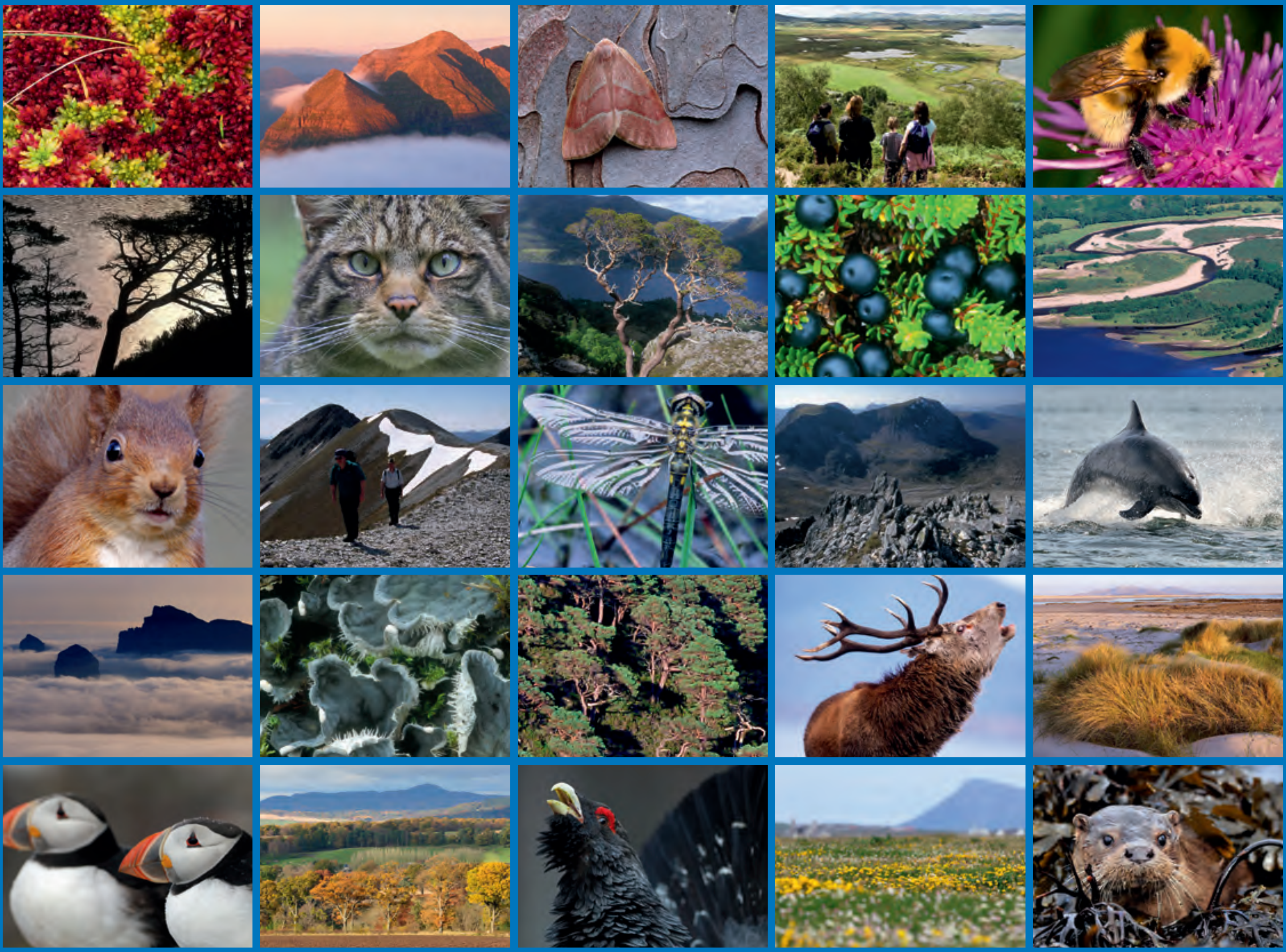
Scottish Natural Heritage
Commissioned Report No. 684

The Scottish Beaver Trial: Stream and loch hydrology monitoring 2009-2014, final report



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COMMISSIONED REPORT

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The Scottish Beaver Trial: Stream and loch hydrology monitoring 2009-2014, final report

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COMMISSIONED REPORT

Summary

The Scottish Beaver Trial: Stream and loch hydrology monitoring 2009-2014, final report

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Keywords

Beaver; hydrology; stream; loch; monitoring; Knapdale; water level; rainfall.

Background

A five-year trial reintroduction of the European beaver to Knapdale, Argyll, began in spring 2009. An independent monitoring programme was established to investigate the effects that beavers might have upon particular aspects of the natural heritage were they to be released more widely in Scotland. The freshwater science aspects considered and already reported on include aquatic vegetation; damselflies and dragonflies; fish; water chemistry; fluvial geomorphology and river habitat. This report focuses on hydrology. A network of automatic rainfall gauges, stream level and loch level recorders was operated for the period of the trial at strategic locations to monitor any hydrological changes on the lochs and streams within the Knapdale area. This was supported by manually read stage boards on all water bodies. This report presents the findings of analyses of these data.

Main findings

The potential for beavers to modify hydrogeomorphic processes through their habitat engineering activities (dam building plus tree felling and canal construction) is well recognised. At Knapdale beavers constructed dams at four main locations, close to the outflow or inflow of standing waters. Effects on hydrology at these sites include:

- temporarily increased storage in larger lochs (Loch Linne/Fidhle system), extending for several weeks, due to damming of the outflow;
- elevation and stabilisation of water levels in small lochs (Dubh Loch and Loch Un-named (North));
- a possible small delay in the timing of peak flow relative to a control stream caused by upstream retention.

The most striking change was caused by a dam on the outflow of a small pond, Dubh Loch, which caused a rise in water level of 1.1m. From a peak in November 2011 levels have gradually declined in line with reduced beaver activity at this site and increased dam porosity.

Interpretation of findings is hindered by the short time periods over which some dams were active (less than 4 months), differences in catchment characteristics between control sites and test sites and the influence of commercial timber harvesting on the rate and timing of runoff in some catchments. However, in comparison to published studies the effects observed are rather subtle and we conclude that beavers have had mostly minor effects on hydrology at Knapdale over the period of the trial. This is consistent with the very small effects on stream physical habitat at Knapdale, already reported by Perfect *et al.* (2015).

There are probably two major sets of reasons for the limited influence of beavers on hydrology at Knapdale. First, low numbers of animals are present and the dams that they have constructed to date have, with the exception of the dam on Dubh Loch, been small and poorly-sealed structures. These dams are also isolated rather than being closely grouped, in which case reported effects tend to be more pronounced. Second, the Knapdale catchment naturally attenuates runoff due to its extensive forest cover and significant potential for water storage in lochs and valley floor peats. Such circumstances will greatly moderate any additional effects of habitat engineering by beavers on hydrology. In agricultural settings or where higher densities of animals occur and are required to exploit sub-optimal habitat a higher level of habitat engineering and associated hydrological effects should be expected.

The possibility of more significant impacts on hydrology at Knapdale remains if the beaver population increases naturally or is supplemented in the future and animals then set up territories away from their preferred standing water habitat. Having established a hydrological baseline and suitable monitoring network in this area it will be valuable to maintain hydrological monitoring into the future should the size and distribution of the beaver population change.

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Acknowledgements

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Analysis of the hydrology data was possible through a partnership between SWT, SNH and the University of Stirling's Centre for River Ecosystem Science as part of the monitoring of the Scottish Beaver Trial. The authors thank the Royal Zoological Society of Scotland (RZSS), the Scottish Wildlife Trust (SWT) and FCS for their help and cooperation. The RZSS and SWT also contributed funds to the wider monitoring programme.

1. INTRODUCTION

A five-year trial reintroduction of the European beaver (*Castor fiber*) in Knapdale, Argyll began in spring 2009. The trial investigated the potential to return the species to Scotland after a 400 year absence following unsustainable levels of hunting (Kitchener and Conroy, 1997).

The joint licence application for a trial, submitted in 2007 by the Royal Zoological Society of Scotland and the Scottish Wildlife Trust, identified the opportunities that a scientifically monitored, time-limited trial could provide. Those relevant to the area of study covered by this report include:

- studying the ecology of the beaver in the Scottish environment;
- assessing the effects of beaver activity on the environment, including a range of land uses; and
- generating information that could inform further releases of beaver in sites with different habitat characteristics.

Other suggested areas of study included: beaver health; public health; socio-economic effects; and the impact on specific species of conservation concern.

A detailed account of beaver releases at Knapdale and population trends over the course of the trial is provided by Harrington *et al.* (2015). In summary, a total of 16 beavers were released into the Knapdale Forest beaver trial area in mid Argyll between May 2009 and September 2010. The aim was to establish a minimum of four breeding pairs within the first two years of the trial. These animals established four separate family groups that produced 14 kits, although kit survivorship was poor. By the close of the trial in May 2014 it is thought that 8 adults and possibly two kits were still present.

The ecological effects of the reintroduced beavers on the environment were monitored from 2009 to 2014, principally through the use of repeated ecological surveys. Pre-reintroduction baseline data were collected in 2008. Surveys covered various components of the woodland and freshwater ecosystems present at the site, including, in the latter case, aquatic and semi-aquatic macrophytes, the dragonfly fauna, fish, fluvial geomorphology, river habitat, riparian habitat, loch and stream hydrology and water chemistry.

A summary of the aims of the hydrological assessment is given in Section 1 and previous research on the effects of beavers on hydrology is briefly reviewed in section 3. Section 4 describes the characteristics of the study area. The methods used for collection and analysis of loch level, stream level and local rainfall data are presented in section 5 and these data are analysed and presented in section 6. Finally the results are discussed in the context of Knapdale and their relevance to Scotland as a whole.

2. AIMS AND OBJECTIVES

2.1 Aims

The monitoring programme for hydrology was designed with the aim of assessing the effects of beaver activity on hydrology across the stream and loch network at Knapdale. Its purpose was to detect changes in stream hydrology over the five-year period of the Scottish Beaver Trial and to assess the extent to which these changes could be ascribed to habitat engineering by reintroduced beavers. The work therefore takes account of water level regimes in lochs and streams with and without the influence of beavers and assesses differences in hydrological characteristics in the light of published findings.

2.2 Objectives

This study had a number of key objectives

- Utilise hydrological monitoring data collected over the 5 year period of the Scottish Beaver Trial to provide an assessment of the influence of habitat engineering by beavers on loch and stream levels within the Knapdale catchment.
- Consider the appropriateness of the hydrological monitoring network for assessing possible effects of beavers.
- Assess the potential for future effects on hydrology at Knapdale given changes in the status of the beaver population.
- Discuss the implications of these findings for Scotland given a wider scale reintroduction of beavers.

3. EFFECTS OF BEAVERS ON HYDROLOGY

Beavers are ecosystem engineers noted for their ability to modify their local environment to improve its habitat value which then can potentially affect a range of hydrogeomorphic processes and dependent organisms (Naiman, *et al*., 1986; Rosell *et al*., 2005).

Beavers construct dams to maintain a submerged entrance to their lodge or burrow and to provide increased access to suitable food resources (aquatic macrophytes and small trees) whilst reducing the risk of predation. The hydrological effects of beaver dams have long been known (Ruedemann & Schoonmaker, 1938; Rutherford, 1955) and, prior to the large scale expansion of human populations, it is likely that beavers were a major influence throughout their range on stream hydrology and sedimentation patterns (Butler & Malanson, 2005).

Acting in the same way as in-stream accumulations of large wood, beaver dams reduce flow and sediment transport by varying amounts and therefore directly influence channel morphology. Dams are most likely to be constructed on low gradient, low order streams with soft, well-wooded banks (Naiman *et al*., 1986). There have been a number of recent reviews of the hydrogeomorphic effects of beaver dams (Gurnell, 1998; Collen & Gibson, 2001) that emphasise several key themes. These include the following:

- Reduced stream energy due to a reduction in upstream channel slope, accompanied by an increase in water depth (Burchsted & Daniels, 2014).
- Increased sedimentation within ponded areas (Butler & Malanson, 2005; Levine & Meyer, 2014).
- Increased retention of water during peak events leading to a reduction in the height of the downstream peak, an increase in the duration of the event and a reduction in the rate of rise and fall (Burns & McDonnell, 1998; Nyssen *et al*., 2011).
- In dry weather conditions stored water is released thus enhancing baseflow (Hammerson, 1994).
- Increased recharge of the riparian aquifer next to ponded areas compared with free-flowing channels (Hood & Bayley, 2008).

Some of these features are illustrated in Figure 3-1 by contrasting the water levels recorded above and below a series of beaver dams located on an agricultural stream in Tayside (McLean, 2011). This example clearly demonstrates the attenuation of the flood peak, the decreased rate of recession and the increase in baseflow attributable to the retention of water behind dams.

All these effects vary with channel topography, flow regime, the size and permeability of the dam, its permanence, and the spacing between dams (Gurnell, 1998). For example, high dams that span the full channel and are watertight (e.g. sealed with vegetation and fine sediment) will retain more water than small, incomplete and poorly sealed structures (Meentemeyer & Butler, 1999), which are easily overtopped and leaky. A high density of dams (10-20 dams per km) located over a short section of watercourse will tend to have a greater influence on hydrogeomorphic processes than a single isolated structure (Nyssen *et al*., 2011).

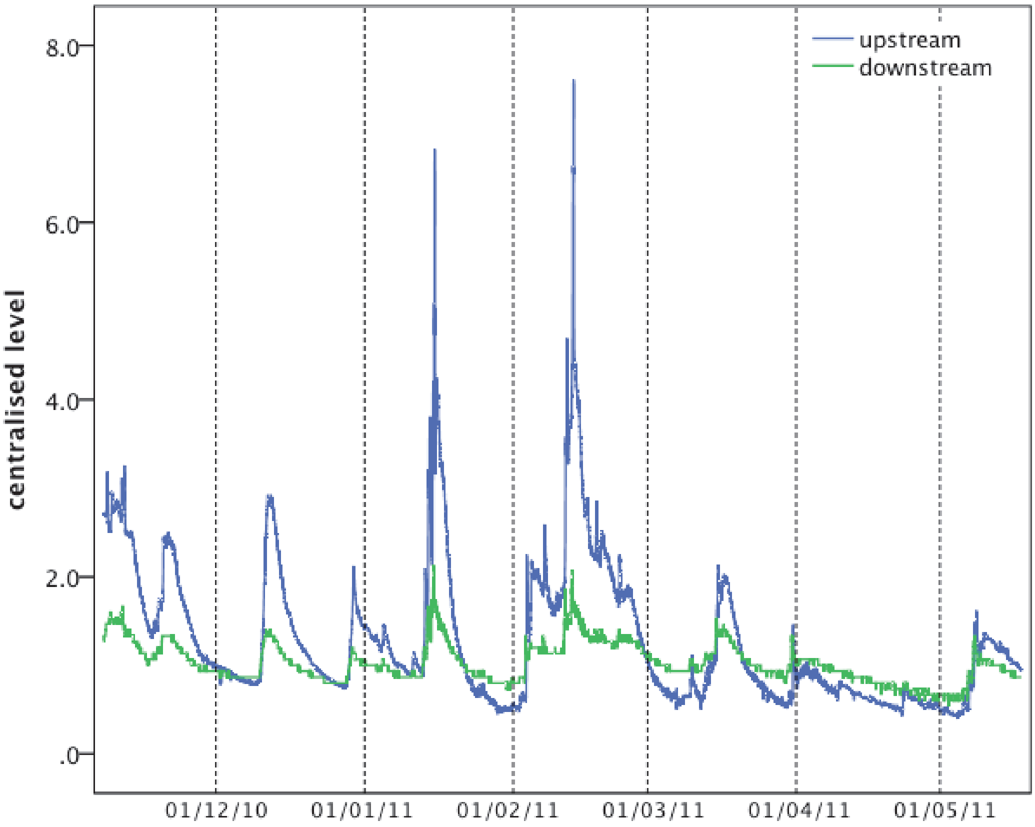

Figure 3-1 Centralised water levels (value divided by median) based on recording at 15 minute intervals immediately upstream and downstream of a series of beaver dams on an agricultural stream in Tayside (data from McLean, 2011). The recording period runs from 7th November 2010 to 17th May 2011 (vertical dotted lines indicate months). Note the reduced height of peaks, reduced rate of recession and increased base-flow during dry weather periods at the downstream site.

In the case of Knapdale we can expect that beaver dams located on loch outflows will cause a rise in loch water level, while dams on watercourses will affect the downstream flow regime compared with upstream sections or control streams due to water retention. However, the density of beavers at Knapdale is low (equivalent to 0.2 colonies per km of watercourse) compared with published studies (Gurnell, 1998). Monitoring the distribution of animals at Knapdale (Harrington *et al*., 2015) and their effects on aquatic vegetation (Willby *et al*., 2014) also indicates that they have mainly been resident on standing waters. Consistent with this, monitoring of stream physical habitat suggests that effects of beavers on flowing watercourses have been minor (Perfect *et al*., 2015). Thus, although the potential for effects on hydrology exists, present evidence suggests that any effects should be fairly modest.

4. STUDY AREA CHARACTERISTICS

Knapdale is located at the northern end of the Kintyre peninsula, west of the town of Lochgilphead (Figure 4-1). The Knapdale area has a mild temperate climate with an annual mean temperature of 9.2°C and annual mean rainfall of 1925mm (based on climate data for the period 1981-2010 for the closest station, Lephinmore, which lies 18km NE of Knapdale). Monthly rainfall reaches a maximum in December and January, falling to a minimum from April to June (http://www.metoffice.gov.uk/public/ weather/climate/gcunu3mny).

The region is drained by a network of small, low order streams that cover a total distance of about 20km. Channels are typically less than 2m wide with a gravel or cobble substrate, although some low gradient sections are locally silted (Perfect *et al.*, 2015). Typical examples of local water courses are shown in Figure 4-2. Surface drainage is typically south-westerly in accordance with the local topography which is mostly low lying and characterised by a series of ridges formed by folding of metamorphic rocks (Stephenson & Merritt, 2010). Many of the streams draining to the north have been impounded to form reservoirs to supply water to the Crinan canal. These are not considered in the present study. Within the study area there is historical evidence that some watercourses have been diverted or channelized to allow agriculture and commercial forestry.

