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Time variable effectiveness and cost-benefits of different nature-based solution types and design for drought and flood management

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ABSTRACT

Nature Based Solutions (NBS) for water resources management have potential to mitigate climate change impacts, including more frequent flooding and droughts. Successful uptake requires more knowledge on the effects of NBS type and design on high and low flows. The cost-benefits of NBS impacts on these and water yield are also essential. Here, we used a modelling framework to explore the impacts of two common NBS types (Runoff Attenuation Features [RAFs] and tree planting), both varying in design, specifically location and scale. Data from an upland Scottish catchment (~1km^2) informed a coupled physically-based hydrological (MIKE SHE) and hydraulic (MIKE 11) modelling approach. NBS scenario effects on high and low flows, as well as groundwater recharge were compared and hydrological indices specific to the whisky industry informed the study site's 25-year cost-benefit analysis. Overall, tree planting reduced low flows and recharge of groundwater, whereas RAFs had a positive but smaller effect. Both NBS types reduced high and medium flows, although tree planting reduced high flows less than RAFs. RAF design, particularly increases in storage volume spread over greater areas, increased effects on all aspects of flows and recharge. Greater areas of planting increased effects on all but the highest flows. NBS type and design affected timing of water storage availability, retention and transfer, but this also depended on antecedent wetness, so these should all be considered for optimal performance or avoiding negative effects. The cost-benefit analysis revealed that RAFs would be a financially feasible NBS approach for enhancing low flows, whereas tree planting would not. This study highlighted that implementing a modelling framework alongside cost-benefit analysis could help optimise type and design of NBS for cost-effective management of specific local water availability issues. Critically this could inform NBS implementation for management of flood and drought impacts, likely to become more frequent in future with climate change.

Introduction

Nature Based Solutions (NBS) can contribute to mitigating the impacts of climate change on water resources management [1]. For those in rural areas reliant on private supplies or for industry, balancing water resources can be challenging [2,3]. Even in temperate areas like the UK, periods of drought as well as floods increasingly require adaptable management solutions under climate change [4–6]. Currently, hard-engineering approaches are most common, as investments can be justified by demonstrable impacts irrespective of location. However projections suggest that these approaches will become adequate and more adaptable solutions will be necessary [7,8].

NBS approaches for water resources management in upland headwater catchments can be designed to increase infiltration, storage in the landscape or intercept quick flow pathways, thus reduce peak flows or increase low flows. Headwater NBS examples include tree planting, buffer strips, storage ponds on land or in streams, or in-stream woody debris dams and leaky barriers [9–12]. They also have a wide range of environmental benefits such as diversification of habitats thus increasing biodiversity, climate regulation through increased carbon storage and improvements to air and water quality [12–15]. Although NBS may provide solutions, several barriers prevent practitioners from investing in them [16,17]. Areas that require more evidence include: 1) NBS effects during different hydro-climatic conditions, 2) comparisons between different NBS types and designs and 3) information on cost-benefits [18–20].

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Considering the effects of NBS through different hydro-climatic conditions is important, as an appropriate design could simultaneously address multiple water resources challenges [21–23]. Despite developments in the last two decades, knowledge on NBS functioning in temperate upland headwaters has predominantly been gained for flood mitigation [11,24]. Less is known about NBS effects on groundwater recharge and water yield during low flows, despite this being essential for industries reliant on water supply [2,25]. Studies on NBS for integrated management of floods as well as droughts are scarce. If considered in isolation, focussing on managing low flows only could be problematic if the attenuation of water for greater infiltration opportunity could lead to less available "new" storage for multi-day flood events [26]. Studies simultaneously investigating NBS impacts on high, low flows and recharge could therefore help to inform optimised design, risk assessment, and cost-benefit analyses, ultimately increasing uptake [16,27,28].

Few studies show direct comparisons between different types of NBS, and for a specific type, how NBS design relates to effectiveness through both high and low flows. The specific design, including location and scale of NBS, is key to successful implementation [23,29–31]. Location-specific factors such as their position, associated land use, soils and geology affect the interception of flow pathways, potential infiltration and recharge [22,32,33], whilst the affected area, size, volume or density of NBS affect the mitigation potential for different scales of events [34].

Runoff Attenuation Features (RAFs) and tree planting are two common NBS types which in temperate regions are both predominantly designed for flood management but are implemented and effective at different spatial and temporal scales. RAFs are typically more locally implemented measures, functional immediately after construction [35]. RAFs are soft engineered measures designed to store and attenuate rapid runoff [34,36] by controlling the discharge rate (i.e., 'leakiness'). These measures target flood level flows and include measures such as Leaky Barriers [21,37]. If in suitable locations, increased infiltration to recharge groundwater may improve catchment resilience to drought [21,38,39], although there are only a few studies that evaluated effects of RAFs on low flows [21,23,40].

Tree planting provides a NBS example which is spatially widespread, but takes time to establish [41]. Flows are reduced by rainfall interception, increased surface roughness slowing overland flow, and greater water use, evapotranspiration and infiltration increasing available soil water storage [42–44]. Effects on the highest of flows are often disputed [45]. For low flows, most suggest trees reduce water yield [46], but effects can be site specific as others report that increased infiltration, water retention and recharge to groundwater increase yield, and trees may modify rainfall patterns over regional to continental scales, reducing drought intensity [47].

