Environment Agency

using science to
create a better place

Climate change, recreation and navigation

Science report: SC030303

ea/br/e/sci/v1

SCHO0707BMZG-E-P

The Environment Agency is the leading public body protecting and improving the environment in England and Wales.

It's our job to make sure that air, land and water are looked after by everyone in today's society, so that tomorrow's generations inherit a cleaner, healthier world.

Our work includes tackling flooding and pollution incidents, reducing industry's impacts on the environment, cleaning up rivers, coastal waters and contaminated land, and improving wildlife habitats.

This report is the result of research commissioned and funded by the Environment Agency's Science Programme.

Published by:
Environment Agency, Rio House, Waterside Drive, Aztec West,
Almondsbury, Bristol, BS32 4UD
Tel: 01454 624400 Fax: 01454 624409
www.environment-agency.gov.uk

ISBN: 978-1-84432-797-3

This report is printed on Cyclus Print, a 100% recycled stock, which is 100% post consumer waste and is totally chlorine free. Water used is treated and in most cases returned to source in better condition than removed.

Further copies of this report are available from:
The Environment Agency's National Customer Contact Centre by emailing enquiries@environment-agency.gov.uk or by telephoning 08708 506506.

Author(s):
R. Lamb, J. Mawdsley, L. Tattersall, M. Zaidman

Dissemination Status:
Publicly available / released to all regions

Keywords:
Strong stream advice, climate change, low flows, navigation, High flows, recreation.

Research Contractor:
JBA Consulting, South Barn, Broughton Hall, Skipton, BD23 3AE
+44 (0)1756 799 919

Environment Agency's Project Manager:
Naomi Savory, Richard Fairclough House, Knutsford Road, Warrington.

Science Project Number:
SC030303

Product Code:
SCHO0707BMZG-E-P

Science at the Environment Agency

Science underpins the work of the Environment Agency, by providing an up to date understanding of the world about us, and helping us to develop monitoring tools and techniques to manage our environment as efficiently as possible.

The work of the Science Group is a key ingredient in the partnership between research, policy and operations that enables the Agency to protect and restore our environment.

The Environment Agency's Science Group focuses on five main areas of activity:

- **Setting the agenda**: To identify the strategic science needs of the Agency to inform its advisory and regulatory roles.
- **Sponsoring science**: To fund people and projects in response to the needs identified by the agenda setting.
- **Managing science**: To ensure that each project we fund is fit for purpose and that it is executed according to international scientific standards.
- **Carrying out science**: To undertake the research itself, by those best placed to do it - either by in-house Agency scientists, or by contracting it out to universities, research institutes or consultancies.
- **Providing advice**: To ensure that the knowledge, tools and techniques generated by the science programme are taken up by relevant decision-makers, policy makers and operational staff.

Steve Killen Head of Science

Executive summary

The Environment Agency is the operating authority for almost 1,000 km of navigable waterways of environmental and economic importance, including the River Thames. There are an estimated 32,000 registered boat users on these rivers, with the Thames, Nene and Ouse accounting for the vast majority.

The Environment Agency's responsibilities include maintenance of safe passage, provision of facilities for the public and the operation of locks, sluices and other structures. Government policy aims to increase the economic and social benefits offered by waterways, by encouraging their use for leisure, tourism and sport, and by protecting historic features, enhancing biodiversity and encouraging freight and passenger transport.

The future impacts of climate change may affect the way in which the Environment Agency can meet these policy objectives. This report explores the projected implications of climate change for the management of navigable waterways. The report concentrates on the impacts of climate change on boat users' experiences of the waterways, although we also consider implications for sustainable management of the navigations and their infrastructure.

In this study, we examined the operational impacts of climate change projections at high flows and low flows. At high flows, it may be necessary to close a river for navigation by issuing Strong Stream Advice (SSA) warning notices to boat users, and by opening locks and sluices. SSA warnings have been issued on the Thames, Nene, Great Ouse and Ancholme. At very low flows, shallow depths may stop boat passage. Before this situation occurs, however, the Environment Agency may also restrict the operation of locks to reduce water conveyance downstream.

The Environment Agency's method for recording the occurrence of SSAs varies from river to river. Long records are available for the Thames in paper form, and part of the record was digitised for this analysis. Spreadsheet records exist for the Nene and Great Ouse. There are almost no hard data recorded on restrictions that have occurred as a result of drought conditions. According to Environment Agency reports, only the 1976 drought caused severe disruption to navigation on the Thames.

Using the information available, two climate change indicators were used to track operational impacts on navigations. For high flows, we found that threshold rates could be identified for the occurrence of SSAs by comparing SSA records with gauged river flow data. For low flow restrictions, the key variable was the 30-day running average daily flow. An event corresponding to the 1976 drought was used as an indicator of impacts on navigation.

The impacts of climate change on navigation were investigated using existing impacts models to explore projected changes in the two indicator variables. For high flows, we analysed modelled river flow data, produced for previous Department for Environment, Food and Rural Affairs (Defra) and Environment Agency research, for the Thames under the UKCIP-02 climate change scenarios. The headline results predicted fewer SSA closures in the future. However, the particular scenario used for modelling was relatively dry, and modelled impacts on flood flows could vary greatly from place to place. Additionally, these results derive from only one climate model, one hydrological model and two emissions scenarios, and therefore do not represent several important sources of uncertainty.

Threshold flows for SSAs were generally found to be less severe than peak flood discharges used for planning and design in flood risk management. This report does not discuss the

engineering implications of more severe flood flows, which are the subject of a large body of engineering guidance and Defra and Environment Agency research.

For low flows, we were able to use a probabilistic climate change impacts analysis, which accounted for uncertainty in climate modelling, emissions scenarios and impacts models. The analysis showed an increasing probability, compared to the recent past, of extreme low flows that could disrupt navigation.

The key recommendations of this report are:

1. The Environment Agency should modernise its processes for recording Strong Stream Advice (SSA) and other operational measures (such as weir and sluice adjustments and restrictions on lock operation at low flows).

2. Strong Stream Advice (SSA) events, consistently recorded for navigable rivers, could provide a useful climate change indicator.

3. The Environment Agency should ensure that the maintenance and performance of navigation assets for flood flows are aligned with its flood risk management practices, by adopting a risk-based approach to maintenance, planning and design for navigation infrastructure.

The research priorities identified by this report are:

1. The Environment Agency should carry out probabilistic impacts modelling for navigations, particularly on the frequency and duration of SSAs and flood flows. This work may identify assets considered to be at risk and incorporate more detailed hydraulic model analysis for one or more case studies.

2. The Environment Agency should identify mitigation strategies, such as improved boat design or changes in locking practice, which could help to counter the impacts of future drought restrictions. Possible environmental constraints and opportunities for channel maintenance should be identified.

Contents

1 Background and aims

1.1 Navigable waterways in England and Wales

1.1.1 General

There are approximately 5,100 km of navigable inland waterways in England and Wales (see *Waterways for tomorrow*, Defra, July 2000). The responsibility for navigable waterways rests with a number of bodies, chiefly British Waterways (BW) and the Environment Agency. British Waterways operates the greatest proportion of the network by length, but the Environment Agency operates navigations on number of rivers of strategic importance, notably the River Thames. These are shown in Figure 1.1.

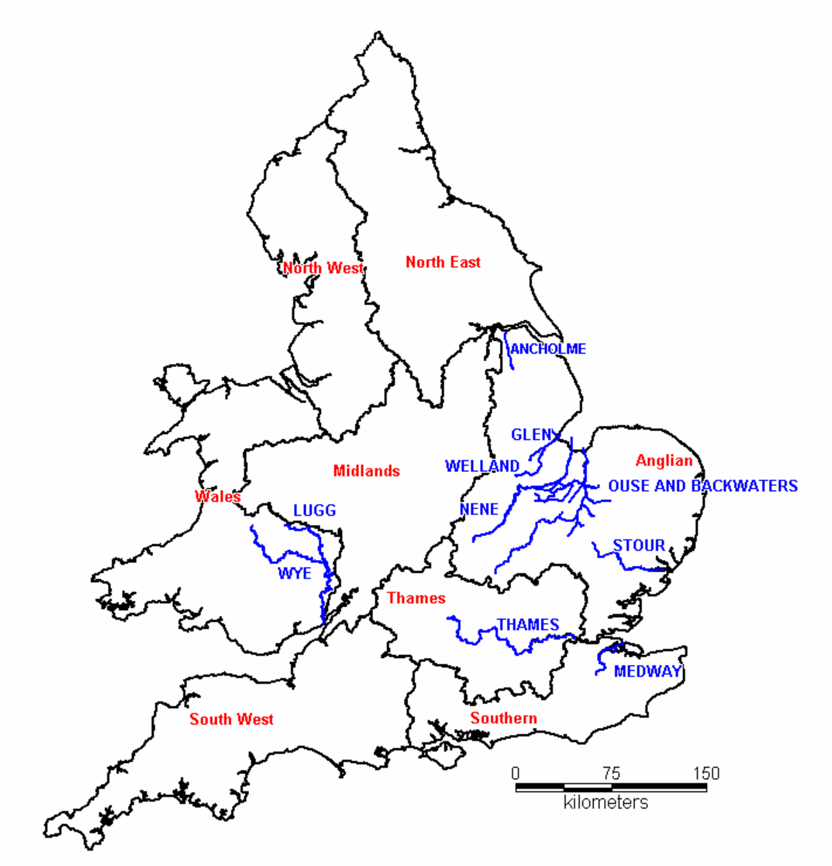


Figure 1.1: Environment Agency regions and navigable waterways in England and Wales.

1.1.2 Navigable waterways managed by the Environment Agency

The Environment Agency is the navigation authority for the rivers Ancholme, Glen, Great Ouse, Lugg, Medway, Nene, Suffolk Stour, Thames, Welland and, since 2002, the Wye. The report, *Your rivers for life: A strategy for the development of navigable rivers 2004-2007*, records 32,000 boats registered on the navigable rivers, which are also used by around 80 per cent of rowers and canoeists.

The Thames, Nene and Ouse account for almost all (some 95 per cent or approximately 30,000) registered boat users of navigations managed by the Environment Agency. By contrast, the Medway, for example, has only about 750 users.

1.2 Planning a sustainable future

The navigations depend on their infrastructure to provide safe and reliable passage for recreational (or other) users. However, these infrastructure assets, which include locks, weirs, sluices and moorings, are in many cases ageing and in general need to be maintained to ensure sustainable operation. The value of these assets is estimated to be approximately £250 million. A grant from the Department for Environment, Food and Rural Affairs (Defra) of around £30 million over three years will help to improve the most at risk structures, but a more comprehensive 15-20 year plan is needed to renew assets across the board.

As part of this longer term planning, the impact of climate change on the design life of the assets needs to be considered, to ensure that the Environment Agency can maintain public access to its waterways and safe use of the network under changing flow conditions. The design life for navigation assets is assumed to be at least 50 years. It is therefore necessary to consider the impact of climate change as far ahead as the 2080s.

1.3 Restrictions on navigation

1.3.1 Low flow restrictions

The two most important restrictions that may affect river users during periods of low flow are inadequate depth and restrictions on the operation of locks. The Environment Agency operates locks, weirs and sluices on its navigations so as to maintain adequate depths for boating, as well as to achieve environmentally acceptable flows and depths. Under drought conditions, it may be necessary to restrict the number of times lock gates are opened, to help retain water in the channel upstream. This will affect boat users, who may have to queue or hold off from moving through locks for a period of time. Restrictions on boating because of inadequate water depth are more obvious matters of safety or access.

Drought restrictions of this type have been very rare in the past, with the summer of 1976 being the only severe and prolonged case.

1.3.2 High flow restrictions

Restrictions on boat users during periods of high flow are primarily driven by safety and operational concerns. When the river is high, there are obvious risks to boat users. There are also risks involved in operating locks and other structures that can be damaged by the forces present in high flow conditions, or by debris. Furthermore, locks may need to be reversed (that is, held open) to maximise conveyance for flood management.

When high flows make the river unsafe for navigation, the Environment Agency issues a Strong Stream Advice (SSA) to close the river. Strong Stream Advice conditions are by no means rare events.

1.4 Motivations for this study

In 2003, the Thames waterway was closed to users for large parts of the winter because high flows made it unsafe to operate locks on the river. The Environment Agency needs to know whether closures of this type are set to become more or less likely under climate change scenarios, to help in planning asset renewal and also to communicate to the public why the work is needed. Annual registration fees charged to boaters, which add up to about £7.5 million, are increasing to raise revenue for this maintenance work.

Similarly, drought has to be considered. There have been no severe restrictions on recreational users of the Thames because of lack of adequate flow since 1976. However, following a dry winter in 2005/06, preparations were in place for possible restrictions over the summer of 2006.

This study was commissioned to support the Environment Agency in planning for the sustainable management of its navigations. The project aims to:

- review data and monitoring practices to establish whether the Environment Agency has good enough information to assess climate change impacts on recreation and navigation;
- identify suitable climate change indicators and parameters;
- apply climate change scenario projections to assess the 'headline' impacts of future climate on recreation and navigation;
- identify possible adaptation strategies.

2 Data collation

2.1 Introduction

There is no standardised, central database of operational restrictions on the Environment Agency's navigable rivers. It was therefore necessary to seek information on current practices and historical records on a case-by-case basis. This involved discussion with Environment Agency staff in the regions, primarily navigation officers and members of the flood forecasting and water resources teams. However, some information initially assumed to be available was found not to exist in practice. This chapter summarises the data that have been collated, and also where gaps in the records exist.

2.2 Data requirements

The data requested for this project were as follows:

- description of current practice in the issuing of Strong Stream Advice (SSA);
- description of current plans for setting low flow restrictions;
- historical records of SSAs issued;
- historical records of low flow restrictions;
- hydrometric data for correlation with SSAs and low flow restrictions;
- Gepgraphical Information Systems (GIS) data relating to the Environment Agency's navigable waterways and assets.

2.3 Operational data for navigations

Table 2.1 summarises information gathered during the period January to June 2006. The table is considered to be up to date at the time of writing; however, the Environment Agency's methods for recording data on navigations are undergoing change and therefore data availability is also evolving. Furthermore, procedures and data resources vary between the Environment Agency's navigations. .

Table 2.1: Summary of information received

	SSA issued	**SSA records**	**Boat traffic data for low flows**	**Trigger settings for SSAs**	**Flow data**	**Drought plan**
Wye	No	No	No	No	No	No
Lugg	No	No	No	No	No	No
Thames	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**
Medway	No	No	**Yes**	No	**Yes** [2]	No [1]
Nene	**Yes**	**Yes**	No	No	Yes	No
Great Ouse & Tribs	**Yes**	**Yes** [3]	No	**Yes**	**Yes** [4]	No
Welland	No	No	No	No	No	No
Glen	No	No	No	No	No	No
Stour	No	No	No	No	No	No
Ancholme	***Yes***	*Began Nov 05*	No	No	No	No

Notes
[1] Navigation team looking to develop drought plan
[2] Drought years only
[3] For the period 2000-2006
[4] Offord flow gauge

2.3.1 Strong Stream Advice (SSA)

SSAs are boards that are issued to boaters when it is considered too dangerous due to high river levels to continue boating. SSAs are not issued on every navigable river and each river has different lengths and methods for recording their occurrence.

Records of SSAs are available for the Thames, Great Ouse and Nene, although only the Thames has records of more than a few years. Procedures for issuing SSAs (that is, trigger settings) exist for the Thames and Great Ouse.

2.3.2 Low flows restrictions

Only the Thames has a drought plan to specify the operation of control structures on the river under low flows. There are data to indicate the number of boats passing through locks on Thames and Medway. In principle, these figures could support analysis of restrictions at low flows; however, in practice they are lumped into annual totals prior to 2000, which means that the data cannot be explicitly associated with periods of low flow in the hydrometric record.

2.4 Summary of data available for Environment Agency navigations

2.4.1 River Wye

The River Wye is 251 km long and rises in the mid-uplands of Wales, flowing through Ross-on-Wye and Monmouth before entering the Severn Estuary at Chepstow. The upstream navigation extent is from Bigsweir (approx SO538051) upstream to Hay Town Bridge (approx SO228426). The Environment Agency does not issue SSAs and there is no record of issuing them. The Wye has no navigation assets.

2.4.2 River Lugg

The River Lugg rises near Presteigne, Wales and flows through Herefordshire, England, including the town of Leominster. It is then met by a tributary, the River Arrow, then onto a confluence with the River Wye, which it joins at Mordiford, 14 km downstream of Hereford and 72 km from its source. The Lugg navigation length is between its confluence with the Wye and Presteigne town bridge.

The Environment Agency does not issue SSAs; however, there are water level indicator boards located at Leominster that are used to check the level if the boat user is going upstream.

2.4.3 River Medway

The Medway flows for 112 km from Turners Hill in West Sussex through Tonbridge, Maidstone and the Medway towns in Kent to the River Thames at Sheerness. The Medway navigation is 31 km of freshwater river above its tidal limit; it starts at Allington Lock near Maidstone and extends to the footbridge immediately downstream of the Leigh flood regulating barrier just west of Tonbridge.

The Environment Agency does not issue SSAs and there are no records of SSAs having been issued. Asset information exists in the form of asset name, estimated value and estimated cost to replace.

Information was received regarding the number of boats passing through Allington Lock from 2002-2004. The locking numbers were estimated at 10 per day in the summer at weekends and one to three during the week.

At the time of writing, the Medway navigation team were looking into producing a drought plan for the Medway that would involve similar measures to the Thames. This would primarily be shared locking and if necessary, the manual working of the sluices to reduce water loss. It is also possible to limit Allington lock movements to high tide, to prevent water loss from the bottom pen.

2.4.4 Great Ouse and tributaries

The Great Ouse and its tributaries, the rivers Cam, Lark, Little Ouse and Wissey, comprise the major navigation in the Fens and East Anglia, providing about 240 km (150 miles) of navigable waterway. The river has several sources close to the villages of Syresham and

Sulgrave in Northamptonshire. It flows through a number of towns including Brackley, Milton Keynes and Huntingdon, before entering the Wash at Kings Lynn.

The Ouse does issue SSAs and records were obtained from September 2000 to March 2006. The SSA is triggered on the Great Ouse when flows reach 40 $m^3 s^{-1}$ at Offord flow gauging station, which is situated between St Neots and Huntington. Usually this coincides with the locks being reversed for the flood discharge. This means the vee doors are chained open and the guillotine gate is used to discharge flood waters in the same manner as a flood defence sluice structure.

SSA signs which are permanently fitted at all of the locks sites are then opened to display the SSA message. The SSA is withdrawn when the flow falls below 40 $m^3 s^{-1}$ and the procedure is reversed, that is, the locks are returned to normal and the signs are closed. The SSA message is a standard message similar to the River Nene. The procedure has been in place for a number of years.

SSAs are recorded by filling in a blue square on a spreadsheet for the whole day that the SSA is issued. They are summed at the end of every month. This method for recording the SSA will be discussed later, as there is scope for it to be improved.

2.4.5 River Welland

The Welland rises near Market Harborough in Leicestershire, then flows eastwards to Ketton, Stamford and Spalding. After running for 56 km it then flows into the Wash at Fosdyke Bridge. The Welland is navigable from Hudds Mill Stamford to the Fulney Lock in Spalding. The Welland does not have SSAs issued on it.

2.4.6 River Glen

The River Glen rises in Lincolnshire Limestone Ridge, to the east of Grantham. The upstream navigation limit is from Tongue End to Surfleet Seas End where it joins the River Welland. The Glen navigation officers do not issue SSAs, but may do in the future with an increase in traffic.

2.4.7 River Stour

The Stour rises in eastern Cambridgshire and is 76 km long. On its journey to the North Sea at Harwich it passes through Haverhill, Cavendish and Dedham Vale. SSAs are not issued on the River Stour.

2.4.8 River Ancholme

The River Ancholme rises south of Bishopbridge and passes through Brigg and flows into the Humber at South Ferriby. The Ancholme is navigable for 27 km from the entrance of the River Humber at South Ferriby to Harlem Lock at Snitterby.

The SSA is activated at South Ferriby by the lock keepers. The records for SSAs only began in November 2005 and since then no SSA has been issued. Navigational asset information exists and was used in this study.

2.4.9 River Nene

The River Nene rises near Badby, Northamptonshire; it continues its course through Northampton, and then onto the rural part of the city of Peterborough. It then continues its journey to the Nene washes in the Fens, where it flows through Wisbech and Sutton Bridge in Lincolnshire, and then enters the North Sea at the Wash.

The Environment Agency navigation for the Nene starts at the junction with the Northampton arm of the Grand Union Canal near Cotton End Lock and extends for 147 km, ending at Bevis Hall just upstream of Wisbech. There are 38 locks on the Nene, from Northampton to the Dog-in-a-Doublet Lock beyond Peterborough, after which the river is tidal.

The Nene does issue SSAs. Records received for this study cover July 1999 through to March 2005. The Environment Agency operates a reverse locks procedure, using the lock to discharge flood waters, which closes the affected locks to navigation. Warnings are issued before reversing the locks and an 'all clear' follows once they have been reset.

We were informed by navigation officers that low flow warnings are not issued on the Nene at present, but a drought management plan is being developed that would include navigation aspects. The Nene is not heavily used for navigation and as such, the lockage flows in dry periods are not a major component of the flow at Orton gauging station (Peterborough), and hence navigation interests are not that significant.

2.4.10 River Thames

Of all navigable rivers, the Thames has the longest and the most comprehensive record of SSAs being issued. Furthermore, the Thames has the longest record of gauged river flows at Kingston and is the only navigation with a full drought plan. For these reasons, further analysis in this study was concentrated on the Thames. Data for the Thames are described in more detail below.

2.5 River Thames navigation data

2.5.1 Strong Stream Advice boards

A SSA is issued using red and yellow boards as signals for navigators. Red boards tell boaters to stay off the river when it is dangerous because of high flows and/or debris load, and have been issued since the 1890s. Yellow boards are advisory and indicate that the navigation is hazardous. Yellow boards have only been used since the 1970s.

2.5.2 Weir settings

SSAs are issued when the adjustable gates at a weir reach certain predefined positions. The levels for triggering an SSA on the Thames were set by navigation officers, based on experience and local technical consultation. The levels do take account of changes over time at the weirs and other adjacent structures. A spreadsheet developed by Thames region details the weir 'tackle' (the position of the gates) at which the yellow or red boards should be issued. The weir settings, once decided, were issued as formal procedure to the lock keepers. An example is shown in **Table 2.2**.

A further complication with issuing SSA at locks is that it is common for the warning boards to be issued before the weir tackle has reached the defined position; this is done to allow the lock keeper some leeway to increase flow over the weir if the river continues to rise.

Table 2.2: Example of weir tackle at Northmoor Lock

Total tackle	Yellow boards out	Red boards out	Red boards in	Yellow boards in
36 x Top Sets Paddle and Rymer 36 x Middle Sets Paddle and Rymer 22 x Bottom Sets Paddle and Rymer	30 x Paddles (any)	47 x Paddles (any)	47 x Paddles (any)	30 x Paddles (any)

2.5.3 Lock blocks

SSAs are issued at each of the locks along the Thames. However, the locks are operated in groups known as ‘blocks’, listed in Table 2.3. For example, the locks between St Johns and Godstow make up the Northmoor block. It is only when the Northmoor lock has reached its required weir setting for the yellow boards that the locks upstream will issue a board. The locations of the Thames locks are shown in **Figure 2.1**.