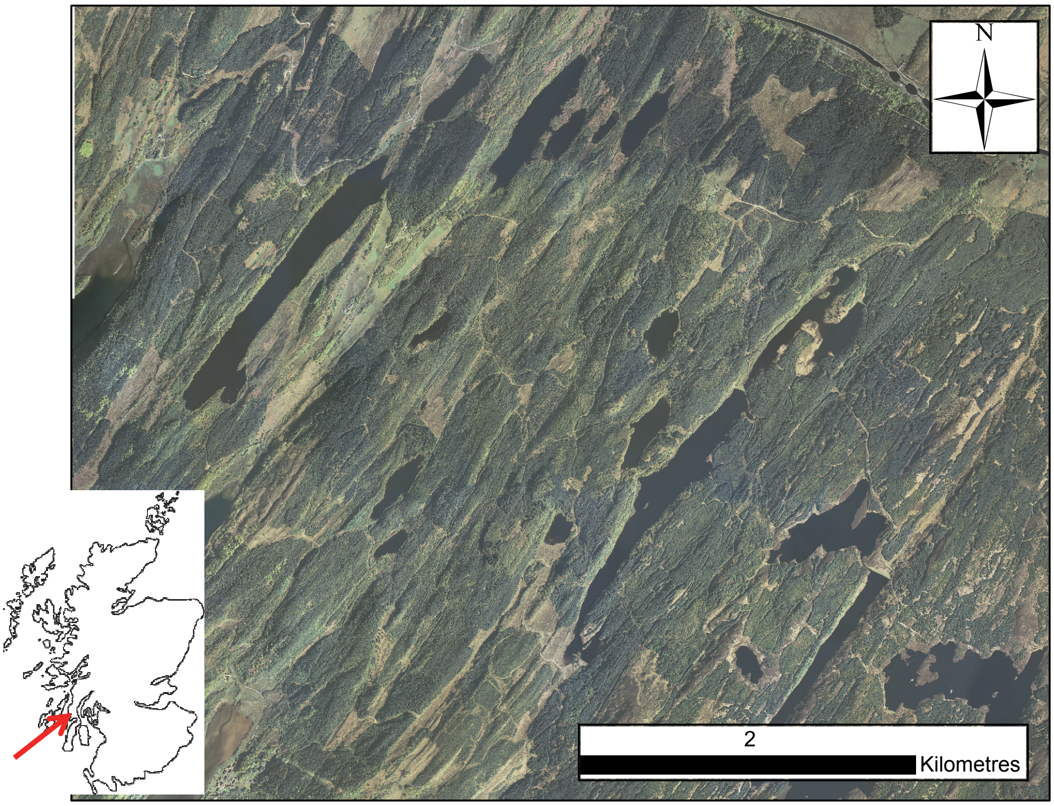

Figure 4-1 General physical and land cover in the Knapdale area based on a georectified 2008 aerial image provided by Ordnance Survey. Inset shows location of Knapdale. Image data reproduced by permission of Ordnance Survey on behalf of HMSO. © Crown Copyright. All rights reserved.

Figure 4-2 Examples of typical stream and loch habitat in the beaver trial area. Clockwise from top left: Inflow to Loch Fidhle; outflow from Loch Coille-Bharr; Loch Linne; Loch Unnamed (North).

The Knapdale streams are naturally buffered due to storage of runoff within standing waters that in total account for about 20% of the catchment area. Examples of typical standing water habitat are shown in Figure 4-2. The dominant land cover in the beaver trial area is native broad-leaved woodland and commercial conifer forestry (Figure 4-1) that together serve to further reduce the responsiveness of watercourses to rainfall, although many of the lowest lying areas have been converted to permanent pasture with sub-surface drainage.

5. METHODS

5.1 Hydrological monitoring

In March and April 2009 nine automatic water level recorders (i.e. integrated pressure transducers with data loggers (model OTT Orpheus Mini)) were installed at strategic locations (Figure 5-1; Table 5-1). A typical stream water level recording set up is illustrated in Figure 5-2 The choice of locations partly reflected positioning of stage boards that were installed in 2002 as part of a planned phase of monitoring to support an earlier licence application for the release of beavers. Locations also took account of the potential for upstream beaver activity in either lochs or streams and the need for ease of access to equipment for data downloading. Two recorders were used to record loch level (Loch Linne/Fidhle and Loch Losgunn). Others were placed on inflow or outflow channels from the main lochs and in one case on a control stream (Barnagad Burn) near Achnamara which has minimal upstream storage provided by standing waters. In November 2011 two further recorders were installed to monitor changes in the level of other water bodies (Dubh Loch and Loch Un-named (North)) following construction of beaver dams. All recorders were set to log water levels every 15 minutes based on the average of readings taken at 5 minute intervals.

Standard stage boards 1m high with 1cm graduation were installed on each of the 10 main standing water bodies, using boat jetties or posts to anchor the boards. A further six stage boards were installed alongside the water level recorders at each of the stream sites (Figure 5-1).

Automatic rainfall gauges were installed at three locations in the Knapdale area next to sites with a stage board and water level recorders (Figure 5-1). For most of the trial period the model used was the Global Water RG200. One rain gauge of a different design employed at Creagmhor (site 10) had to be replaced in June 2011. All rainfall gauges were of the tipping bucket design in which each tip (equivalent to 0.2mm of rainfall in the RG200 model) is recorded.

Data from level and rain gauge loggers were downloaded to a laptop at typical intervals of 4-6 weeks. Each downloading event was accompanied by a stage board reading for calibration purposes, plus a record of battery changes or any necessary adjustment to the position of the pressure transducer or stage board.

All equipment was installed by SNH staff and downloaded or read by Scottish Beaver Trial or SNH staff. All stage board readings were taken by several observers and have been assumed to be free from error in subsequent analyses. No data were collected during December 2010 and January 2011 when all lochs were frozen and rain gauges were removed from the field during this period.

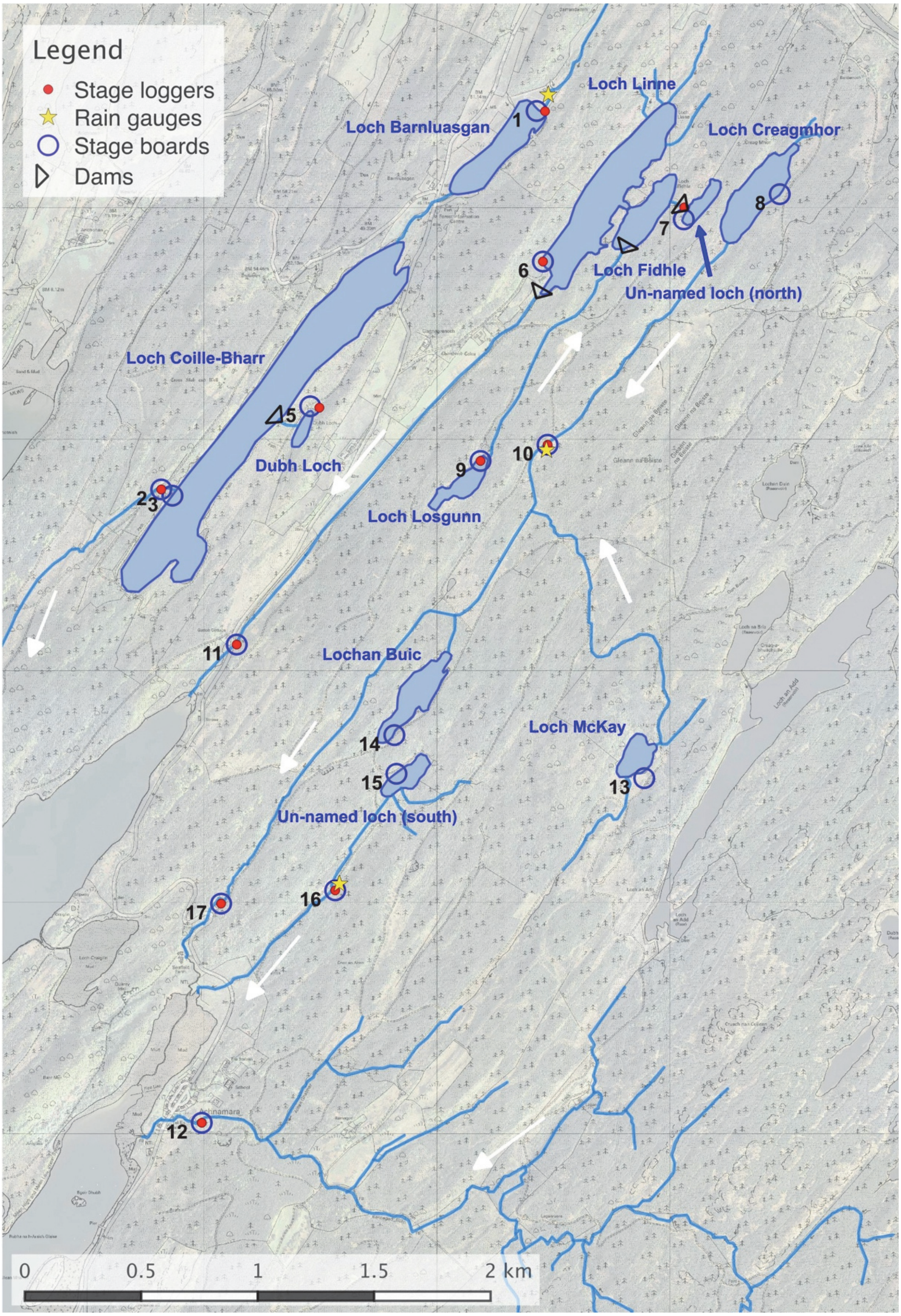

Figure 5-1 Distribution of instrumentation at Knapdale used for hydrological monitoring. Site identifiers are given in Table 5-1. Mapping data reproduced by permission of Ordnance Survey on behalf of HMSO. © Crown Copyright. All rights reserved.

Table 5-1 Description and locations of hydrological monitoring equipment employed at Knapdale over the period April 2009 to June 2014

Site No.	Location	NGR	Type	Stage board	Level recorder	Rain gauge	Beaver dam influenced
1	Un-named burn - Loch Barnluasgan	NR 79500 91400	inflow	*	*	*	
2	Un-named burn - Loch Coille-Bharr	NR 77817 89783	outflow	*	*		
3	Loch Coille-Bharr	NR 77865 89756	loch	*			
5	Dubh Loch	NR 78500 90100	loch	*	*		*
6	Loch Linne	NR 79456 90767	loch	*	*		*
7	Un-named loch (north)	NR 80061 90949	loch	*	*		*
8	Creagmhor Loch	NR 80473 91058	loch	*			
9	Loch Losgunn	NR 79188 89906	loch	*	*		
10	Un-named burn - Creagmhor Loch	NR 79476 89976	outflow	*	*	*	
11	Un-named burn - Loch Linne (Gariob Cottage)	NR 78141 89113	outflow	*	*		*
12	Barnagad Burn / Alltan Ghabhar (Achnamara)	NR 77991 87048	outflow	*	*		
13	Loch McKay	NR 79891 88536	loch	*			
14	Lochan Buic	NR 78818 88722	loch	*			
15	Un-named loch (south)	NR 78827 88555	loch	*			
16	Un-named burn - Un-named loch (south)	NR 78564 88050	outflow	*	*	*	
17	Un-named burn - Loch Buic	NR 78074 87993	outflow	*	*		

Note that site 4 was deleted from the monitoring network but the coding of sites has been maintained for consistency with downloaded data.

Figure 5-2 Water level recorder (at time of data downloading) and stage board set up on Un-named Burn at Gariob (site 11)

5.2 Treatment of data

5.2.1 Stage board readings

The stage board reading data was 97% complete for all date x site combinations apart from Dubh Loch where the board had proved hard to locate and by November 2009 had been completely submerged. Where data were missing for other locations they were estimated based on a linear regression between the data for that site and the site with the most closely related data. All missing values were predicted to lie within the standard deviation of the mean of the available data for the site (i.e. they were not outliers). Since predicted values accounted for only 2-5% of the data for a given water body and because regression coefficients were high (r^2 = 0.65-0.9) no additional allowance was made for the additional uncertainty in predicted values. All recorded instances of stage board adjustment were incorporated into the data. No obviously erroneous values were present in the dataset based on correlation with data either from other comparable sites, or where available, automatically recorded water levels.

5.2.2 Stream level data

All data were first checked against manual stage board readings for anomalies or drift and any adjustments in positioning of equipment recorded at the time of data downloading were applied to the subsequent data. Given the relatively long time series of data (5 years) that covered multiple high flow events of different magnitudes, coupled with an initial assessment showing relatively long response times of streams to rainfall events, all level data were converted to daily maxima. No stage-discharge relationships were available from which to derive discharge and the data referred to therefore deal exclusively with runoff depths at the point of logging.

5.2.3 Loch level data

Loch levels showed comparatively low variation on a within-day basis and consequently all data were standardised to daily maxima, which is the same as the stream data. No attempt was made to populate short periods of missing data associated with ice cover or battery failure. Automatically recorded water level data from Loch Losgunn collected in 2014 were rejected as they were not correlated with rainfall or water levels in other lochs suggesting that the pressure transducer may have become blocked or was no longer securely attached to its mounting.

5.2.4 Rainfall data

Rainfall data from the three different gauges were highly correlated (r^2=0.95 to 0.97; p<0.0001) on the basis of the daily total recorded. To provide the best representation of rainfall across the study site on a daily basis, we used the average daily values from across the available gauges. Data from at least two gauges were available for 83% of the five-year period. For 7% of the duration of the study sub-zero temperatures prevented rainfall collection by any gauges (mostly over the winter of 2010/11), although it can be assumed that rainfall under these conditions was minimal. For an initial five month period at the start of the study, only a single rainfall gauge (Creagmhor, site 10) operated successfully, although a gauge at Barnluasgan (site 1) had also been deployed. During this time there were several periods when stream flow indicated that recent rainfall had occurred yet no rainfall was recorded suggesting that the rain gauge at Creagmhor had become blocked by leaves or small twigs. Unfortunately this means there is not a reliable rainfall record for the duration of the period that the beaver dam on the outflow of Loch Linne was active (although, based on stream flows the most significant rainfall events still appear to have been captured). From October 2009 onwards a third rain gauge was operational at site 16 beside the un-named outflow burn from Loch Un-named (south). From this time onwards if rainfall was available for only one or two gauges we used the relationship between the rainfall from those gauge(s) and the average of all gauges when all three were operating to correct for any bias associated with using a subset of the three gauges during some data periods to estimate rainfall. Mean rainfall based on the average of data from all three gauges was 3.9±5.7mm, compared to 4.6±5.7mm for dates when rainfall was interpolated because only one or two gauges were operational. No additional allowance has been made for the additional variation inherent in interpolated data because in practice the error in the predicted values is very small.

5.3 Data analysis

5.3.1 Definition of dam treatments

For the purpose of the analyses described below beaver dams constructed in the Loch Linne catchment (Figure 5-1) during the trial were assigned to different treatment levels in order to assess their possible effects on loch or stream hydrology. The three treatment levels are defined in Table 5-2; (i) dammed outflow (2009), (ii) free flowing (2010 and 2011) and (iii) upstream catchment dams (2012 and 2013). Further details on the individual dams and their construction are given in section 6.3.

Table 5-2 Assignment of beaver dams in the Loch Linne catchment to different treatments

Location	Dates		Year(s)	Treatment
	From	To		
Outflow from Loch Linne	June 2009	Sept 2009	2009	Dammed outflow
Undammed	Oct 2009	Oct 2011	2010, 2011	Free flowing
Inflow to Loch Fidhle	Nov 2010*	end of trial	2012, 2013	Catchment dams
Outflow from Loch Unnamed (North) into Loch Fidhle	Oct 2011	end of trial	2012, 2013	Catchment dams

* Although construction of this dam began in November 2010 it was considered too small based on visits in May and September 2011 to be capable of affecting flows.

5.3.2 Relationships between loch water level and rainfall

To assess the relationship between rainfall and loch water levels in the presence and absence of beaver dams in the Loch Linne catchment, levels were regressed against cumulative rainfall over periods increasing by an increment of one day. General linear models (GLM) were used to describe this relationship, with the dam treatments (Table 5-2) being used as additional predictors. Analyses were carried out using SPSS version 19.0. The same approach was used to assess the possible sensitivity of water levels in Loch Losgunn to logging of forestry in the surrounding catchment. Rainfall acted as the covariate in the model and logging (pre or post) as an additional factor. In all cases it should be noted that these analyses lack any suitable control because the majority of water level recorders were deployed on streams, while the only lochs on which automatic water level recording was undertaken were influenced by beavers or forestry. Although dam building by beavers and forestry were the only hydrologically relevant changes in these specific catchments over the duration of the trial, the experimental design prevents us from stating with certainty that the water level responses observed are due only to these factors.

5.3.3 Loch water level regime

To describe the stability of loch water levels in different periods, the coefficient of variation (i.e. the standard deviation divided by the mean) was used. Loch water level range was also determined, based on the difference between maximum and minimum stage board readings, and then related to loch catchment area.

5.3.4 Indicators of stream hydrological regime

A number of simple indices were used to quantify the hydrological regime at different stream stations following suggestions by Gordon *et al.* (2004) or approaches used previously to assess effects of beaver dams or large wood accumulations on the hydrological characteristics of low-order streams.

Baseflow: this was determined by the hydrograph separation method using the local minimum approach which links levels immediately prior to the ascending limb with those at the tail of the descending limb (Gonzales *et al*., 2009)

Height of peak: peaks were defined where there was a doubling of baseflow over a period of up to 48 hours following an inspection of candidate peaks and the rate of response to rainfall across streams at Knapdale unbuffered by headwater storage. The Peak Over Threshold (POT) method was used to define individual peaks when these occurred in close succession. To qualify as a discrete peak, the trough between adjacent peaks had to be no more than two thirds of the height of both peaks, based on the method used for peak definition in the National Rivers Flow Archive (http://www.ceh.ac.uk/data/nrfa/data/peakflow_pot.html). The height of each peak was then expressed as the height above the baseflow depth. Over the period of interest 69 discrete peak events were identified using this approach.

Time to peak: this is the time in days between the peak on the index stream and the peak corresponding to the same rainfall event on the test stream (Nyssen *et al*., 2011).

Duration of peak: the duration of each event was defined by the length of time in days before flow returned to the baseflow depth or until there was another qualifying peak.

Volume of peak: the volume of each peak was estimated by the height of the peak multiplied by half of the duration of that peak, as defined above.

Ratio of height of peak to duration: this reflects the average rate of rise and descent in water level associated with an event and was estimated by the height of the peak divided by its duration).