Understanding how NBS type and design affect their impact through contrasting hydro-climatic conditions is thus required to inform implementation guidelines. Models enable simulation of this, avoiding installation of multiple NBS and extensive monitoring campaigns [29]. Although modelling is associated with uncertainties, these can be reduced by calibrating models with local empirical data, and results can provide useful insights into direction of change [48,49]. Given NBS affect processes at different spatial scales, modelling also enables extraction of results at relevant scales for e.g., cost-benefit analyses, to address issues specific to local surroundings or stakeholders. In Scotland for example, this could involve the whisky industry concerned with abstraction limits and water availability through low flow periods [50,51].

Hydrological indices that characterise water storage and flow provide a quantitative, comparable way to measure the extent of change at a specific location, thus avoiding difficulties in assessing NBS impacts which act over different temporal and spatial scales [52]. Examples of indices include the Standardised Stream Flow Index (SSFI) [53,54], or those that compare the value, or number of occurrences in a certain time period above or below a threshold [55]. High flow indices are commonly used in economic evaluations of flood risk, while low flow indices are relevant for water users reliant on steady water supplies [52,56]. Thus, use of models and hydrological indices enables simulation and evaluation of potential impacts of different NBS scenarios, which can inform cost-benefit analysis.

Here we implemented a hydrological/hydraulic model based on data collected during a period covering a range of hydro-climatological conditions, including drought, at Blairfindy catchment, NE Scotland, from which the Glenlivet distillery abstracts water for whisky production [38]. Our main aim was to compare the effects of two types of NBS; RAFs and tree planting, through contrasting hydro-climatic conditions and understand the cost-benefits for management of water availability through low flows specifically. We also considered different designs for each of the two NBS types. More specifically, our objectives were to: a) Determine the context of the study period with hydrological indices and contrasting hydro-climatic conditions; b) Compare effects of a range of NBS scenarios (i.e., different types and designs) on those indices, and through contrasting conditions; and c) Conduct cost-benefit analysis to assess the feasibility of NBS for enhancing water availability through low flows.

Study area and methods

Fig. 1 demonstrates the overall methodology. First, baseline conditions for Blairfindy catchment were modelled, informed by empirical data. Secondly, six NBS scenarios, two NBS types of varying designs, were developed and their effects on hydrological indices were explored using the modelling framework. Finally, a cost-benefit analysis of NBS scenarios, informed by on-site costs and industry-relevant hydrological indices, was conducted.

Study site

The Blairfindy catchment (0.9 km^2) is a headwater of the river Livet (102 km^2), which eventually drains into the Spey (Fig. 2a,b). It is in many ways typical for rural uplands in the Scottish Highlands, and a full detailed description can be found in Fennell et al. [23,38]. Briefly, the catchment is north-facing, has a mean elevation of 438 m.a.s.l. and snow provides ~7% of the ~900 mm mean annual precipitation. Daily air temperatures average 6.2 ºC; and Potential Evapotranspiration (PET) is relatively low (~450 mm/year). Deep groundwater is provided via fractures and faults in the crystalline bedrock and an interspersed limestone member, and till and shallow drift deposits provide active storage [38,57]. Humus-iron/iron podzols are found throughout the west of the catchment. These relatively freely-draining soils support heather shrubs (*Erica spp and Calluna*), grazed acidic grassland and a small coniferous woodland (Fig. 2d) [57]. This plantation is 40–100 years old and managed for timber. In the east, hillslope soils are poorly-draining peaty gleys and thicker peats covered by heather shrubs (*Erica spp*) and moss [58]. The Glenlivet Distillery, a key Scotch whisky producer, abstracts stream and groundwater (~95 mm/year rainfall equivalent) from the Blairfindy catchment. This occurs year-round, except for a two- to four-week "shutdown period" for maintenance. This closure occurs in the summer and often coincides with warmer drier weather, so production is not affected by low flows and higher stream temperatures. However, outside of the shutdown period, if stream discharge is <Q_{95} at Blairfindy outlet for 7 consecutive days, distillery production ceases due to inadequate water supply. In an attempt to intercept and attenuate runoff for infiltration and recharge of groundwater resources for supply in these dry periods [36], leaky barrier RAFs were installed in headwater ephemeral stream channels in December 2020 (Fig. 2e) [18,21].