Table 2.3: River Thames lock blocks

Lock group name	Locks in block
Northmoor	St Johns to Godstow
Osney	Osney to Iffley
Clifton	Sandford to Clifton
Goring	Days to Mapledurham
Soning	Caversham to Shiplake
Marsh	Marsh to Boveney
Romney	Romney to Bell Weir
Chertsey	Penton Hook to Shepperton
Sunbury	Sole Member of the Group
Molesey	Sole Member of the Group
Teddington	Sole Member of the Group

2.5.4 Thames region SSA records

Thames region has records of weir tackle movements (named in this study as “tackle sheets”) since the 1890s (see Table 2.4). The tackle sheets are recorded at every lock on the Thames. Paper tackle sheets are held at the Environment Agency offices in Reading, but have recently been scanned and are held on a searchable database of jpeg images to assist with frequent requests for research purposes. For this project, a copy of the image library and the database software was made available to JBA Consulting. The database of scanned images is effectively an electronic library rather than a structured, relational database. Hence, use of the records still requires manual reading and extraction of any required information.

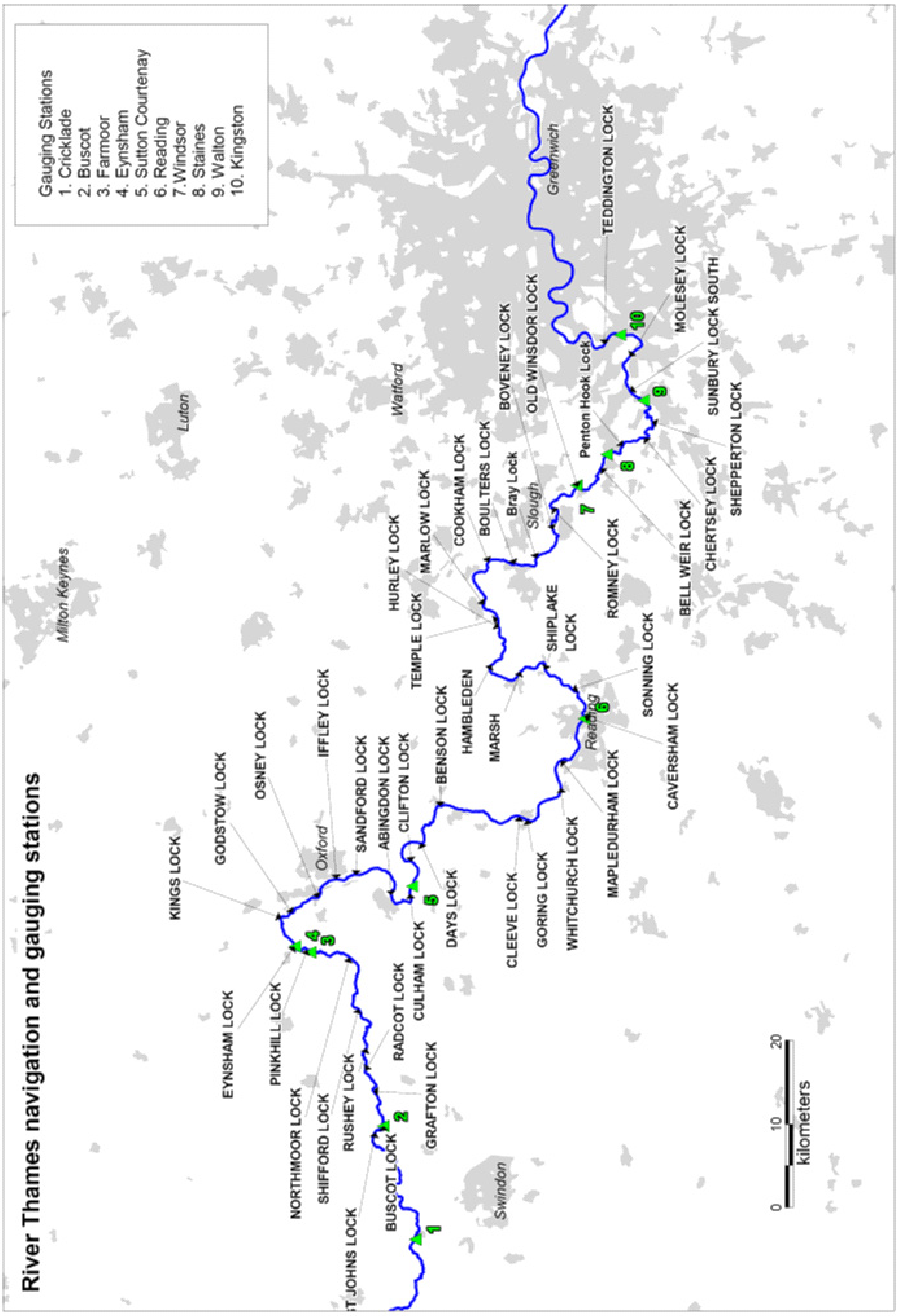
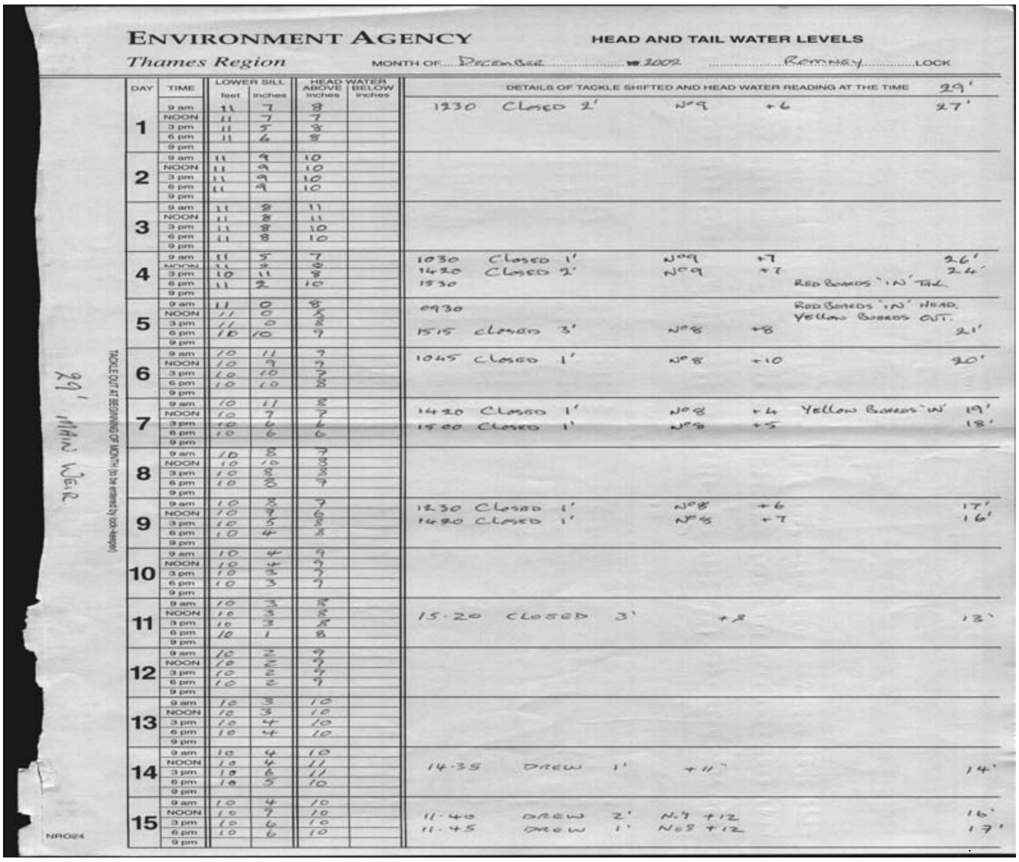


Figure 2.1: Navigation structures and gauging stations on the River Thames.

Table 2.4: Example tackle sheet



ENVIRONMENT AGENCY HEAD AND TAIL WATER LEVELS

Thames Region MONTH OF December 2002 Romney LOCK

TACKLE OUT AT BEGINNING OF MONTH (to be entered by lock-keeper)

29' Main Weir

DAY	TIME	LOWER SILL feet	LOWER SILL inches	HEAD WATER ABOVE inches	HEAD WATER BELOW inches	DETAILS OF TACKLE SHIFTED AND HEAD WATER READING AT THE TIME 29'
1	9 am	11	7	8		1230 Closed 2' No9 +6 27'
	NOON	11	7	7		
	3 pm	11	5	8		
	6 pm	11	6	8		
	9 pm					
2	9 am	11	9	10		
	NOON	11	9	10		
	3 pm	11	9	10		
	6 pm	11	9	10		
	9 pm					
3	9 am	11	8	11		
	NOON	11	8	11		
	3 pm	11	8	10		
	6 pm	11	8	10		
	9 pm					
4	9 am	11	5	7		1030 Closed 1' No9 +7 26'
	NOON	[illegible]	[illegible]	[illegible]		1420 Closed 2' No9 +7 24'
	3 pm	10	11	8		1530 Red Boards 'in' Tail
	6 pm	11	2	10		
	9 pm					
5	9 am	11	0	8		0930 Red Boards 'in' Head.
	NOON	11	0	5		Yellow Boards out.
	3 pm	11	0	8		1515 closed 3' No8 +8 21'
	6 pm	10	10	9		
	9 pm					
6	9 am	10	11	7		1045 Closed 1' No8 +10 20'
	NOON	10	9	7		
	3 pm	10	10	7		
	6 pm	10	10	8		
	9 pm					
7	9 am	10	11	8		
	NOON	10	7	7		1420 Closed 1' No8 +4 Yellow Boards 'in' 19'
	3 pm	10	6	6		1500 Closed 1' No8 +5 18'
	6 pm	10	6	6		
	9 pm					
8	9 am	10	8	7		
	NOON	10	10	8		
	3 pm	10	8	8		
	6 pm	10	8	7		
	9 pm					
9	9 am	10	8	7		1230 Closed 1' No8 +6 17'
	NOON	10	7	6		1420 Closed 1' No8 +7 16'
	3 pm	10	5	8		
	6 pm	10	4	8		
	9 pm					
10	9 am	10	4	9		
	NOON	10	4	9		
	3 pm	10	3	7		
	6 pm	10	3	9		
	9 pm					
11	9 am	10	3	8		
	NOON	10	3	8		15-20 CLOSED 3' +8 13'
	3 pm	10	3	8		
	6 pm	10	1	8		
	9 pm					
12	9 am	10	2	9		
	NOON	10	2	9		
	3 pm	10	2	9		
	6 pm	10	2	9		
	9 pm					
13	9 am	10	3	10		
	NOON	10	3	10		
	3 pm	10	4	10		
	6 pm	10	4	10		
	9 pm					
14	9 am	10	4	10		
	NOON	10	4	11		14-35 DREW 1' +11" 14'
	3 pm	10	6	11		
	6 pm	10	5	10		
	9 pm					
15	9 am	10	4	10		
	NOON	10	7	10		11-40 DREW 2' No7 +12 16'
	3 pm	10	6	10		11-45 DREW 1' No8 +12 17'
	6 pm	10	6	10		
	9 pm					

NR024

For this study, we digitised the records for Eynsham Lock and Teddington Lock. These locations were chosen to represent the upper and lower reaches of the Thames respectively, and to coincide with good quality flow records at Eynsham and Kingston gauging stations. The transcription provided a structured database of SSA records from 1974-2004 at Teddington and 1990-2004 at Enysham.

2.5.5 Quality of SSA records for the Thames

Of importance to this study was the quality of information contained within the tackle sheets. Although the records of weir tackle movements date back to the 1890s, the actual recording of SSAs only began in the 1970s for the majority of locks.

The records varied greatly in quality. Transcription required some degree of interpretation of the paper records, in particular because the terminology used to denote strong stream warnings varied. Sometimes the boards were called “danger boards” (DB) or “stream boards” with no distinction made between the yellow and the red boards, even after the yellow boards had been introduced. Secondly, there was also some inconsistent note taking, for example in cases where the tackle sheets did not record when boards were brought back in, which may have biased estimates of SSA flow thresholds towards higher values (see discussion of SSA trigger thresholds later in this report).

2.5.6 Thames drought restrictions

Information was gathered about drought restrictions from various sources within the Environment Agency. At the time of publishing this report, the Thames was the only region to have a fully operational drought plan, which was written in response to the 2005 drought. The plan has a number of trigger points prompting various actions and sets out appropriate liaison between Environment Agency staff in implementing these.

Severe restrictions on navigation have not occurred since 1976. Under low flow conditions, the Environment Agency will initially seek voluntary restrictions by asking boaters to wait for other vessels to arrive before passing through locks, in order to maximise the traffic density for each release of water through a lock. Under more severe conditions, locks or reaches of the river may be closed. Unfortunately, no record was available to give details of these restrictions in 1976. From 15 May 2006, the Environment Agency issued voluntary restrictions on the Thames due to concerns over low water levels following recent dry winters, although these are believed to have been a precautionary measure.

2.6 Hydrometric data

2.6.1 Parameters chosen for analysis

Rainfall, discharge and level were considered as analysis parameters. Level was rejected because although it might often provide a direct link with triggers for restrictions on navigation, it was not easily linked to climate change projections without a rating curve or hydraulic modelling.

Rainfall had the advantages of being a relatively direct link with climate change and having long records from gauged data. However, we could expect a less direct link to navigation impacts than with discharge.

We therefore concentrated on flows data to provide a physical link between navigation restrictions and climate. The retrieval of hydrometric data is not discussed further in this report, since the Environment Agency has well-established procedures for supplying gauging station records from its WISKI hydrometric database. Hydrometric records (daily and sub-daily flows) were obtained for this study via routine data requests. Additionally, daily mean gauged and naturalised flows were retrieved from the National River Flow Archive (NRFA). The long reconstructed daily flow record of Jones *et al.* (2006), modelled based on historical meteorological records) was also obtained.

The hydrometric data collated for analysis on the Thames, Nene and Great Ouse are summarized as follows:

2.6.2 Thames

Eynesham gauging station

- Daily mean flows for 1951 to March 2006.
- Fifteen minute flows 1992 to 2006
- Reconstructed (modelled) daily flows 1865 to 2002.

Kingston gauging station

- Daily mean flows for 1883 to 1985
- Fifteen minute flows April 1985 to February 2006.

2.6.3 Great Ouse

Offord sluices

- Daily mean flows for 1970 to 2006
- Instantaneous flows (varying sample interval) 1994 to 2006.

2.6.4 Nene

Orton gauging station (used for low flow calculation)

- Daily mean flows for 1939 to 1996.

Wansford gauging station (used for high flow calculation)

- Fifteen minute flows 1996 to 2006.

3 Navigation restrictions at high flows

3.1 Introduction

Strong Steam Advice (SSA) notices are issued when navigation on the river is potentially hazardous. The decision to issue the SSA is made by Environment Agency staff, most of whom are working at the locks on the rivers. Navigation officers base their decision on a combination of water levels, velocities and flows but in general without a formal flow trigger level.

SSAs affect navigation by restricting river use by boats in two ways: frequency of restrictions and duration of the SSA. The impact of SSAs that occur in the summer months is of most concern, because that is when most recreational boat use takes place. However, SSAs are more common in winter.

To assess the impact of climate change on the frequency of SSAs, it is necessary to relate the warnings to river flows, or possibly rainfall. Projections of changes in future flows or rainfall due to climate change can then be used to predict the frequency of SSAs.

The duration of a SSA can be measured because the warning is formally withdrawn when the river is perceived to be safe again for boating use. The duration might be expected to be relatively short in the summer, as high flows are often the result of convective rainfall events, which generally are of short duration. The duration of SSAs was investigated in this study and is reported later in this report.

Two possible ways of linking SSA warnings to flows were identified:

- number of days per month of SSA related to monthly mean flow, or rainfall;
- flow threshold when SSA issued and threshold when withdrawn.

The first approach would not allow the duration of an individual SSA event to be considered, but would give the duration per month of restrictions to boating.

3.2 Historical data for SSAs

To apply either of these methods, historical records of when SSAs were issued and withdrawn were required, as well as flow rates in the river at these times.

As explained in Section 2, SSAs are not yet routinely issued on many of the navigable rivers and records are only available for the Thames, Nene and Great Ouse. The method of issuing warnings also differs. On the River Thames, the SSA is a two-stage process with a yellow warning (a yellow board) followed where necessary by a red board. The yellow board means “all unpowered vessels are advised to moor up until the stream abates; powered vessels may proceed”. The red board warning means the flow is higher and “boaters are strongly advised not to enter the river or navigate in these conditions”. For the rivers Nene and Great Ouse, only the equivalent of the red board is issued.

For these rivers, records extend back only from 1999 or 2000 but for the River Thames, they start from about 1974 (Table 3.1).

The criteria for issuing the SSA may have changed over time. Hence, it was thought better to restrict the use of historic records on the River Thames to the relatively recent past, that is, 1990 to present. This historic record was long enough to establish a threshold flow for the issuing and withdrawing of an SSA. The data used are summarised in Table 3.1.

Table 3.1: SSA warning data used in threshold analyses

River	Start of SSA record used	End of SSA record used
Nene	July 1999	March 2005
Bedford Ouse	September 2000	March 2006
Thames	January 1990	December 2005

Flow records for the rivers were obtained from the Environment Agency and the National Water Archive (Table 3.2). There are several gauges on the three rivers, especially on the Thames. Two were selected for the Thames, Eynsham in the upper Thames above Oxford and Kingston as the lowest station on the Thames. For the River Nene, the station at Wansford is used by the Environment Agency for monitoring navigation and was used for this analysis. It is also the lowest station on the river, with flow records covering the period of SSA warnings. For the River Great Ouse, the gauging station used for analysis is on the Bedford Ouse at Offord, which is the station used by the Environment Agency for monitoring navigation and for triggering SSAs.

Table 3.2: River flow data used in SSA threshold analysis

River	Gauging Station	Station number	Area (km2)	Time interval
Thames	Eynsham	39008	1616	Daily
	Kingston	39001	9948	Daily
Nene	Wansford	32010	1530	15 min
Bedford Ouse	Offord	33026	2570	15 min

3.3 SSA and monthly flow data

One of the simpler ways to assess the impact of climate change on SSA restrictions is to develop a relationship between monthly flow data and SSAs. To this end, the SSA record for the River Nene was analysed as a test case.

The number of days per month when SSAs were in force was calculated, as shown in Table 3.3.

Table 3.3: SSA days per month – River Nene

Month	No days SSA/mth							
	1999	2000	2001	2002	2003	2004	2005	mean
1	n/a	10	22	6	31	23	0	15.3
2	n/a	2	24	26	25	17	0	15.7
3	n/a	9	25	11	9	0	0	9.0
4	n/a	27	27	0	0	7	n/a	12.2
5	n/a	5	9	0	0	11	n/a	5.0
6	n/a	3	0	0	0	0	n/a	0.6
7	0	0	3	1	0	0	n/a	0.7
8	0	0	0	2	0	12	n/a	2.3
9	0	5	0	0	0	0	n/a	0.8
10	0	13	11	14	0	18	n/a	9.3
11	0	30	2	28	0	11	n/a	11.8
12	15	31	10	31	0	0	n/a	14.5

The number of days per month of SSA with mean monthly flow is plotted in Figure 3.1.

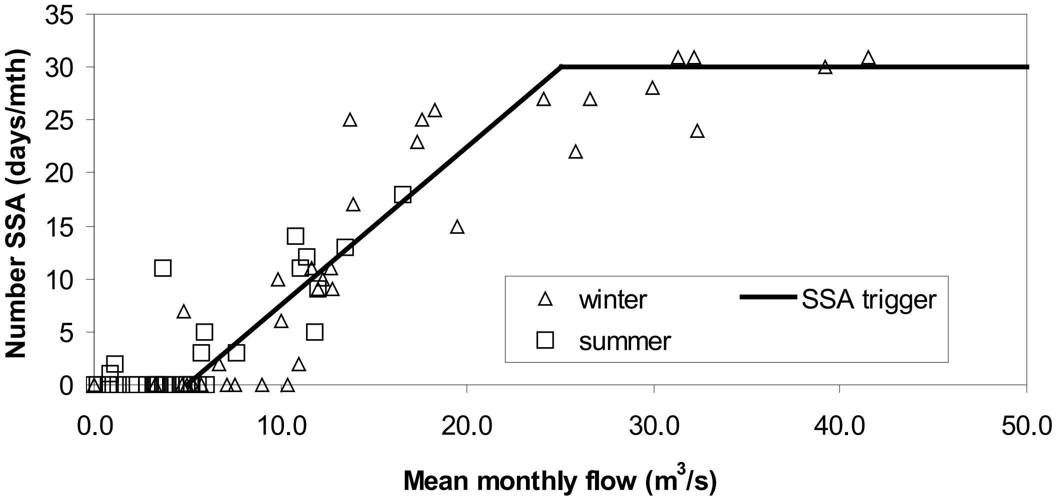


Figure 3.1: Number of days of SSA per month related to mean monthly flow, Nene at Wansford, 1999-2005

A relationship, fitted by eye, between the variables is shown in Figure 3.1. As expected, this relationship shows that, in general, the higher the flow the more days of SSAs per month. However, the relationship is not a precise one and if used to predict the number of days of SSA per month, could give very misleading results. For example, one data point shows 25 days of SSA for a flow of about 14 $m^3 s^{-1}$, where the relationship would predict only about 14 days of SSA; another point shows zero SSA days for a flow of about 11 $m^3 s^{-1}$, where the relationship would predict about eight days.

Because the relationship between SSA days per month and flow was not thought to be precise enough, a relationship between flow and individual SSA warnings was investigated.

3.4 SSA warnings and flow thresholds

According to Environment Agency staff, the SSA on the Bedford Ouse is issued when the flow exceeds 40 $m^3 s^{-1}$. However, for the rivers Thames and Nene, the link between the SSA warning and flow was not known. To see if a consistent relationship existed between flow and the issue or withdrawal of the warning for these rivers, the data shown in Table 3.1 and 3.2 were analysed.

3.4.1 River Nene

Flow data from the River Nene at Wansford were available at 15-minute intervals, but only the day the SSA warning was recorded were available, with no precise time of it being issued or withdrawn. Because of this limitation, initially daily flow data were used for the analysis for the period July 1999 to March 2005. Results are shown in Figure 3.2.