5.3.5 Comparison of flow regime in beaver-influenced and control streams

To enable comparison of flow conditions between years and/or treatments where rainfall is likely to vary, the standard approach is to divide discharge by rainfall. In the absence of a reliable rainfall record we have instead used the daily maximum water levels for the Barnagad Burn at Achnamara (site 12), which are available for the entire period of interest (with the exception of 2 weeks in September 2013) as an indicator of effective rainfall. This stream has minimal headwater storage and has never been influenced by beavers but in terms of dimensions and catchment characteristics is comparable to watercourses elsewhere at Knapdale. Recorded levels at Achnamara had a stronger relationship with levels on the un-named stream at Gariob than any of the other gauged stream sites thus supporting the use of the Barnagad Burn as a comparator.

To assess the effects of dam building on downstream water-courses we then compared the various indicators of hydrological regime in the unnamed stream at Gariob (site 11) with the Barnagad Burn at Achnamara in relation to the three dam treatments shown in Table 5-2. All comparisons were based on a common period in each year from 1 June to 30 September since this covered the period in 2009 when the Loch Linne outflow dam was active, as well as providing coverage of a wide variation in intensity of runoff events. Beaver activity, including maintenance of dams, commonly diminishes during the winter (Novakowski, 1967) when runoff events are also likely to be of a sufficient size for dams to be filled and frequently overtopped. The summer therefore represents an ideal period to estimate the influence of beaver dams on hydrology.

Two approaches were adopted to analyse these data. The first used mixed models where the random effect is defined by a peak event identifier, in this case the date of the event. This has the effect of pairing the peaks by giving each peak its own intercept and these intercepts then have their own (assumed to be normal) distribution. The fixed effects to be tested were the stream (a two level factor: Barnagad and Gariob), treatment (a three level factor: free flowing, downstream and catchment dams) and month (a four level factor: June, July, August and September) plus all two-way interactions (i.e. stream x treatment, stream x month and month x treatment) and the three-way interaction (i.e. stream x month x treatment). The major effects of interest here are the interactions of stream x treatment or stream x month x treatment. These indicate that the two streams respond differently to the different treatments (stream x treatment interaction) or the pattern of variation between months within a treatment period differs between treatments and burns (stream x month x treatment interaction). Month was included in the models, not because of any explicit interest in the effect of month (on average it gets wetter from May to September) but because any variation in the response variable due to month can then be accounted for.

For all peak flow measurements the data were skewed and so the natural logs of the data were used and the normal distribution was assumed. To cope with zero measurements some number had to be added onto each datum prior to log transformation. This number depended on the data themselves and the transformed data were then examined using quantile plots to ensure that the assumption of normality was valid. The final decision on the appropriateness of a model fit was based on the distribution of the model residuals. Peak duration could not be modelled in this way as the random effects caused a problem in the model residuals. This could only be removed by the use of a generalised linear model (i.e. no random effects). Since this was not an entirely satisfactory approach, the second approach described below was used as an alternative. The variable ‘time to peak’ could not be modelled using mixed models as it is by default a difference between the streams and was modelled as such (see next approach).

For all analyses, R version 3.1.3 was used. As the log-transformed data could be assumed to follow the normal distribution, a linear mixed model was used to explain the data. The lmer() function in the lmerTest package was used to fit these models as this uses the Satterthwaite approximation to calculate the *p*-values.

The second approach was to take the difference between the two streams for each peak. The drawback of this approach is the loss of information on the sources of variation for each stream. Also, it means that main effects other than stream cannot be explored since the main effects in this model are effectively the same as the stream x treatment and stream x month interactions in the mixed modelling approach. When using differenced data the full model consisted of month, treatment, and their interaction. The value of an intercept that differs from zero is to reveal a difference between the streams. It can be compared with the stream main effect in the mixed effects model. The treatment main effect in this approach can be compared with the stream x treatment interaction in the mixed models and is the variable of most interest.

For peak duration, the differences between the streams could be assumed to follow the normal distribution and so were modelled with a linear model using the lm() function in the stats package. The ‘ time to peak’ data were already in the form of a difference between the two streams as the variable is defined by the difference in days (or ‘lag’) between the start of a peak event in one stream and the start of the same peak event in the other stream. The data (as integers) for ‘time to peak’ were skewed, running from -1 to +4. Adding 1 to these data allows the data to be modelled using the Poisson distribution (whose minimum is zero). The variance of the time to peak data was smaller than expected under the Poisson distribution and so the quasi-Poisson distribution was used to correct for this.

For the linear mixed effects models (i.e. where the normal distribution can be assumed), two approaches were taken for model selection. The first was to use the automated stepwise procedure in the step() function from the lmerTest package. This uses the *F*-test to decide on which variable to remove at each step starting from the saturated model. The second approach was to manually compare the models using the anova() function from the lmerTest package which allows the models at each step to be explored. First the full model was examined using anova() which shows the significance of each variable. The model was then refitted with the variable least likely to be important removed. Interactions were always removed before their counterpart main effects. Alternative models were then refit in anova() using the maximum likelihood to determine if the variable removed made a significant difference to the fit of the model.

For the approach based on modelling the difference, model selection was undertaken using the function drop1() from the stats package, which uses the *F*-test or Chi-Square test as appropriate. After deciding on the ‘best fitting model’, this model was explored further via relevelling of the factors to isolate the main differences.

6. RESULTS

6.1 Regional weather conditions over the monitoring period

Publicly available Meteorological Office raw data for the long term monitoring station at Dunstaffnage were used to obtain an indication of weather conditions over the trial period relative to the long-term average (1972-2014 http://www.metoffice.gov.uk/pub/data/weather/uk/climate/stationdata/dunstaffnagedata.txt). Dunstaffnage lies 45km north of Knapdale but is subject to the same Atlantic weather systems and so experiences a similar temperature regime as well as amount and pattern of rainfall distribution. An appreciation of weather conditions over the trial period is relevant to subsequent discussions on the effects of beavers on hydrology and how these effects change between years and the types of dams that have occurred at different times.

The rainfall and temperatures during the trial are shown in Figure 6-1 along with the long-term averages (1972-2014). The first two winters of the trial (2009/10 and 2010/11) were very cold and dry with average monthly minimum temperatures in December and January at or below zero which is 2-3^{o}C below the long-term average (1972-2014). In the first of these winters, rainfall from December to March was only 36% of the average. In the second winter, rainfall in November and December was 43% of the average. January and February 2013 were slightly colder than average but the other winters during the trial were comparatively mild and wet. This was especially the case for the period September to December 2011, which experienced 70% more rainfall than the average for this period. In the winter of 2013/14 rainfall from December to February was 51% higher than average. Summer conditions during the trial were generally closer to the norm but May and June, typically the two driest months of the year, received unusually low rainfall in 2010 (43% of average) and 2013 (57% of average), whilst May 2011 was exceptionally wet with total rainfall over three times higher than the average.

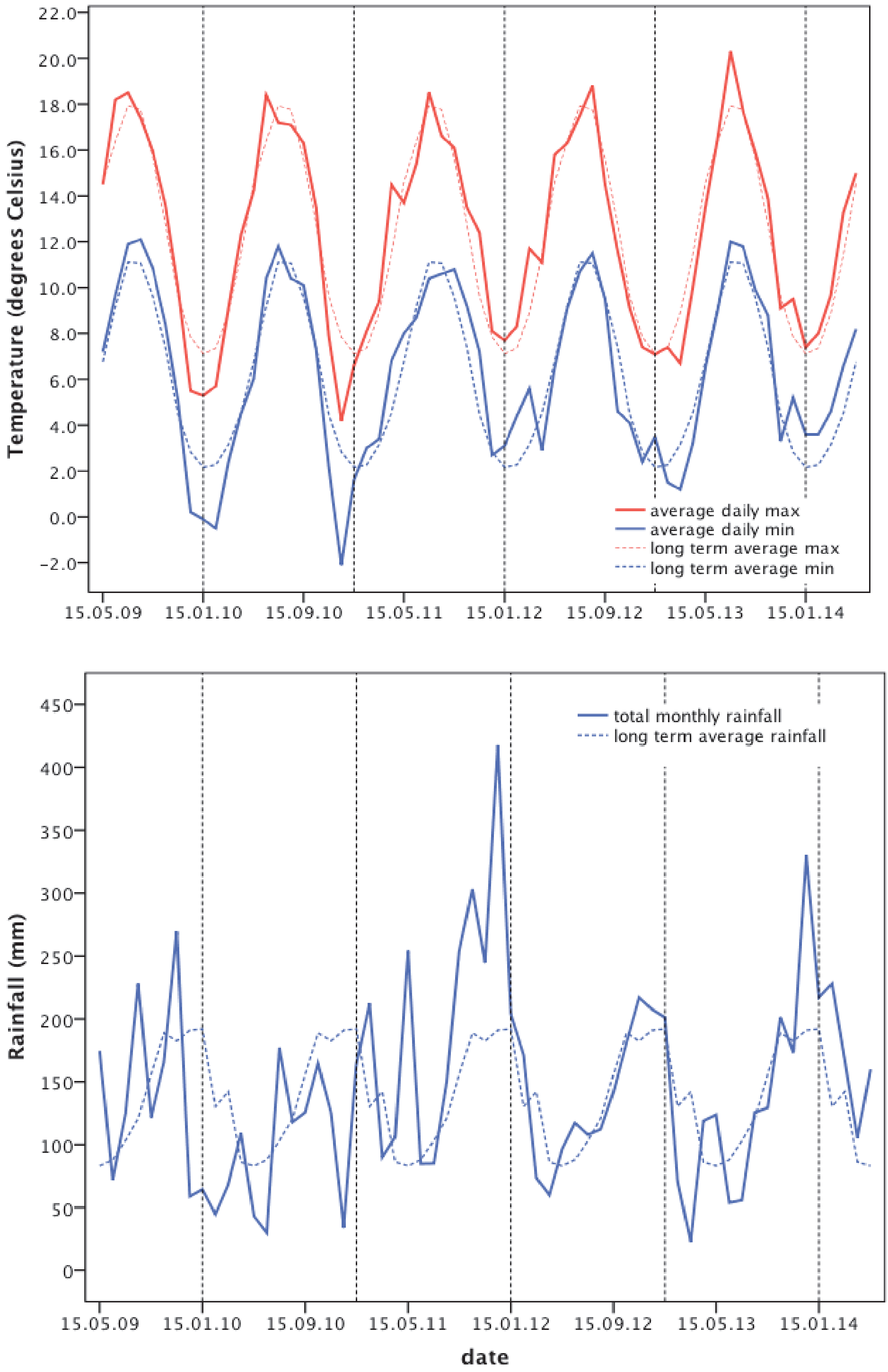

Figure 6-1 Temperature (upper) and rainfall (lower) for Dunstaffnage (45km north of Knapdale) for the trial period (May 2009-2014) and relative to long-term average conditions for the period 1972-2014.

6.2 Water level characteristics of the lochs

Standing waters at Knapdale are mostly of small to modest size but are large relative to their catchment areas (median ratio = 0.19) and, as such, would be expected to have a relatively stable regime and narrow water level range (Wetzel, 2001). This is confirmed from inspection of the stage board readings. The median water level range (i.e. difference between recorded maxima and minima) was 0.38m, ranging from 0.63m in Loch Un-named (South) to 0.22m in Loch McKay (Table 6-1). Range generally increased with a decline in the loch to catchment area ratio, although there were too few data to establish a significant relationship between these variables. The water level in Dubh Loch was increased by a maximum of 1.1m as the result of a beaver dam on the outflow (see 6.3.4). In the absence of this increase the water level in Dubh Loch is likely to have been very stable, probably varying by less than 0.2m, given the small catchment of this loch, pre-trial visits at different times of year, and based on the extensive emergent vegetation present.

Table 6-1 Water body characteristics of the Knapdale lochs in terms of influences on water level regime

Loch name	National Grid reference	Altitude (m)	Loch area (ha)	Catchment area (ha)	Loch to Catchment area ratio	Water level range (m)	COV of level	Beaver influence
Dubh Loch	NR784902	38	1.6	3.6	0.44	1.08	0.17	Y
Creagmhor Loch	NR803910	68	5.2	19.7	0.26	0.32	0.19	N
Loch Barnluasgan	NR792912	43	5.3	42.0	0.13	0.45	0.33	N
Loch Coille-Bharr	NR782901	32	33.4	177.1	0.19	0.47	0.20	N
Loch Linne+Loch Fidhle	NR797910	39	16.5	102.3	0.16	0.51	0.17	Y
Loch Losgunn	NR791898	68	2.1	12.2	0.17	0.33	0.21	N
Un-named loch (N)	NR801910	68	1.1	4.3	0.26	0.38	0.16	Y
Lochan Buic	NR789889	49	3.9	15.4	0.25	0.35	0.26	N
Loch McKay	NR798886	142	1.9	10.0	0.19	0.22	0.10	N
Un-named loch (S)	NR788885	47	1.6	11.0	0.15	0.63	0.51	N

Note: COV refers to the coefficient of variation of level (i.e. standard deviation/mean)

6.3 Hydrology of beaver-influenced water bodies

6.3.1 Loch Linne outflow dam

During summer 2009 the pair of beavers released onto Loch Linne constructed a dam in the channel about 200 metres downstream of the loch outflow. At its peak this structure was about 0.4m in height (Figure 6-2). At the same time two lower (0.1m high) but longer dams were constructed upstream at the point where the loch first converges into an outflow (Figure 6-2). Figure 6-3 suggests that construction of these dams started almost immediately after beavers were released on to Loch Linne at the end of May. From June-September 2009, Loch Linne experienced a progressive filling phase. The difference between the water levels of this loch and in the outflow stream near Gariob cottage (2km downstream) increased during this period. In early October 2009 the main Linne outflow dam was removed in line with the conditions of the release licence, although the two smaller dams upstream may have remained functional for slightly longer.

Comparison between the pre- and post-dam removal phase in 2009, or with the same period in 2011 (Figure 6-3) shows that water levels in Loch Linne would normally rise quickly, reaching a peak 1-2 days after levels peak at Gariob, thereafter declining by 0.2-0.25m over the following 15-20 days or until the next runoff event. The peak at Gariob occurred earlier than at Loch Linne because the intervening 2km section of channel is straightened (thus accelerating passage of water) and the immediate catchment at Gariob is mostly permanent pasture bounded by a steep valley side to the south. This means that locally derived runoff is delivered quickly to the channel. Conversely, on Loch Linne the catchment is almost entirely wooded and includes standing waters. These delay the runoff from the feeder streams into the loch. Also, the outflow is heavily overgrown (Figure 6-2) which adds to the bottleneck effect created by the outflow.

Figure 6-2 Examples of beaver dams at Knapdale. Clockwise from upper left: inflow to Loch Fidhle (May 2013); secondary dam on outflow of Loch Linne (Sept 2009); main dam on outflow of Loch Linne (Sept 2009); Outflow dam on Loch Un-named (North) (May 2013). All pictures N. Willby.

At the highest levels recorded in Loch Linne, the stream at Gariob varied considerably in stage during the dammed period, with both high and low water levels. High water levels would be typical under unconstrained wet weather flow and low water levels would occur during dry periods when the loch level remained high owing to its dammed outflow (Figure 6-4). Although the outflow dam was associated with some of the highest water levels recorded in Loch Linne over the five year study period, it is notable from Figure 6-4 that levels at least as high, and occasionally higher, did occur on Loch Linne in the absence of any impoundment.

The relationship between levels in Loch Linne and at Gariob is clarified by Figure 6-5 which explores the relationship of the loch level to the preceding rainfall under different levels of damming. The relationship between the water levels of Loch Linne on each day and the accumulated rainfall leading up to that day were tested for just that day up to the preceding 15 days' rainfall. It was found that loch levels were best related to the rainfall total delivered over the previous 12 days. During both the free-flowing (r^2 = 0.61; $p<0.0001$) and the catchment dams periods (r^2 = 0.64; $p<0.0001$) loch level was highly responsive to rainfall over this previous period. However, during the period when the loch outflow was dammed this sensitivity was greatly reduced (shown by the significant outflow dam x rainfall interaction term in Table 6-2) and the relationship with rainfall was considerably weaker (r^2 = 0.11; p = 0.004). It is also notable that during the phase when catchment dams were intercepting inflow to Loch Linne the loch level was slightly but significantly higher (Table 6-2). The cause of this is unclear. Upstream dams might have maintained inputs to the loch during dry weather periods via stored water. Another possibility is that direct felling by beavers adjacent to the outflow channel or increased wood inputs to the littoral zone of Loch Linne through felling have, over time, led to an increased blockage effect in the outflow channel, thus raising levels in Loch Linne without a dam itself being present.

Table 6-2 Parameter estimates for a general linear model relating water levels in Loch Linne to the accumulated rainfall in the preceding 12 days and the type of damming.

Parameter	Coefficient	Std. Error	*t*-value	*p*-value
Intercept	0.4500	0.0040	101.598	<0.001
12 day cumulative rainfall	0.0030	0.0001	33.324	<0.001
Catchment dams	0.0200	0.0060	3.191	0.001
Outflow dam	0.1450	0.0160	9.034	<0.001
Catchment dams x rainfall	-0.0001	0.0000	-0.483	0.629
Outflow dam x rainfall	-0.0010	0.0000	-3.098	0.002

Note: the free-flowing treatment is used as the reference category for assessing the effect of the outflow dams or catchment dams and the intercept term for this treatment (i.e. 'intercept') is the predicted water level when there is no rainfall. The treatment main effects (i.e. 'Catchment dams' and 'Outflow dam') are the differences between the free-flow treatment and these treatments when there has been no rainfall. The '12 day cumulative rainfall' is the slope of the relationship between water level and rainfall during the free-flowing period. The 'Catchment dams x rainfall' and 'Outflow dam x rainfall' are the interactions. These give the differences in the slope for the water level and rainfall relationship between these periods and the free-flow period. A significant difference means that the relationships during the relative two periods are different.