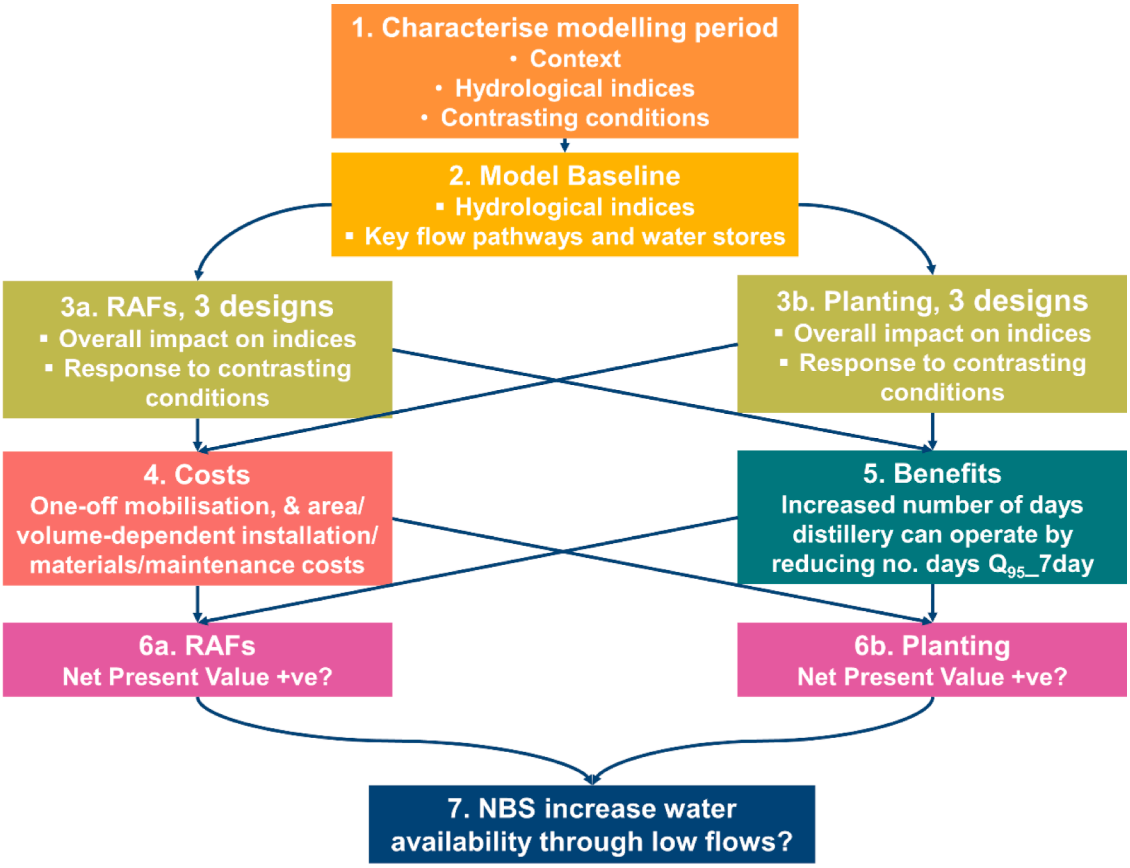

Fig. 1. Flow chart showing general methodology. Nature Based Solutions (NBS) scenarios include two NBS types, Runoff Attenuation Features (RAFs) and tree planting, and for each type three designs were tested.

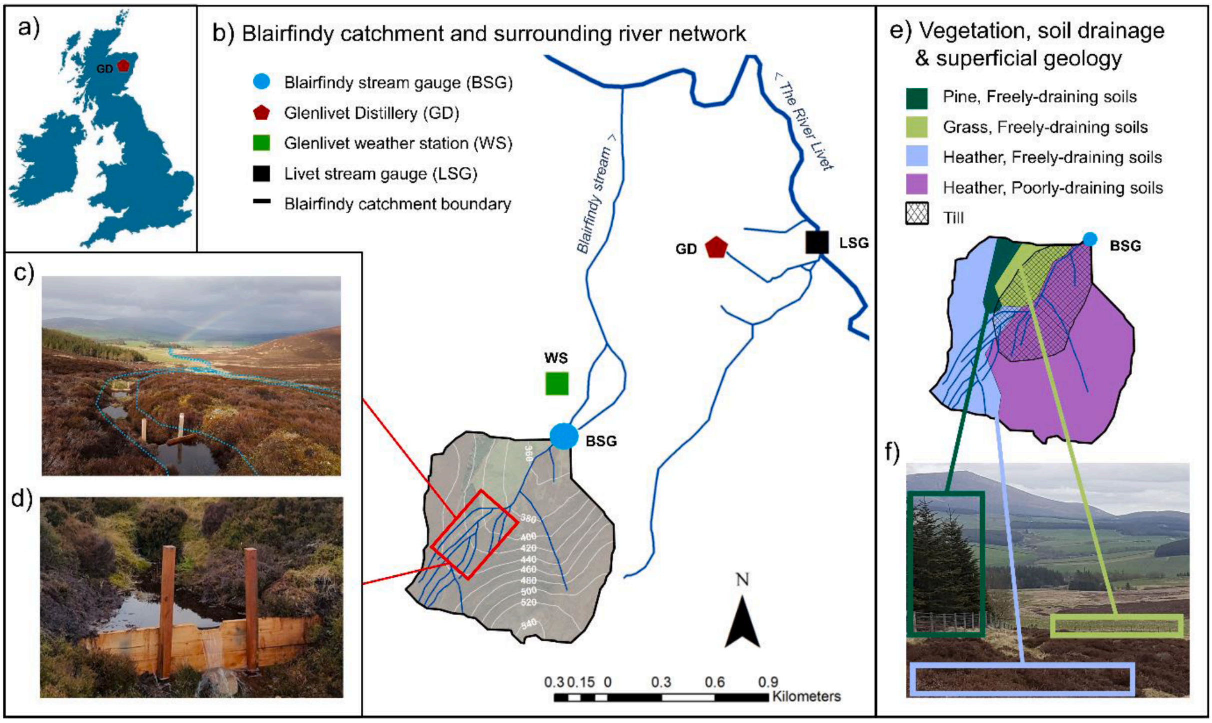

Fig. 2. Blairfindy catchment (a) in the UK; (b) as a small (0.9 km^2) tributary to the river Livet (102 km^2), with local monitoring equipment, satellite imagery overlain with the river network, 20 m contours [59] and red box around river network area into which Runoff Attenuation Features (RAFs) (~2m^3 storage each) were installed (c) view downstream from where RAFs have been installed with river network outlined (d) front view of timber RAF showing width and notch size (e) vegetation and soils distinguished by drainage properties, and superficial geology [60,61] and (f) vegetation types showing maturity of trees as simulated in model.