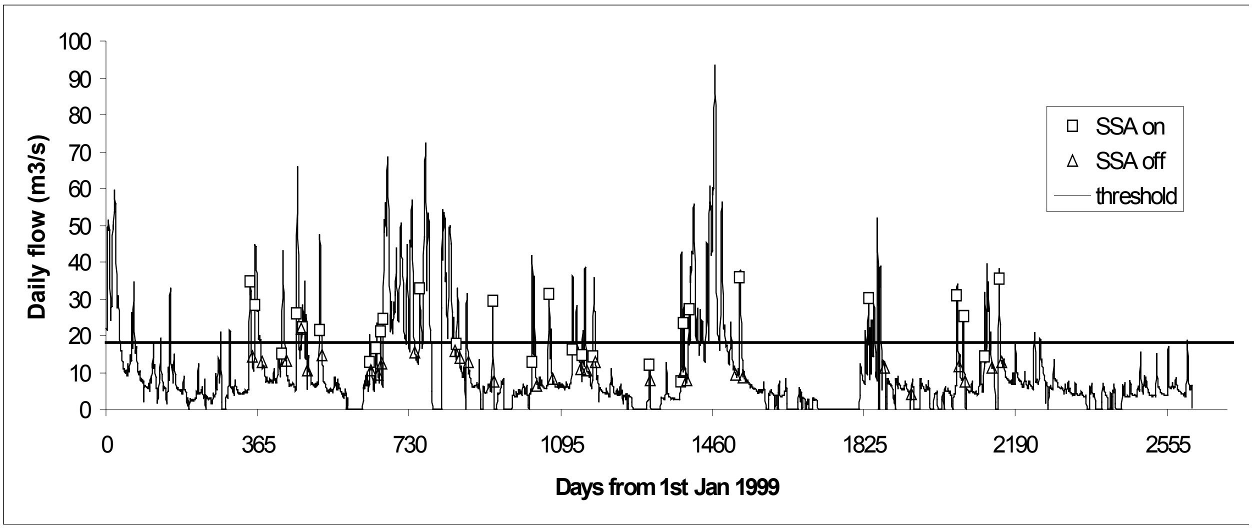


Figure 3.2: SSA threshold with daily flows, Nene at Wansford, 1999-2005

The day when the warning was issued is shown with a square and when it was withdrawn, with a triangle. The data did not always record both the day of issue and the day withdrawn, hence not all could be paired.

A threshold flow for the *issuing* of the warning was estimated at 18 $m^3 s^{-1}$. This was a visual mean and there was clearly some variability around this threshold (7.6 to 35.7 $m^3 s^{-1}$, with an arithmetic mean of 22.7 $m^3 s^{-1}$), but most events that exceeded this threshold were accompanied with a warning (after the start in July 1999). Some SSAs were issued significantly below the flow threshold, however. To show this more clearly, a shorter part of the record is given in Figure 3.3.

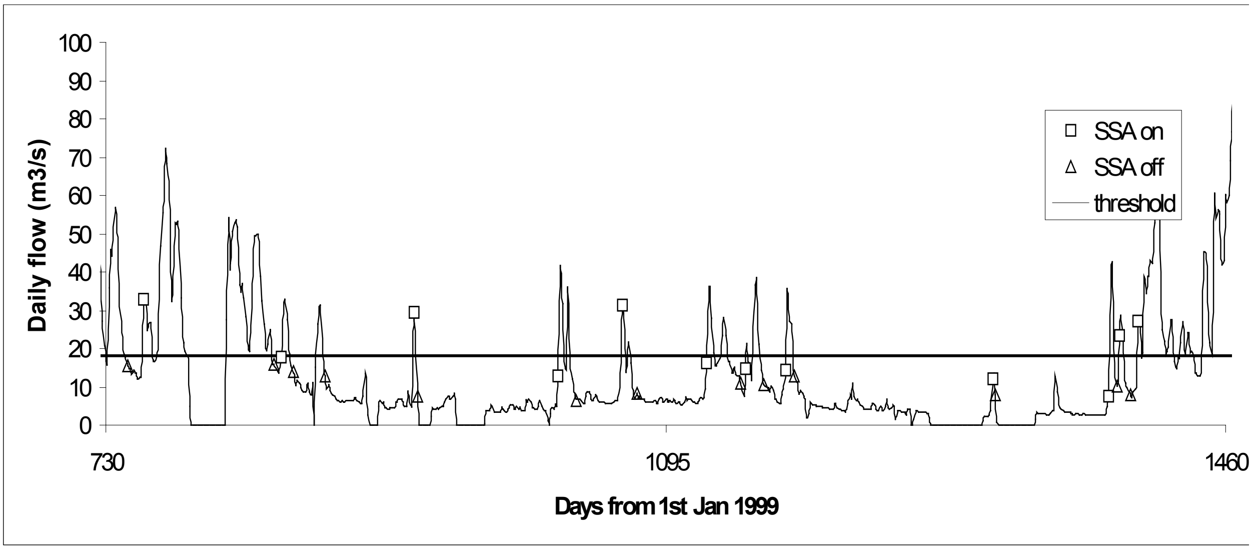


Figure 3.3: SSA threshold with daily flows, Nene at Wansford, 2001-2002

The variability was larger than desired and so the flows on each day an SSA was issued were considered in more detail. For the period in the second half of Figure 3.3 (covering 2002), flows every 15 minutes were considered and are shown in Figure 3.4.

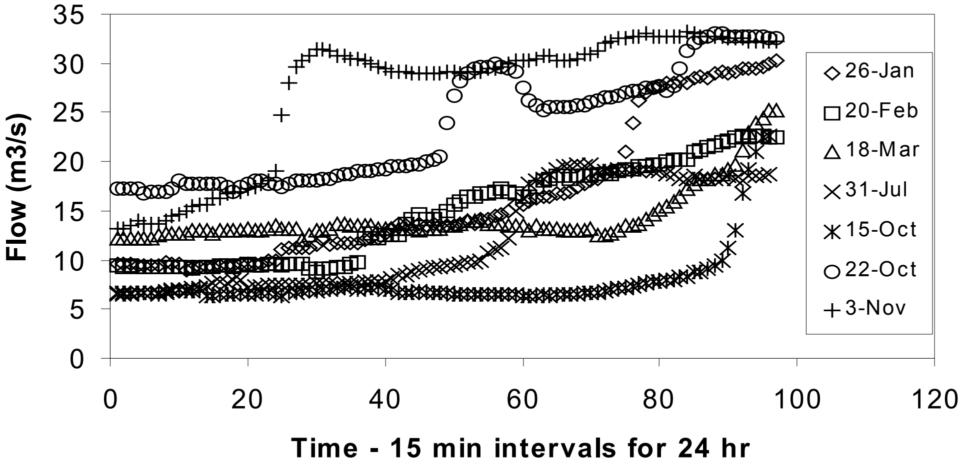


Figure 3.4: SSA threshold with 15 min flows, Nene at Wansford, 2002

For all the days shown when SSAs were issued, the flow started the day below 18 $m^3 s^{-1}$ and exceeded this flow by the end of the 24-hour period, including the 15 October event when the average flow for the day was only 7.6 $m^3 s^{-1}$. Thus, the issuing of warnings might be more closely linked to flow than it appeared from the daily analysis.

An analysis using three-hourly flows showed a somewhat better link to a flow threshold than for daily flow (see Figure 3.5). This was clearest with higher flows towards the end of 2002, when the variability of flow around the threshold was a little smaller than for daily flows. It could have been much smaller with knowledge of the exact three-hour period to use, but as this was not available a fixed time period, from 00:00 to 03:00, was assumed for all days.

The three-hour data suggested the threshold should be a little lower than the 18 $m^3 s^{-1}$ originally chosen – it was thus revised to 15 $m^3 s^{-1}$. Analysis of the other years supported this conclusion.

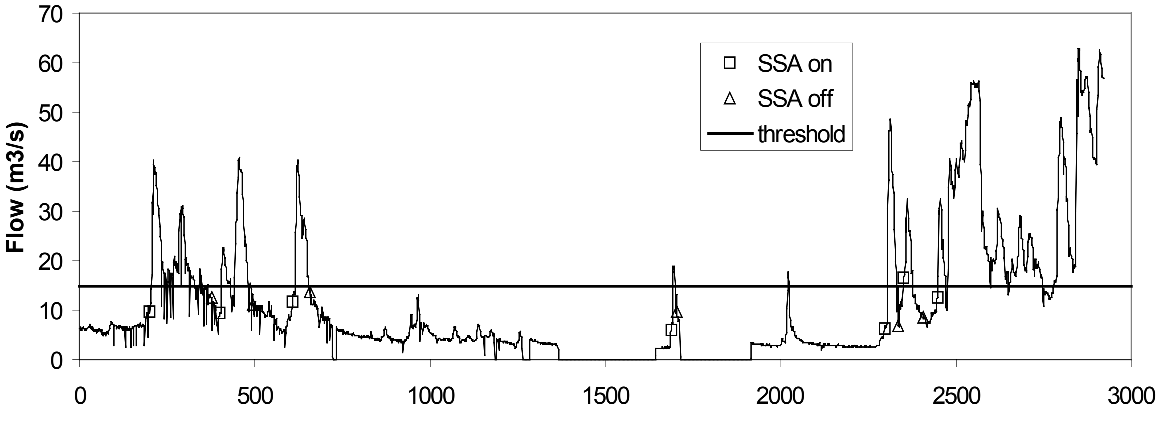


Figure 3.5: SSA threshold with three-hour flows, Nene at Wansford, 2002

The threshold flow when the SSA is withdrawn appears to be a little lower, perhaps because the Environment Agency wants to make sure the flow is not going to rise again and so waits a little longer. The threshold for withdrawing the SSA is not shown, but appears to be about 12 $m^3 s^{-1}$. The average of the flows for the years 2000-2004 are 13.8 and 11.5 $m^3 s^{-1}$ for the SSA issue and withdrawal respectively. These are close to the thresholds selected.

There appears to be a close relationship between river flow and the issuing of an SSA warning, but because of the lack of information on the exact time of issue and the ability of the Nene to change flow significantly during a 24-hour period, this relationship is somewhat obscured.

We chose a flow threshold of 15 $m^3 s^{-1}$ as our best estimate of the true value. On almost all occasions that the flow exceeded this rate, an SSA was in effect. The threshold was slightly different to the mean of the flows when SSAs were issued, but it was thought to be a better estimate than the mean.

The flow threshold of 15 $m^3 s^{-1}$ is approximately the daily Q16 on the flow duration curve, that is, the flow that is exceeded on average only 16 per cent of the time.

3.4.2 River Great Ouse

A similar analysis was carried out for the Great Ouse using flow data from Offord. As this catchment was almost 70 per cent larger than the Nene at Wansford, and the time of issuing the SSA warning was again not recorded, daily flow data were used to try to establish a flow trigger.

According to the Environment Agency, a flow trigger has been established for this river and is 40 $m^3 s^{-1}$. We carried out a similar analysis to the Nene to check this threshold, but more importantly to see if our analysis approximated the true threshold.

The SSA data available for the Bedford Ouse started in September 2000 and ended in March 2006. The duration of SSAs per month are shown in Table 3.4. The data show a similar concentration of SSAs in the winter as for the Nene, not surprisingly as they are adjacent rivers, and a mean duration of SSA when issued of eight days. There are very few SSA days in the summer months (only one episode, in August 2004).

Table 3.4: SSA days per month – River Bedford Ouse.

Month	No days SSA/mth								mean when >0
	2000	2001	2002	2003	2004	2005	2006	mean	
1	n/a	18	6	0	7	0	0	5.2	10.3
2	n/a	20	13	0	12	0	0	7.5	15.0
3	n/a	20	0	0	0	0	1	3.5	10.5
4	n/a	13	0	0	0	0	n/a	2.6	13.0
5	n/a	4	0	0	4	0	n/a	1.6	4.0
6	n/a	0	0	0	0	0	n/a	0.0	0.0
7	n/a	0	0	0	0	0	n/a	0.0	0.0
8	n/a	0	0	0	8	0	n/a	1.6	8.0
9	0	0	0	0	0	0	n/a	0.0	0.0
10	11	8	0	0	0	0	n/a	3.2	9.5
11	25	0	17	0	6	0	n/a	8.0	16.0
12	21	6	4	0	0	0	n/a	5.2	10.3
total/mean	57	89	40	0	37	0	1	3.2	8.1

These SSA data were plotted on the daily flow hydrograph for the whole period of SSA data in Figure 3.6. Again, the issue of an SSA is shown with a square and the removal with a triangle. Not all the data show a removal of an SSA to the corresponding issue, so the data are not complete. The threshold of 40 $m^3 s^{-1}$ is shown in the figure. It appears to be a reasonable value, with similar variability around the threshold as for the River Nene.

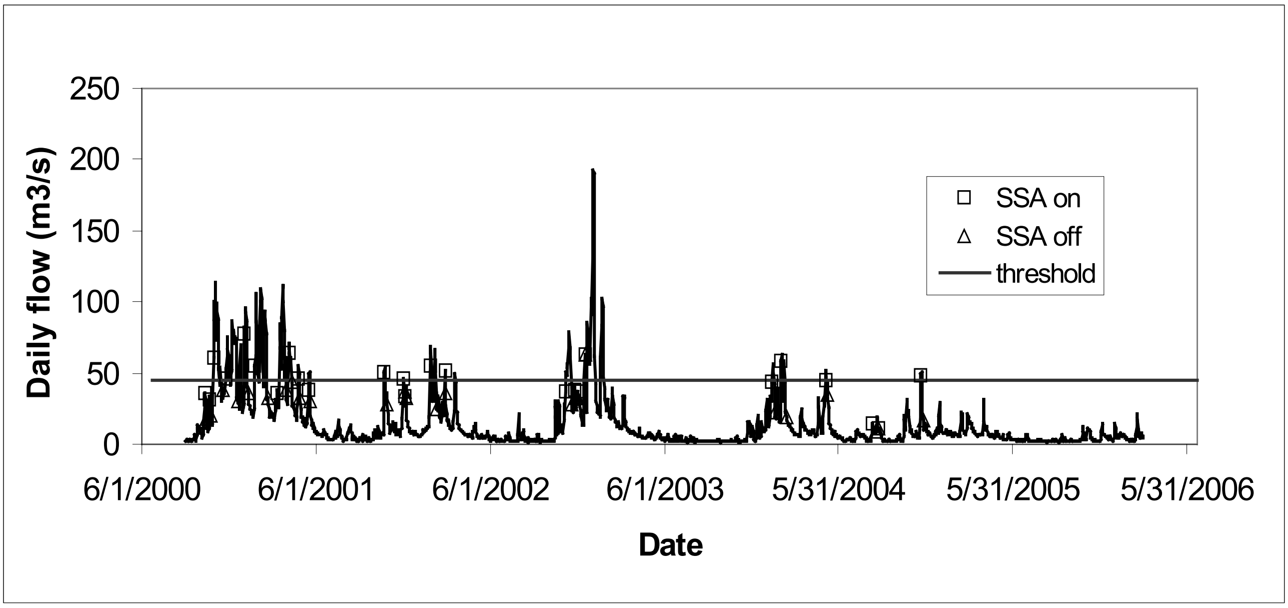


Figure 3.6: SSA threshold with daily flows, Bedford Ouse at Offord, 2000-2006

A shorter period of record is shown in Figure 3.7, so that the relationship between flow and the issue or removal of an SSA is clearer. The period chosen includes the highest flows in the period.

The data for this period show that a warning was in effect whenever the flow was in excess of 40 $m^3 s^{-1}$, except for a small event in late March 2002 (the fourth small peak on the hydrograph) and the striking absence throughout the major event in early 2003. The last SSA was issued and withdrawn on the same day, according to Environment Agency records, at a flow of 62.8 $m^3 s^{-1}$. As these data appear at odds with the rest of the data in the period and at odds with the Environment Agency's stated threshold of 40 $m^3 s^{-1}$, the data were investigated further by looking more closely at the early period of SSAs, shown in Figure 3.8.

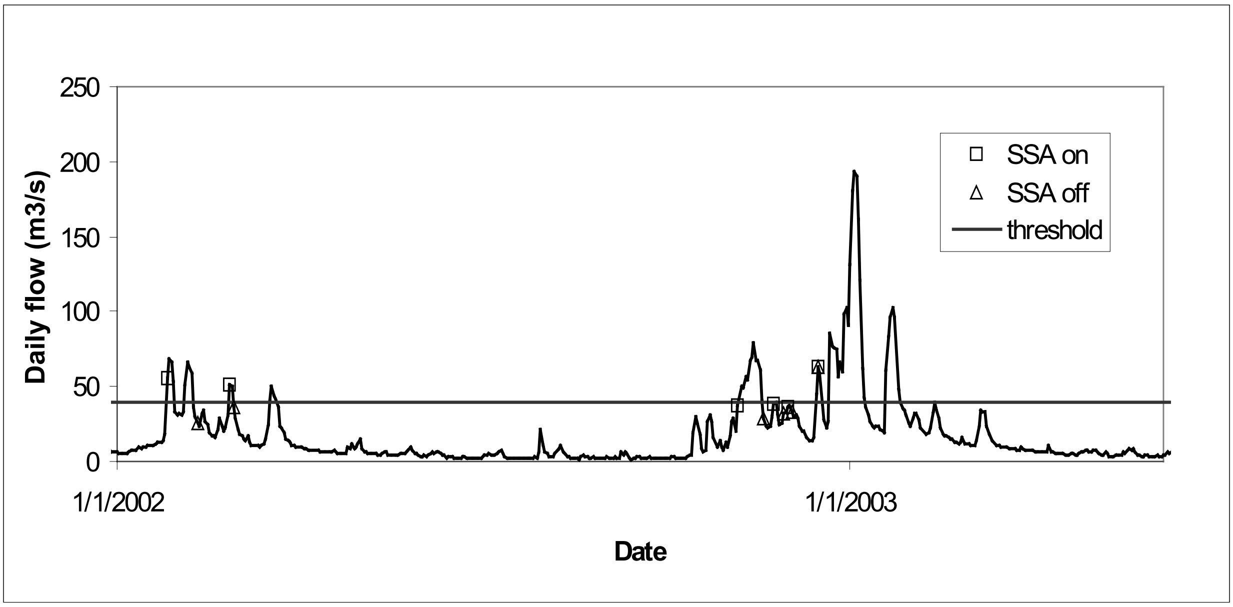


Figure 3.7: SSA threshold with daily flows – R Bedford Ouse at Offord 2002-2003

In Figure 3.8, it is clear that an SSA was in effect whenever the flow was above 40 m^3 s^{-1} (with the exception of a short peak in the middle of the hydrograph) and at no time was the SSA withdrawn until the flow was below 40 m^3 s^{-1}. Although on some occasions the flow appeared well above 40 m^3 s^{-1} when the SSA was issued, this is likely to be caused by the lack of detail of exactly when during the day the warning was issued.

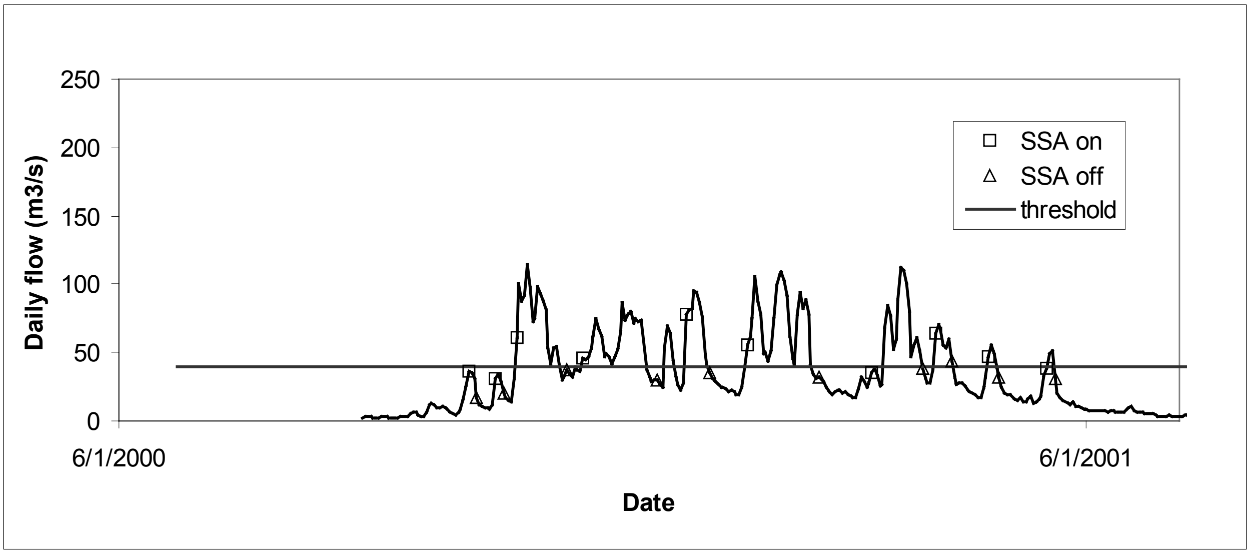


Figure 3.8: SSA threshold with daily flows – R Bedford Ouse at Offord 2000-2001

The SSA and flow data generally supported the threshold of 40 m^3 s^{-1}, as reported by the Environment Agency, for issuing an SSA for the Bedford Ouse. The variability around this flow demonstrated in the figures was similar to that for the River Nene. It may be caused partly by the lack of knowledge of exactly when during the day the warning was issued, and partly by simple practicalities of issuing warnings, uncertainty as to whether the flow would continue to rise, and availability of duty officers or lock staff to make final decisions.

The withdrawal of the SSA occurred at a slightly lower flow than for the issue, as it did for the Nene, presumably for similar reasons. The average daily flow for the issue of the warnings was 45 m^3 s^{-1} and for the removal, 30 m^3 s^{-1}. Again, we selected the threshold based on observation of the hydrograph as much as the mean flows.

The SSA threshold of 40 m^3 s^{-1} has a daily probability of exceedance of eight per cent.

3.4.3 River Thames at Eynsham

The River Thames at Eynsham, upstream of Oxford, has a catchment area similar in size to the River Nene at Wansford. Using daily flow was feasible, but shorter time periods might be necessary to refine the estimate of a suitable flow threshold. Therefore, initially daily flows were used to try to establish a flow threshold for the issuing of SSAs.

As mentioned earlier, on the River Thames yellow boards and red boards are issued as part of the SSA warring. Initially, only the red board data were used in the analysis. SSA data available for the Thames at Eynsham started in 1990 and ended in December 2004. The duration of SSAs per month for the period from 1999 is shown in Table 3.5. The data showed a similar concentration of SSAs in the winter as for the Nene, and a mean duration of SSAs of 8.4 days, very similar to the Bedford Ouse. There were essentially no SSAs in the summer months during this period or indeed during the period from 1990.

Table 3.5: SSA days per month - River Thames at Eynsham 1999-2004

Month	No days SSA/mth (red)							
	1999	2000	2001	2002	2003	2004	mean	mean when>0
1	31	30	19	0	30	8	19.7	23.6
2	5	0	0	0	2	0	1.2	3.5
3	3	0	13	4	0	0	3.3	6.7
4	0	29	21	0	0	0	8.3	25.0
5	0	5	0	0	0	0	0.8	5.0
6	0	0	0	0	0	0	0.0	0.0
7	0	0	0	0	0	0	0.0	0.0
8	0	0	0	0	0	0	0.0	0.0
9	0	0	0	0	0	0	0.0	0.0
10	0	1	0	0	0	8	1.5	4.5
11	0	30	0	0	0	1	5.2	15.5
12	10	31	0	10	0	0	8.5	17.0
total/mean	49	126	53	14	32	17	4.0	8.4

SSA data for the period from 1990 were plotted on the daily flow hydrograph shown in Figure 3.9. Again, the issue of an SSA is shown with a square and the removal with a triangle. Not all the data show a removal of an SSA to the corresponding issue, because the data are not complete. A threshold flow of 35 $m^3 s^{-1}$ is shown in the figure, which appears to be a reasonable value with similar variability around the threshold as for the rivers Nene and Bedford Ouse.