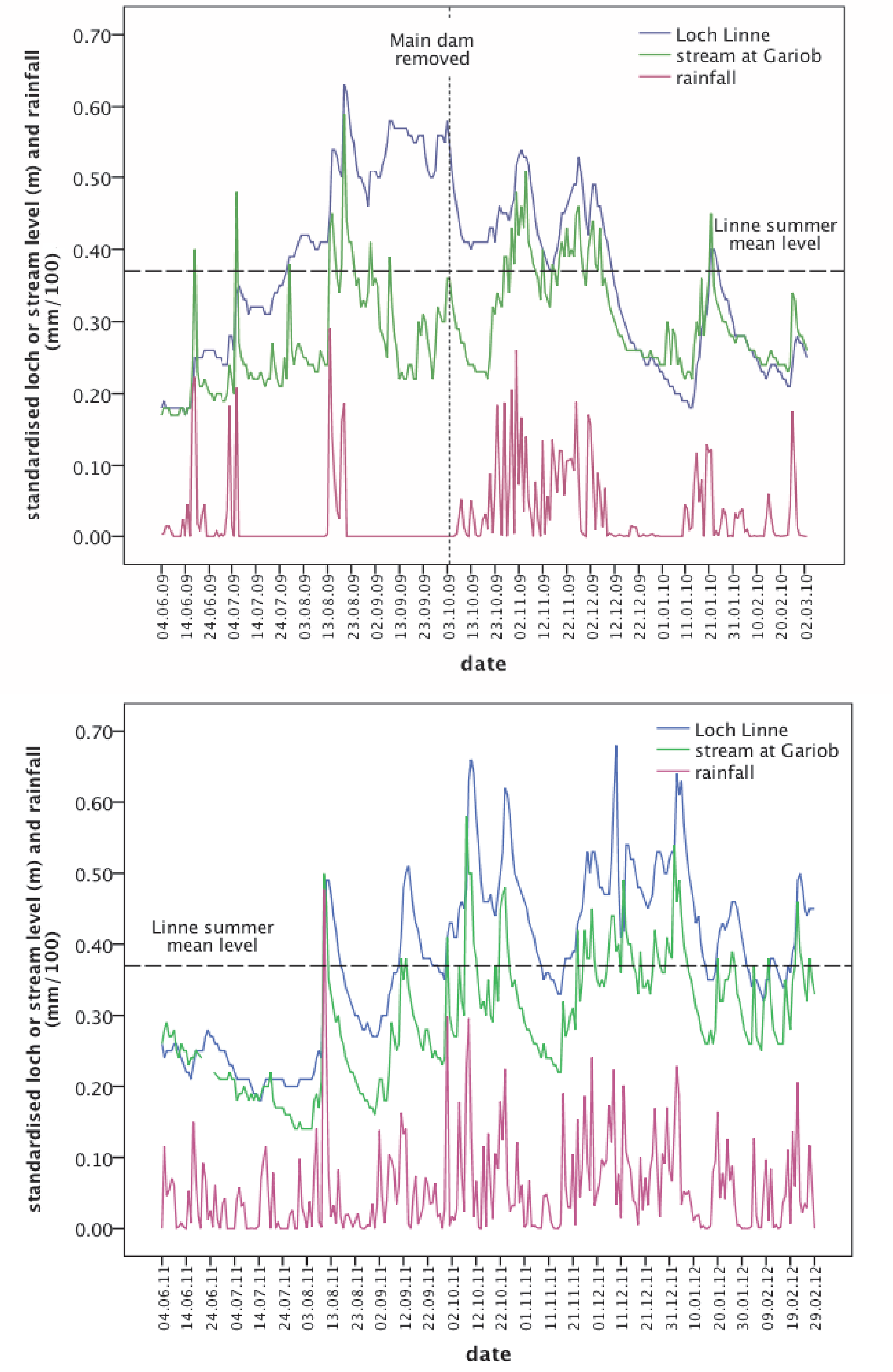

Figure 6-3 Water levels in Loch Linne and its outflow stream at Gariob from June to February. The upper plot includes a period of dam building activity and subsequent dam removal on the Loch outflow during 2009 while the lower plot covers a period in 2011/12 when no dams were present on the outflow. Note that there are several periods in 2009 when the rainfall signal is incomplete.

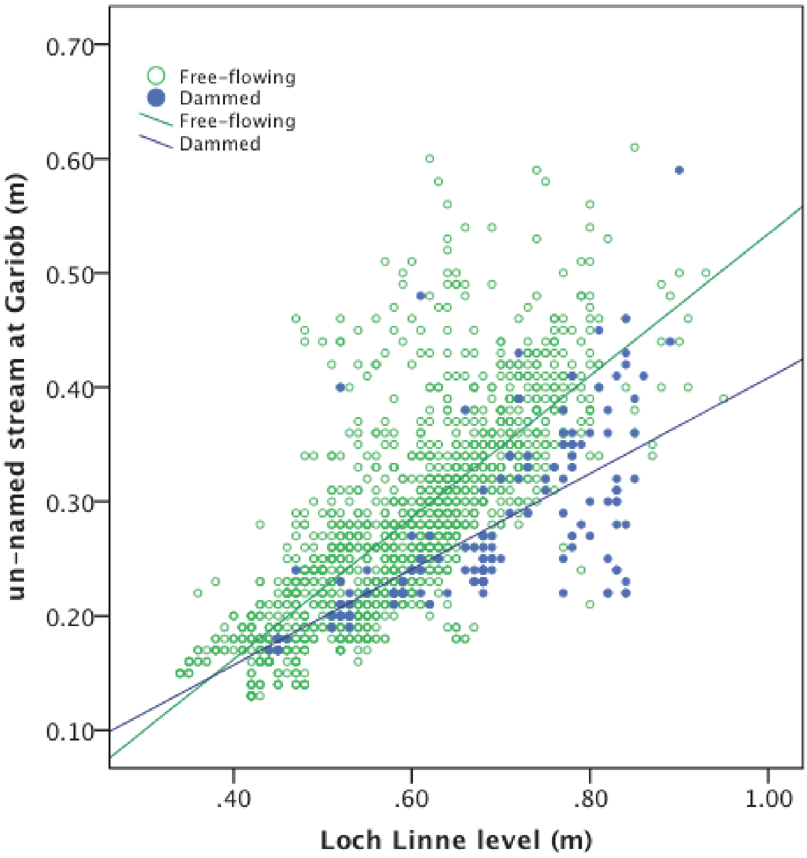

Figure 6-4 Daily maximum water levels on the un-named stream at Gariob compared to levels upstream in Loch Linne during and outwith the period when the Loch Linne outflow was dammed.

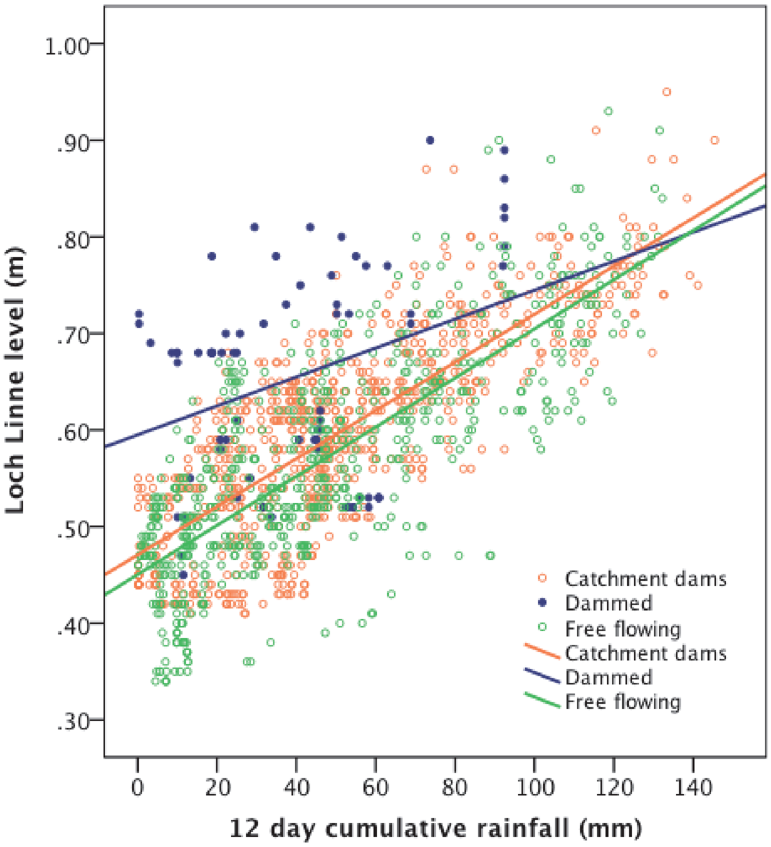

Figure 6-5 Water levels in Loch Linne in relation to rainfall over the preceding 12 days showing effect of outflow and upper catchment dams in relation to free flowing conditions.

6.3.2 Outflow dam on Loch Un-named (North)

From October 2011 onwards beavers on Loch Un-named (north) began the construction of a low dam on the outflow of this loch (Figure 6-2) that connects it via a cascade over an escarpment into Loch Fidhle. In December 2012 an automatic water level recorder was installed on Loch Un-named (north). From this point onwards water levels remained stable, fluctuating by only 0.15m, with a late spring minimum consistent with the months of lowest rainfall. In contrast to several other water bodies there is no evidence of a decline in water level in Loch Un-named (north) during spring 2012 after this loch was overfilled in late 2011. This suggests that the surrounding mire may have proved effective at absorbing excess precipitation, thus reducing the fluctuation in water levels (Figure 6-6).

Prior to the dam being constructed the only available level data for this loch are from stage board readings. These provide a baseline for comparison of stability in water levels relative to other similar water bodies. For both the pre- and post-damming periods, the coefficient of variation was calculated for Loch Un-named (north) and other lochs of similar size and inflow characteristics (Loch Losgunn and McKay) (Table 6-3). The coefficient of variation in water level in Loch Un-named (north) was lower following damming but in other comparable water bodies increased or remained similar over the same period.

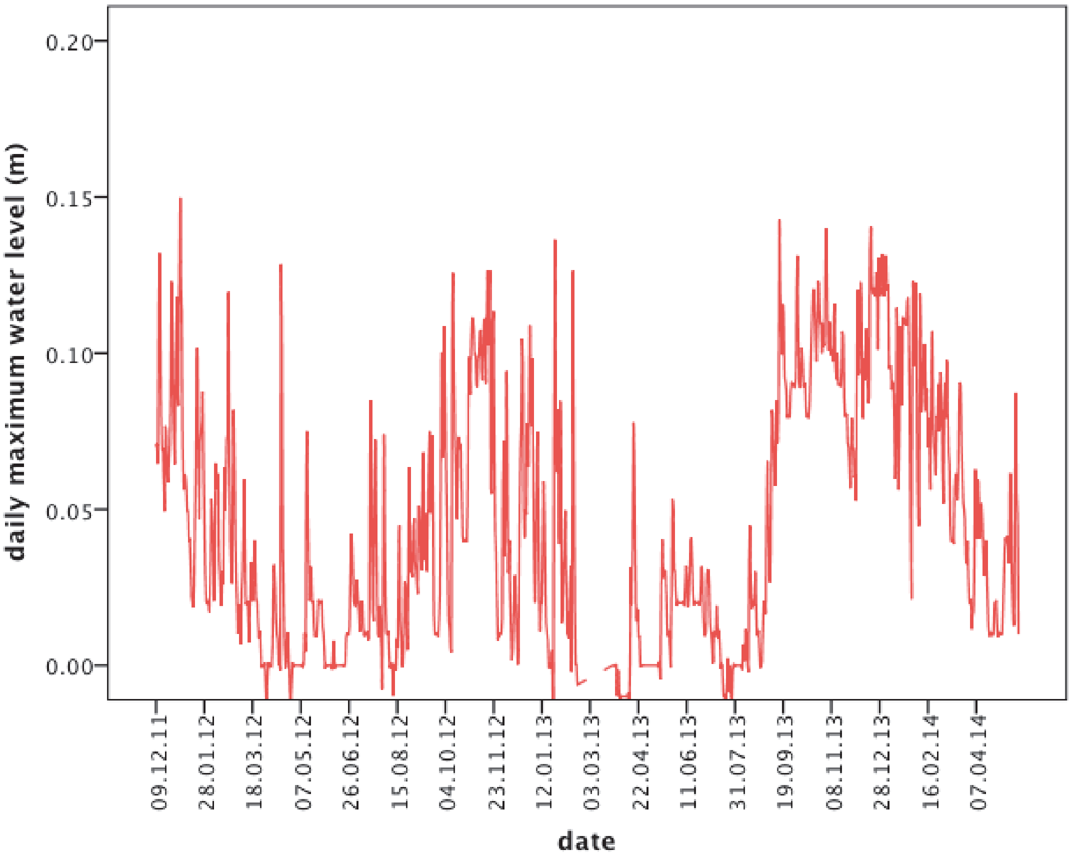

Figure 6-6 Water levels in Loch Un-named (north) based on automatic water level recording since December 2011.

Table 6-3 Coefficients of variation in water levels in three comparable lochs based on stage board readings in the periods prior to and after construction of the dam on the outflow of Loch Un-named (north).

	Un-named (N)	Losgunn	McKay
Pre-dam phase (n=26)	0.080	0.111	0.084
Post-dam phase (n=28)	0.037	0.177	0.104

6.3.3 Inflow dam on un-named stream from Loch Losgunn to Loch Fidhle

In autumn 2010 the Loch Linne/Fidhle beaver family began to construct a dam on the inflow to Loch Fidhle from Loch Losgunn. This is the major surface water input to the Loch Linne system. The dam structure is described and illustrated in Perfect *et al.* (2015). Initially this dam was composed only of small birch twigs and was a fairly temporary structure. It is unlikely to have had a significant additional influence on flow into Loch Fidhle beyond that of a typical small wood jam which occur at high frequency on many Knapdale streams (Perfect *et al*., 2015). However, by 2012 this dam had been reinforced and increased in height (Figure 6-2) and by 2013 a smaller secondary dam had been constructed 30m upstream. These dams were commonly bypassed under high flow and appear to be more permeable than the Dubh Loch dam, but even so it is likely to have impeded flow into Loch Fidhle and subsequently Loch Linne, especially under low flow conditions.

There are no direct hydrological measurements that can be used to assess the effects of these structures. Section 6.4 considers the possible combined effects of all the dams in the upstream part of the Loch Linne catchment (sections 6.3.2 and 6.3.3) on the flow in the outflow stream from Loch Linne relative to a control stream.

6.3.4 Outflow dam on Dubh Loch

Having been originally introduced to Loch Coille-Bharr, beavers moved quickly to the adjacent Dubh Loch which was originally a small well-vegetated pond. This water body sits in a small basin with a diffuse inflow from the south through fen peat and a poorly-defined outflow to the west into Loch Coille Bharr over a distance of 100m. Having colonised Dubh Loch, beavers began to dam the outflow into Loch Coille Bharr. Precisely when this commenced is unclear; there was no evidence of a rise in water level in late September 2009 yet a dam of over 1m high had been constructed by late November of that year. No stage board readings are available for this period and readings only started in May 2011 when a new stage board was erected and calibrated against the old submerged stage board. In early December 2011 an automatic water level recorder was installed on Dubh Loch. Stage board readings and staining on the stage board suggest that Dubh loch was at its maximum depth at this time. This is consistent with the high rainfall during the preceding three months, which was 52% above the average for this period. When mapped in May 2012 the area of Dubh Loch was found to have increased by 4.7 times from a pre-damming baseline of 0.38ha to 1.79ha (Willby *et al*., 2014).

The most striking feature of the level data for Dubh Loch is the gradual but consistent drop in level by a total of 0.3m between December 2011 and June 2014 (Figure 6-7). Mapping in May 2013 also confirmed that the area of the water body had decreased since May 2012 (Willby *et al*., 2014). Given that stage board readings reveal a gradual increase in level by 0.15m over the period from July to December 2011 it is quite likely that the early part of the subsequent decline is simply a re-adjustment in level following a prolonged period of exceptionally high rainfall (December 2011 received 2.2 times the long term average and was the wettest in the last 32 years). A decline in level during the first half of 2012 is shown by several other small water bodies at Knapdale, including Loch McKay and Loch Losgunn, which were not affected by beaver dams. Water levels on Dubh Loch then remained stable until May 2013 following which they have declined further. June and July 2013 were especially dry, receiving only 57% of their average rainfall yet the period December 2013 to February 2014 was again very wet, with 51% more than the average for this period, which should have been more than adequate to correct the summer deficit.

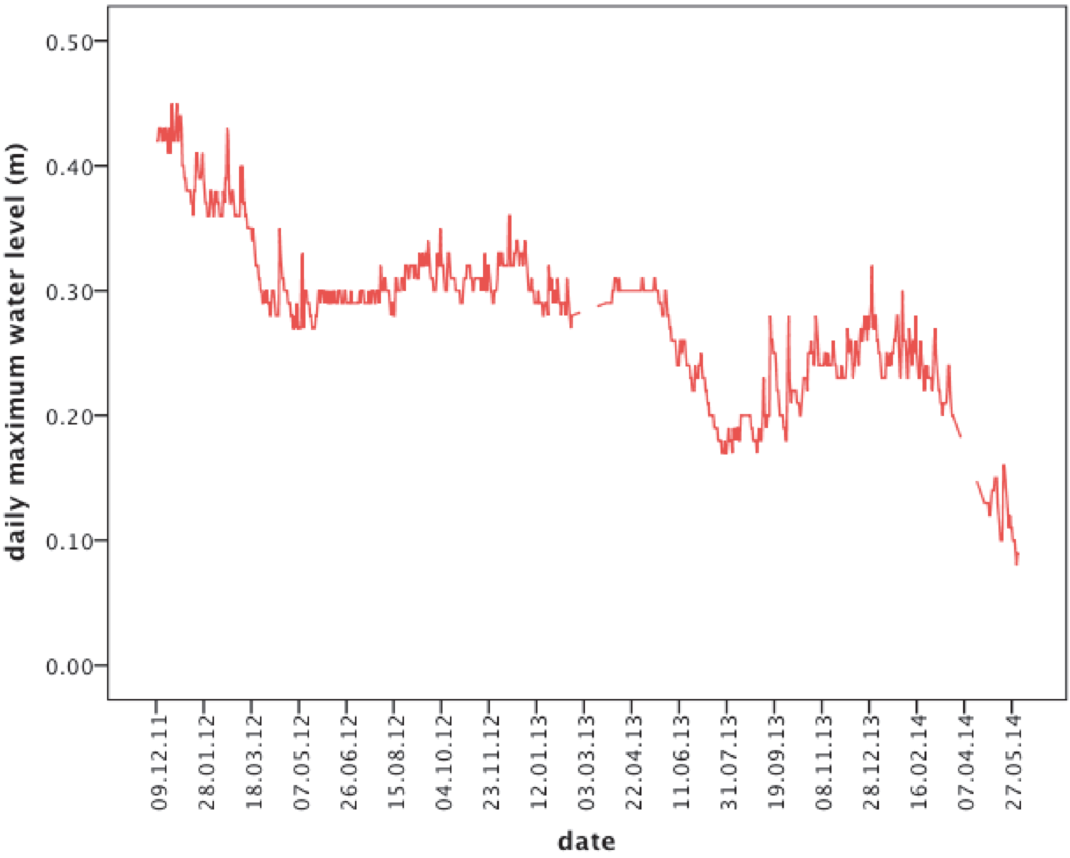

Figure 6-7 Water levels in Dubh Loch from December 2011 onwards based on automatic water level recording.