Data sources

Precipitation, air temperature and Potential Evapotranspiration (PET) data were collected from Blairfindy weather station (Fig. 2b) at 15-minute intervals (24/05/2018–17/12/2020) and summarised for use in the model on a 6-hourly time-step as in Fennell et al. [23]. To extend the record pre-24/05/2018, local gauging (the Livet) and weather station data (01/01/2000–24/05/2018) were scaled for Glenlivet (detailed in Fennell et al. [38]).

Blairfindy stream 15-minute discharge data were obtained from the catchment outlet (23/02/2018 onwards) and averaged to 6-hourly periods (Fig. 2b; Fennell et al. [38]). Distillery abstraction data (2009–2020) were averaged and added evenly to the discharge data to estimate streamflow without abstractions. At the weather station, soil volumetric water content data (VWC) were obtained from grass, freely-draining soils (Fig. 2b). End-Member Mixing Analysis data from Fennell et al. [38] provided daily estimates for groundwater contribution to discharge.

Hydrological indices and periods of contrasting hydro-climatic conditions

The long-term Standardized Streamflow Index (SSFI) [62,63] was used to evaluate how the study period, thus NBS results a) fit into the long-term context locally, and b) could be used to evaluate potential impacts and cost-benefits in future with climate change [52,56]. SSFI was calculated whereby mean SSFI was zero so low and high flows could be identified [62,63], based on weekly time periods to complement the distillery's water availability limitations. SSFI uses the same scale as standardised precipitation index (Supplementary materials Table 1). This allowed for the results to be evaluated in the cost-benefit analysis alongside predicted directions of change in rainfall seasonality and air temperatures for the Scottish Highlands in the next 25 years. It thus provided a “soft comparison” to determine whether the study period could provide insights for potential future conditions with climate change [2].

The Q_{95} (low flows), Q_{50} (medium flows), Q_{10} (high flows), total catchment recharge and hydrological indices relevant for industry, were used to assess the model's ability to simulate different aspects of observed discharge and low flow periods of concern for industry. The hydrological indices relevant to industry were: (1) the number of occurrences (days) for which discharge is less than the Q_{95} (Q_{95}_1day), to highlight low flow conditions, and (2) the number of occurrences (days) this continued for 7 consecutive days (Q_{95}_7day), to highlight when distillery production halts. All six indices were consistently calculated over the calibration and validation period and provided a baseline for NBS scenario comparison. Four periods of contrasting hydro-climatic conditions with different antecedent wetness were selected to compare trends in NBS scenario response. These periods were based on rainfall and discharge analysis in Fennell et al. [38]: Dry summer (15/06/18–05/09/18); Dry winter (15/09/18–15/12/18); Wet summer (10/05/19–05/08/19); Wet winter (15/10/19–01/01/20).

Table 1
Runoff Attenuation Features' (RAFs) location and combined volumes, and planting with design and total area planted.

RAFs	Details	Total volumes (m^3)
RAFs_Ephem	Ephemeral streams, 40 small	80
RAFs_Throughout1	Throughout network, 80 small	140
RAFs_Throughout2	Throughout network, 80 large	300
Planting		Area planted (hectares)
Plant_Strips	Infiltration strips	10
Plant_Riparian	30 m riparian buffer	12
Plant_FreeDrain	Freely-draining soils	30

Model setup

To compare NBS scenarios, we chose a MIKE SHE/MIKE 11 modelling framework. Previous successful application in Blairfindy catchment has been used to investigate the impacts of RAFs], and was developed here further based on the same baseline model structure. MIKE SHE, a fully-distributed 3D-catchment hydrological model, dynamically-coupled with MIKE 11, a 1D-hydraulic model [64] enabled detailed river network modelling with structures (e.g. RAFs) and spatial variation of areas and locations of different land use for planting scenarios [65], key to addressing the aims of the study.

The baseline model structure (Supplementary Materials, Fig. 1) and setup is detailed in Fennell et al. [23] and was informed by catchment function understanding from empirical data and maps [23,38]. Upper layers of land use and unsaturated soil zones were fully-distributed, using the 2D-diffusive wave approximation and finite difference method for overland flow and Gravity flow and Green and Ampt [66] infiltration for unsaturated soil processes. Conceptual interflow and baseflow reservoirs represented saturated soil zones and geology and used the linear reservoir method for saturated flow [67].

Four vegetation/soil units were represented in the model. These included heather (25% catchment area), pine (4%) and grass (9%) on freely-draining soils; and heather on poorly-draining soils (62%) (Fig. 2). Baseflow reservoirs distinguished between faster-moving groundwater in shallower glacial till and slow-moving groundwater in deep, fractured bedrock.

The model topography was based on a 5 m resolution Digital Terrain Model (DTM) [68], averaged in MIKE SHE over a 15mx15m grid cell mesh which discretized the catchment. The MIKE 11 river network was derived from the DTM using ESRI ArcGIS tools and adjusted based on field measurements of the channels (Fig. 2) [23]. MIKE 11 channel flow was simulated by 1D-approximations of Saint-Venant equations [64]. River segments shown to dry out (based on observations through drought, [38]) were assigned a “leakage coefficient” (calibrated), and lost water to baseflow reservoirs, whereas those maintained by groundwater were “gaining” streams and received baseflow from baseflow reservoirs.

Manual sensitivity analysis informed parameterisation, reducing 60 parameters in total, to 32 fixed and 28 sensitive parameters requiring calibration [69]. Parameter ranges and values were taken from literature and field data (Supplementary materials, Table 2). Model inputs were precipitation, PET and air temperature. Actual Evapotranspiration (AET) was simulated with the Kristensen and Jensen [70] method.