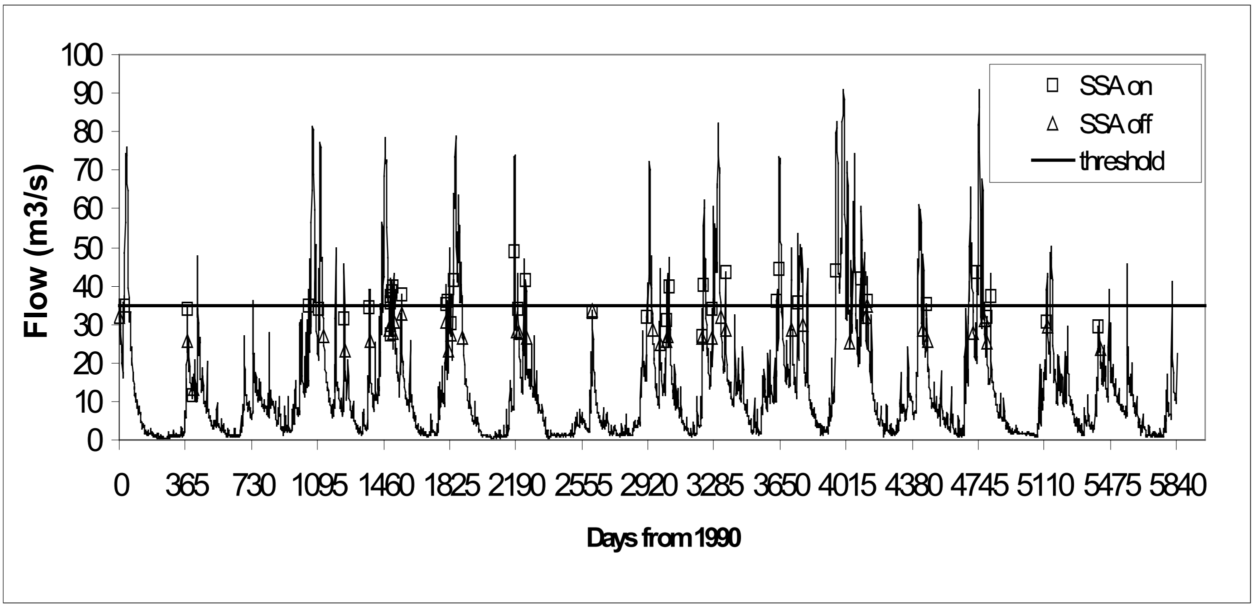


Figure 3.9: SSA threshold with daily flows, Thames at Eynsham, 1990-2005

To inspect the threshold further, the period from October 1992 to June 1995 was plotted in Figure 3.10. This showed that SSAs were issued close to this threshold flow of 35 $m^3 s^{-1}$. There was only one major event above this flow where an SSA did not appear to have been issued – the event in the middle of the figure around day 1450 (Dec 1993). There is a record of a red board SSA being withdrawn at the end of this event (29 Jan 1994) but no record of one being issued – clearly an omission in the data. There is a record of a “BDB” being issued about this time (which could perhaps be shorthand for a “red board”). It was issued when the daily flow was 41 $m^3 s^{-1}$ and 27 $m^3 s^{-1}$ the day before – consistent with a threshold of 35 $m^3 s^{-1}$.

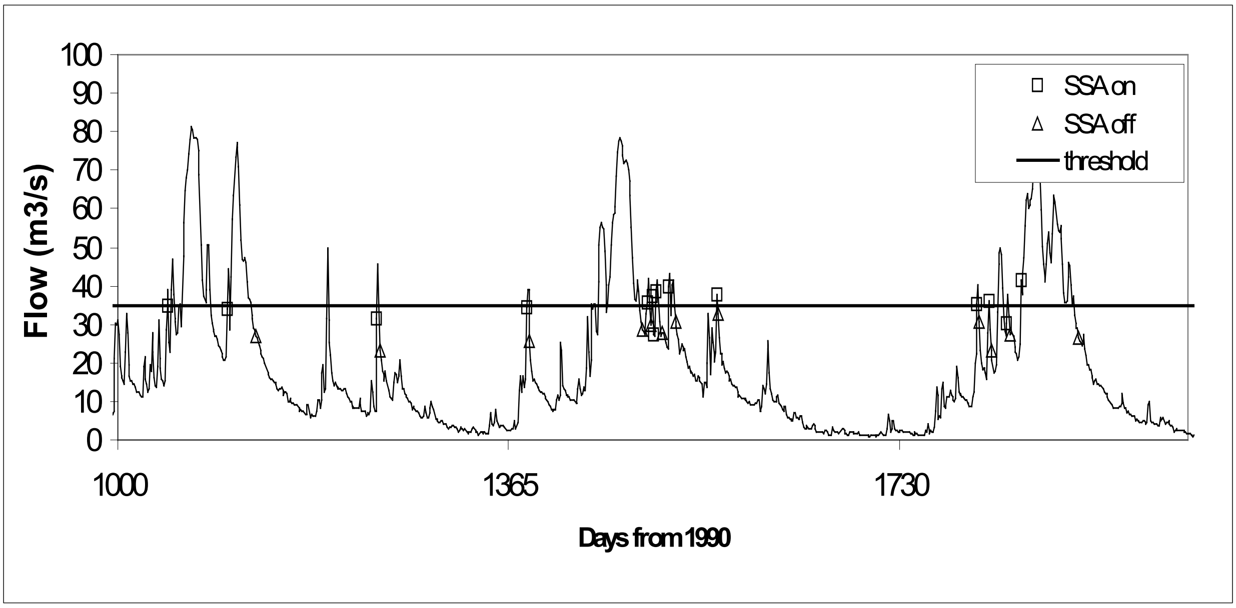


Figure 3.10: SSA threshold with daily flows, Thames at Eynsham Oct 1992-June 1995

For these data, the time of issue was recorded and so the flow threshold could be looked at further. A subset of the data was considered for this purpose from 1999 through 2004. Most warnings were issued in working hours, as expected. The average of the 15-minute flows at the time the SSAs were issued was 36.6 $m^3 s^{-1}$ and ranged from 29.6 to 42.7 $m^3 s^{-1}$. For the withdrawal of SSAs, the average 15-minute flow was lower, 28.9 $m^3 s^{-1,}$ with a range from 25.3 to 34.7 $m^3 s^{-1}$. These data confirmed that the threshold chosen from the daily analysis was very similar to one obtained with more detailed information, giving more confidence to the thresholds chosen so far.

The withdrawal of the SSA occurred at a slightly lower flow than for the issue, as it did for the Nene, presumably for similar reasons. The average daily flow for the issue of the warnings was 35.7 $m^3 s^{-1}$ and for the removal 27.8 $m^3 s^{-1}$.

The SSA issue threshold of 35 $m^3 s^{-1}$ has a probability of exceedance of eight per cent.

3.5 River Thames at Kingston

The River Thames at Kingston has a catchment area of almost 10,000 km^2 and is almost four times the size of the Bedford Ouse, the largest of the catchments considered so far. As we managed to use daily data to set the threshold for the Bedford Ouse, daily data was deemed to be adequate for the Thames at Kingston.

SSA data available for the Thames at Kingston (Teddington Weir) have been recorded for many years. We transcribed the data from 1975, but to ensure that the criteria for issuing the SSAs was consistent, only the more recent years 1990-2004 were used to establish an SSA threshold.

The duration of SSAs per month for the period from 1999 is shown in Table 3.6. The data showed a similar concentration of SSAs in the winter as upstream at Eynsham, and a mean duration of SSAs of eight days, very similar to Eynsham and the Bedford Ouse. There were essentially no SSAs in the summer months during this period or indeed during the period from 1975.

Table 3.6: SSA days per month - River Thames at Kingston 1999-2004

Month	No days SSA/mth							mean when >0
	1999	2000	2001	2002	2003	2004	mean	
1	29	7	25	5	30	8	17.3	17.3
2	2	1	23	11	4	0	6.8	8.2
3	2	5	24	5	3	0	6.5	7.8
4	0	23	14	0	0	0	6.2	18.5
5	0	0	0	0	0	0	0.0	0.0
6	0	0	0	0	0	0	0.0	0.0
7	0	0	0	0	0	0	0.0	0.0
8	0	0	0	0	0	0	0.0	0.0
9	0	0	0	0	0	0	0.0	0.0
10	0	6	0	0	0	0	1.0	6.0
11	0	30	0	0	0	0	5.0	30.0
12	9	31	0	10	0	0	8.3	8.3
total/mean	42	103	86	31	37	8	4.3	8.0

SSA data for the period from 1995 to 2004 were plotted on the daily flow hydrograph shown in Figure 3.11. Again, the issue of an SSA is shown with a square and the removal with a triangle. Not all the data show a removal of an SSA to the corresponding issue, because the data are not complete. A threshold flow of 175 $m^3 s^{-1}$ is shown in the figure, which appears to be a reasonable value with similar variability around the threshold as for the rivers Thames at Eynsham, Nene and Bedford Ouse.

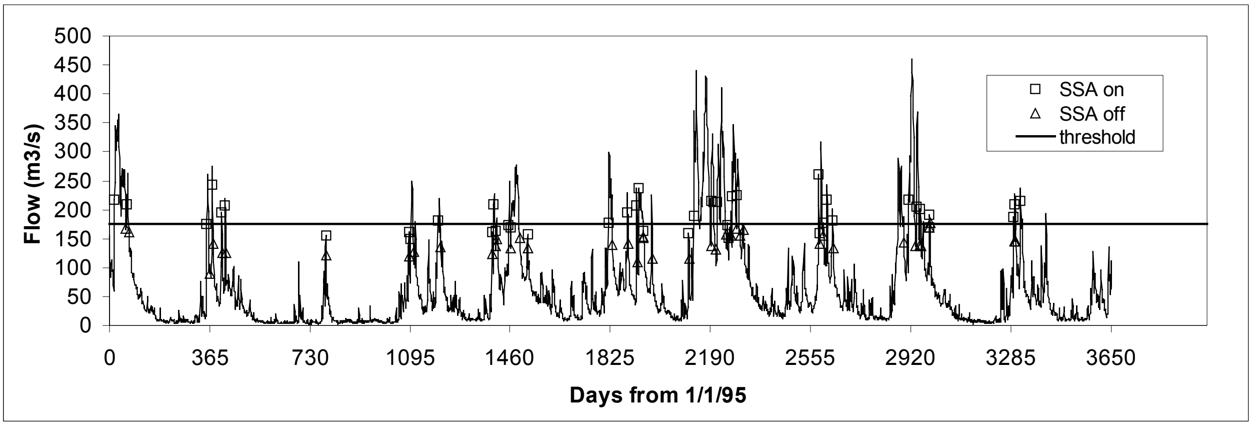


Figure 3.11: SSA threshold with daily flows – River Thames at Kingston 1995-2004

To inspect the threshold further, the period from June 2000 to March 2003 was plotted in Figure 3.12. This shows the SSAs were issued close to this threshold flow. There was only one major event above this flow where an SSA did not appear to have been issued: that is the event towards the right of the figure around day 2880 (November 2002). There is a record of a red board SSA being withdrawn at the end of this event (4 Dec 2002) but no record of one being issued – clearly an omission in the data.

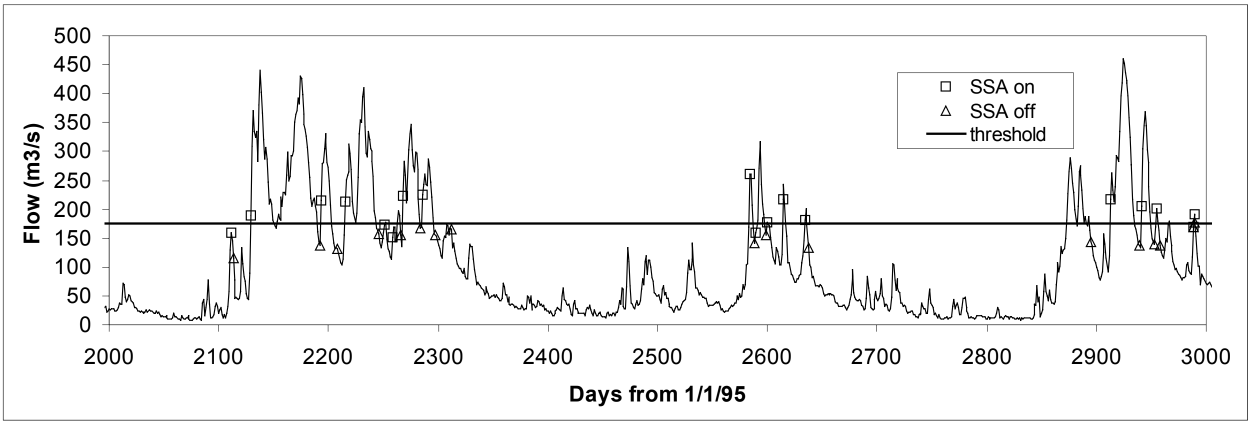


Figure 3.12: SSA threshold with daily flows, Thames at Kingston, June 2000 to March 2003

Data recording the time that the SSAs were issued were available. However, given that analysis of the Eynsham data confirmed that daily analysis was sufficient, these 15-minute flow data were not analysed.

The withdrawal of the SSA occurred at a slightly lower flow than for the issue, as it did for all other rivers. The average daily flow for the issue of the warnings was 192 $m^3 s^{-1}$ and for the removal, 141 $m^3 s^{-1}$. The chosen threshold was a little lower than the average, but was thought to be closer to the intended threshold; the higher actual flow is likely a reflection of delays in the issuing of the SSA.

The SSA issue threshold of 175 $m^3 s^{-1}$ has a probability of exceedance of eight per cent based on the observed flow duration curve. The threshold for withdrawal appears to be 145 $m^3 s^{-1}$.

3.6 Probability of exceedance of thresholds

For the assessment of the impacts of climate change on navigation, it was important to estimate how often SSAs are currently issued.

We had data on SSAs issued for the three rivers and four locations for various periods, but for two locations for periods of less than 10 years. This meant that simply estimating the frequency of SSAs within these periods was likely to be misleading, because of the sampling error associated with such short records. A better approach would be to use the flow thresholds estimated so far and determine their probability of exceedance from flow duration curves (FDC). FDC use daily flow data from much longer periods, in the case of Kingston up to 120 years.

FDCs are routinely determined for all gauges within the National River Flow Archive (Centre for Ecology and Hydrology, Wallingford), as they contain important information for uses of the data. For our purpose, we needed the best estimate of the exceedance probability for each river and in principle, the longest homogenous record available was necessary for this.

Flow thresholds and the probability of exceedance of the flow for the issuing of an SSA are shown in Table 3.7.

Table 3.7: Probability of exceedance of SSA issue threshold

River	Location	SSA issue m3/s	SSA withdrawal	Prob of exceedance of issue
Nene	Wansford	15	12	16
Bedford Ouse	Offord	40	30	8
Thames	Eynsham	35	28	8
Thames	Kingston	175	145	8

Estimates were based on published FDCs for the Thames at Eynsham and Kingston and Bedford Ouse at Offord (National Water Archive). An example is shown in Figure 3.13 for the observed flows at Kingston on the River Thames.

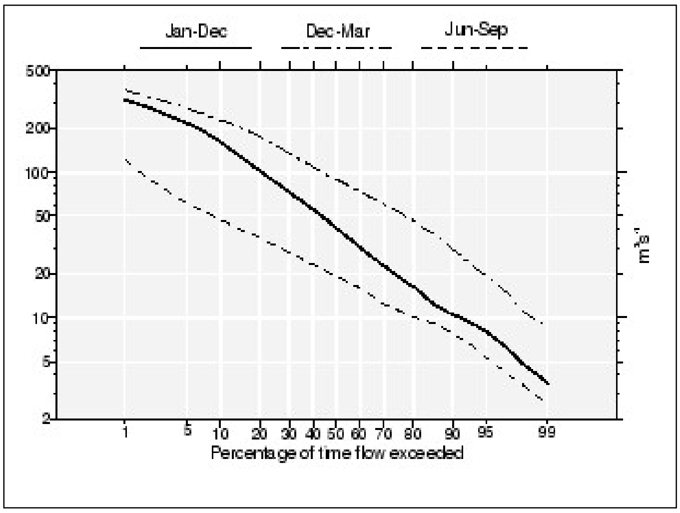


Figure 3.13: Daily flow duration curve of River Thames at Kingston from National Water Archive

Flows in the River Thames are significantly affected by artificial influences, such as abstractions and effluent returns, especially at low flows. In general, it is important to distinguish between observed and naturalised flows for an FDC for this river, as they can be quite different. Naturalised flows are an attempt to reconstruct the river flow as it would have been without these artificial influences; they are routinely estimated for the Thames at both Kingston and Eynsham. The impact of naturalising flows at the higher flows we considered is likely to be small.

For the River Nene at Wansford, daily flow data were only available from 1997. Using these data gave a probability of exceedance of 16 per cent for the flow threshold of 15 m^3 s^{-1}. There were much longer flow records available for Orton on the Nene for the years before 1997 (Wansford largely replaced the gauge at Orton). The FDC is published for Orton and if the threshold is scaled according to their respective catchment areas (1,634 to 1,530 km^2 for Orton and Wansford respectively), the probability of exceedance from the Orton FDC gives a slightly lower exceedance probability of 16 per cent. It is this value that has been used.

3.6.1 Summary

Initially, we stated that high flows restrict navigation in two ways, either through the frequency of restrictions, especially in summer, or the duration of the SSA.

The analyses carried out here cover both, in part, where frequency and duration are covered by the percentage of time that flow thresholds are exceeded. For example, for the Nene at Wansford the SSA threshold when the warning is issued is exceeded 16 per cent of the time. Hence, restrictions will occur for 16 per cent of the time.

The chosen thresholds capture most of the days when SSAs were recorded as being in force. For the Nene, 79 per cent of occurrences are captured, while the corresponding capture rate for the Great Ouse is 84 per cent. For the Thames, the capture rates are 91 per cent at Kingston and 100 per cent at Eynsham. These statistics are for the period from 1999 to the present (slightly different times for each river, but generally a period of 2,000 to 2,500 days) and assume that, given a threshold flow for issuing an SSA, the SSA is then withdrawn when the flow subsequently drops back below that threshold. In practice, there tends to be a small lag between flows on the recession limb of the hydrograph crossing below the threshold flow and the withdrawal of the SSA; this accounts for some of the SSA days not captured by the chosen thresholds.

It is only for the Thames at Eynsham that more SSA days are predicted by the threshold than were recorded. Some SSA days predicted by the threshold are not recorded in the data, that is, they appear to be false positives. There are 12, 28, 28 and 89 false positive days for the Nene, Ouse, Thames at Kingston and Eynsham, respectively. These false positive days may reflect some inconsistency in the records of when SSAs were in force, especially for longer periods when the flow was above the threshold but no SSA was recorded. But it seems possible that some short periods of a few days were recorded correctly, when the Environment Agency may have decided not to issue the SSA based on a prediction that a peak in flow would be of short duration.

The analyses carried out here do not consider how long on average each restriction will last, nor whether the restrictions will occur every year. The data records are too short for a meaningful analysis of the durations of individual SSA restrictions, although from the data it is clear that restrictions do not occur every year and the durations of SSA vary from a day or two to several months.

It is also clear for all rivers that SSAs do not generally occur in the summer months (June to August), an encouraging result for much river navigation. But there are navigation users in winter and hence SSA restrictions will cause difficulties.

3.7 Climate change projections

3.7.1 Approach

We found that a suitable indicator for climate change impacts on the frequency of SSAs was a threshold flow that would, in general, correspond to a point on the flow duration curve. This followed from the observation that SSAs tend to be in force for several or tens of days every year (at least, on the rivers for which records have been kept).

To examine the projected impact of climate change on the occurrence of SSAs, we required information describing changes in the flow duration curve for future time slices. The flow duration curve may change in a non-linear way, depending on the interactions over time of changes in rainfall and evaporation as determined by a downscaled climate model. Hydrological modelling is necessary to simulate the net effect of these changes on the flow regime.

Climate change impacts on river flows have been modelled for high flows for the Thames at Kingston as part of previous research funded by the Defra/Environment Agency joint *Flood and coastal erosion risk management* (FCERM) programme. The work was undertaken by CEH Wallingford and reported in detail in Reynard *et al.* (2004). For this project, resources did not allow for new modelling of climate impacts. We therefore obtained results from the CEH Wallingford simulations for re-analysis.

The original impacts simulations were analysed by CEH Wallingford to look at projected changes in extreme high flows, that is, flows in the tail of the probability distribution. The analysis therefore used standard flood frequency techniques to assess the probability or return period of events that occur, on average, much less often than once per year (in fact, the greatest attention was given to a flood that would occur on average only once in a 100-year period).

In this study, the event in question (the occurrence of an SSA) would be much more frequent and it was thus appropriate to use daily mean flows rather than flows on the annual maximum scale. In other words, we needed to know the frequency (or probability) of days when the flow would exceed a given threshold, which is usually represented in hydrology by the flow duration curve (FDC). The FDC should be distinguished from the flood frequency curve, which represents the frequency (probability) of an event in which the flow exceeds a given (high) value. For annual maximum data, this event is more strictly a year containing such an exceedance.

3.7.2 Results

For this study, the same continuous flow simulations (Reynard *et al.*, 2004) were re-processed to provide flow duration curves, shown in **Figure 3.14**.

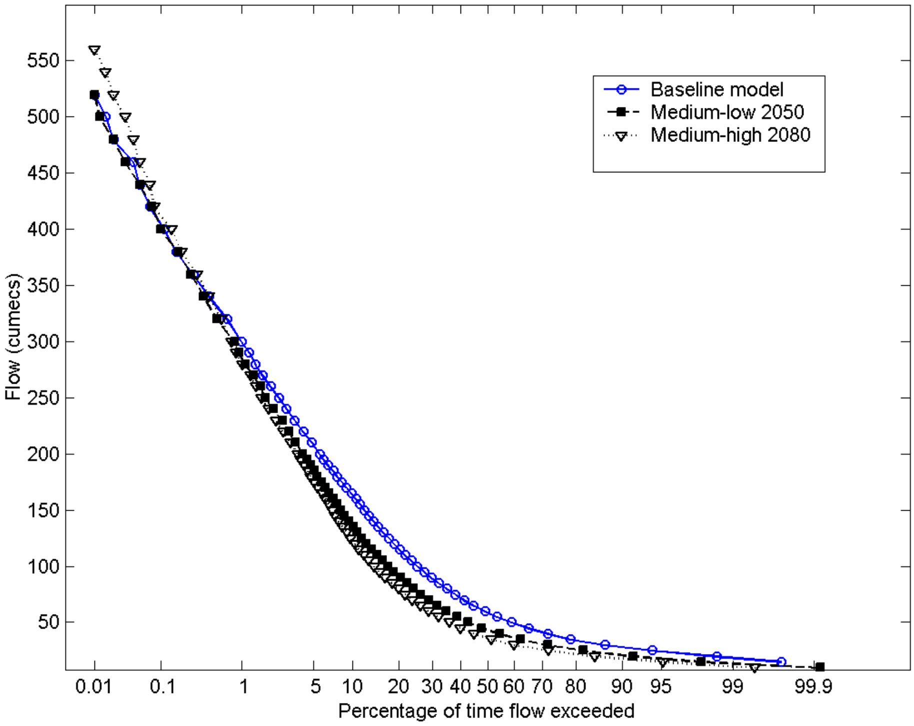


Figure 3.14: Flow duration curves for baseline (1961-90) and future decadal river flow simulations for the Thames at Kingston.