The overall impression, reinforced by field surveys in May and September since 2011, is that Dubh Loch is gradually losing water. Some of the initial loss may simply reflect the adjustment following overfilling in late 2011 (referred to in 6.3.3), but, unlike other lochs, this loss has continued in Dubh Loch. Recent monitoring (February 2015) indicates a continued decline in level. The loss of water in Dubh Loch is surprising as there should be significant potential through storage in peat and local groundwater to buffer losses. There are various possible explanations for these losses. Firstly, evaporative losses may have increased given the significant rise in extent of shallow marginal habitat that has become exposed over time through dieback of trees and subsequent loss of shading. Second the dam may have increased in permeability or lost some of its height due to settlement of material, drying of exposed peat used to pack the dam, or sinking of the dam base into the surrounding submerged peat. The crest of the dam is now well vegetated which will add further weight to the structure (Figure 6-8). Visits in September 2013 and May 2014 to Dubh Loch revealed that the water level was at the crest of the dam at the time. Combined with the drop in levels this implies that capacity is falling partly due to a reduction in dam height. Use of Dubh Loch by beavers has declined since August 2013 with animals now more commonly residing in the south-west corner of Loch Coille Bharr. Maintenance of the dam by beavers may therefore have declined. A third possibility is that change in the structure of newly submerged peat or fracturing of peat from the existing basin has opened new flow paths for seepage into the surrounding fen or drainage into Loch Coille-Bharr. A final related possibility is that canal building by beavers in the south part of the site has disrupted the inflow of water, although given the continuity of the saturated peat this seems unlikely.

Figure 6-8 Condition of the dam on the outflow of Dubh Loch in May 2013 (left picture) and May 2014 (reverse angle, right picture).

6.4 Other changes in the Knapdale catchments during the study period

The only notable change with potential hydrological consequences to occur during the study period was harvesting of commercial forestry in the catchment of Loch Losgunn in spring 2012. These operations affected about 40% of the loch catchment area and there is compelling evidence that they altered its hydrological characteristics.

An analysis of the relationship between water levels in Loch Losgunn and cumulative rainfall over different preceding time periods showed that levels were most closely related to rainfall received on the same and the previous day. The short time period compared with the 12 day cumulative rainfall total identified in the case of Loch Linne (section 6.3.1) reflects the small size and steepness of the Loch Losgunn catchment. A GLM relating total rainfall received on the same and the previous day to water levels in Loch Losgunn, showed there to be a highly significant (*p*<0.0001) additional effect of harvesting (pre or post) on water levels. This is based on automated water level recording, with modelled levels being 4.9±0.05cm higher in the post harvesting period with respect to rainfall (Figure 6-9).

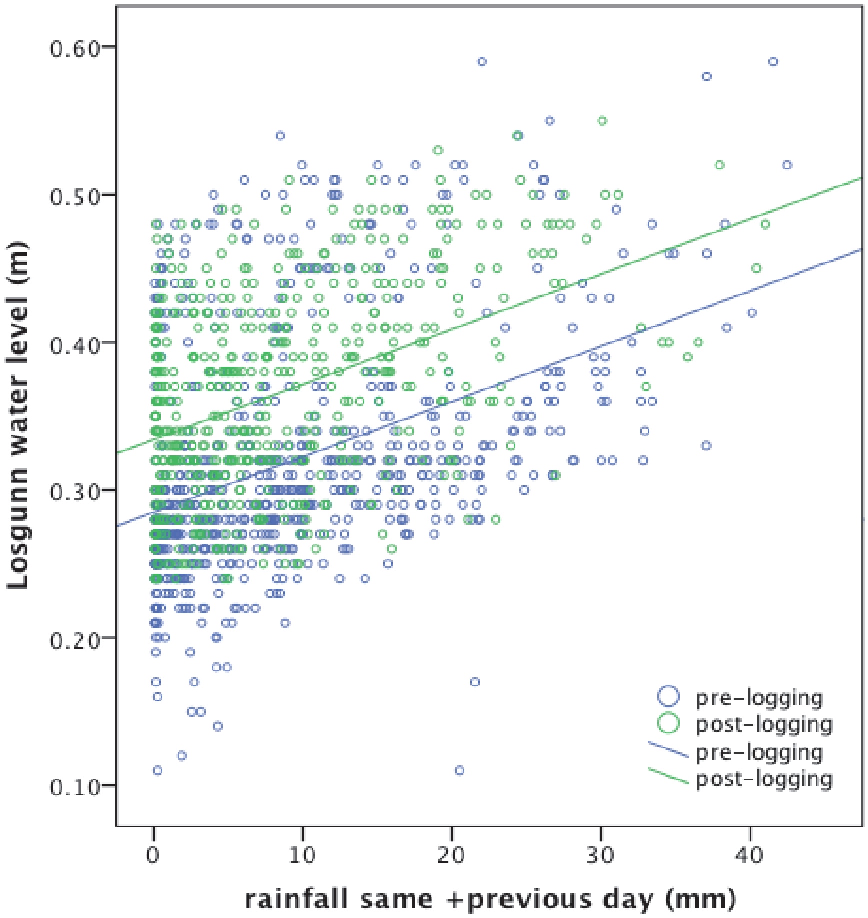

Figure 6-9 Relationship between automatically recorded water levels in Loch Losgunn and recent rainfall in the periods pre-and post-forest harvesting.

Second, using ANOVA to compare stage board levels in the two time periods, of all the lochs where beavers did not exert a direct influence on drainage, Losgunn is the only loch to have shown a significant (p<0.001 with Bonferroni correction for multiple comparisons) increase in level (from 31.4±11.6cm to 38.2±13.9 cm) between the pre- and post-tree harvesting period (Figure 6-10).

Taken together these findings indicate that less runoff is being retained by the catchment of Loch Losgunn and so is being delivered at a faster rate into the loch during or following rainfall and/or is being retained in the loch for longer after a rainfall event. The Loch Losgunn outflow is especially small and therefore conducive to retention of this extra runoff. These findings in themselves are unremarkable since the disruptive effects on runoff of clear felling commercial forestry are widely recognised (Roberts & Crane, 1997), although their exact nature is often difficult to predict (Tetzlaff *et al*., 2007). However, they are significant in the present context because they prevent us from concluding that any downstream hydrological changes (see section 6.5) are exclusively the result of interruptions to flow caused by beaver dams.

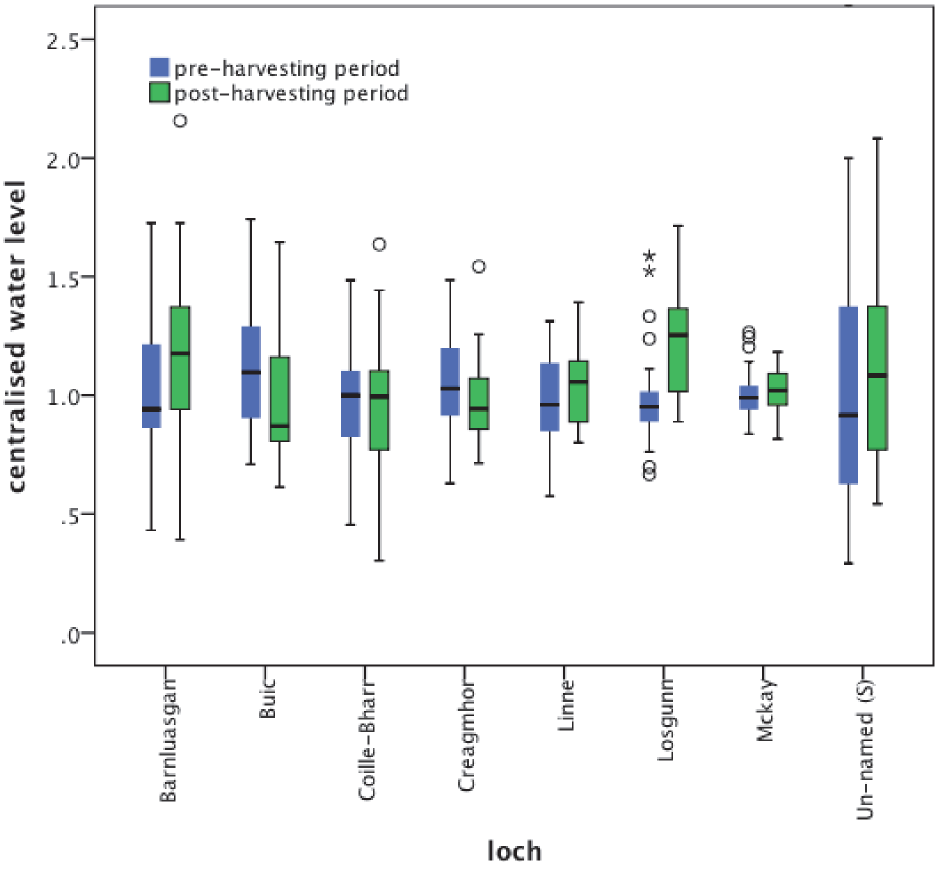

Figure 6-10 Comparison of centralised water levels (value divided by median) based on stage board readings for eight lochs in the period prior to forest harvesting at Loch Losgunn (April 2009 to March 2012; n=30) and in the subsequent period (April 2012 to June 2014; n=24).

Note: Bars show median value (black line); interquartile range (coloured box); whiskers delimit the most outlying samples that lie less than 1.5 box lengths from the upper or lower quartile. Circles and stars are outliers and extreme values respectively.

6.5 Effects of dams on stream hydrological regime

The potential consequences of dam building in the Loch Linne catchment were assessed by comparing the automatically logged water level at Gariob on the un-named outflow stream from Loch Linne with a site near Achnamara on the Barnagad Burn. The latter is minimally influenced by upstream standing waters and has never experienced any beaver activity and is therefore treated as a control. The site at Gariob should reflect any effects on hydrology of dam building in the upstream catchment since it incorporates the structures described above in 6.3.2 and 6.3.3. There is no suitable comparator for Dubh Loch and, since it accounts for only 2% of the Loch Coille-Bharr catchment the likelihood of a detectable change in the water level of this loch or its outflow stream is considered to be very small.

Three ‘treatments’ were evaluated (Figure 6-11). Firstly the dammed outflow on Loch Linne (2009) during which 16 peak events were defined; second, a free-flowing phase (2010 and 2011) when dams were either absent or very small (30 peak events); and a final phase when dams were present only in the upper parts of the catchment of Loch Linne (2012 and 2013) on the inflows from Loch Losgunn and Loch Un-named (North) (27 peak events). A basic comparison of flows between the control and test site in these periods in shown in Figure 6-12.

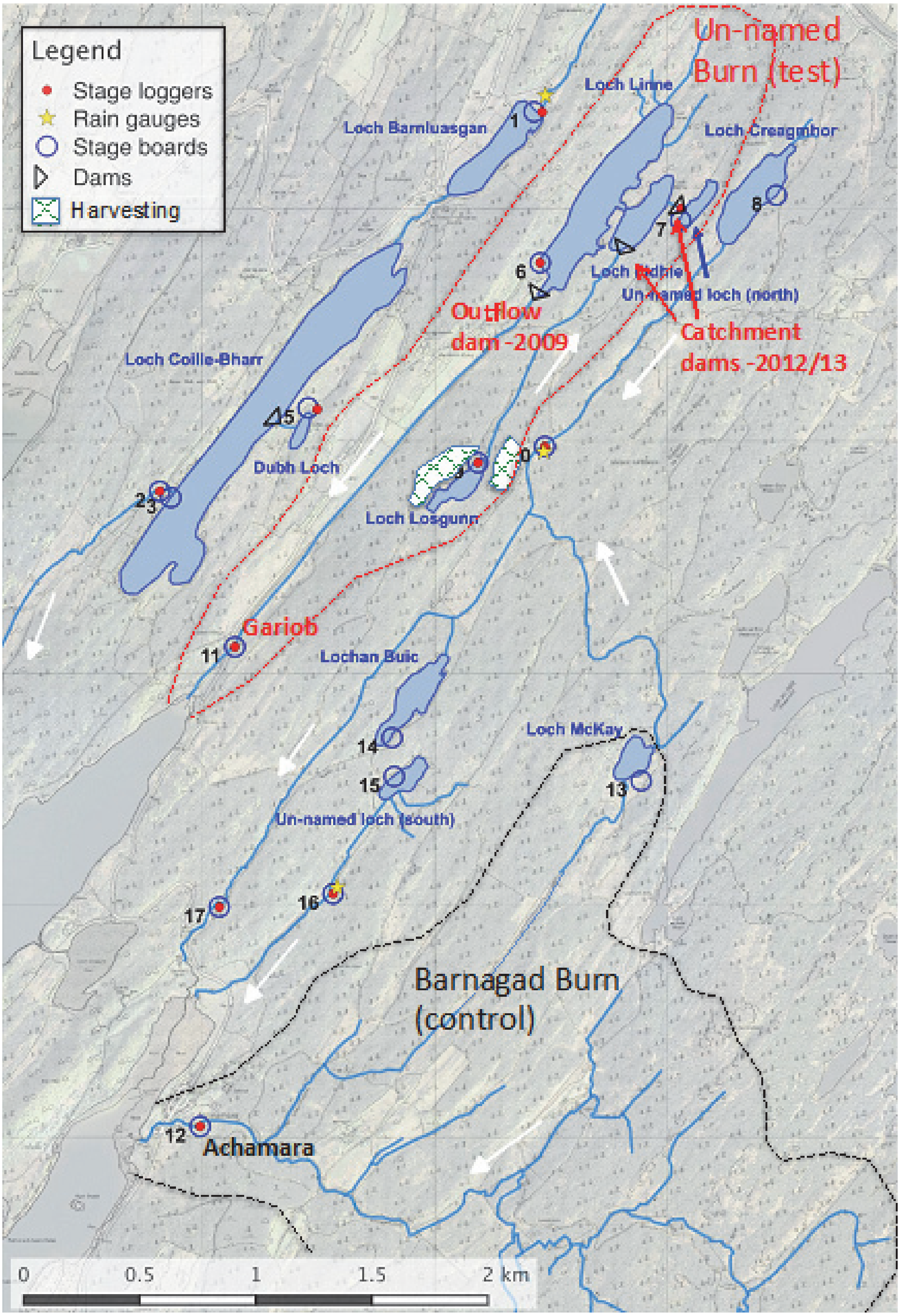

Figure 6-11 Location of test catchment (un-named outflow burn from Loch Linne) and control catchment (Barnagad Burn), showing position of instrumentation and allocation of dams to different 'treatments'. Mapping data reproduced by permission of Ordnance Survey on behalf of HMSO. © Crown Copyright. All rights reserved.

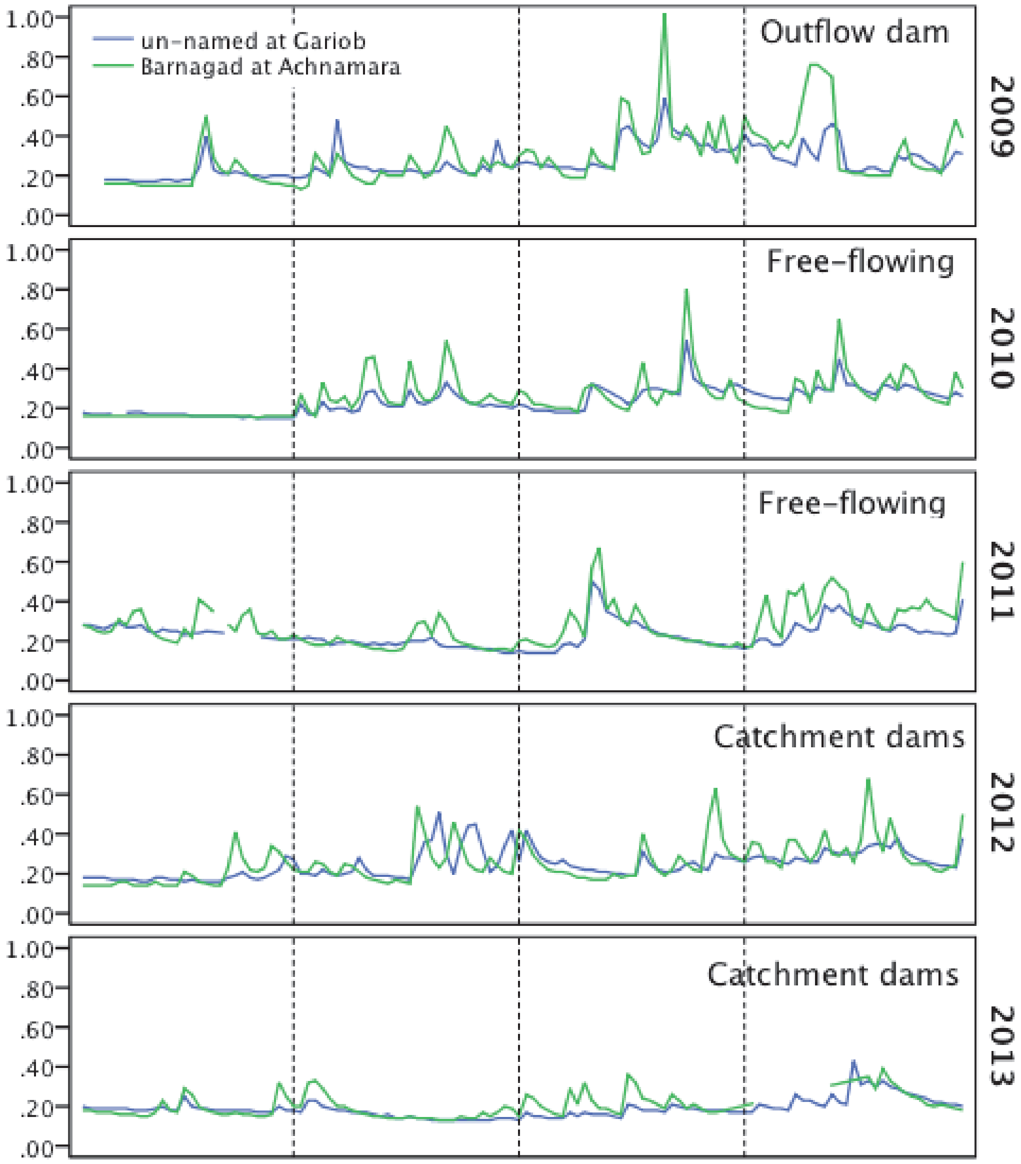

Figure 6-12 Water levels at Gariob downstream of Loch Linne and at the control site on the Barnagad Burn at Achnamara in five summers (1 June to 30 Sept). Dashed vertical lines correspond to the start of each month.