Table 2
Cost estimates from Highland Conservation Ltd. (private communication, 2020) and Sylvestrus Ltd. (private communication, 2014) quotes for 20 small Leaky Barrier Runoff Attenuation Features (RAFs) and 10 hectares (ha) planting, and general values for each approach.

Letter	Details	Costs (£)	
		RAFs (x20 small = 40 m^3)	Planting (10 ha)
V	Mobilisation to site	2000	2000
P	Preparation/ installation	3500	31,500
W	Materials/trees	500	9000
M	Maintenance	1000	1500
General values			
	Maintenance frequency	Once every 5 years[*]	Once every 5 years
	Reinstallation (years)	20–30 (for hardwood RAFs)	0
	Discount Factor	3.5%	3.5%

[*] Or as required depending on intensity of flood events.

Model calibration, evaluation and validation

We used a 6-hourly timestep for the baseline model, with defined periods for model spin-up (01/01/2015–22/02/2018), calibration (23/02/2018–01/07/2020) and validation (02/07/2020–17/12/2020). Latin Hypercube sampling was used to generate 20,000 parameter sets. The parameter sets were then run in a Monte Carlo analysis to calibrate the baseline model against observed stream discharge. A combined objective function (COF) of equally weighted Kling-Gupta Efficiency (KGE) [71] and Volumetric Error (VE) was chosen for this. This ensured that both high and low flow dynamics, and the model ability to accurately represent the overall water balance would be assessed [72,73]. The top 5% of parameter sets were selected first based on COF performance. Then the top 20 of the 5% were chosen so that the model's internal dynamics represented conditions observed in the catchment [48]. This evaluation required saturated hydraulic conductivity for heather, poorly-draining soils to be lower than heather, freely-draining soils [74,75], and average VWC for freely-draining soils beneath pines to be less than for heather and grass [76]. The validation period and COF was then used to assess the final 20 runs, and if within a similar range to calibration period, were accepted as the model baseline [77].

NBS scenarios

Different designs of RAFs and tree planting (Table 1, Fig. 3) were modelled using the 20 baseline parameter sets across the study period (01/01/2015–17/12/2020). Comparison between baseline and NBS scenarios was made just for the calibration and validation period. For each scenario, with the 20 parameter sets, the percentage change from the baseline was summarised as; 1) overall mean for hydrological indices (Q_{10}; Q_{50}; Q_{95}, recharge, Q_{95}_1day, Q_{95}_7day), and 2) flow and recharge dynamics through contrasting hydro-climatic conditions. This captured the direction of change whilst accounting for model uncertainty. To improve robustness of approach, types of NBS were compared using the full ranges from the different designs for each type. Comparisons between designs were conducted within each NBS type.

RAF designs (Table 1, Fig. 3) were based on those in Fennell et al. [23], and involved; (1) the scenario informed by existing RAFs in ephemeral streams (RAFs_Ephem), (2) those of the same size, spread throughout the river network (RAFs_Throughout1) and 3) those throughout the river network with greater volumes (RAFs_Throughout2). Between RAFs_Ephem and RAFs_Throughout1 the effect of location (primarily soil type, but also aspect, geology and elevation) and scale (area affected) could be compared. Between RAFs_Throughout1 and 2 the effect of scale (increased volumes) could be compared. RAFs were modelled in MIKE 11 using the integrated structure module, with the weir equation. Initial height (0.5 m), width (channel width), notch size (1/5th of width) and locations were specified based on wooden RAF in-field geometry (as in Fig. 2e), reducing model uncertainty [11,22]. In other scenarios, RAFs were spread evenly throughout the river network, and height was increased (up to bank height) to increase RAF volumes. Total combined RAF scenario volumes were calculated based on the RAF geometry and river network topography.

Tree planting designs (Table 1, Fig. 3) involved; 1) infiltration strips (cross-slope planting), 2) riparian planting and 3) planting the full area of freely-draining soils. Between infiltration strips and riparian planting the impacts of location, (including aspect, soil type, geology and elevation) could be compared. Between the latter two and planting the full area of freely-draining soils, the impacts of location and scale i.e., total area of planting could be compared (Table 1, Fig. 3). Planting was simulated only on freely-draining soils, given more likely successful colonisation [78,79]. This was implemented by using vegetation/soil parameters for baseline pine, freely-draining soils, (as these parameters had been calibrated) and changing the shapefile areas or locations of planting (as in Fig. 3d). The parameter sets represented well-established trees, with high infiltration benefit and moderate increase in roughness [43]. Simulated infiltration strips ran along contour lines to intercept flow pathways and ~30 m in width to be comparable with riparian planting (30 m optimum for temperature control [20]). Planting across all of the freely-draining soils represented the potentially maximum effect on flows and water yield.

Cost-benefit analysis to determine NBS feasibility

The Cost-Benefit Analysis (CBA) was conducted to evaluate the NBS approaches for the management of low flows for the distillery, thus we focussed on the Q_{95}_7day index. The CBA was limited to a financial analysis to reflect the initial priorities of the target users i.e. industry, providing opportunity for incorporation of natural capital benefits in future [80].