The simulations were driven by UKCIP-02 scenarios. CEH Wallingford provided data for the decades starting in 2020, 2050 and 2080. The UKCIP-02 emissions scenarios used were medium-low and medium-high. The projections were compared with a baseline simulation for 1961-1990. We plotted only the 2050 medium-low and 2080 medium-high data to illustrate the range of projected impacts.

It has been reported elsewhere (CEH Wallingford, 2001; Defra, 2003) that the UKCIP-02 scenarios can lead to an increase in the magnitude of peak flows on the annual maximum scale, although the type of impact depends on how spatial and temporal downscaling are applied. In other words, simulations show that the climate change scenarios lead to more intense, frequent flood flow events. The higher emissions scenarios lead to a greater impact, and impacts increase with time into the future. The same projections are reflected here, in that by the 2080s, flows in the upper tail of the FDC are modelled as increasing relative to 1961-90 under the medium-high scenario.

However, the flow duration curves also show a projected decrease in daily mean flows for both illustrated scenarios and time slices over most of the flow regime. The indicator flow for triggering SSAs at Kingston is 175 $m^3 s^{-1}$ (the 8th percentile of the FDC). For the 2050s, this indicator flow becomes approximately the 6th percentile on the FDC, and by the 2080s it becomes approximately the 5th percentile point. The differences between impacts for the medium-low and medium-high emissions scenarios are less than one percentage point on the FDC.

To summarise, SSAs, currently in force for about eight per cent of days on average, are projected to occur on only six per cent of days by the 2050s, with a further reduction to five per cent of days by the 2080s. These percentage values translate to approximately 29 days per year for the baseline period, 22 days per year for the 2050s and 18 days per year for the 2080s. It is, however, possible that these changes may be within the range of variability in baseline conditions or uncertainty in modelling.

3.7.3 Seasonality

One important aspect that cannot be examined with these simulation results is the possibility that climate change may affect the seasonality of SSAs, which would be significant for navigation and recreation.

Climate change scenario predictions for the UK often tend to indicate increased storminess, particularly over summer periods, driven by higher temperatures and therefore increased convective thunderstorm activity. Should this occur, then there may be implications in that summer is the period of peak recreational use of rivers, and also the period when the least experienced boaters are more likely to be on the river.

However, in a large catchment, the impact of short convective storms on flows is likely to be less severe than on a small river. If conditions are generally drier, summer base flows can be expected to become lower, as indicated both in the model results here and in the separate analysis of low flow conditions in the following section of this report. Furthermore, active management of weir structures, as on the Thames, may be able to modulate storm pulses. It is therefore speculative to suggest that summer storms will become a problem for navigation and recreation.

4 Navigation restrictions at low flows

4.1 Introduction

Low flow restrictions on navigation may occur for two reasons. Firstly, there may be insufficient depth of water to allow boat passage or access to the river at very low flows, and hence the risk of boats grounding. Secondly, the opening of lock gates could be reduced or stopped during drought conditions so as to help reduce drainage and maintain water in the river channel.

The history of restricting navigation at low flows is very limited, indeed so rare that there is not a widely recognised name for 'low flow warnings', comparable to the high flow SSA. According to a recently produced drought plan for the Thames, if the draft is inadequate for river navigation "it would be necessary to restrict the navigation via a Harbour Masters notice to mariners that would state revised drafts". The criteria for restricting navigation on the Thames are covered in the drought plan.

As with SSAs, the frequency of these restrictions and their duration are of concern to boat users. The restrictions would occur in the summer when the impact on boat use would be greatest and it is likely that the duration in a significant drought year would be quite long, perhaps months rather than days.

Boat users would be restricted when the depth in a river stretch was too shallow for the boats to navigate. However, as with SSAs, depth is closely related to flow rate at these locations and hence relating the low flow warning to flow would be the best way to relate to climate change. As flow does not change rapidly in drought years, except possibly from artificial influences, daily flow would be adequate for analysis.

4.2 Historical records of flow restrictions

Of the three rivers we studied for SSAs, only the River Thames had any record of low flow restrictions for navigation. According to navigation officers with the Environment Agency's Thames region, the only restrictions known in the last 40 years or so were in 1976. This information was supported by anecdotal evidence from a lock keeper of 33 years experience at Pinkton Lock on the Thames. There were no written reports available from the Environment Agency.

With the limited availability of historic data, other sources of information on this topic were sought. The drought plan for the Thames region (Environment Agency, 2005) outlines the actions to be taken by waterways staff operating across the Thames region in the event of a low flow situation. The plan, which was produced in response to the 2005 drought, lists a number of trigger points for a variety of actions and describes the minimum water levels that the Environment Agency is required to maintain at lock locations within the river. It reports the draft available to boat users at these locks when minimum water levels are in effect and translates these into consequences of further reductions on water level at critical locations.

The plan lists water supply abstractions which may have a major impact on the flow and levels in drought conditions. It also outlines the Environment Agency's responsibility to achieve a balance between maintaining water levels for navigation, public water supply and flows to support the ecology of the river during prolonged periods of drought. The plan describes some of the actions that the Environment Agency should take in a prolonged drought to meet its responsibilities. Examples of drought plan actions are shown in **Table 4.1**.

Table 4.1: Examples of actions from the River Thames drought plan for navigation in or around the Eyhsnam Lock

Triggers	Actions around the Eynsham lock
Lower Thames Operating Strategy triggers 600 MLD Kingston flow level.	Survey and carry out repairs to any large leaks at lock gates and weir sluices.
Lower Thames Operating Strategy triggers 400 MLD Kingston flow level.	Voluntary delays to lock passage of 15 minutes where locks are not full and few boats are waiting to pass in opposite direction.
Application for a drought permit lock group area.	Group Ten weirs to be staunched as appropriate from Osney upstream. Close Godstow , Pinkhill, and Northmoor fish passes.
Enactment of a drought permit lock group area.	Lock cycles restricted to once every half hour and locks closed out of hours. Harbour Masters notice issued and Nav line updated.

Unfortunately, the plan relates these actions and their associated triggers to water levels rather than flows. Furthermore, the translation from water levels to river flows is not simple and would require detailed hydraulic modelling at specific locks. This is largely due to the control of water levels through gate settings of structures adjacent to locks and the artificial influences of major water supply abstractions which may vary according to flow. The hydraulic modelling required is beyond the scope of this research project.

In summary, there is only a single record of navigation restrictions due to drought, and this occurred on the Thames in 1976. Whilst there are set water levels at many locations on the Thames below which navigation will be restricted, there is no simple way of relating these to flow rates. In any case, it is clear that restrictions at low flows have been quite rare, but that rarity cannot be determined without further analysis.

This study therefore proposed to use historic flow data at two locations on the Thames, Eynsham and Kingston, in conjunction with low flow frequency analysis techniques to investigate the occurrence of low flow events on the River Thames and, in particular, estimate the recurrence probability of the 1976 drought event.

4.3 Thames flow data

4.3.1 Gauged daily flow series

Daily river flow data were available on the Thames at Kingston for just over 120 years (from 1883 to 2004), the longest record in the UK. Additional daily flow data from 1 January 2005 to 13 July 2006 were obtained directly from the Environment Agency. The record was a composite based on a number of gauging methods applied, as shown in **Table 4.2**.

The early part of the record (pre-1974) is based on the weir and locks at Teddington, which is a 70 m complex of gates, sluices, weirs and locks. The record is subject to a number of uncertainties, including underestimation at low flows due to leaks and loss of water when locking, particularly prior to the major refurbishment in 1951. A single-path ultrasonic was installed at Kingston in 1974, followed by a multi-path ultrasonic in 1986, which is thought to provide high quality flow measurements. The 1951-1986 flows have recently been reworked based on data from the single-path ultrasonic coupled with a current meter calibration on downstream water levels at Teddington Weir. Further detail is given by the NRFA website (www.nwl.ac.uk/nrfa).

Table 4.2: Gauging methods applied to derive daily mean flows for the Thames at Kingston

Date range	Gauging method	Data quality/sources of uncertainty/notes
1986 -present	Mulit-path ultrasonic at Kingston	Provides high quality flow measurement across the full range of flows.
1974-1986	Single-path ultrasonic at Kingston	Note 1951-1986 data recently reworked.
1951-1974	Derived from Teddington Weir, with tailwater rating	Major refurbishment of Teddington Weir in 1951, leading to improved accuracy. Daily flows only. Note 1951-1986 data recently reworked.
1883-1951	Derived from Teddington Weir	Poor accuracy, substantial underestimation of low flows. Daily flows only.

4.3.2 Naturalised daily flow series

To understand the impact of climate change on low flow extremes, it is important to remove the impacts of changes in water management of the river and so naturalised flows are preferable.

A daily series of naturalised flows from 1 January 1883 to 31 December 2004 was provided to us for the purposes of the study. Naturalisation was carried out to adjust the gauged flow record to account for river regulation, public water supply abstraction, effluent returns and industrial and agricultural abstraction. The greatest uncertainty in naturalised flow data was at the lowest flows.

4.3.3 Annual minimum series from gauged and naturalised time series

Gauged daily flow series

D-day duration annual minima (calendar years) were derived from the gauged time series. As shown in **Figure 4.1**, the most severe low flow in the post-1951 period occurred during 1976, although the years of 1989/90 and 1995/96 also recorded low flow periods. In the earlier part of the record, there were very low flows in the Thames during 1921, 1934, 1944 and 1949. Due to the uncertainties associated with this early record, it is perhaps unwise to compare the severity of the events in absolute terms.

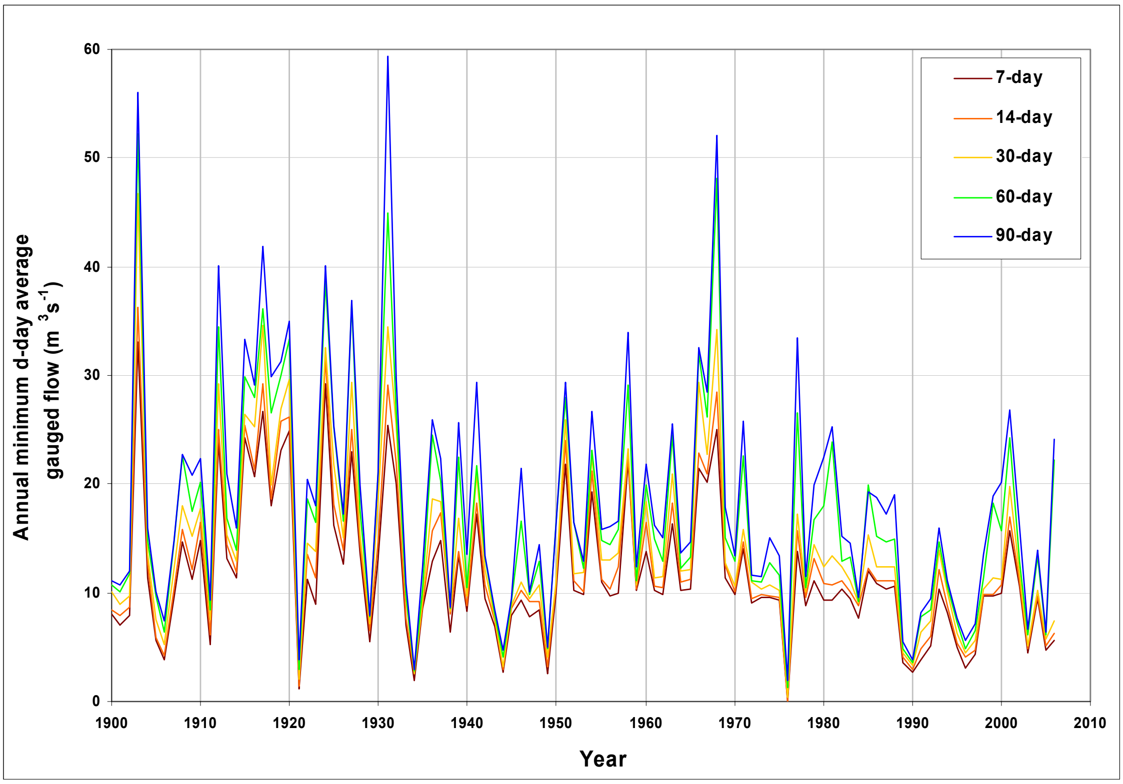


Figure 4.1: Variation in annual minimum flows derived from gauged data for the Thames at Kingston

The timing of low flow events, based on the derived annual minima, shows that the predominant low flow period is July to September. On some occasions, the low flow event has carried on through the autumn and into January or February of the following calendar year. All derived annual minima were checked to ensure that the summer minima rather than any carry-over events were captured as the annual minima (adjustments had to be made for 1922 and 1997). An alternative approach would be to use a hydrological year starting on 1st March. Note also that in the driest years, there is less variation in the minima across different durations than in other years.

A brief review of trends in the annual minimum series where D = 30 was carried out by considering the mean annual minima achieved over consecutive overlapping 40-year periods within the record (1883-1922, 1884-1923, …, 1966-2005, 1967-2006). The sample length of 40 years was chosen for consistency with later frequency analysis. These were compared against the long-term average AMIN30 value (14.26 m^3 s^{-1}) in **Figure 4.2**, which illustrates a trend towards lower flows in recent years. The values shown are serially correlated, as each shares 39 years with its neighbour.

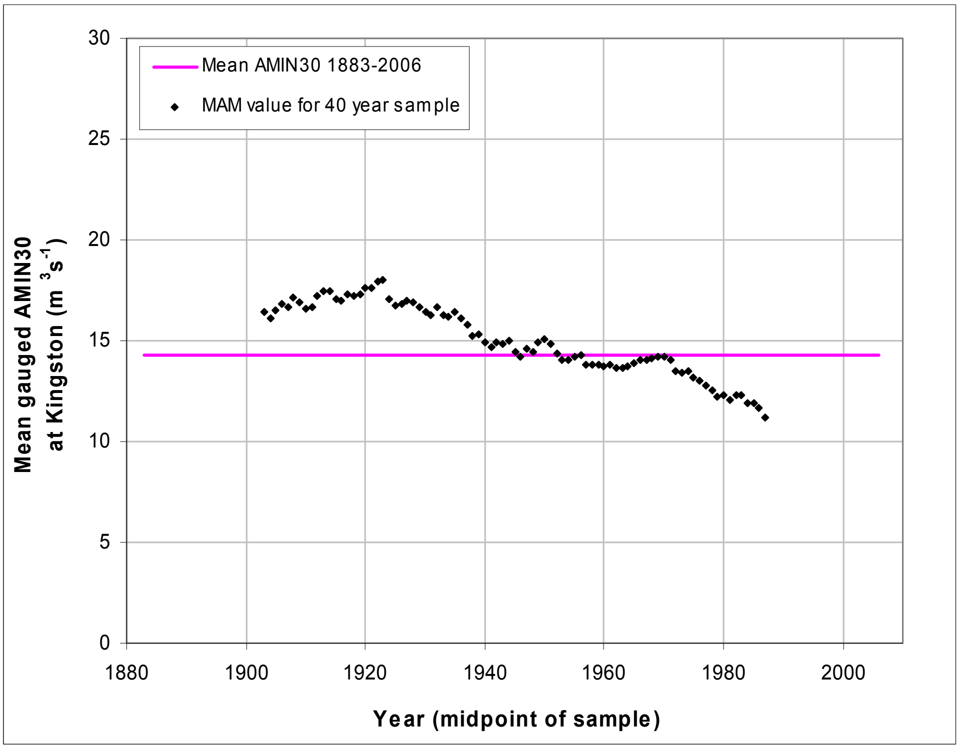


Figure 4.2: Variation in mean annual minimum for running 40-year blocks derived from gauged data for the Thames at Kingston

Naturalised daily flow series
D-day duration annual minima (calendar years) were also derived from the naturalised time series using the same methods as for the gauged data. Here a different pattern emerged, with post-1951 minima generally higher than those earlier in the century, with the exception of the 1976 event, as illustrated in **Figure 4.3**.

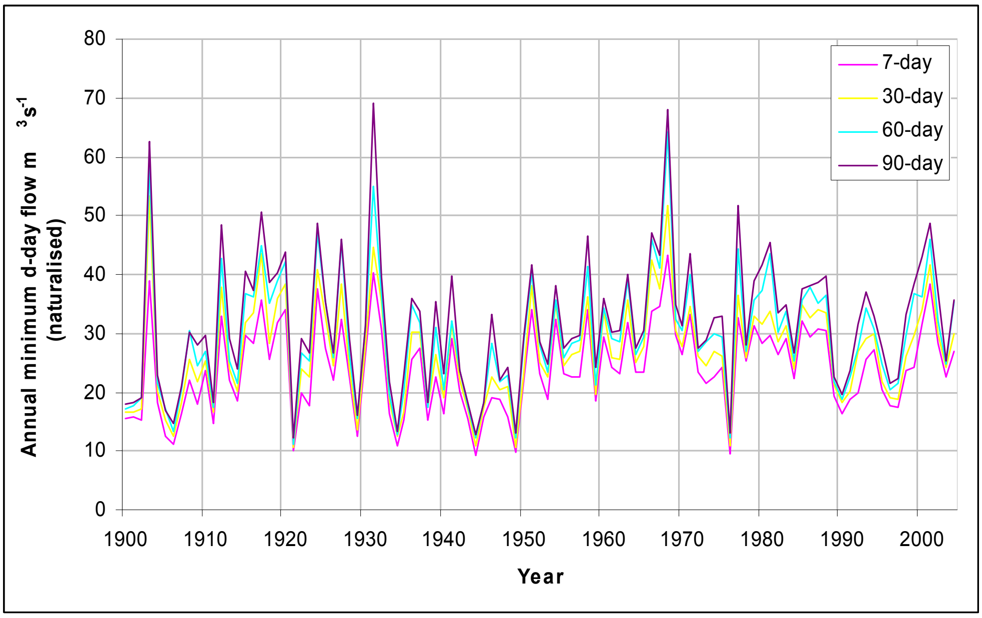


Figure 4.3: Variation in annual minimum flows derived from naturalised data for the Thames at Kingston

A brief review of trends in the naturalised annual minimum series was carried out using the same approach as for the gauged data. Mean annual minimum (MAM) values were calculated based on a 40-year running average derived from the 1883-2004 AMIN30 series. These were compared against the long-term average AMIN30 value (26.01 $m^3 s^{-1}$) in **Figure 4.4** which, in contrast to the gauged case, illustrates a trend towards higher minimum flows in recent years.

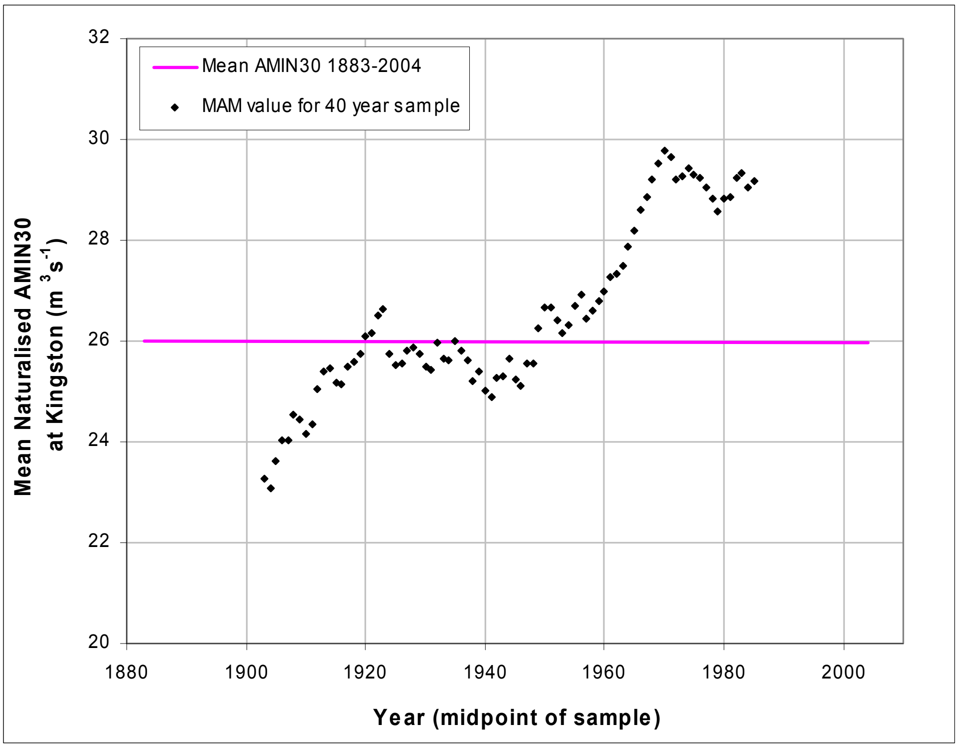


Figure 4.4: Variation in mean annual minimum for running 40-year blocks derived from naturalised data for the Thames at Kingston

4.3.4 Comparison of gauged and naturalised annual minima

The adjustments applied by the Environment Agency to account for artificial influences on the gauged flow record for Kingston are complex and depend on a number of factors. As a result, there is greatest uncertainty in the naturalised flow series during periods of low flow. At mean daily flow, the ratio of naturalised to gauged flow is 1.2 (about 20 per cent of the natural flow is lost through abstractions and so on). However, as lower flows are considered the amount lost becomes proportionally larger. During low flow periods, the residual flow may be as little as 30 per cent of the natural flow. The differences between gauged and naturalised flows are discussed later in the context of the 1976 drought.

Table 4.3: Comparison of gauged and naturalised annual minima for Kingston

Flow index ($m^3 s^{-1}$)	Gauging series	Naturalised series
Minimum daily flow	0.01	7.37
Maximum daily flow	800	806
Mean daily flow	65.83	78.43
Lowest AMIN30	0.41	10.50
Highest AMIN 30	46.68	53.27
MAM 30	14.46	26.01

4.4 Low flow frequency analysis

4.4.1 Exploratory analysis for the Thames at Kinston

For the frequency analysis of low flows, the duration to be analysed is important as it can change the results significantly. Typically durations of seven, 10, 30 and 90 days are used for this type of analysis. Perhaps the most appropriate duration for navigation restrictions is 10 to 30 days, as drought restrictions will generally last for much more than a day and may extend to a month or more. We chose the 30-day duration for further analysis as a typical duration for the more major disruptions to navigation.

The 30-day duration minimum flow for each year was identified from the naturalised daily series (the AMIN dataset), and these were ranked. The lowest 20 years are shown in **Table 4.4**.