It is important to be aware of the limitations of this approach since the distribution of dams relative to the positioning of the instrumentation dictates that there is no replication of the treatment levels; the apparent effect of dams on flows in the Linne outflow stream could also therefore be the result of other factors affecting this catchment only which coincide with the influence of the dams. This possibility is discussed in the sections below when models indicate the effect of the different dam treatments to be significant.

6.5.1 Height of peak

In principle, based on published evidence, one would expect a reduction in the height of peak at Gariob relative to the control stream during the periods that dams were effective, with strongest effects being associated with the outflow dam. This would be reflected in a significant stream x treatment interaction.

The natural logs of the peak height + 0.1 was used to model these data. The best fitting model to explain the variation in peak height is shown in Table 6-4. Comparison of the full model with the full model minus the treatment effects using the R function anova() indicated a significant difference between the models suggesting the possibility of a weak treatment effect although this was not evident in the best fitting model.

Table 6-4 The ANOVA table from the best fitting mixed model for the peak height data

Explanatory variable	Sum of squares	Mean sum of squares	Numerator degrees of freedom	Denominator degrees of freedom	*F*-value	*p*-value
Stream	8.05	8.05	1	68.969	151.38	< 0.001
Month	0.35	0.12	3	68.995	2.35	0.080
Stream x Month	0.55	0.18	3	68.969	3.73	0.015

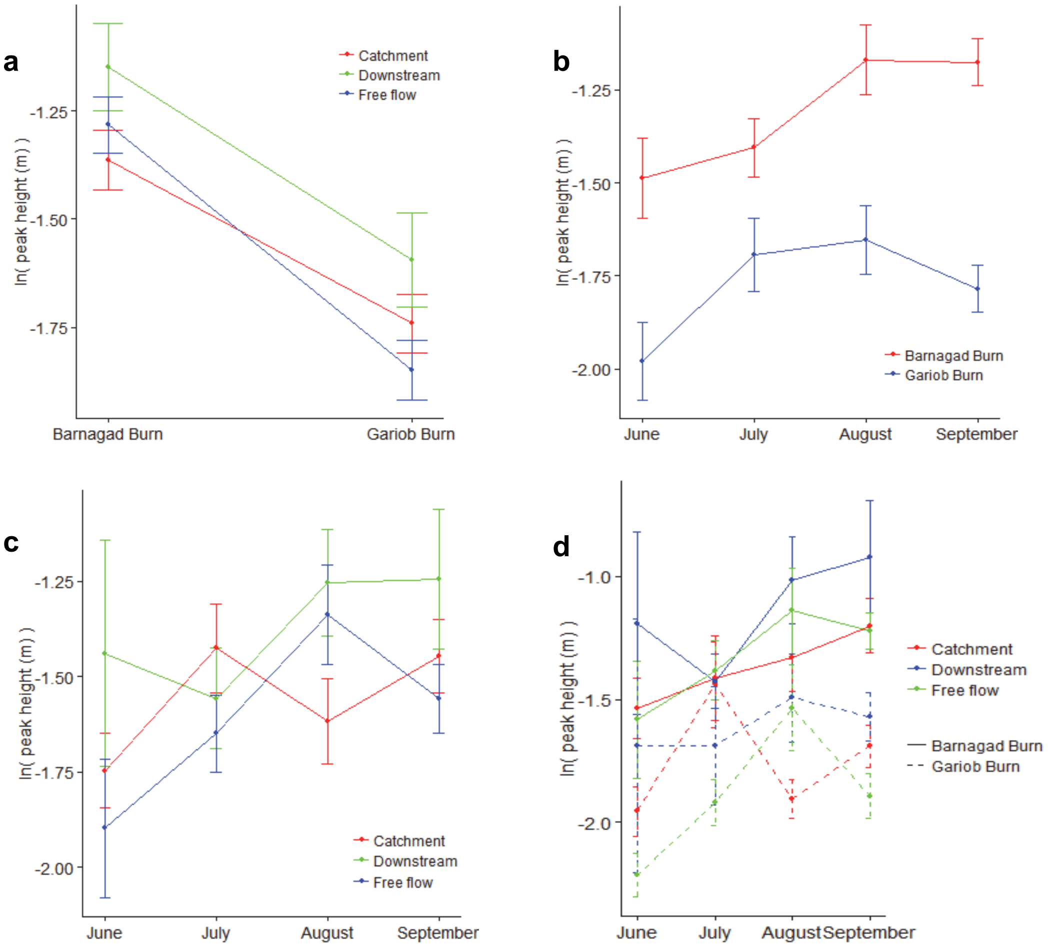

Figure 6-13 Heights of peak events at Gariob and on the Barnagad Burn showing (a) stream x treatment interaction; (b) stream x month interaction; (c) treatment x month interaction; (d) stream x treatment x month interactions. Bars are ± 1 standard error.

The month main effect was not significant in this model, but its interaction with stream was. This means that overall, there is no difference between the months, but the streams do have different month-to-month patterns (Figure 6-13b).

Exploring the best fitting model via relevelling of the factors, it was found that Barnagad Burn had higher peaks than at Gariob (Figure 6-13a), as would be expected from the lack of upstream storage in the Barnagad catchment. Both streams had their smallest peaks in June and increased in July (Figure 6-13b). In August, the streams diverged and whilst the peak heights at Gariob stabilised at this point, in Barnagad Burn they continued to increase until September when they then stabilised. There is no clear evidence that treatment interacted with stream in a manner that would suggest a significant effect of dams on peak levels (Figure 6-13a) and the only strong hint of a difference in the pattern of variation in level across months within treatments and between streams comes from the relatively high July peak levels at Gariob during the catchment dam treatment (Figure 6-13d).

6.5.2 Duration of peak flow

Variation in the duration of peak flows was modelled based on the differences between the two streams for each peak event in the different month and treatment periods. The best fitting model was found to be the full model, i.e. with treatment, month and their interaction. Table 6-5 gives the ANOVA table for this model. The treatment main effect was not significant, but its interaction with month was. This suggests that the overall difference between the streams is similar during all treatment periods, but that these differences fluctuate, with different patterns within each treatment period. The month effect was significant because the Barnagad Burn had longer duration peaks in June and July than the burn at Gariob, but there was no difference between them in August and September. There was no overall difference in peak duration during each treatment period, but peak duration fluctuated within each treatment period and with different patterns (Figure 6-14). Generally there was a more pronounced pattern of monthly differences during the free-flowing period, whereas the month-to-month fluctuations in the differences between the streams were smaller during the periods when dams were present (Figure 6-14). Given that the two streams might be expected to diverge most during the periods when the dams impose additional upstream storage this is the opposite response to that expected. There is therefore no evidence in this study that the Linne dam or the upstream catchments dams extended the duration of periods of peak flow at Gariob relative to the duration of these flows in the Barnagad Burn.

Table 6-5 The ANOVA table from the best fitting model for the difference in peak duration between the Gariob and Barnagad Burns data.

	Degrees of freedom	Sum of squares	Mean of squares	*F*-value	*p*-value
Treatment	2	4.46	2.23	0.70	0.500
Month	3	36.19	12.06	3.80	0.015
Treatment x Month	6	68.80	11.47	3.61	0.004
Residuals	57	181.10	3.18		

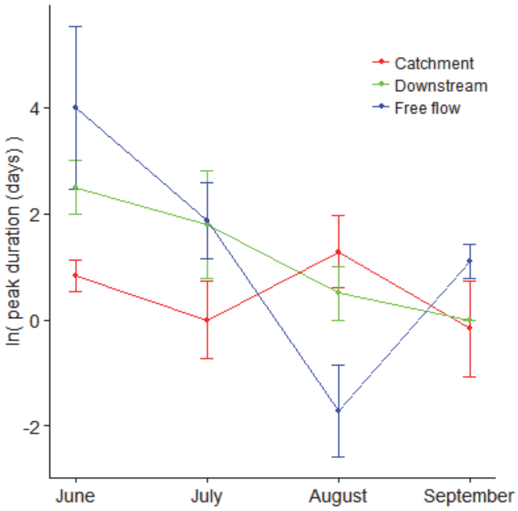

Figure 6-14 Monthly pattern of differences in peak duration on the Barnagad Burn at Achnamara relative to Gariob during the three treatment periods. Bars are ± 1 standard error.

6.5.3 Volume of peak

The natural logs of the peak duration + 0.025 was used to model these data. The best fitting model to explain variation in peak volume was the full model, i.e. with treatment, stream, and month main effects plus all their two-way interactions and the three-way interaction term. Table 6-6 gives the ANOVA table for this model. In this model the only two significant effects were streams and the three-way interaction. This suggests that overall, there is no difference between the treatments or months, but that peak volume fluctuated between months and in different patterns in each treatment period and in each stream.

Table 6-6. The ANOVA table for the best fitting model for the peak volume data.

	Sum of squares	Mean sum of squares	Numerator degrees of freedom	Denominator degrees of freedom	*F*-value	*p*-value
Stream	34.94	34.94	1	56.99	96.77	< 0.001
Treatment	1.26	0.63	2	57.00	2.27	0.113
Month	2.51	0.84	3	57.00	2.34	0.083
Stream x Treatment	1.32	0.66	2	56.99	2.56	0.086
Stream x Month	2.34	0.78	3	56.99	2.46	0.072
Treatment x Month	1.89	0.31	6	57.00	1.02	0.421
Stream x Treatment x Month	6.33	1.05	6	56.99	3.42	0.006

Exploring the data further it can be seen that Barnagad had bigger volume peaks than Gariob (Figure 6-15a,b), as would expected from the larger catchment area and lower upstream storage. There was no overall difference between the months or treatments (Figure 6-15c), but peak volume fluctuated between months within treatment periods and streams with different patterns (Figure 6-15d). Thus, in Barnagad, there was no difference in the volume of peaks during any of the three treatments. In Gariob, the peak volumes in the downstream dam period behaved similarly to those at Barnagad but during the free-flowing period and the catchment dam period they fluctuated from month to month with noticeable peaks in July during the catchment dam period and August in the free-flowing period (Figure 6-15d).

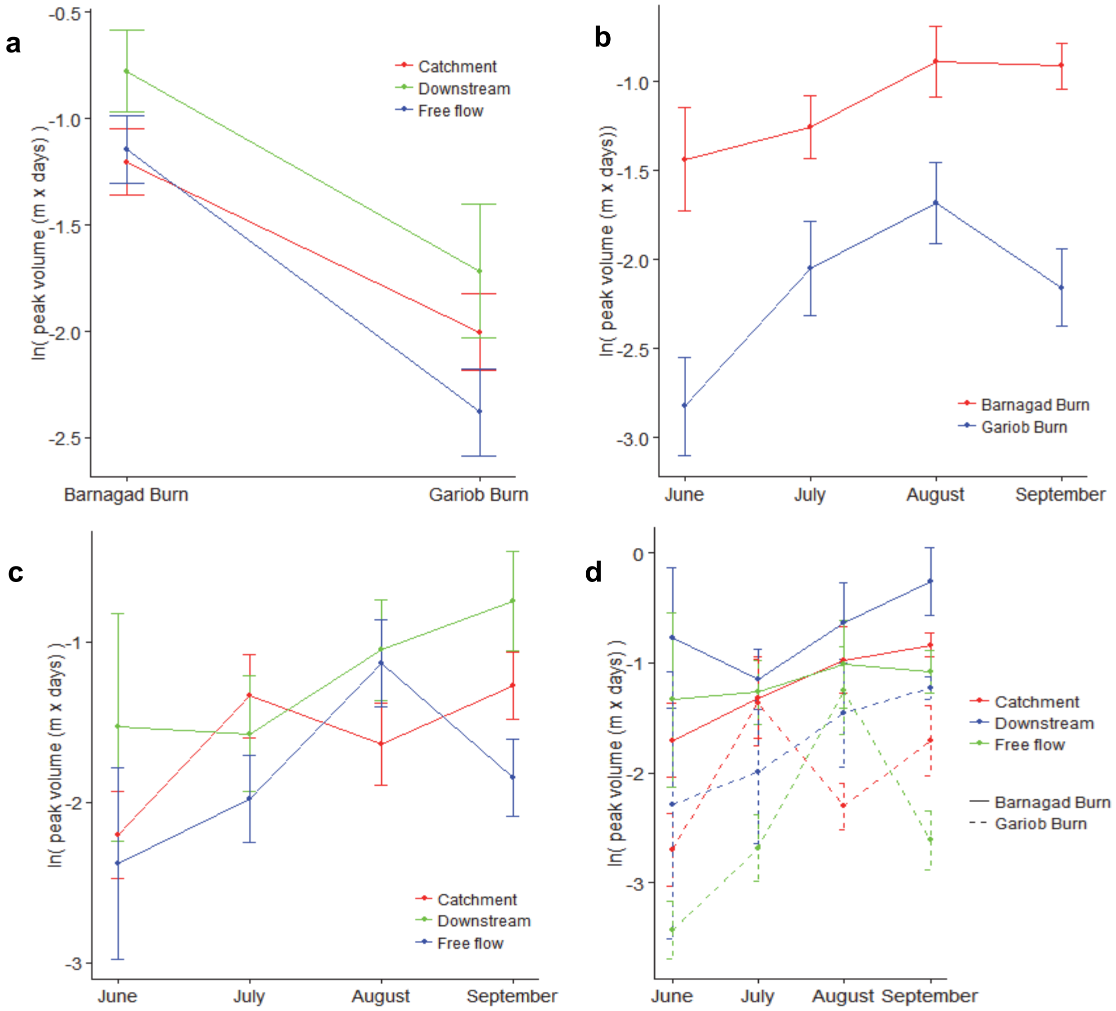

Figure 6-15 Peak volumes at Gariob and on the Barnagad Burn showing (a) stream x treatment interaction; (b) stream x month interaction; (c) treatment x month interaction; (d) stream x treatment x month interactions. Bars are ± 1 standard error.

6.5.4 Rate of rise

The natural logs of the peak duration +0.02 was used to model these data. The best fitting model to explain the variation in the rate of rise was the model with stream, month, and their interaction (Table 6-7). Again, there was a significant difference between the streams, but not the months despite the interaction between the two being significant. This suggests that there was no overall difference in the rate of rise between the months, but the pattern of fluctuations from month to month in each stream was different.

Table 6-7. The ANOVA table for the best fitting model for the rate of rise data.

	Sum of squares	Mean sum of squares	Numerator degrees of freedom	Denominator degrees of freedom	*F*-value	*p*-value
Stream	7.81	7.81	1	64.98	99.89	< 0.001
Month	0.24	0.08	3	64.99	1.08	0.364
Stream x Month	0.99	0.33	3	64.98	4.54	0.006

Upon further inspection of the best fitting model, it was found that Barnagad had faster rates of rise than Gariob at all levels of treatment (Figure 6-16a). This is largely what would be expected from a poorly buffered catchment. In Gariob, the rates of rise did not change within the year, whereas on the Barnagad Burn, they increased between July and August (Figure 6-16b). Since the stream x treatment interaction term was not significant there is no evidence that damming affected the rate of rise during peak flow events.

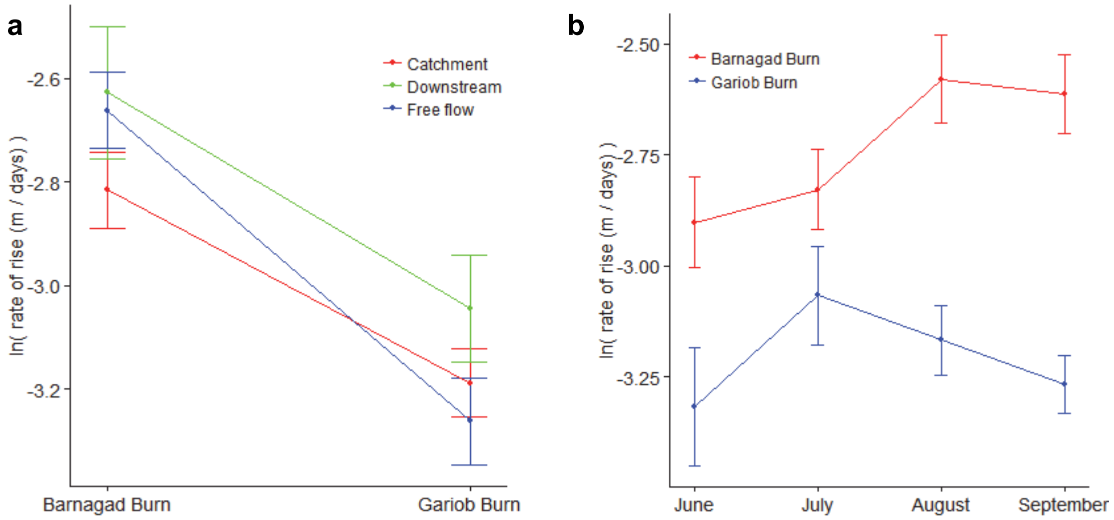

Figure 6-16 Rates of rise at Gariob and on the Barnagad Burn showing (a) stream x treatment interaction; (b) stream x month interaction. Bars are ± 1 standard error.

6.5.5 Time to peak

The best fitting model for the time to peak data included treatment and month as main effects, but not their interaction (Table 6-8). The lack of a significant interaction term means that there was insufficient evidence that the month-to-month pattern differed within each treatment period.

Upon further inspection of the best fitting model, it was found that there was a difference in the time to peak between the streams during the catchment dams period (delay in time to peak in the burn at Gariob of 1.07 ± 0.18 days relative to the Barnagad Burn) that was absent in either the free-flowing period (when the burn at Gariob peaked ahead of the Barnagad Burn by 0.12 ± 0.17 days), or the downstream dam period (delay at Gariob of 0.19 ± 0.24 days); (Figure 6-17a). There was also peak in the lag times during July (Figure 6-17b) that was most pronounced in the catchment dams period (Figure 6-17c). This same feature is evident in the data for 2012 shown in Figure 6-12. There was no difference between the other months.

Table 6-8 The deviance table for the best fitting model for the time to peak data.