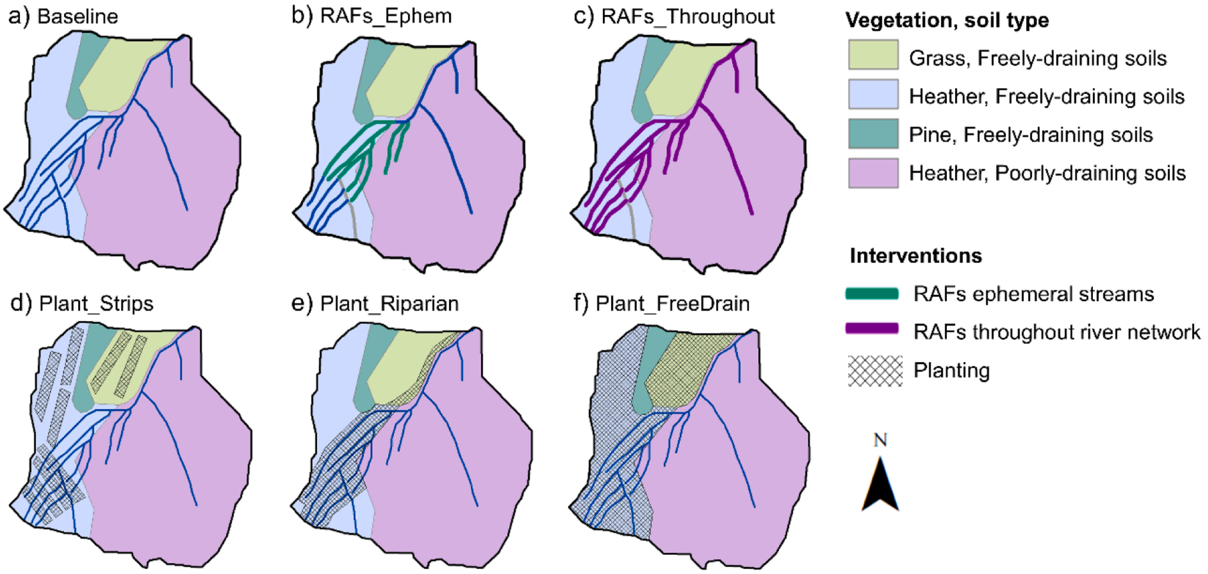

Fig. 3. (a) Baseline scenario, and Nature Based Solution (NBS) scenarios for: Runoff Attenuation Features (RAFs) in (b) ephemeral streams (Ephem) and (c) throughout river network (Throughout), volumes 1 and 2; and planting (d) hillslope infiltration strips (Strips), (e) the riparian zone (Riparian) and (f) freely-draining soils (FreeDrain).

The costs and benefits are evaluated for a certain time period and summarised as their present value (present cost: PV(C) Eq. (1), and benefits: PV(B) Eq. (2)):

$$PV(C) = \sum_{t=0}^{n} \frac{C_t}{(1+r)^t} \tag{1}$$

$$PV(B) = \sum_{t=0}^{n} \frac{B_t}{(1+r)^t} \tag{2}$$

Where B_t and C_t denote the benefits and costs, respectively, in year t. Here $t = 25$ years given this represents the estimated average lifetime of distillery assets and hardwood RAFs, whilst being close to targets for climate change adaptation [81]. The discount factor r arises from the fact that individuals give a higher value to present benefits or costs than to those in future. Here $r = 3.5\%$ as in recent local assessments [82]. The net present value (NPV) of each scenario was then derived from Eq. (3), and if positive, the scenario may be recommended.

$$NPV = PV(B) - PV(C) \tag{3}$$

Costs can be calculated using the factors in Tables 1 and 2, and Eq. (4):

$$Ct = V + A\left(P + W + M\frac{t}{5}\right) \tag{4}$$

Hardwood Leaky Barrier RAFs (as simulated) are estimated to require reinstallation every 25 years. Thus, Costs (C) in 25 years ($t = 25$) includes V, the one-off cost of mobilisation to site (location/access-dependant, for Glenlivet B-road <5 km away, access via tracks). The available quote was for RAF combined volumes=40m^3, so to estimate costs for modelled RAF scenarios of greater volumes (Table 1), a multiplication factor A was applied (RAFs_Ephem: $A = 2$; RAFs_Throughout1: $A = 3.5$; RAFs_Throughout2: $A = 7.5$). The following are multiplied by A: P=installation, labour, supervision and machinery hire; W=materials and M=cost of 2 days maintenance once every 5 years (hence t/5). The cost per structure (~£300–500 for one small RAF, width 2 m x height 0.5m+, ~2m^3 storage) was at the lower end of costs reported for similar size structures elsewhere in the UK. For example, Belford catchment leaky barriers were~£100–1000 [34] and Bowmont catchment engineered log jams were ~£230 [83], although costs depend on RAF design, material availability, access and inflation.

For planting, costs (C) were calculated using Eq. (4) for 25 years ($t = 25$), and V=one-off initial mobilisation cost. Then depending on planted area, (quoted area = 10 hectares), land preparation, fertilisation and installation P, and plants W, are multiplied by A (Plant_Strips: $A = 1$; Plant_Riparian: $A = 1.2$ and Plant_FreeDrain $A = 3$). Quotes for planting are local, and although likely an overestimate, the same rates were applied when scaling to larger areas, as in Dittrich *et al.* (2019). The cost per hectare of planting (approx. ~£4500/hectare) was within the range reported elsewhere e.g. Pickering £2200–7800 and Bowmont ~ £3500–5000 [18]. In practice, these costs depend on site access, tree species and fencing requirements. Maintenance M, was also area-dependant (as in Dittrich et al., [82]), and accounted for once every 5 years. Compensation of agricultural land lost to farmers was not included, as potential costs were small compared to model uncertainties [82,84].