Table 4.4: Minimum annual 30-day naturalised flows on River Thames at Kingston (1883-2004) and Eynsham (1865-2002)

	Kingston		Eynsham	
Rank	Year	naturalised	Year	reconstructed
1	1921	10.5	1911	0.053
2	1949	10.7	1870	0.074
3	1976	10.8	1874	0.403
4	1944	10.9	1955	0.56
5	1898	11.1	1976	0.586
6	1899	12.1	1893	0.654
7	1934	12.4	1906	0.848
8	1907	12.5	1940	0.903
9	1929	13.5	1921	1.051
10	1905	15.3	1964	1.196
11	1893	15.4	1990	1.2
12	1896	15.6	1996	1.283
13	1885	16.2	1995	1.289
14	1901	16.6	1984	1.33
15	1911	16.7	1896	1.347
16	1900	16.7	1989	1.36
17	1935	16.7	1868	1.403
18	1903	17.1	1934	1.457
19	1943	17.2	1898	1.484
20	1938	17.3	1949	1.484

Surprisingly, for Kingston only one of the most extreme 20 droughts has occurred in the last 50 years (in 1976). The flow on this occasion was only 10.8 $m^3 s^{-1}$. The next driest 30-day flow in recent years was in 1990 when the flow rate was 18.2 $m^3 s^{-1}$ (ranked 24th).

For Eynsham, the results are quite different. There are eight years in the last 50 in the top 20 droughts and the driest five years differ significantly to the Kingston data. The reason for these differences is not clear. The Eynsham data (Jones *et al.*, 2005) are reconstructed natural monthly flows generated with a regression model that uses rainfall and potential evaporation data to generate the flows. The catchment is also much smaller at Eynsham and hence may respond more quickly to shorter intense droughts. But whatever the reason, the distribution of droughts in the last 50 years appears more realistic than for Kingston.

There were no navigation restrictions in 1990 when the naturalised flow at Kingston was 18.2 $m^3 s^{-1}$, and there were restrictions in 1976 when the naturalised flow was 10.8 $m^3 s^{-1}$. Therefore, navigation restrictions will start between these two naturalised flows. It seems that in 1990 navigation restrictions were not anticipated, and they were severe in 1976 with attempts to back pump water to maintain water levels in some reaches of the Thames (for example, the reach between Pinkton and Eynsham lock). The threshold for navigation restrictions is likely to be significantly above the 1976 flow but significantly below the 1990 flow, perhaps around 12 to 15 $m^3 s^{-1}$.

To estimate the probability of occurrence of a 30-day (naturalised) flow in the range 12 to 15 $m^3 s^{-1}$, frequency analysis was performed on the naturalised AMIN(30) flow record from Kingston on the Thames. The results are shown graphically in **Figure 4.5**.

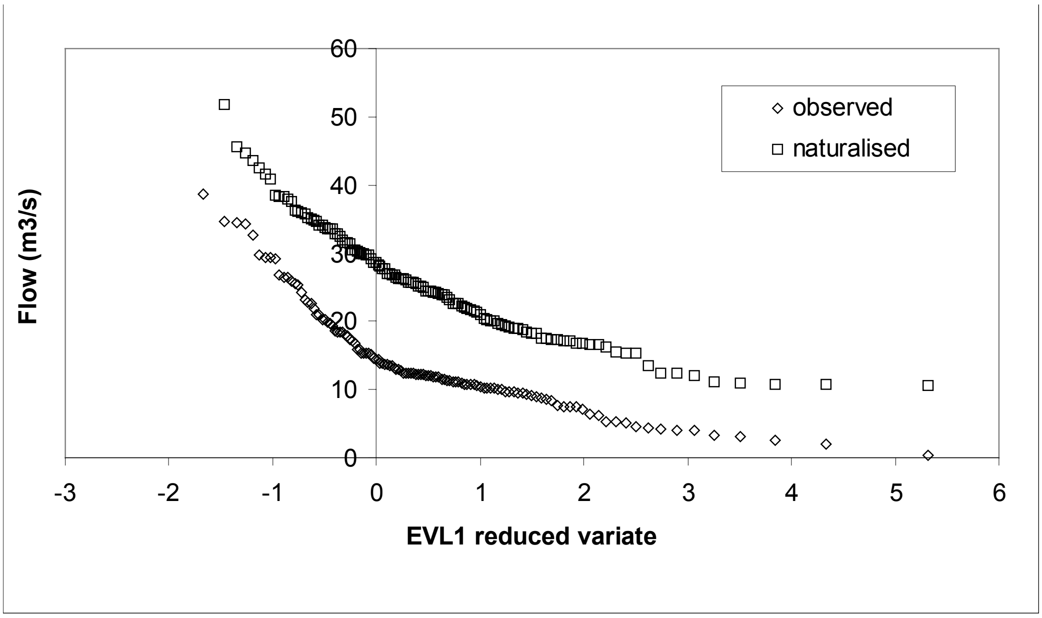


Figure 4.5: Low flow frequency analysis of 30-day annual minimum flows from Thames at Kingston 1883-2004 – observed and naturalised

The figure shows the annual minimum 30-day flow from each of the years from 1883 to 2004, plotted against the reduced variate for an EV1 distribution for least flows (the mirror image of the well known EV1 or Gumbel distribution for high flows). The reduced variate, y, is related directly to the return period of the flow, T, using the equation $y = -\ln(-\ln(1-1/T))$. Hence, a reduced variate of 1.5 equates to a five-year return period, a reduced variate of 2.97 to a 20-year return period and a reduced variate of 3.9 to a 50-year return period. Also shown for information are the annual minimum data of observed flow. It is clear that these are much lower than the naturalised flows, showing how much abstractions reduce the flow in the Thames in drought years.

The lowest naturalised flows in the last 120 years seem to asymptotically approach 10 $m^3 s^{-1}$. This suggests sufficient ground water storage in the catchment to maintain this flow even in quite severe droughts, to at least a return period of 250 years. Whether this storage can be drained so that the flow will rapidly decline in even drier years cannot be assessed from this analysis, and would require a detailed investigation of the hydrogeology of the catchment beyond the scope of this study.

The minimum flow from 1976 is the third lowest on the figure of naturalised flows (actually the lowest of observed flows) and the 1990 flow the 24th lowest – the reduced variate for 1976 is about 3.8 and for 1990 about 1.5. These reduced variates translate to return periods of 45 and five years respectively. Flows in the range of 12 $m^3 s^{-1}$ to 15 $m^3 s^{-1}$ have return periods of about 25 to 15 years respectively, based on this graphical analysis (a better estimate is made later).

It appears that navigation restrictions on the Thames due to low flows are likely to occur about every 20 years, based on this analysis of naturalised flows.

This result can also be assessed in the light of the long reconstructed flow record for Eynsham. As mentioned earlier, these data were generated from monthly rainfall and differ in some important respects from the Kingston data. However, they do offer another estimate of the likelihood of navigation restrictions and are thus worth analysing.

Plotting the data in the same way as for Kingston produces a graph that tends asymptotically to zero flows (see Figure 4.6). The return period of the 1976 drought from this graph is approximately 25 years and the 1990 drought, approximately 15 years. Although these estimates differ somewhat from the Kingston results, an event for which restrictions are expected to occur would lie somewhere between the 1976 and 1990 values, consistent with a return period of about 20 years.

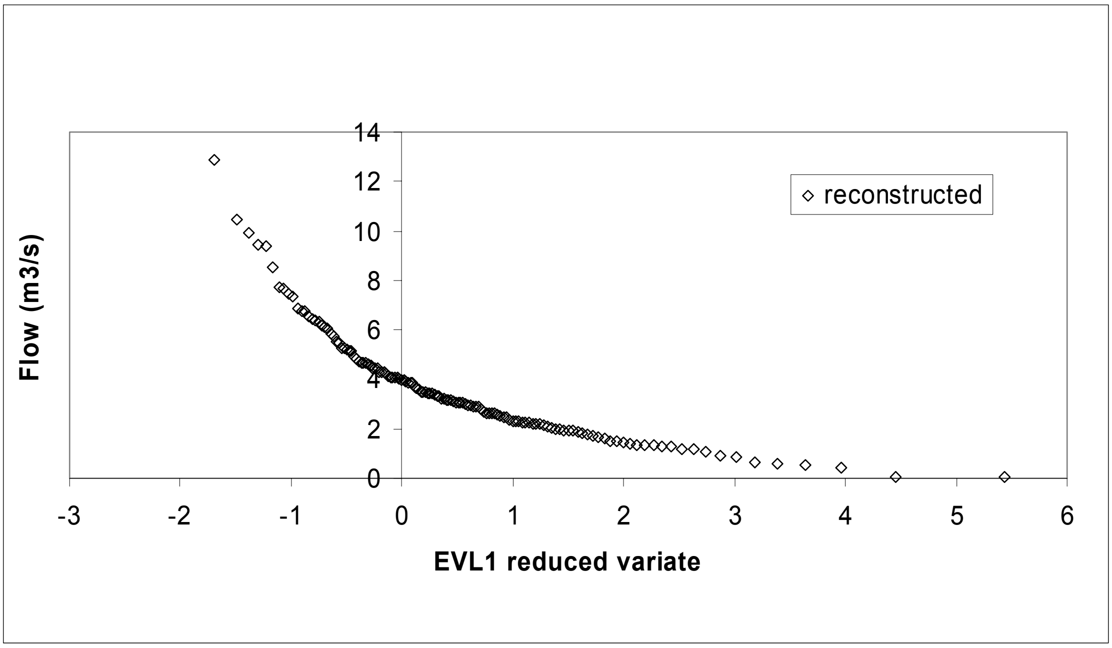


Figure 4.6: Low flow frequency analysis of monthly annual minimum flows from Thames at Eynsham 1865-2002 using reconstructed data of Jones *et al.* (2005).

This result assumes that artificial influences on the river will remain constant in the future. As there is a Lower Thames Operating Agreement for the Thames (under Section 20 of the Water Act), which controls abstractions from the Thames according to river flows, management in future droughts is likely to be relatively constant.

The frequency analysis using the EVL1 distribution and a graphical presentation is useful to show how natural flows in the Thames decline in drought years. It was accurate enough for us to identify a likely frequency of navigation restrictions. However, for the analysis of the impacts of climate change on the frequency of such restrictions, a less subjective fitting of a probability distribution was used.

This exploratory analysis to determine the frequency of drought restrictions used plotting position formulae to estimate exceedance probabilities for the AMIN data. However, plotting positions are not always suitable for small sample sizes. Instead, a statistical distribution can be fitted to the data to provide an estimate of the low flow frequency curve.

4.4.2 Statistical analysis, requirements and assumptions

A method for deriving low flow frequency curves from UK flow data is given by Zaidman *et al*. (2002). A similar method is described in Tallaksen and van Lanen (2004). The aim of the analysis is to determine the likelihood that the flow at a particular site will persist below a particular level, and this is achieved by fitting extreme distributions to the sample of annual minimum flows derived from the daily flow time series.

The requirements/assumptions of the method may be summarised as follows:

a) each annual minimum should typify the overall character of the low flow season in the stated year;
b) all the annual minima must originate from a single statistical population (with the same mechanism controls);
c) the sample data should be stationary, that is, there should be no significant trends over time;
d) the sample data should be independent, where the annual minima from one year should not influence the annual minima occurring in the next;
e) the sample size should be large (characterising a T-year event requires a minimum record length of T/2, but ideally a record length of 2T would be used).

Given earlier discussion, it is open to question whether assumptions (c) and (d) hold true. For (d), there was indeed a small year-to-year auto-correlation in the naturalised AMIN(30) series, but this was found to be barely statistically significant (at $\alpha = 0.05$) and not thought likely to cause undue bias in fitting the low flow frequency distribution.

4.4.3 Approach to for fitting distributions

The method of L-moments, as described by Hosking and Wallis (1997), has been used for the distribution fitting technique. JBA Consulting has an in-house suite of software applications already written that implement these techniques from first principles. The software uses our VB6 adaptations of public domain subroutines (http://lib.stat.cmu.edu/) to sample the L-Moment/L-Moment ratios of a dataset via probability weighted moments (PWM) and to estimate distribution parameters.

The program allows distribution fitting by the L-moment approach to be applied to annual minimum series of any length. However, the analysis is limited to the GEV distribution. The GEV is the traditional choice of distribution for low flow frequency analysis as it encompasses the EV1 (Gumbel), EVII (Frechet) and EVIII (Weibull) extreme value distributions, applications of which have been widely reported in the literature. In addition Zaidman *et al*. (2002) showed that GEV distribution was appropriate for many catchments in the UK when fitted to AMIN30 or AMIN60 series.

The input requirements for the program are a comma separated file with a header on line 1, and data on line 2 onwards. Outputs include the derived sample L-moments and location, shape and scale parameters of the fitted distribution. Associated quantiles are also output. A user interface allows the input and output files and model parameters to be specified.

4.4.4 Low flow frequency (LFF) curves derived using naturalised AMIN30 series

GEV distributions were fitted to AMIN30 series derived from the naturalised daily flow record for Kingston. Due to uncertainties associated with the pre-1951 portion of the record, the fitting procedures were applied to three series as follows:

a) the 1883 to 2004 inclusive AMIN30 series (122 observations);
b) the 1951 to 2004 inclusive AMIN30 series (54 observations);
c) the 1883 to 1950 inclusive AMIN30 series (68 observations).

Details of the fitted parameters are given in Table 4.5. The resulting low flow frequency curves (LFFC) are shown in **Figure 4**.7. The shape of the 1951-2004 curve is different to that for the 1883-1950 period, particularly for low probability (rare) events. A comparison of the flows for various quantiles is given in

Figure 4.8, and this clearly illustrates that the curve for the 1951-2004 period predicts larger flows for specified probabilities than the 1883-2004 curve.

Table 4.5: Parameters of the LFFC for the Thames at Kingston (naturalised)

Series	No values	Median $m^3 s^{-1}$	SD	Distribution	Location (Xi)	Scale (a)	Shape (k)
1883 - 2004	122	25.4	74.4	GEV: EVIII	22.4	7.92	0.15
1951 - 2004	54	28.2	48.9	GEV: EVIII	26.3	6.48	0.19
1883 -1950	68	22.0	82.2	GEV: EVII	19.3	6.93	-0.04

There are a number of reasons why the curves might be different, including sampling differences (with fewer data points leading to a poorer fit and biased dataset). However, the main reason is that there are more severe low flow events in the pre-1951 portion of the naturalised flow record than in the post-1951 period. Natural climate variability (with the early part of the century being relatively dry compared to later), under-recording of flows prior to 1951 and uncertainties related to naturalisation probably all contribute to this effect.

For comparison, we can refer also to simulated monthly flow series for 1865-2002, which were derived from rainfall data using regression models by Jones *et al*. (2006). These data, which were produced for 15 catchments (including the Thames at Eynsham) and take account of naturalisation, indicate more spatially extensive drought periods in the earlier part of the record than in recent years, with 1870, 1887, 1921 and 1933/4 being especially significant. However, the same authors also suggest that the historical rarity of warm, dry summers is no longer a reliable guide to their contemporary frequency, citing the recent cluster of relatively dry years between 1976 and 1995.

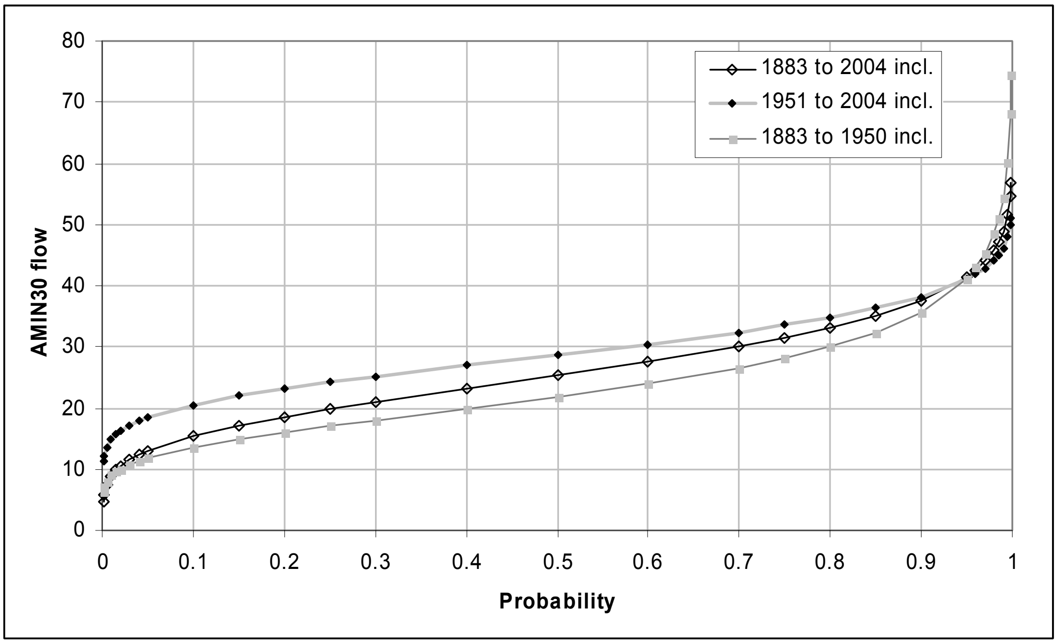


Figure 4.7: Low flow frequency curves for the Thames at Kingston derived by fitting the GEV distribution to naturalised AMIN30 series

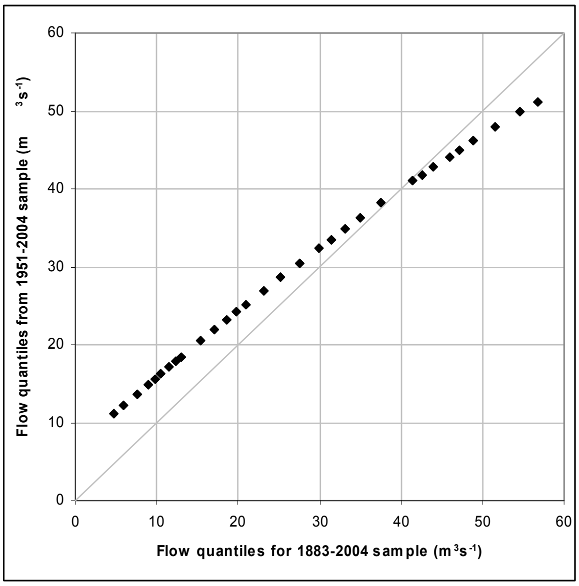


Figure 4.8: Comparison of flow quantiles for AMIN30 series derived from 1951-2004 and 1883-2004

The effect of the trend in naturalised low flow on the shape of the low flow frequency curve was investigated by considering consecutive 40-year periods, starting with 1883-1922 and ending with 1967-2004 and fitting the GEV distribution separately to each. The results, summarised in **Figure 4.**9, show the curve progressively changing in shape as the 40-year sample moves forward in time. Note that the percentile limits shown are approximate, where accurate confidence limits would need to be derived using resampling methods or similar, but the results do reflect the influence of natural variability and uncertainties in naturalisation.

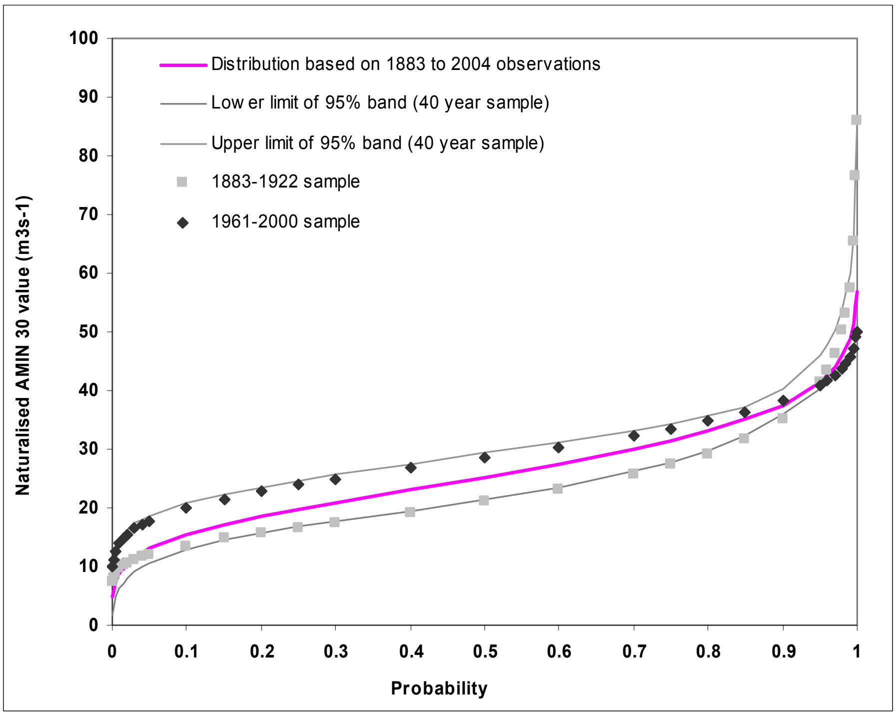


Figure 4.9: Comparison of flow quantiles for naturalised AMIN30 series derived from the periods 1951-2004 and 1883-2004.

4.4.5 Recommended Q-F relationship for the Thames at Kingston

Despite uncertainties associated with the early part of the record, it is recommended that low flow quantiles, derived from applying LFFC procedures to the 1883-2004 record, be used. This is because it produces more reasonable return period estimates for extreme events. For example, using the 1951-2004 curve suggests a 1,300-year return period for the 1976 drought, which seems unreasonably high, whereas the corresponding estimate from the 1883-2004 curve is a more plausible 44 years.

4.5 The 1976 low flow event for the Thames at Kingston

4.5.1 Observed flow conditions during the 1976 drought

From research carried out in an earlier phase of the project, it is thought that the 1976 drought is the only low flow event of the modern era that has led to significant impacts or restrictions on navigations in the River Thames. The drought resulted from an extended dry spell lasting from early 1975 to late 1976. In particular, the 1975/76 winter period was exceptionally dry, leading to negligible recharge and depleted groundwater levels prior to the summer of 1976. Gauged and naturalised daily flows for the 1975 to 1977 period are shown in
Figure 4.10.

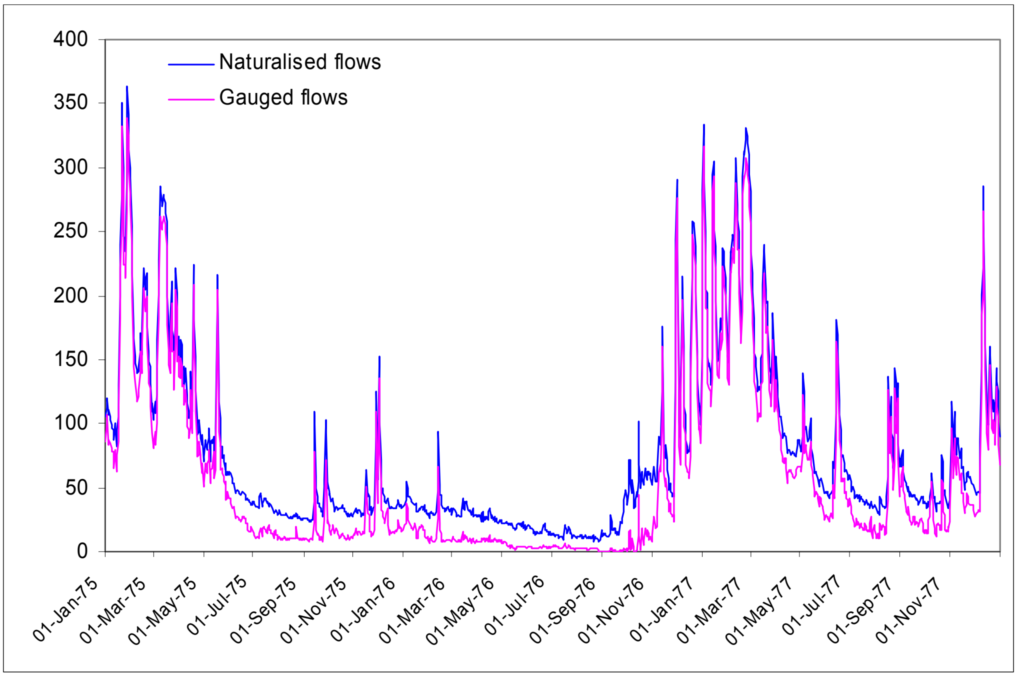


Figure 4.10: Gauged and naturalised daily mean flows at Kingston during the 1975 to 1977 period

During the 1976 drought, gauged flows were generally below 5 $m^3 s^{-1}$ between May and September 1976 inclusively, and below 2 $m^3 s^{-1}$ between mid-August and the end of September. The minimum gauged daily flow was just 0.01 $m^3 s^{-1}$, which occurred periodically between 27 August 1976 and 20 September 1976. At this time the river was reduced to a narrow channel and at Kingston, it was possible to walk from one bank to the other without getting wet! Mean monthly flows for June, July and August respectively were 3.29, 3.36 and 1.91 $m^3 s^{-1}$ respectively. Flows did not recover significantly until November 1976.