	Degrees of Freedom	Deviance	Residual degrees of freedom	Residual deviance	*p*-value
NULL			72	52.38	
Treatment	2	15.21	70	37.17	< 0.001
Month	3	6.46	67	30.71	0.001

Although increased time to peak is an expected consequence of beaver dams it is impossible to ascribe the observed effects uniquely to beaver dams as, from spring 2012 onwards, inflows from Loch Losgunn into Loch Fidhle were potentially influenced by clear felling in the Loch Losgunn catchment. The results reported in section 6.4 indicate that storage in the loch itself increased after clear felling which may have contributed to a delay in the time to peak downstream. The clear felling is also likely to have increased the amount of wood entering the watercourse downstream, which is likely to have increased upstream retention of water (Gregory *et al*., 1985). Log stacking practices, which commonly involve temporary stacking of timber across small water courses, may also have contributed to upstream retention. On the other hand, tree harvesting will accelerate water loss from the catchment and therefore, where runoff is not intercepted by the loch, flow would be expected to peak more quickly. Figure 6-12 suggests that delays in time to peak were most acute in 2012 in the months immediately following tree harvesting. However, a comparison between flows at Gariob and the Barnagad Burn over winter 2011/12 (prior to harvesting but when the Losgunn outflow dam was active) and 2012/13 (after harvesting) indicated that the mean time to peak in the burn at Gariob relative to the Barnagad Burn was very similar in both periods. This is contrary to what would be expected if the harvesting itself had exerted a major influence on runoff patterns further downstream. Changes over the summer of 2012 in the integrity of the beaver dam controlling flow from Losgunn into Fidhle might explain some of the variation in time to peak. However, regular assessments of the condition of individual dams were not made. Any specific effect of beaver dams at Knapdale on time to flood peak therefore remains uncertain.

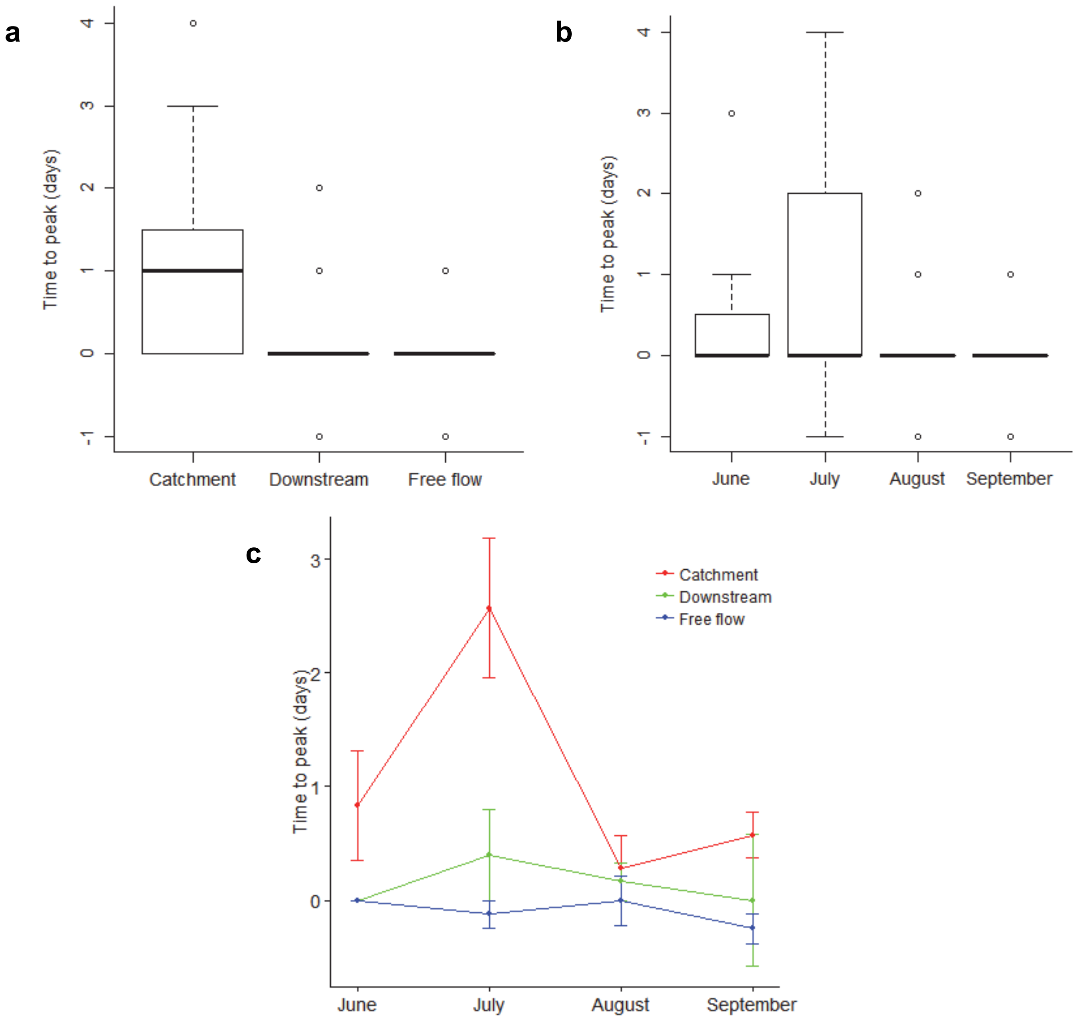

Figure 6-17 Comparison of time to peak in the burn at Gariob relative to the Barnagad Burn in relation to (a) treatment, (b) month and (c) month x treatment. Bars are ± 1 standard error

6.5.6 Baseflow depth

The significance of the different terms in the best fitting model for baseflow depth (natural log transformed data) are shown in Table 6-9. These terms are explored further in Figure 6-18. The burn at Gariob had deeper baseflows than the Barnagad Burn at all times and the term ‘stream’ identity therefore dominates the model (Figure 6-18a). Baseflow fluctuated within and between treatment periods such that during none of the treatment periods had baseflow consistently higher or lower than during the other periods. Also, none of the months had consistently higher or lower baseflow than other months. However, as might be expected, baseflows across all treatments were higher in September than earlier in the year (Figure 6-18b). Overall, baseflow was higher during the free-flowing period of 2011-12 than the other periods (Figure 6-18a). This tendency is most evident in June and September (Figure 6-18c).

The pattern of fluctuation between months within a treatment period was the same in both streams (Figure 6-18d). This indicates that the cause(s) of fluctuation, such as the distribution of rainfall, affected both streams equally, and that stream-specific factors such as beaver dams did not influence baseflow. Thus, for example, although baseflow depths were higher during August 2009 (Figure 6-18c) when the outflow dam on Linne was present, the same pattern also applied in the undammed Barnagad Burn (Figure 6-18d).

The data thus provide no evidence that dam building by beavers has influenced baseflow depths in affected streams relative to a control stream. This suggests that the delay in time to peak described in 6.5.5 results in insufficient additional storage to boost flows once peaks have subsided. This is unsurprising in view of the low height and poorly sealed nature of most of the dams (Figure 6-2).

Table 6-9 ANOVA for best fitting model for baseflow depths

	Sum of squares	Mean sum of squares	Numerator degrees of freedom	Denominator degrees of freedom	*F*-value	*p*-value
Treatment	0.01	0.005	2	60.99	9.20	< 0.001
Month	0.02	0.007	3	60.99	9.78	< 0.001
Stream	0.75	0.751	1	71.67	1612.66	< 0.001
Treatment x Month	0.02	0.003	6	60.99	6.56	< 0.001

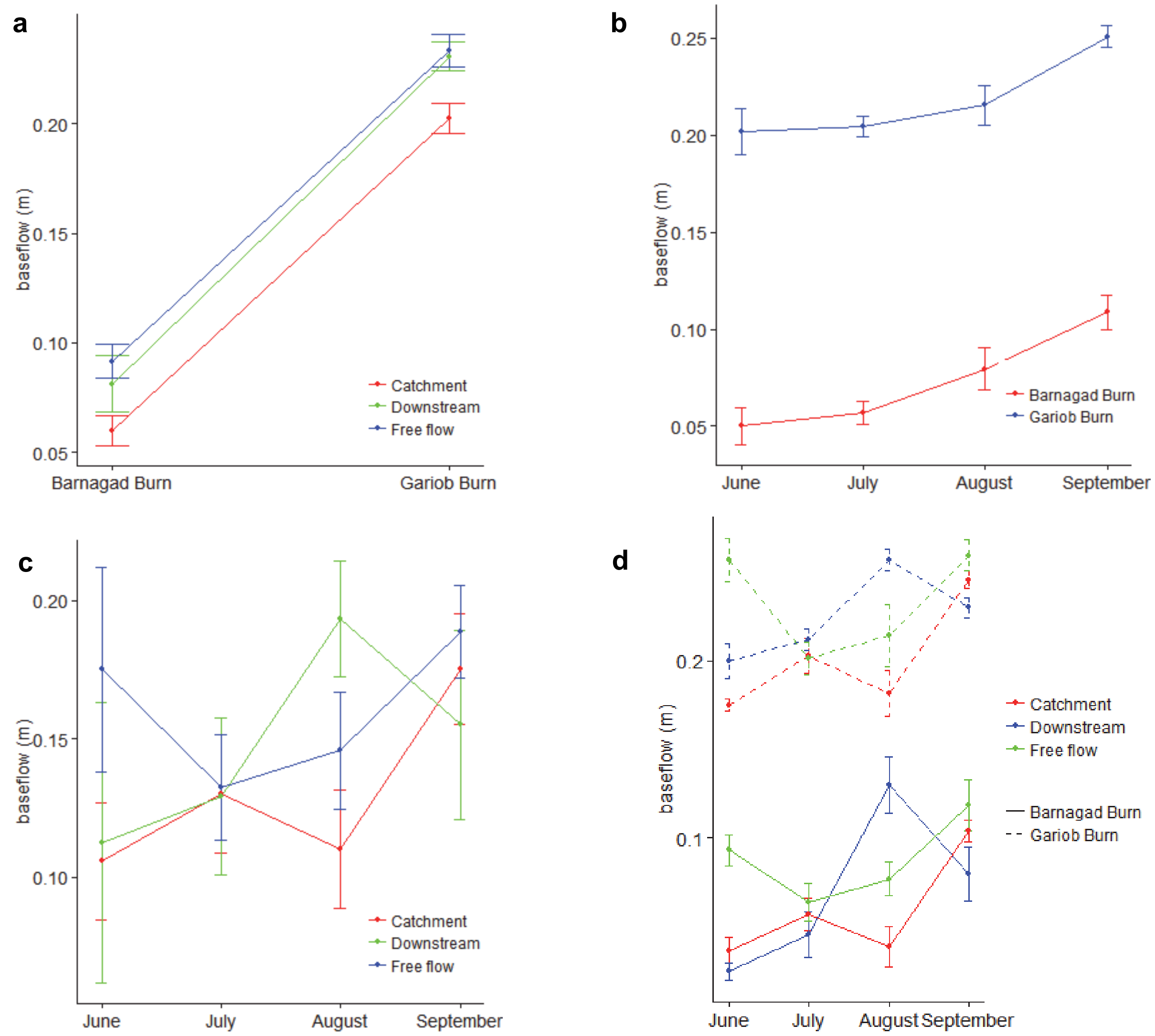

Figure 6-18 Baseflow levels at Gariob and on the Barnagad Burn showing (a) stream x treatment interaction; (b) stream x month interaction; (c) treatment x month interaction; (d) stream x treatment x month interactions. Bars are ± 1 standard error.

7. DISCUSSION

7.1 General effects

Dam building by beavers appears to have had three discernible effects on hydrology at Knapdale

1. Temporary increases in water level in larger water bodies
2. Increased storage and probably stabilisation of water levels in some small ponds
3. A small delay in time to peak flow in streams downstream of dams on lochs or on their influent watercourses.

In general, these effects, while mostly consistent with those reported elsewhere (reviewed by Gurnell (1998) and Collen & Gibson (2001) and discussed in section 3), are subtle. This is likely to partly reflect the extensively forested nature of the Knapdale catchments, which results in naturally high levels of interception of rainfall and subsequently reduces the runoff. It is also likely to reflect the small numbers of beavers present (8-10 animals at the close of the trial) and the high availability of standing water habitat. This standing water habitat reduces the need for dam building and acts to store runoff further. The lack of any multiple dam systems, in which hydrological effects tend to be magnified (Nyssen *et al.*, 2011), is probably also influential.

7.2 Increased water level in larger lochs

Lake water levels are determined by the balance between inputs from precipitation, surface runoff and groundwater influx and losses from outflow, seepage to groundwater and evaporation. Lake water levels rise and are likely to remain high following precipitation because water enters the water body from its catchment at a faster rate than it can leave due to the bottleneck effect created by the lake outflow. Beaver dams enhance this bottleneck by imposing a partial or complete barrier across the outflow of varying height and permeability. Even in the absence of a true dam it is conceivable that an accumulation of beaver-generated wood within the outflow channel of a lake could increase roughness sufficiently to increase the residence time of water.

Although damming of lake outflows by beavers is probably a common occurrence, its hydrological consequences have rarely been reported. This is probably because natural lake water level regimes are rarely well resolved unless they are of major water resource significance. It could also reflect a genuine lack of major influence by beavers on the hydrology of lakes since non-significant effects generally tend to be under-reported in the scientific literature. Variation in stream flow below lakes is naturally dampened by upstream storage and any additional effects of beaver dams on flow may therefore also be considered relatively inconsequential.

Beavers dammed the outflow of Loch Linne almost immediately after they were introduced to this site. The water level rise of up to 0.25m was modest in absolute terms but accounted for half of the natural water level range of the loch and occurred over a period of less than 3 months. This imposed significant stress on marginal vegetation during summer 2009, although following the removal of the dam, these effects were reversed and undetectable by 2011 (Willby *et al.*, 2014).

In October 2009, the outflow dam on Loch Linne was fully dismantled in accordance with one of the conditions imposed by the release licence. This stated that dams would not be permitted on those lochs lying within the Special Area of Conservation (SAC), which supported oligotrophic and mesotrophic aquatic vegetation of the type for which the SAC was partly designated. Although these licence conditions were later amended for research purposes there were no further attempts by beavers to dam the outflow of this water body. It is therefore possible that the potential hydrological effects of this dam are underestimated because a longer-lived structure would have been periodically reinforced, heightened and more efficiently sealed. Given the behavioural drivers for dam-building by beavers, lake outflow dams are likely to be fairly low in height. Nevertheless, applied to comparatively large water bodies such as Loch Linne (17ha in area) even quite small dams could potentially retain significant volumes of water. Over a sufficiently long period of time beaver dams on larger water bodies might be expected to contribute to increased water level variation if impoundment causes the maximum water level to rise through storage but permeability of the dam allows drawdown to continue in line with the pre-dam minimum water level. Because the outflow dam on Loch Linne operated for only a short period (four months) and we were restricted to manually read stage board data for most of the standing waters it is impossible to verify this effect. However, it should be borne in mind that dam building is designed to stabilise water levels and that beavers tend to avoid lakes with large water level ranges (Gurnell, 1998). Thus, an increase in water level range might be expected over the full life of a dam, but not during the phase where it is being actively maintained by resident beavers.

7.3 Storage in small water bodies

There is good evidence that wetlands formed by beaver dams can dampen water level fluctuations in surface watercourses and promote upstream storage by maintaining a high water table and stimulating groundwater recharge (Grygoruk & Nowak, 2014). In some cases, as a result of groundwater seepage and surface flow around dams, effects have been found to be equally or more positive below dams as above them (Westbrook *et al.*, 2006). Our data suggest that the small dam on the outflow of Loch Un-named (north) served to further dampen water level fluctuations in this water body. This effect was not observed at Dubh Loch over the same period. Here water levels behind a large and initially well-maintained dam peaked in December 2011 but have since gradually subsided by 0.3m, probably linked to a loss of dam height and integrity. Although there is no doubt that the beaver dam itself accounted for the water level rise in Dubh Loch the absence of any pre-damming data on water level regime at this site prevents us from stating how the dam has influenced the regime. Cycles of occupation and abandonment of beaver ponds are well documented (e.g. McMaster & McMaster, 2001) and although the 4-5 year period of occupation of Dubh Loch is relatively short this is consistent with short occupation of small sites of low productivity in Finland (Hyvonen & Nummi, 2008).

7.4 Response of streams

7.4.1 Effects on peak flow

The typical effect of beaver dams is to smooth out the flood hydrograph by trimming the highest flows and prolonging the recession limb (Gurnell, 1998). Variation in flow is thus reduced. Our results provide some evidence for a delay in the passage of the flood peak relative to a control stream during a period when beaver dams were active in the upstream part of the catchment. The average time to peak increased by just over a day during this period, similar to the recent findings of Nyssen *et al.* (2011) in Belgium. Due to the confounding effects of forest harvesting in one sub-catchment it is not possible for us to attribute this effect purely to beaver dams. However, in contrast to typical findings, there is no evidence for a significant reduction in height of peak or increase in the duration of the peak in dam-affected streams at Knapdale. This is consistent with the lack of evidence for a significant influence of beavers at Knapdale on stream geomorphology (Perfect *et al.*, 2015).

Several additional factors at Knapdale impede the interpretation of effects of beaver dams on peak flow. First, the gauged site at Gariob has a local catchment in which permanent pasture with subsurface drainage is a major component. Peak flow at Gariob, although consistently reduced in height as a result of upstream storage in Loch Linne, is virtually concordant with the timing of peak flow on the Barnagad Burn at Achnamara, and on some occasions during the free-flowing phase even preceded the peak on the Barnagad Burn. This suggests that the local catchment at Gariob has a degree of independence from Loch Linne. If the level recorder at Gariob had, by chance, been sited immediately below the Loch Linne outflow dam, it is probable that hydrological effects due to the dam would have been more easily distinguished. However, as it is, the observable effects of dams appear to be spatially quite small. Second, land use change caused by clear felling of forestry around Loch Losgunn in spring 2012 may have contributed to increased flow relative to the undisturbed forested Barnagad catchment in that and subsequent years. This would mask any reduction in peak flows that might have occurred due to storage behind dams. Third, the situation at Knapdale is unusual in the sense that other studies have focussed on headwater stream systems where storage potential in the absence of beavers is naturally low. At Knapdale there is already considerable storage potential in standing waters and extensive valley floor peat deposits. This may restrict the ability to detect any additional storage effect of beaver dams on peak flows, especially when these dams are of limited capacity. Burns & McConnell (1998) found that retention during peak events was more likely if the pre-event storage in beaver dams was low. If dams are small and commonly close to capacity, due to high rainfall and input from soil water, the scope for retention during high runoff events will be reduced accordingly. A final related factor, noted by Perfect *et al.*, (2015), is a trend for increasing frequency of wood in Knapdale streams over the 5 year monitoring period. This appears to relate to a high incidence of major storms between December 2011 and May 2012 that served to increase wood inputs. It is therefore possible that a component of the retention and delayed time to peak that occurred during the catchment dams period reflects the effect of inputs of storm-derived wood which have been previously shown to increase time to peak (Gregory *et al.*, 1994). Although storm-derived wood inputs applied to both beaver-influenced and control streams it is unclear if the hydrological consequences of this were the same in both catchments and whether this could have affected the ability to discern a specific effect of beaver dams.