Benefits Bt, were calculated using Eq. (5) in the potential value of whisky produced per day E (on average 2.50 £/L; 60,000 L/day raw spirit product) for reducing the number of days for which production must stop D when threshold Q_{95}_7day is reached; the model baseline Bl average is 32 days:

$$Bt = E(Bl - D) \tag{5}$$

Uncertainty was calculated based on the results obtained from the 20 model parameter sets for the number of days Q_{95}_7day, so cost-benefits are summarised as a mean with maximum and minimum values. The CBA conclusions depend on initial assessment of the modelling period, whether representative of conditions which may be experienced in the next 25 years (section 2.3) thus must be considered with this limitation.

Results

The model period in the long-term context

Several weeks of a SSFI of between −1.5 and −2 were recorded, which suggested “severely to extremely dry” conditions were experienced through 2018 (Fig. 4). In particular, the duration of dry conditions in 2018 was unlike any other period except for one in 2003. The extreme nature of the drought was also clear from the observed discharge and associated hydrological indices, highlighting lower water availability for the distillery (Table 3). Through the “dry summer” and subsequent “dry winter” until February 2019, low rainfall (Fig. 5a) dictated that streamflow decreased and 52 instances (days) of Q_{95}_1day occurred. Although low flow days were not always consecutive, there were three main periods in August–October of Q_{95}_7day (Fig. 5b), where this could have affected distillery production.

A particularly long period of high flows through 2019–20 followed with increased precipitation inputs, again unusual in the 20-year context (Fig. 4). *Re*-wetting of the catchment into “wet summer” featured several large precipitation events (20–30 mm/day), to which discharge responded and then returned to baseflow relatively quickly (Fig. 5a,b). This was again observed through the “wet winter” which also featured several snow events.

Model baseline

The model represented observed discharge reasonably well (Fig. 5) through the calibration period (KGE max=0.54; VE max=0.62; combined objective function (COF) max=0.5), which improved during the less extreme validation period (KGE max=0.65, VE max=0.60; COF max=0.6). The rate of catchment re-wetting after the drought was slightly over-predicted (Fig. 5). The model captured baseflow well, and although peak flows were slightly over-predicted, comparison between the observed and mean simulated model discharge showed good representation of the hydrological indices (Table 3) although the Q_{95}_7day was overestimated (obs=7; sim=32). Over the 20 parameter sets the Q_{95}_7day ranged between 15 and 46 days, so the lower end of the model predictions was closer to the observed.

The model reproduced the lower and higher water content of the freely and poorly-draining soils well (Fig. 5c). Although mean simulated VWC (of 20 baseline parameter sets) for all vegetation/soil types was not as low as observed in freely-draining soils with grass during the drought, the dynamics were otherwise well-captured throughout the rest of the modelling period. VWC comparison between heather and pine on freely-draining soils showed pine was more variable as would be expected given the higher ET rate (Fig. 5d) and local observations [76]. Greater mean daily ET estimates resulted for pines compared to heather or grass during summer, but with similar rates during winter, suggested the model captured the expected relative differences in ET processes. The plausible relationship between the simulated VWC and ET of pine and the other vegetation types present on freely-draining soils justified the use of the 20 baseline parameter sets for representation of pines in planting scenarios. The model ability to simulate the hydrological indices reasonably well, suggested it would provide a suitable baseline on which to test the impacts of NBS scenarios.

Effects of type and design of NBS scenarios on hydrological indices and through contrasting hydro-climatic conditions

Differences in NBS type could be observed from their effects on high and low flows and recharge. For Blairfindy, RAFs were overall two to six times more effective than tree planting at reducing high flows

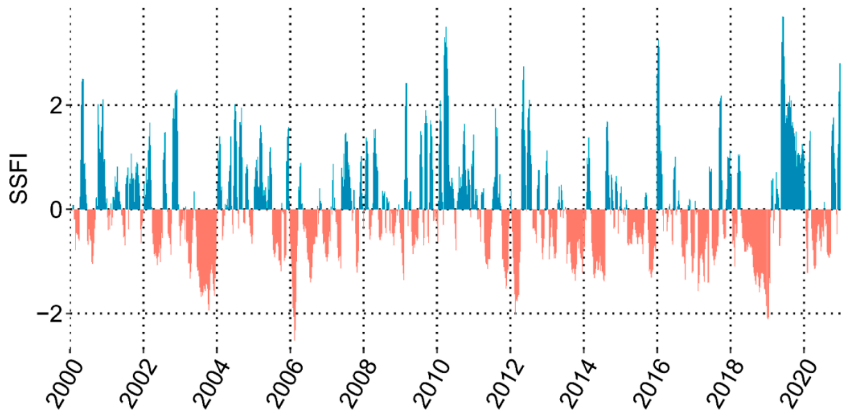

Fig. 4. Blairfindy stream weekly Standardized Streamflow Index presented at weekly intervals.

Table 3
Hydrological indices and those which are industry relevant for observations, model baseline and Nature Based Solution (NBS) simulations, including tree planting and Runoff Attenuation Features (RAFs). Mean% change from the baseline was used, and direction of change was consistent for the majority of the 20 parameter sets, with no major outliers.