4.5.2 Navigation and residual flow requirements in relation to observed flows in 1976

The critical head water levels (HWLs) at Teddington Lock needed to maintain adequate draught of 0.3 m for navigation is 0.075 m above local datum. It is not clear what stage and flow values at Kingston gauging station this HWL corresponds to (or whether it is possible to calculate this).

However, according to the drought plan for Thames waterway, the present agreed (between the Environment Agency and public water supply abstractors) residual flow at Teddington Weir/Kingston is 800ML/D under normal circumstances, dropping to 300 ML/D in extreme conditions. This corresponds to gauged flows of 9.2 to 3.5 $m^3 s^{-1}$ respectively.

In 1976, the gauged flow was below the 3.5 $m^3 s^{-1}$ threshold for about 32 per cent of the year (nearly 120 days). Flows were below the residual flow threshold of 9.2 $m^3 s^{-1}$ for about 60 per cent of the year (nearly 220 days). This implies there would have been severe navigation impacts for several months during 1976, particular during the May to September period.

4.6 An indicator flow for navigation restrictions in 1976

Within the context of the study, it was important to estimate a naturalised AMIN30 value corresponding to navigation restrictions imposed at Kingston. We use naturalised flows to remove effects of changes in demand and to be consistent with climate impact modelling.

Figure 4.11 illustrates a range of d-day running average (naturalised) flows over the 1975-1977 period. As there was little day-to-day change in flows over the 1976 spring and summer, the curves for the different durations converge during this period. At the onset of navigation impacts, say on 1 May 1976, the 30-day running average flow was 23 $m^3 s^{-1}$. By the 1st July the figure was 14 $m^3 s^{-1}$. The lowest 30-day average flow during 1976 (the annual minimum) was 10.8 $m^3 s^{-1}$ and this occurred at the end of August.

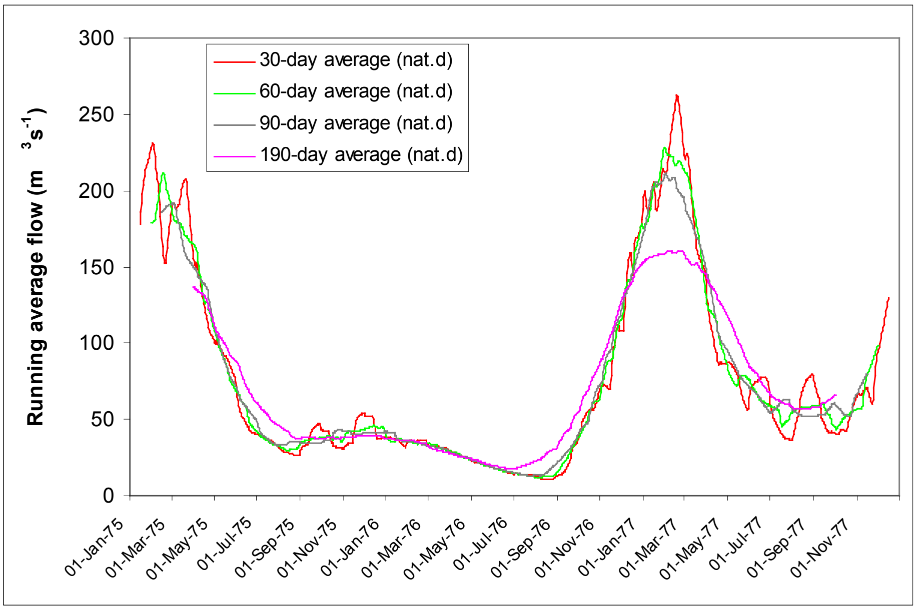


Figure 4.11: Running average d-day flows during the 1975-1977 period

From this, we could identify a suitable value of the naturalised 30-day indicator flow representative of disruption to navigation. There were no reports of restrictions in 1990, when the naturalised 30-day AMIN was 18.2 $m^3 s^{-1}$. There were severe restrictions in 1976, when the naturalised 30-day AMIN was 10.8 $m^3 s^{-1}$. The 1976 indicator flow must therefore be somewhere within this envelope. Taking 30-day periods corresponding as closely as possible to calendar months, the naturalised 30-day average flow for May 1976 was approximately 23 $m^3 s^{-1}$, which, inferring from 1990, should not imply restrictions on navigation.

The June 1976 naturalised flow was approximately 14 $m^3 s^{-1}$, which lies within the envelope defined by the 1990 (no restrictions) and 1976 (severe restrictions) 30-day annual minima. In the absence of detailed data on the restrictions (and given the fact that drought restrictions are progressive), the June 30-day naturalised flow of 14 $m^3 s^{-1}$ was adopted to represent the restriction of navigation on the Thames.

4.7 Estimated return period for the 1976 indicator flow

Our initial graphical analysis gave an estimated return period of approximately 45 years for the 1976 naturalised 30-day annual minimum flow. The corresponding estimate provided by the fitted GEV distribution was 44.7 years.

The graphical analysis gave an estimated return period for the 1990 naturalised 30-day annual minimum flow of approximately five years. The corresponding estimate from the fitted GEV distribution was 5.3 years.

We can therefore expect that navigation restrictions may occur for drought events having a return period somewhere between five and 45 years (when assessed on the basis of naturalised 30-day average flows).

More precisely, if we adopt the suggested indicator value of 14 $m^3 s^{-1}$ then, based on the low flow frequency distribution fitted to the naturalised record, we can say that conditions of this severity are to be expected with a return period of 14.8 years. Given the unavoidable uncertainty inherent in these calculations, it is reasonable to round this value to a return period of 15 years.

The use of naturalised flow records permits data from a long period of record to be used in assessing the rarity of drought conditions. However, any changes to the Thames operating agreements, allied to the introduction of the drought plan, mean that the impacts on boating of such conditions might not be the same in a future drought as they were in 1976. For instance, progressive restrictions on locking and different approaches to limiting abstraction might result in a natural event of the same rarity as 1976 having a more prolonged impact on navigation, but one that could be less severe at times.

4.8 Climate change projections

4.8.1 Basic methodology

The analysis here extends previous work to model the impacts of projected climate change scenarios on low flows in the River Thames within a probabilistic framework. The methodology for the probabilistic simulation is described in detail by Wilby and Harris (2006). In summary, the approach uses Monte Carlo simulation to generate a large number of realisations of possible future river flows, by sampling from a range of climate change projections. These projections comprise the following components

- emissions scenario
- climate model output
- downscaling technique
- hydrological impacts model structure
- hydrological impacts model parameters.

The probabilistic approach tries to represent acknowledged uncertainty in these factors by sampling randomly (but with prescribed weights) within each dimension, to build up a distribution of the final target parameters, in this case river flows, that represents the combined uncertainty.

Previous work has examined changes in Q95 (the 95th percentile flow) for water resource purposes. For this study of navigation impacts, more extreme low flows are relevant. We therefore carried out a new analysis to examine changes in annual minimum naturalised flows.

To do this, the simulation procedure of Wilby and Harris (2006) was repeated, but instead of extracting Q95 from the simulated flow data, the annual minimum 30-day flows were provided. This involved a re-calibration of the monthly flow regression model (REGMOD), which was carried out by the Environment Agency. The Environment Agency provided 2,000 realisations of a transient simulation from 1961 to 2100.

4.8.2 Initial review of simulated data

Figure 4.12 shows the range of AMIN30 magnitudes demonstrated in the 2,000 scenario runs for each of the years between 1960 to 2100.

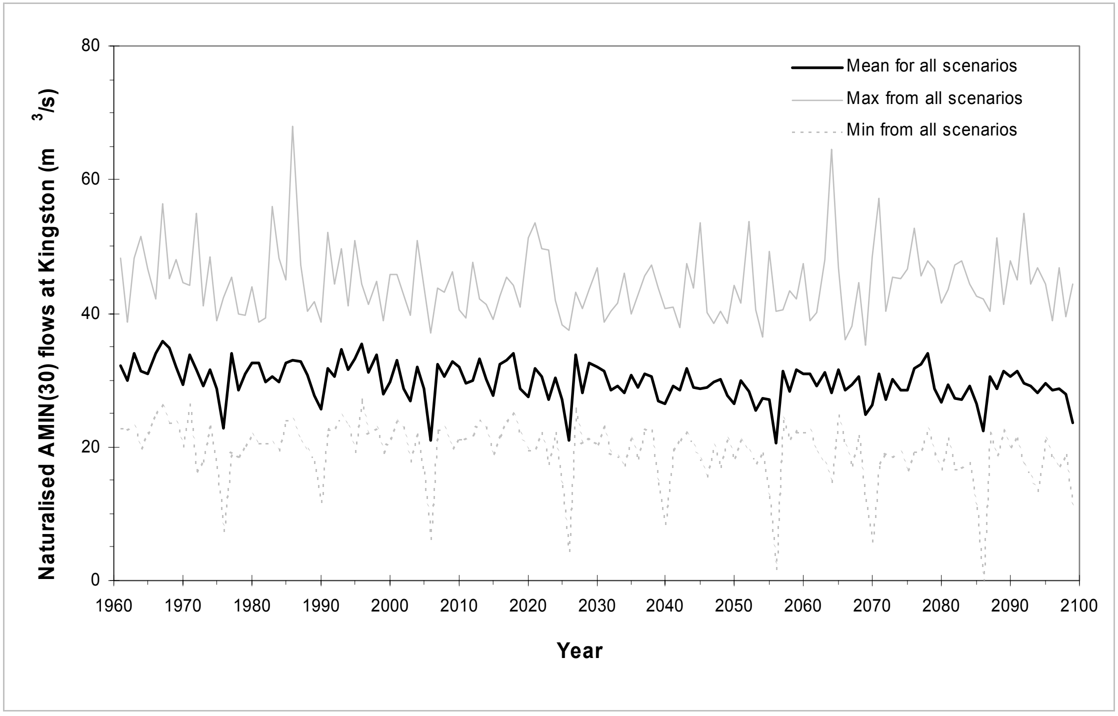


Figure 4.12: Variation in 30-day annual minima derived when climate change scenarios are applied to the Thames at Kingston

It is apparent that over time, there is a trend towards more scenarios having lower AMIN values in the future than at present. It is also clear that there is some periodicity in the data, at around a 15-year cycle.

The increased likelihood of lower AMIN30 events in the future can be readily demonstrated by a simple empirical cumulative distribution function (CDF) plot for annual minima in different decades, as shown in Figure 4,13. The plot also shows greater variability in the future (possibly a function of uncertainty in the modelling as well as a climate change impact).

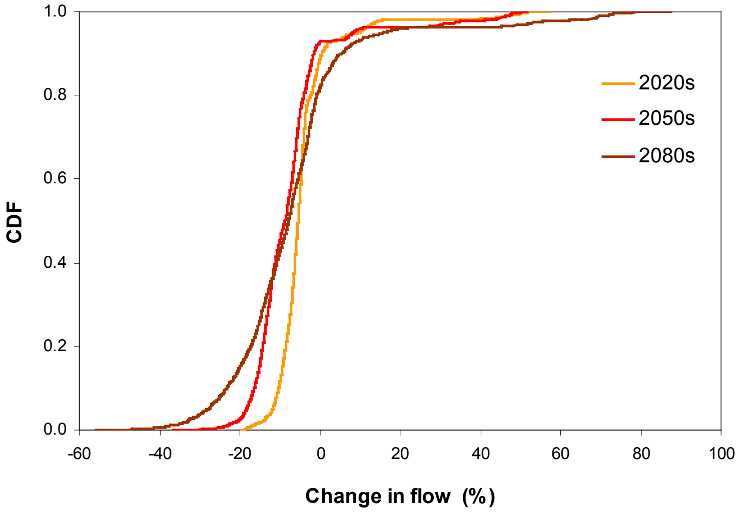


Figure 4.13: Variation in 30-day annual minima derived when climate change scenarios are applied to the Thames at Kingston

4.8.3 Comparison with observed data 1961 to 2006

The scenario AMIN30 data for the period 1961-2005 were compared to the observed naturalised series for Kingston. This comparison is shown in Figure 4.14, and indicates that, on average, the scenarios can be thought of as a realistic representation of trends and approximate magnitude of AMIN30 events at Kingston. Observed extremes during the period are captured by some realisations within the scenario data.

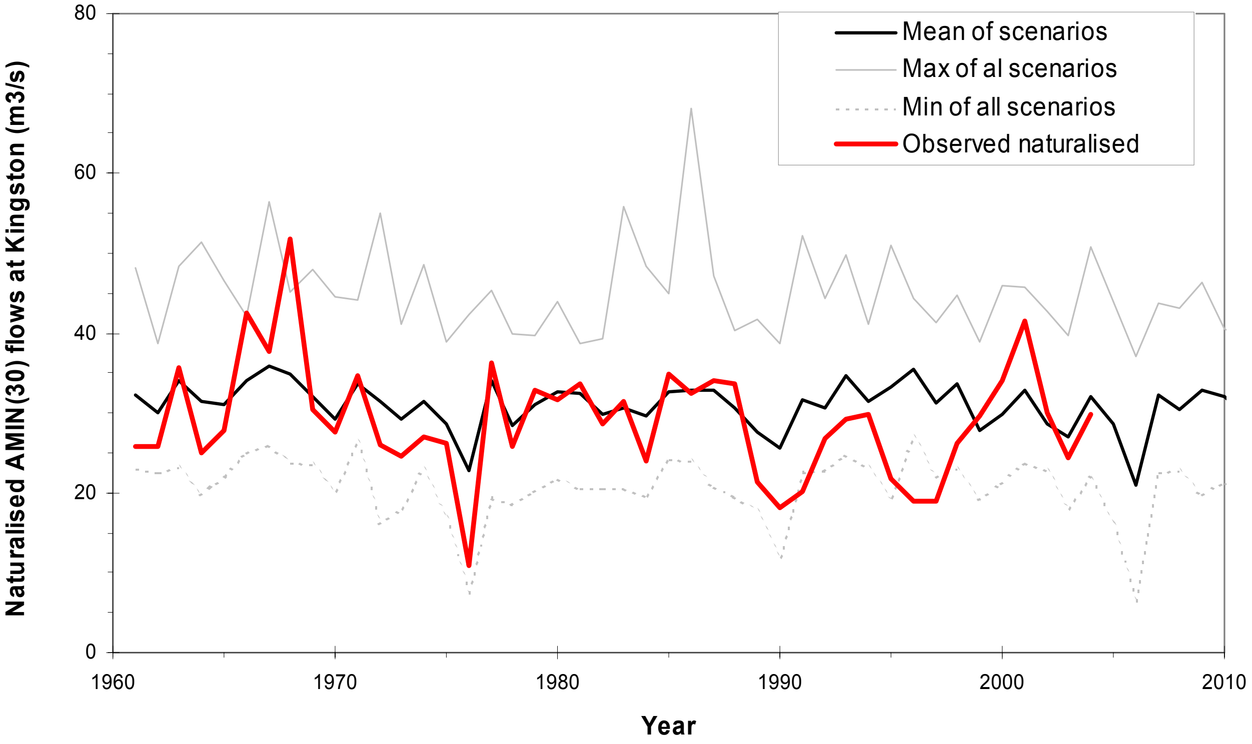


Figure 4.14: Variation in annual minimum flows derived from gauged data for the Thames at Kingston compared with scenario AMIN series.

4.8.4 Probabilistic low flow frequency impacts analysis

The aim of the analysis was to determine whether low flow events, represented by AMIN30, would become more frequent in future as a result of climate change. The approach taken was to apply distribution fitting techniques in order to determine low flow frequency curves for different time slices of the AMIN30 series. corresponding to each of the 2,000 scenario runs. The method of L-moments was applied as the parameter estimation technique, using the same software as for estimating return periods from observed data.

The idea was to look at how the frequency of a low flow event of specified magnitude might change in the future. A limitation of this approach, however, is that distributions fitted to very small samples can be misleading. As a compromise, the analysis was carried out on 40-year time slices (where each sample would contain 40 values). As the scenarios covered a period of 140 years from 1961-2100, it was decided to investigate the following time slices:

Table 4.6: Time slices for which frequency analysis was applied

Years included in slice	**No AMIN30 values in slice**	**Mid-year of slice**
1961-2000	40	1980
1981-2020	40	2000
2001-2040	40	2020
2021-2060	40	2040
2041-2080	40	2060
2061-2100	40	2080

AMIN30 values from the time slices listed above were extracted from each of the 2,000 scenario time series, giving 12,000 series to be analysed in all.

To examine projected changes in the frequency of an event that could cause severe disruption to navigation and recreation, we calculated the change in return period between a 1961-2000 baseline and subsequent 40-year time slices for AMIN values corresponding to a range of baseline return periods. This allowed some separation between the problem of identifying the indicator event for restrictions on navigation (previous section) from the frequency analysis of climate change projections.

To determine the projected changes in return period for a baseline indicator event, the following procedure was applied for each Monte Carlo realisation:

1. Fit GEV distribution to the AMIN(30) series for of the baseline period and each of the future time slices.

2. Use the GEV quantile function to calculate the AMIN(30) flow corresponding to the specified indicator return period.

3. For the AMIN(30) flow calculated in step 2, use the relevant fitted GEV distributions to determine the corresponding return period for each future time slice.

4. Determine the change in return period.

The end result of this method is an empirical distribution of projected changes in the frequency of the indicator event.

4.8.5 Results

To provide a measure of the overall central tendency of the changes, we tabulated the median projected return period for AMIN(30) events having a range of baseline return periods from 10 years to 50 years. The median was chosen to represent the average of the realisations because it is less influenced by outliers than is the mean.

Table 4.7: Simulated future occurrence of the 1961-2000 T-year 30-day mean flow

Return period (years) – median of 2,000 scenarios					
1961-2000	**1981-2020**	**2001-2040**	**2021-2060**	**2041-2080**	**2061-2100**
50.0	43.7	19.7	15.3	19.1	18.7
25.0	21.5	11.8	9.6	10.1	10.0
15.0	12.8	8.3	6.5	6.5	6.5
10.0	8.7	6.2	4.8	4.6	4.7

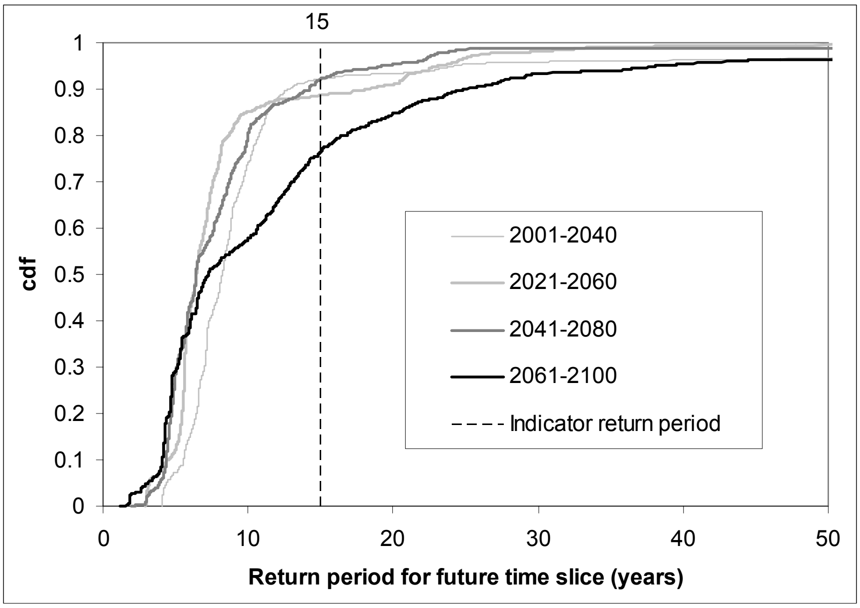
The average outcome of the 2,000 probabilistic simulations was that low flows corresponding to the present T-year minimum would become more common in future (for all values of T examined), with a smaller average interval between recurrence (or an increased probability of occurrence in any given year).

For some individual realisations of the Monte Carlo simulation, the AMIN flow corresponding to the present T-year low flow event was modelled as becoming rarer in future, but the overall tendency towards increasingly frequent low flow events can be seen in Figure 4.15, which plots the distribution of return period changes for baseline events of T = 15 years (the suggested indicator event for the 1976 restrictions) and a more extreme event of T = 50 years, shown for comparison.

Taking the median return period in each time slice, by 2080 we can expect that the AMIN flow corresponding to the present 15-year event will have a return period of less than 10 years. For the baseline 50-year event, the projected median return period at 2080 is 19 years. This change is not predicted to occur gradually. Rather, by 2020 the results would lead us to expect an event of either magnitude to be more than twice as likely to occur in any given year.

The probabilistic analysis applied here allows these results to be placed in the context of uncertainty about climate modelling, downscaling and hydrological impacts modelling. The steeper the distribution function curve, the less scatter there is in the distribution of simulated impacts. As expected, the distributions show greater variance for the most distant time horizon (2061-2100), reflecting uncertainty in climate models and divergence between scenarios.

All sets of simulation results show a strong positive skew, that is, the distributions have a long tail of large return periods, although the bulk of the results are smaller values. Given that the physical parameter being evaluated is the annual minimum flow, this implies that a few of the Monte Carlo realisations simulate river flow regimes in which a low flow event as severe as 1976 becomes very rare indeed. This is quite possible, and **Figure 4.**2 showed that some of the 2,000 MCS realisations might produce AMIN(30) series in which there are no extreme low flow events.