7.4.2 Effects on baseflow

Many studies suggest that beaver dams are effective at increasing baseflow to downstream reaches (Nyssen *et al.*, 2011), sometimes even transforming intermittent streams to permanent watercourses (Collen & Gibson, 2001). However, in contrast, retention has sometimes been found to be so efficient that flow downstream, outwith major runoff events, is eliminated (Meentemeyer & Butler, 1999). Water stored behind beaver dams is released during dry weather periods through overtopping at the lowest point of the dam, through leakage underneath the base of the dam and via seepage through the dam face. The lower and leakier a dam is and the lower the gradient of the upstream watercourse, the less water a dam will retain. As well as releasing stored surface water the discharge of water from groundwater reserves recharged during prolonged periods of storage is likely to contribute to elevated baseflow.

The present study was unable to demonstrate increased baseflow below beaver dams. The dams at Knapdale were mostly small and (with the exception of Dubh Loch) therefore had limited capacity to store additional water because the low stream gradient prevented the formation of obvious beaver ponds. The dam on the outflow of Loch Linne served to increase the residence time of water in the loch and created a situation where loch level was relatively insensitive to preceding rainfall (Figure 6-5). Nevertheless there was no clear effect on baseflow downstream at Gariob supporting the suggestion above that spatially, any effects of dams are quite small.

The upstream catchment dams were comparatively small. The capacity for retention at high flow is likely to have been rather limited on the stream carrying flow from Loch Losgunn and this dam was observed to be readily overtopped, even at modest flow. There is no evidence that baseflow at Gariob during the presence of these catchment dams differed from the time when no dams were present. However, it is possible that saturation of the surrounding peats during high flow served to increase the storage effect of the upstream catchment dams, which was then transmitted as increased baseflow into Loch Linne when downstream water levels subsided. Figure 6-5 indicates marginally but significantly higher (+2.5cm) water levels in Loch Linne relative to preceding rainfall when the dams on the inflows from Loch Losgunn and unnamed north were active, than during fully free-flowing periods. Evidently however, this small increase in loch depth was too small to translate into a significant increase in baseflow further downstream at Gariob.

7.5 Study design and instrumentation

In published studies three basic approaches have been used to investigate the effects of beaver dams on hydrology.

- Use of long time series data for a single site covering pre- and post-damming periods. For example, Nyssen *et al.* (2011) used a 25-year record of discharge and flow from a baseline period to construct flow duration curves and compared these with curves from a subsequent 5 year period from the same site during which dams were active. However, the absence of a suitable control in such situations is likely to be problematic unless it can be stated with confidence that no other hydrologically relevant changes have occurred in parallel.
- Paired catchment studies of several sites over a common period of time where undammed sites act as a control against which to assess the effects of otherwise similar dammed sites (Burns & McDonnell, 1998).
- Intensive short term *in situ* studies that compare inflows and outflows above and below one or more dams. For example, Nyssen *et al.* (2011) and McLean (2011) used this approach on dams built in series over a short section of channel to estimate the level of retention by dams and their effect on the height and timing of downstream peaks.

In the present study, with the benefit of knowledge of where beavers would be most active, automatic water level recorders could probably have been better sited. As it was, the approach used was speculative and needed to accommodate the possibility of beaver activity on both lochs and streams across the entire area. The area as a whole was well-instrumented and, without a reliable phone signal that would have allowed the use of telemetry-based equipment, significant effort had to be devoted to equipment maintenance and downloading. It would have been advantageous to have daily monitoring of water levels from all lochs that were dammed, or alternatively on their outflow just downstream of the dam, both before and after the period of damming as well as from undammed lochs to provide a suitable control. This would have aided comparison of upstream versus downstream effects, would have reduced the influence of differences in catchment land use on runoff patterns at downstream gauges and provided more control sites. If a well-constructed dam had been allowed to remain in place on the Linne outflow it would have been valuable to deploy gauging above and below this dam. Commercial timber harvesting was not an issue that had been envisaged at the outset of the trial and in hindsight it would have been beneficial if this could have avoided the Loch Linne catchment.

7.6 Future consequences for Knapdale hydrology

The incidence of dam building by the Knapdale beaver population is low and any hydrological effects are correspondingly small. In the event that the current population remains stable or expands, an increase in dam building on streams can be expected. This is likely as the most readily exploited resources associated with lochs and their margins become depleted and habitat modification is required to facilitate safe access to resources in sub-optimal habitat. There is an extensive resource of small willow and birch, on which beavers preferentially feed at Knapdale (Iason *et al.*, 2014), bordering many sections of watercourse. This provides the material required for dam construction, and, being small and mostly low gradient, such channels will be easily dammed. The stabilising effects of upstream lochs on stream flow will also assist dam building and reduce the frequency of breaches. Beavers typically occupy territories for several years, before abandoning them and then returning several years later. Wright *et al.* (2003) quote average occupancy of 4 years (range 1-20) for *C. canadensis* in the Adirondack Mountains, US, while Hyvovevn & Nummi (2008) found animals to return after 9 years, following occupancy times of 2-3 years. Colonisation of other water bodies at Knapdale and modification of their outflow characteristics is therefore probable in the near future. There is some evidence for this since the end of the trial period (May 2014) as one animal had moved to Loch Barnluasgan, which had never been utilised over the five-year trial period. Also, other animals (presumably from the adjacent Lochan Buic) had dammed the outflow of Loch Un-named (south) in October 2014 (R. Campbell-Palmer pers. comm.). Hydrological monitoring of the outflow of this site is ongoing. If the Knapdale beaver population persists for long enough, a return to current territories in the future is also likely.

If the numbers of animals decline, any dams on stream systems are likely to fail within a few years or to contract to the point where their influence is indistinguishable from that of natural in-stream wood features. The hydrological signal of beaver dams is already weak and little change would be needed to obscure it altogether. The loss of the dam on Loch Un-named (north) will see a gradual return to baseline water levels with this change likely to be buffered by influx of water from the surrounding mire. Catastrophic failure of the dam on Dubh Loch is very unlikely as the head of water is stable due to the very small upstream catchment area. Instead, a slow disintegration of the dam and loss of retention should be expected over the next 5 years accompanied by colonisation of exposed sediments by sedges or re-establishment of birch and willow.

7.7 Future implications for Scotland

While the results presented here may typify the situation that will be encountered in forested catchments with extensive standing water, low densities of animals and few dams, they are unlikely to be representative of small stream systems in sparsely-wooded agricultural environments. Here, in order to create suitable conditions, beavers are more likely to engineer habitat by dam building (Halley & Rosell, 2003). This will likely include cascade systems formed from multiple dams constructed in series over a short length of watercourse whose hydrological influence will be greater than that of dams occurring in isolation (Nyssen *et al.*, 2011).

In agricultural situations water and sediment retention within dams is likely to provide increased flow stability by buffering floods and increasing baseflow. This reduces the inherent flashiness of catchments with artificially low retention. For example, on one cascade dam system in Tayside, McLean (2011) found that over the period November 2010 to May 2011 the time to peak was delayed on average by 18 hours below a series of beaver dams, compared with a position immediately upstream of them. Also, the flood peak was reduced by 50-70% at the outflow of the dam system compared with its inflow. Baseflow during the driest periods was 20-30% higher below the dam system than above it (see Figure 3-1). These findings are highly consistent with the study by Nyssen *et al.* (2011) involving Eurasian beavers in Belgium. Effects such as these are likely to increase the height of the water table within the adjacent riparian zone, with further implications for riparian vegetation cover and channel stability. The hydrological effects described by McLean (2011) also translated into geomorphic responses, such as significant storage of fine sediment behind dams (Law *et al.*, pers. comm.), which were never observed at Knapdale (Perfect *et al.*, 2015). Beaver dams are, however, dynamic and transient structures on the time scale of years. Although Gurnell (1998) concluded that dam failures were rare based on a lack of published reports, experience suggests that breaching of individual structures and their repair or replacement elsewhere on a reach is probably commonplace (Nyssen *et al*., 2011; authors' personal observations). Such events appear to be most frequent following peak winter rainfall and may increase where flows are flashier (e.g. due to topography or modification of land cover). Dam breaches followed by brief episodes of flow instability until dams are repaired or rebuilt should therefore be regarded as the norm.

A growing interest in ecologically-based, less physically disruptive restoration methods has raised the profile of beavers, both in North America and Europe, as potential architects of the restoration of degraded streams (Palmer *et al*., 2009). Even in the absence of beavers, check dams or log emplacements are commonly employed in restoration projects to emulate the small-scale discontinuities created by beavers (DeVries *et al*., 2012). There are also clear parallels between beaver dams and naturally-occurring large wood features, whose importance in regulating hydrogeomorphic processes is widely appreciated (Gurnell, 1998). Beaver dams act to reduce stream energy, and, coupled with increased sedimentation, should consequently reduce rates of channel incision (Pollock *et al*., 2014). While the current emphasis is on restoration of physical habitat through reinstatement of natural hydrogeomorphic processes, the potential for increased headwater retention within beaver dam systems also has the potential to contribute to natural flood management and to reduce overall flood risks downstream (Collen & Gibson, 2001).

8. CONCLUSIONS

The hydrogeomorphic effects of beavers have long been known and are detailed extensively in the scientific literature. Some of these effects are reproduced at Knapdale as a result of dam-building by beavers. The major effects include:

- temporarily increased storage in larger lochs due to damming of the outflow;
- elevation and stabilisation of water levels in small lochs
- a possible delay in the timing of peak flow on water courses downstream of dams

However, the hydrological effects observed at Knapdale generally appear to be diminished compared with published studies. This is attributed to the low density of animals and the lack of dams built in series over short lengths of water-course which, elsewhere, generally produce the most pronounced hydrological effects. The naturally retentive nature of the Knapdale catchment, due to the extent of forest cover and high potential storage in standing waters and valley floor peats are also likely to moderate the effects of beavers on hydrology. Those dams that have been constructed, with the exception of the dam on Dubh Loch, are also small and rather poorly-sealed structures that are readily overtopped.

Although it is legitimate to conclude that the hydrological effects of the current beaver population at Knapdale are fairly minor, several factors affect this interpretation. The time scale of the study was relatively short, especially in terms of the duration of the period over which individual dams were effective. Although later revised, the original licence stipulated that dams on SAC lochs should be removed. This permanent dismantling of the dam on the outflow of Loch Linne prevented a more detailed assessment of its possible hydrological effects. The gauging site at Gariob downstream of Loch Linne was influenced by local runoff from permanent pasture that may have been sufficient to obscure the effects of upstream dams. Finally, forest harvesting in one sub-catchment of Loch Linne from April 2012 onwards had a clear effect on water levels in Loch Losgunn and subsequent inflows into Loch Linne. This could have either magnified or diminished the apparent effect of beaver dams.

Habitat engineering by beavers has the potential to significantly influence downstream hydrogeomorphic processes. In well-forested catchments with extensive standing water habitat combined with small populations of beavers and a low incidence of dam building, we conclude that such modifications will be minor.

9. REFERENCES

Burchsted, D. & Daniels, M.D. 2014. Classification of the alterations of beaver dams to headwater streams in northeastern Connecticut, USA. *Geomorphology* **205**, 36-50.

Burns, D.A. & McDonnell, J.J. 1998. Effects of a beaver pond on runoff processes: comparison of two headwater catchments. *Journal of Hydrology*, **205**, 248-264.

Butler, D.R. & Malanson, G.P. 2005. The geomorphic influences of beaver dams and failures of beaver dams. *Geomorphology*, **71**, 48-60.

Collen, P. & Gibson, R.J. 2001. The general ecology of beavers (*Castor* spp.), as related to their influence on stream ecosystems and riparian habitats, and the subsequent effects on fish - a review. *Reviews in Fish Biology and Fisheries*, **10**, 439-461.

DeVries, P., Fetherston, K.L., Vitale, A. & Madsen, S. 2012. 2012. Emulating riverine landscape controls of beaver in stream restoration. *Fisheries* **37**, 246-255.

Gonzales, A.L., Nonner, J., Heijkers, J. & Uhlenbrook, S. 2009. Comparison of different base flow separation methods in a lowland catchment. *Hydrology & Earth System Sciences*, **13**, 2055-2068.

Gordon, N.D., McMahon, T.A., Finlayson, B.L., Gippel, C.J. & Nathan, R.J. 2004. *Stream Hydrology: An Introduction for Ecologists*, 2nd Edition. Wiley

Gregory, K.J., Gurnell, A.M., Hill, C.T. & Tooth, S. 1994. Stability of the pool-riffle sequence in changing river channels. *Regulated Rivers: Research and Management*, **9**, 35–43.

Gregory, K.J., Gurnell, A.M. & Hill, C.T. 1985. The permanence of debris dams related to river channel processes. *Hydrological Sciences Journal*, **30**, 371–381.

Grygoruk, M. & Nowak, M. 2014. Spatial and temporal variability of channel retention in a lowland temperate forest stream settled by European beaver (*Castor fiber*). *Forests*, **5**, 2276-2288.

Gurnell, A.M. 1998. The hydrogeomorphological effects of beaver dam-building activity. *Progress in Physical Geography*, **22**, 167-189.

Halley, D.J. & Rosell, F. 2003. Population and distribution of European beavers (*Castor fiber*). *Lutra*, **46**, 91-101.

Hammerson, G.A. 1994. Beaver (*Castor canadensis*) - Ecosystem alterations, management, and monitoring. *Natural Areas Journal*, **14**, 44-57.

Harrington, L.A., Feber, R., Raynor, R. & Macdonald, D.W. 2015. The Scottish Beaver Trial: Ecological monitoring of the European beaver *Castor fiber* and other riparian mammals 2009-2014, final report. *Scottish Natural Heritage Commissioned Report No. 685.*

Hood, G.A. & Bayley, S.E. 2008. Beaver (*Castor canadensis*) mitigate the effects of climate on the area of open water in boreal wetlands in western Canada. *Biological Conservation* **141**, 556–567.

Hyvonen, T. & Nummi, P. 2008. Habitat dynamics of beaver *Castor canadensis* at two spatial scales. *Wildlife Biology*, **14**, 302-308.

Iason, G.R., Sim, D.A., Brewer, M.J. & Moore, B.D. 2014. The Scottish Beaver Trial: Woodland monitoring 2009-2013. *Scottish Natural Heritage Commissioned Report No. 788*.

Kitchener, A.C. & Conroy, J.W.H. 1997. The history of the Eurasian beaver *Castor fiber* in Scotland. *Mammal Review* **27**, 95-108.

Levine, R. & Meyer, G.A. 2014. Beaver dams and channel sediment dynamics on Odell Creek, Centennial Valley, Montana, USA. *Geomorphology* **205**, 51-64.

McLean, F. 2011. The effect of beaver (*Castor fiber*) dams on nutrient uptake and flood wave attenuation, Angus, Scotland. MSc thesis. University of Stirling.

McMaster, R.T. & McMaster, N.D. 2001. Composition, structure, and dynamics of vegetation in fifteen beaver-impacted wetlands in western Massachusetts. *Rhodora*, **103**, 293–320.

Meentemeyer, R.K. & Butler, D.R. 1999. Hydrogeomorphic effects of beaver dams in Glacier National Park, Montana. *Physical Geography*, **20**, 436-446.

Naiman, R.J., Melillo, J.M. & Hobbie, J.E. 1986. Ecosystem alteration of boreal forest streams by beaver (*Castor canadensis*). *Ecology* **67**, 1254-1269.

Novakowski, N.S. 1967. Winter bioenergetics of a beaver population in northern latitudes. *Canadian Journal of Zoology*, **45**, 1107-1118.

Nyssen, J., Pontzeele, J. & Billi, P. 2011. Effect of beaver dams on the hydrology of small mountain streams: example from the Chevral in the Ourthe Orientale basin, Ardennes, Belgium. *Journal of Hydrology*, **402**, 92-102.

Palmer, M.A., Lettenmaier, D.P. & Poff, N.L. 2009. Climate change and river ecosystems: protection and adaptation options. *Environmental Management*, **44**, 1053-1068.

Perfect, C., Gilvear, D., Law, A. & Willby, N. 2015. The Scottish Beaver Trial: Fluvial geomorphology and river habitat 2008-2013, final report. *Scottish Natural Heritage Commissioned Report No 683.*

Pollock, M.M., Beechie, T.J, Wheaton, J.M., Jordan, C.E., Bouwes, N., Weber, N. & Volk, C. 2014. Using beaver dams to restore incised stream ecosystems. *Bioscience* **64**, 279-290.

Roberts, G. & Crane, S.B. 1997. The effects of clear-felling established forestry on stream-flow losses from the Hore sub-catchment. *Hydrology and Earth System Sciences* **1**, 477–482.

Rosell, F., Bozser, O., Collen, P. & Parker, H. 2005. Ecological impact of beavers *Castor fiber* and *Castor canadensis* and their ability to modify ecosystems. *Mammal Review* **35**, 248-276.

Ruedemann, R. & Schoonmaker, W.J. 1938. Beaver-dams as geologic agents. *Science*, **88**, 523–525.

Rutherford, W.H. 1955. Wildlife and environmental relationships of beavers in Colorado forests. *Journal of Forestry*, **53**, 803–806.

Stephenson, D. & Merritt, J. 2010. *Argyll and the Islands: a landscape fashioned by geology*. Scottish Natural Heritage.

Tetzlaff, D.I.A. Malcolm, I.A. & Soulsby, C. 2007. Influence of forestry, environmental change and climatic variability on the hydrology, hydrochemistry and residence times of upland catchments. *Journal of Hydrology*, **346**, 93–111.

Westbrook, C.J. & Cooper, D.J. & Baker, B.W. 2006. Beaver dams and overbank floods influence groundwater-surface water interactions of a Rocky Mountain riparian area. *Water Resources Research*, **42**.

Wetzel, R.G. 2001. *Limnology: Lake and River Ecosystems*. Academic Press.

Willby, N.J., Perfect, C. & Law, A. 2014. The Scottish Beaver Trial: Monitoring of aquatic vegetation and associated features of the Knapdale lochs 2008-2013. *Scottish Natural Heritage Commissioned Report No. 688*.

Wright, J.P., Flecker, A.S. & Jones, C.G. 2003. Local vs landscape controls on plant species richness in beaver meadows. *Ecology*, **84**, 3162-3173.

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