk Assessment is the main source of flood risk information for rivers and sea and takes flood defences into account. The surface water flooding map was produced with help from local authorities.			E&W		ESRI shapefile		Flood Zone 3 is the Agency's best estimate of the areas of land with a 1% (1 in 100), or greater, chance of flooding each year from rivers, or with a 0.5% (1 in 200) chance, or greater, of flooding each year from the sea. Flood Zone 2 is the Agency's best estimate of the areas of land between Zone 3 and the extent of the flood from rivers/from the sea/from rivers and, or the sea with a 0.1% (1 in 1000) chance of flooding in any year.	**Suitable** for mapping flood plain
Flood maps (SEPA)	River, coastal, surface water and	The coastal flood maps			Scotland	Ongoing				**Suitable** for mapping flood plain

Dataset (ownership)	Description	Derived from	Time period data collected	Spatial resolution	Coverage	Frequency of update	Format	Cost	Attributes	Evaluation
	groundwater flood maps. The river flood map includes hydraulic structures and defences such as bridges, culverts and flood storage areas. The Natural flood management maps identify areas where the alteration or restoration of natural features could be most effective in storing or slowing the flow of water or managing stream sediment.	are based on the Coastal Flood Boundary dataset developed by Defra. The river flood map was developed using a nationally consistent approach using a flood modelling method. The surface water flood map combines information on rainfall and sewer model outputs.								
Flood Alert Areas (EA)	Flood alert areas - generally large expanses of	Based on forecasts (river level/			E&W		ESRI shapefil e			**Not suitable** – based on forecasts

Dataset (ownership)	Description	Derived from	Time period data collected	Spatial resolution	Coverage	Frequency of update	Format	Cost	Attributes	Evaluation
	floodplain within a catchment/sub-catchment or group of catchments that is/are at risk from low impact flooding.	flow info; rainfall info, wind/wave/surge info from Storm Tide forecasting Service)								

Springs and wells

Dataset (ownership)	Description	Derived from	Time period data collected	Spatial resolution	Coverage	Frequency of update	Format	Cost	Attributes	Evaluation
National Well Record Collection / WellMaster hydrogeological database (BGS)	National Well record collection contains >130,000 classified records of water wells, water boreholes and springs in England, Wales and Scotland.	Mostly borehole scans		1:250,000 scale or below.	GB		ESRI shapefile (point data)	Index level data free (Boreholes WMS layer). Detailed data poa.	Detail varies, from basic location info to comprehensive records covering drilling and operation of a borehole (e.g. information on geology, well construction, water levels and yields and	**Potentially suitable** for locating wells and boreholes, but data may be difficult to obtain

Dataset (ownership)	Description	Derived from	Time period data collected	Spatial resolution	Coverage	Frequency of update	Format	Cost	Attributes	Evaluation
									water quality for selection of water boreholes) from WellMaster database.	
Water wells (BGS)	Water wells with water level measurements, aquifer property measurements.			1:250,000 scale or below.	E&W		ESRI shapefile (point data)	Index level data free (Boreholes WMS layer). Detailed data poa.		**Potentially suitable** for locating wells and boreholes, but data may be difficult to obtain