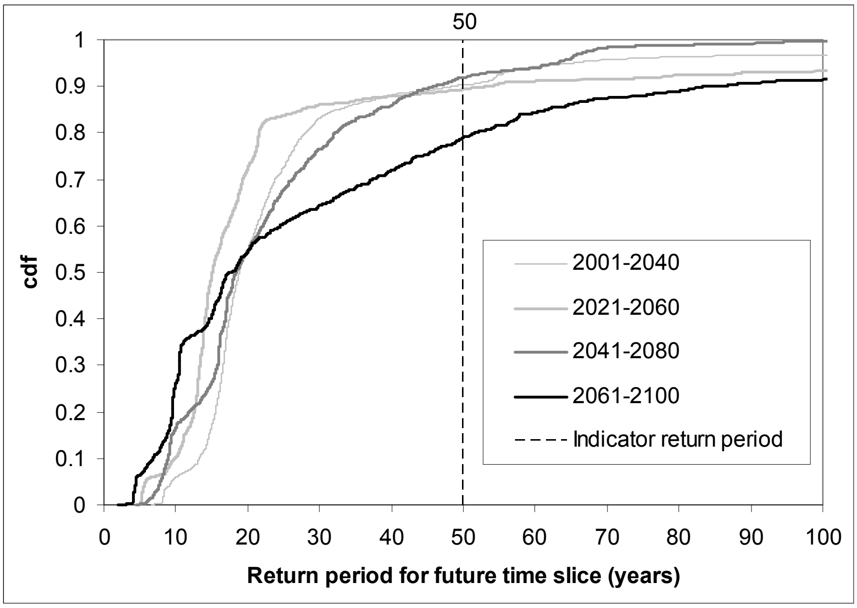


Figure 4.15: Projected future return period distribution functions (cdf) for an 'indicator event' (shown as vertical dashed line) of specified probability in the recent past

It should be recognised that the results in the upper tail are not reliable. The low flow frequency analysis was based on samples of size 40 (that is, 40-year time slices). It is not recommended to estimate return periods from an N-year annual extreme value series of greater than approximately 2N. There will be more confidence in estimates for return periods less than N. For realisations of the climate simulation that contain no extreme low flows, calculating a return period corresponding to a 1976-like event will involve a large, and inherently unreliable, extrapolation of the GEV distribution fitted to the simulated AMIN(30) series. Hence, realisations of future return periods much larger than 80 years should be interpreted merely as indicating wetter conditions that lie somewhere in the upper tail of the impacts distribution. For the 2061-2100 time horizon, about 10 per cent of realisations fall into this upper tail.

However, in all cases examined, at least 75 per cent of realisations indicate future climate scenarios in which there is a greater annual probability of conditions similar to 1976 occurring than in the recent past.

Another source of uncertainty is the apparent difficulty of one of the hydrological models (the CATCHMOD rainfall run-off model) to predict extreme low flows. This was demonstrated in a comparison of predicted annual minimum flow to naturalised flow for the calibration period from 1960 to 2010. Although not shown here, the 1976 30-day annual minimum flow was not well modelled by this hydrological model (16.9 $m^3 s^{-1}$ as opposed to the 10.8 m^3s^{-1} in the naturalised series). This implies that the model may have significantly overpredicted flows in extreme dry years, leading to a bias in 1,000 of the 2,000 Monte Carlo simulations which used this model. If this did occur, the true increase in the frequency of low flows may be even greater than reported here.

5 Discussion

5.1 Indicators for Strong Stream Advice

5.1.1 Threshold flows

By comparing the Environment Agency's records of Strong Stream Advice (SSA) with gauged flow data, we found that it was possible to identify threshold flow values as indicators for SSAs. Although there was some variation in the flows at which SSA notices were issued and withdrawn, there appeared to be consistent patterns where SSA notices came into force at a certain threshold flow and were then withdrawn at a lower flow.

On the rivers where SSAs are used, it is clear that they are not limited to extreme events (as understood in flood management terms). In fact, records show that SSAs occur for flows that are observed between eight and 15 per cent of days on average. The flow duration curve is the appropriate instrument for hydrological analysis in this case.

5.1.2 Data

This study revealed the variation within the Environment Agency's methods for managing and recording SSAs. Only the Thames, Great Ouse and Nene had records. On the Thames, there were well established procedures for managing SSAs. There was a long history of record-keeping on the Thames through paper tackle sheets. We digitised SSA records from scanned images of the tackle sheets, which highlighted the difficulty of interpreting records made in this way, where different terminology, abbreviations or even hand-writing could cause problems.

For the Great Ouse and Nene, SSA records were more recent and were supplied in digital form (as spreadsheets). The spreadsheet formats varied and there was no evidence of any systematic database design principles being applied. For example, in the Great Ouse records, calculation of monthly totals involved counting the numbers of cells shaded blue in a calendar table. The supplied data had inconsistencies between the number of blue cells and the supplied totals. A more robust database would perhaps use ones and zeros to indicate the occurrence (or not) of an SSA, allowing counting to be done safely using a spreadsheet formula.

5.2 Indicators for low flow restrictions

5.2.1 The indicator event

In contrast to SSAs, whilst extreme low flows could potentially have a severe impact on recreation by restricting boating for a period of weeks or more, this situation has been so rare that there is no formalised approach or even descriptive terminology within recreation and navigation. The only instance where the Environment Agency reported severe restrictions on recreational boating was the 1976 drought on the Thames.

The main restrictions would be access (water too shallow) and restricted operation of lock gates to conserve water. There are records for the Thames of river traffic but these do not provide enough detail to identify exactly when restrictions have been in place and how these might relate to gauged river flows.

In view of the limited information and the rarity of low flow restrictions in the recent past, the approach taken here was to use the 1976 drought as an indicator event for low flow restrictions on recreation and navigation. There were many parameters that could be chosen to represent the indicator event. In this study, we used the 30-day mean flow as the representative parameter. This could be calculated from gauged or naturalised daily flow records and was suitable for use in a low flow frequency analysis based on the AMIN30 (annual minimum 30-day flow) series.

5.2.2 Return period of the indicator event

Low flow frequency analysis is a complex process requiring careful application of statistical procedures and interpretation of flow data. An assessment of the rarity of a low flow event depends particularly on how the event is identified and how the flow record is interpreted. Interpretation of the flow record includes judgements about the accuracy of gauging station data, which may be reduced at very low flows, and the application of naturalisation procedures. Naturalisation attempts to remove the influence of artificial abstractions and returns from the flow record so that the naturalised data represent the underlying environmental flows. It can have a significant impact on how the rarity of a given event is assessed, and this aspect becomes most important for extreme low flows.

There has been no comprehensive treatment of the probability of extreme low flows on the Thames, perhaps because British hydrological practice tends to focus on quantiles of the flow duration curve for water resources studies, rather than the probabilities of more extreme low flows. This study identified a need for thorough analysis of more extreme low flow events on the Thames (and possibly other rivers).

We carried out a frequency analysis for the Thames sufficient to understand the scale of event that may affect navigation in the probabilistic climate impacts simulation framework. The analysis suggested that the return period for an event similar to 1976 would be between 10 and 45 years, depending on the point during the evolution of a drought period at which restrictions on river users would become onerous. It is recommended that a more detailed analysis of the flow record, specifically with respect to naturalisation, be undertaken before a definitive value is quoted.

5.3 Results of climate change analysis for high flows

5.3.1 Coverage

The analysis presented here made use of river flow simulations carried out for previous Defra/Environment Agency research to identify climate change impacts on flood flows. Simulations were based on UKCIP-02 scenarios and a calibrated continuous simulation rainfall run-off model for the Thames at Kingston. Other rivers have been modelled in this way, though not any Environment Agency-managed navigations where records of SSAs exist.

5.3.2 ‘Headline’ results

The headline result from the Thames impacts analysis was that the number of days in a year when SSAs occur would reduce under either the medium-low or medium-high UKCIP-02 emissions scenarios. This result was found for both the 2050s and 2080s. When interpreting these results, it should be recognised that UKCIP-02 climate change simulations are thought to be relatively dry compared to other, equally plausible, climate model outputs.

One factor that these results did not illuminate was whether there might be changes in the seasonality of SSAs. In the recent past, SSAs have been concentrated in the winter months when recreational use of the river is at its lowest (and, in particular, casual boat users are least likely to be on the river).

It is well known that future climate projections tend to suggest changes in the seasonality or rainfall (with regional variations over the UK) as well as changes in the distribution of rainfall intensity, with a shift towards greater weight in the upper tail, often summarised as ‘increased storminess’. These effects are masked by the time aggregation in the flow duration curve results used here. However, recent work by Kay *et al.* (2006) using more detailed Regional Climate Model (RCM) outputs to drive hydrological models, has shown that the implications of these changes may not be quite as expected. In particular, this work found that increases in total winter rainfall and winter rainfall extremes could be out-weighed by overall reductions in rainfall through the summer and autumn (combined with increased evaporation), leading to *decreasing* flood flow intensity rather than the expected increases. This finding reflects the attenuating effect of soil moisture and groundwater storage and the way in which these mechanisms are represented in hydrological models.

A further complication is the perception that climate change may lead to increased frequency and intensity of convective summer thunderstorms. There is some concern that these events could have an impact on navigation because they occur precisely when recreational use of the river is at its peak. The discussion of Kay *et al.* would also apply in this case. We note, however, that the same study also found some catchments with greater than expected increases in future flood intensity, and so the overall picture at the extremes is one of great uncertainty.

5.4 Results of climate change analysis for low flows

5.4.1 Coverage

The analysis here was for the Thames because it is the only navigation managed by the Environment Agency where low flow restrictions have been reported and for which a suitable modelling framework exists.

5.4.2 Approach

Building on the work reported by Wilby and Harris (2006), we were able to carry out a probabilistic analysis for low flows on the Thames using 2000 Monte Carlo realisations of coupled transient climate scenario, downscaling and hydrological impacts models supplied by the Environment Agency.

These simulations used results from six climate model predictions, as opposed to the single model used for the high flow analysis.

5.4.3 'Headline' results

The probabilistic simulations suggested an increase in the frequency of severe low flow events on the Thames, with the impact being apparent as early as the period 2001-2040. Taking the 1976 drought as an indicator of navigation restrictions, the results suggested this type of event would become twice as frequent under climate change during this period.

The actual projected return period depends both on the probabilistic model results and the assessment of baseline probability of the indicator event. Using the 30-day mean flow to represent the indicator event, we assigned a return period for the recent past of between 11 and 44 years (depending on exactly how the event is defined), with corresponding projected return periods of between nine and 20 years for the period 2001-2040 and of between five and 19 years for the period 2061-2100.

There are a number of caveats attached to these figures, as follows. The results are based on probabilistic simulation of only 2,000 realisations, a relatively small number for a multi-dimensional problem of this type. The transient nature of the simulations means that the frequency analysis used to determine event rarity suffers from sampling variability. The use of 40-year time slices means that the return period for the indicator event can be determined with reasonable confidence for the majority of realisations. However, as with extremes in flood frequency, a better approach would be to compare much longer simulations from stationary climate runs (for the present day and fixed future time horizons), rather than limited samples from transient simulations. The analysis also samples from a relatively limited set of climate models, emissions scenarios and hydrological models.

Attributing all the indicated changes in the frequency of low flows to the influence of future scenarios of greenhouse gas concentrations cannot be done with great confidence, because of the existing trend in the annual minimum data displayed by the naturalised flow series at Kingston (although not by the reconstructed series for Eynsham). The 40-year moving average annual minimum flow increases by over 20 per cent from the start of the Kingston record to the present day. The increased frequency of low flows reported above are related to the present situation, and hence some of the changes may simply be a return to the drier conditions prevalent in earlier records.

The definition of the indicator event and its rarity was based on information that could be gathered within the time available for this study. It is possible that there are other, credible, definitions that could be used.

5.5 Implications for infrastructure management

Historically, comprehensive information has not been available on the infrastructure assets on the navigable river network. This stems in part from under-funding for asset survey and also from the difficulty of gathering detailed information about structures that are in many cases partially or fully submerged.

The Environment Agency has compiled estimates of its infrastructure with the purpose of reporting to Government on funding requirements for capital investment. The Environment Agency is in the process of collating a database of the navigation infrastructure. Over 125 river reaches, it is estimated that there are approximately 730 assets, some of which comprise multiple components, giving a total of about 1,600 structures. Additionally, navigation infrastructure includes many non-structural elements, such as facilities for boat users, parking and public access. These parts of the infrastructure are included within the Environment Agency's whole-system approach to management of the navigable rivers.

Although construction data are not always available, navigation structures broadly comprise mass concrete, reinforced concrete pile and 'soft engineering' (such as willow) structures. The replacement cost of the infrastructure over the whole network is estimated to be around £700 million. The Environment Agency estimates that 18 per cent of the infrastructure is in critical condition, requiring urgent capital investment within two years. This figure has not been updated for some time, but it may usefully indicate the proportion of structures causing concern.

Data made available for the Thames was limited to lock structures. Of the 44 structures listed, 29 had been surveyed for the Environment Agency, although no conditions codes were available.

The Thames Waterway Plan for 2006 to 2011 (Thames Alliance, 2006), which is public domain, refers to more than 1,000 aspirations for improvements to assets on the navigation. However, the majority of these appear to relate to the provision of amenity facilities such as toilets and car parking. No detailed data was available on capital or maintenance works.

Data available for the Nene identified the names and locations of 153 assets, such as locks and landing stages. No condition grades codes were available.

Data for the Great Ouse included public domain maps showing improvements, similar to the Thames' aspirations, and also condition grades for lock structures and the immediate upstream reaches. Overall, one per cent of assets on the Ouse were reported to be in good condition, 57 per cent in fair condition and 42 per cent in poor condition.

The absence of data available for this project regarding infrastructure condition means that we cannot make specific comments about the implications of climate change for the rivers modelled. But in general, it can be concluded that channel maintenance is likely to be a key part of the response to climate change, in particular to ensure bank stability and keep rivers open during low flow periods. The Environment Agency is keen to promote a whole-life and whole-system approach to infrastructure management. The findings of this project reinforce the message that the maintenance and improvement of fixed structures should not be divorced from channel maintenance.

Our results have concentrated on occurrence of SSAs, which have a low threshold compared to typical flood design standards. It is possible that whilst SSAs may become less frequent, the intensity of real floods may increase at the extremes, with implications for design standards for navigation assets. Defra guidance on climate change in flood risk management should therefore be applied. Again, it should also be emphasised that the SSA findings presented here are based on only one climate model.

Policies and measures adopted for flood risk management should be inclusive of navigations interests. It is important that navigations assets are considered alongside conventional flood defence assets (such as embankments, flood walls and diversion channels) in terms of capital and maintenance programmes.

6 Conclusions and recommendations

6.1 Main conclusions

6.1.1 Knowledge and data

The Environment Agency's procedures for managing high flow (Strong Stream Advice) and low flow restrictions on navigations are not consistently documented. This is not to say that current practice is poor or based on unsound rationale, merely that it is knowledge held organically.

The approaches taken vary from river to river. This again is probably a natural consequence of the different management structures and traffic levels on the rivers.

6.1.2 High flows

It has been possible to infer threshold flows (or ranges of flow) as indicators for the issuing of SSAs on the Thames, Nene and Great Ouse. This makes it possible to link SSAs to climate change projections of hydrological impacts.

Using data from previously published research on climate change impacts on flood flows, it appears that the frequency of SSAs is set to decrease under the UKCIP-02 medium-low or medium-high scenarios for a time horizon up to the 2080s.

This analysis does not take account of possible changes in seasonality or storminess. Recent research suggests that these do not necessarily imply greater flood risk, because of the smoothing effects of greater evaporation on soil moisture deficits (Kay *et al*., 2006). However, results to date have been based on a limited number of climate model and emissions scenarios, and hence do not account for the full range of uncertainties in projected impacts.

6.1.3 Low flows

Recorded low flow restrictions on navigation are very rare indeed, with the 1976 drought on the Thames being the only example reported by the Environment Agency. It is difficult to set specific flow thresholds for such an event for two reasons. Firstly, the event itself is not an instantaneous phenomenon, and secondly, to do so would require accurate low flow rating curves and level data for what are extremely complex hydraulic structures on the Thames. The approach taken has therefore been to use 1976 as an indicator event and to identify flow descriptors that characterise this event.

Low flow frequency analysis was applied to data for the Thames at Kingston generated from probabilistic realisations of future climate change impacts on low flows. This analysis suggests that even by the period 2001-2040, there may be as much as twice the current risk of an extreme low flow event disrupting navigation on the Thames. However, the analysis also reveals a large degree of uncertainty about these projections, especially further into the future.

6.2 Recommendations

6.2.1 Knowledge and data

The present study found that data (formal records) and information of practices and procedures were not always readily accessible to support scientific study or policy making. There could be easy gains for the Environment Agency by reviewing how knowledge and information in the recreation and navigations function are managed, with some attention to database design.

6.2.2 High flows

The current analysis of high flows climate change impacts relies on modelling carried out using (relatively dry) UKCIP-02 scenarios in a deterministic approach. Recognising qualitatively the uncertainties that exist in all stages of the modelling, this should be reviewed using a probabilistic modelling approach.

The headline results from this modelling of the Thames do not suggest that climate change requires a radically different approach to management of the navigation or its assets with respect to flood flows. However, the findings of other work using a high resolution Regional Climate Model for hydrological impacts modelling show considerable regional variation. As climate change scenario data become available at finer spatial and temporal scales, specific impacts modelling should be carried out both for the Thames and other navigations.

The SSA threshold flow approach should be adopted to provide a climate change indicator for operational impacts on navigations.

The engineering performance and sustainability of navigation assets with respect to the more extreme high flows should be aligned with Defra and Environment Agency guidance and research for flood risk management.

6.2.3 Low flows

Probabilistic simulations suggest a strong chance that extreme low flow conditions, sufficient to disrupt navigation, are more likely in the future than in the recent past. This exploratory analysis was carried out for the Thames, but is likely to hold for other Environment Agency navigations, at least in the South and East of England, given that droughts are generally large-scale regional phenomena.

Further work is recommended to investigate the potential impacts of multi-season droughts and the Water Framework Directive on future operation of the Environment Agency's navigations under extreme low flow conditions. Although future studies may consider flow measures of longer duration, it is recommended that the estimated return period of the 30-day mean flow on an annual minimum scale is adopted as an indicator for low flow impacts on navigation.

6.3 Actions

The recommended actions arising from this report are divided into operational activities, which relate to the Environment Agency's recreation and navigation function, and research priorities, which relate to the Environment Agency's science programme.

6.3.1 Operational activities

The recommendations of this report are:

1. The Environment Agency should modernise its processes for recording SSA and other operational measures (such as weir and sluice adjustments).

   The new system should:
   - implement a formal database to record date, time and prevailing conditions (such as flow rate, headwater level) for each event;
   - enable access by navigation officers using a simple interface;
   - run on a PC or handheld device;
   - allow users to update the database directly;
   - allow off-line use, where records can be created locally and uploaded to the main database at a networked office;
   - make use of a web-browser based front end to simplify deployment.

2. The Environment Agency should adopt SSA thresholds and 30-day duration mean flows as climate change indicators for its navigations.

3. The Environment Agency should ensure that the maintenance and performance of navigation infrastructure for flood flow conditions is aligned with flood risk management good practice.

   Specifically, navigation infrastructure management should:
   - include assessment of risks from scour;
   - identify assets that have a joint navigation and flood management function;
   - adopt a risk-based approach to maintenance, planning and design for navigations assets.

6.3.2 Research priorities

The research priorities identified by this report are:

1. The Environment Agency should carry out probabilistic impacts modelling for navigations, particularly on the frequency and duration of SSAs and flood flows.

   This work may identify assets considered to be at risk and incorporate more detailed hydraulic model analysis for one or more case studies.

2. The Environment Agency should identify mitigation strategies, such as improved boat design or changes in locking practice, which could help to mitigate the impacts of future drought restrictions. Possible environmental constraints and opportunities for channel maintenance should be identified. In particular, the relationship between infrastructure management and Water Framework Directive requirements should be assessed (for example, with respect to dredging).

7 References & Bibliography

CEH Wallingford (2001). *Climate change and water management: managing European water resources in an uncertain future.* (ENV4 - CT98 - 0791) Work Package 7 - UK case study. Report to the European Community.

Defra (2000). *Waterways for tomorrow*. (http://www.defra.gov.uk/environment/water/iw/)

Defra (2003). *Impact of climate change on flood flows in river catchments – interim report*. R&D Technical Report W5-032/TR

Environment Agency (2003). *Your rivers for life: A strategy for the development of navigable rivers 2004-2007*. (http://www.environment-agency.gov.uk/subjects/navigation/)

Environment Agency (2005). Drought plan?

Hosking, J.R.M. and Wallis, J.R. (1997). *Regional frequency analysis: an approach based on L-Moments*. Cambridge University Press.

Jones, P.D., Lister, D.H., Wilby, R.L. and Kostopoulou, E. (2006). Extended riverflow reconstructions for England and Wales, 1865-2002. *International Journal of Climatology*, 26, 219-231.

Kay, A.L., Jones, R.G. and Reynard, N.S. (2006). RCM rainfall for UK flood frequency estimation. II. Climate change results. *Journal of Hydrology*, 318, 163-172.

Reynard, N.S., Crooks, S.M. and Kay, A.L. (2004). *Impact of climate change on flood flows in river catchments*. Final Report. Defra/Environment Agency Project W5B-01-050. 100 pp.

Reynard, N.S. Prudhomme, C. and Crooks, S.M. (2001). The flood characteristics of large UK rivers: potential effects of changing climate and land use. *Climatic Change*, 48, 343-359.

Tallaksen, L.M. and Van Lanen, H.A.J. (2004). (Eds) Hydrological drought: Process and estimation methods for streamflow and groundwater. *Developments in Water Science*, 48. Elsevier.

Wilby, R. and Harris, I. (2006). A framework for assessing uncertainties in climate change impacts: Low-flow scenarios for the River Thames, UK. *Water Resources Research*, 42, W02419.

Zaidman, M.D., Keller, V. and Young, A.R. (2002a). *Low flow frequency analysis: Guidelines for best practice.* Environment Agency R&D Technical Report W6-064/TR1.

Zaidman, M.D., Keller, V. and Young, A.R. (2002b). *Probability distributions for "x-day" daily mean flow events*. Final Report. Environment Agency R&D Technical Report W6-064/TR2.

Acknowledgements

The authors are grateful to S. Crooks, T. Marsh and N. Reynard (of CEH Wallingford) and R. Wilby (of the Environment Agency) for making available data generated as a part of previous Defra and Environment Agency research.

The assistance of Russell Robson, Phil Green, Rob Mallett, Sue Cant, Gina Scarre, Lynn Bulbeck and John Garrod of the Environment Agency is gratefully acknowledged.

List of abbreviations

AEP	Annual exceedance probability
AMIN30	Annual minimum 30-day average flow
CDF	Cumulative distribution function
CEH	Centre for Ecology and Hydrology
EV1	Extreme value type I (or Gumbel) distribution
FCERM	Flood and coastal erosion risk management
FDC	Flow duration curve
GEV	Generalised extreme value distribution
HWL	Headwater level
LFF	Low flow frequency
MAM	Mean annual minimum
Q*x*	Flow exceeded x per cent of the time on average (x^{th} percentile of the flow duration curve)
SD	Standard deviation
T	Return period in years
WISKI	Environment Agency hydrometric database

We are The Environment Agency. It's our job to look after your environment and make it **a better place** – for you, and for future generations.

Your environment is the air you breathe, the water you drink and the ground you walk on. Working with business, Government and society as a whole, we are making your environment cleaner and healthier.

The Environment Agency. Out there, making your environment a better place.

Published by:

Environment Agency
Rio House
Waterside Drive, Aztec West
Almondsbury, Bristol BS32 4UD
Tel: 0870 8506506
Email: enquiries@environment-agency.gov.uk
www.environment-agency.gov.uk