Scenario	Hydrological indices				Industry relevant hydrological indices			
	Q_{10} (m^3/s)	Q_{50} (m^3/s)	Q_{95} (m^3/s)	Recharge (mm/day)	Q_{95}_1day (days)	Q_{95}_7day (days)		
					mean	min	mean	max
Observed	0.018	0.007	0.0049		52		7	
Baseline	0.022	0.011	0.0051	1.31	52	15	32	46
Planting	Mean change from baseline (%)							
Plant_Strips	−2.7	−1.4	−4.1	−1.7	66	20	52	74
Plant_Riparian	−3.0	−1.1	−3.6	−1.8	63	19	50	72
Plant_FreeDrain	−2.9	−3.8	−8.3	−2.9	75	22	71	108
RAFs								
RAFs_Ephem	−5	−1.6	1.3	0.075	48	7	26	43
RAFs_Throughout1	−10	−3.1	2.6	0.079	40	4	16	30
RAFs_Throughout2	−13	−3.4	3.2	0.080	39	0	15	39

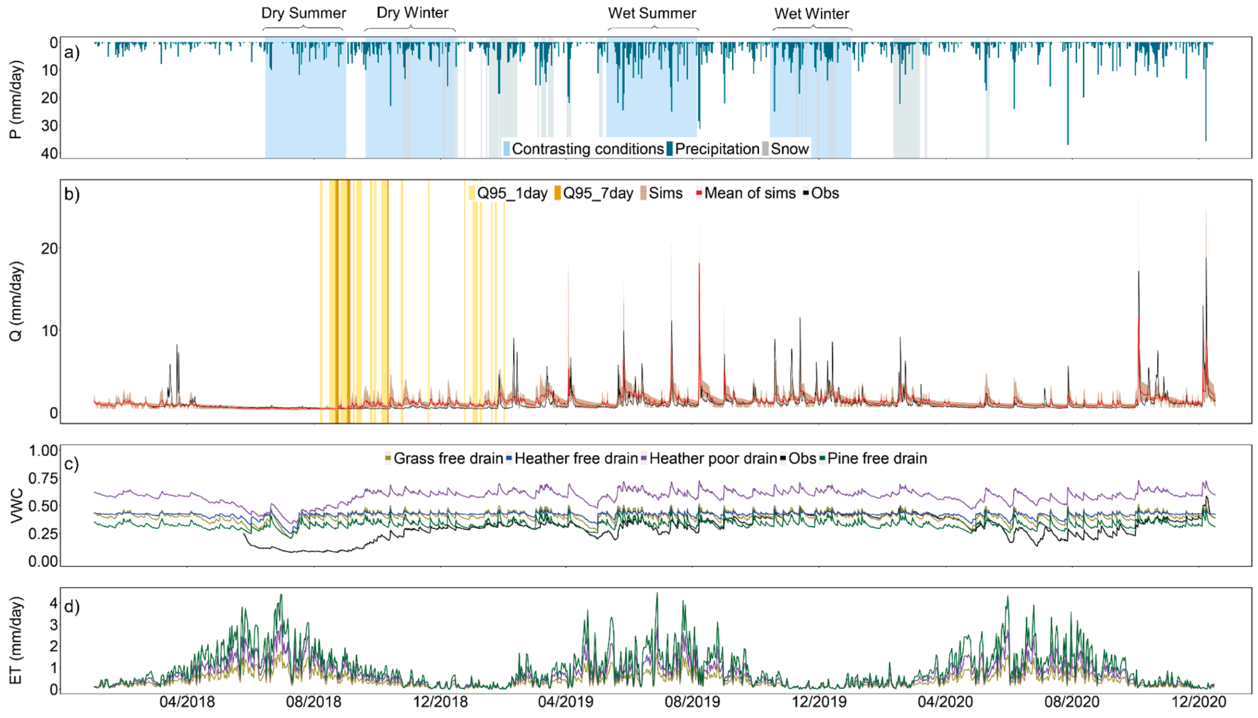

Fig. 5. Model period for (a) observed precipitation, snow and four periods of contrasting hydro-climatological conditions, (b) observed and mean simulated discharge with uncertainty band from top 20 parameter sets and observed discharge Q_{95}_1day and Q_{95}_7day; (c) mean simulated soil volumetric water content (VWC) for each vegetation/soil type and observed grass-freely draining VWC; and (d) mean simulated AET for each vegetation/soil type.

(reductions of ∼5–13% for RAFs, ∼2–3% for tree planting; Fig. 6). Throughout contrasting hydro-climatological conditions, peaks in discharge were reduced by RAFs almost proportional to event size (the greater the event, the greater the reduction, up to a maximum reduction of ∼5–20%), (Fig. 7). Conversely, while tree planting in dry conditions reduced peaks almost twice that of RAFs (dry summer −15–35% and dry winter ∼17.5–40%) (Fig. 7a,b), during wetter conditions with increased soil VWC (smaller soil water deficit), planting was half as effective at reducing peaks compared to RAFs (wet winter planting reduced peaks ∼3–7%, RAFs ∼7–14%) (Fig. 7d). This also affected the mitigation of events with multiple peaks (Fig. 7). In mid-May when two rainfall events occurred close together; planting reduced the first peak by ∼11–30%, but the next larger peak was only reduced by ∼5–10%. RAFs however reduced both peaks to a similar extent (by 7–18%) (Fig. 7c).

RAFs resulted in small overall increases in low flows (Q_{95}, increase of 1.5–3%; Fig. 6), and reduced the number of low flow days (Q_{95}_1day), including those occurring 7 days in a row (Q_{95}_7day) by between 6 and 15 days on average (Table 3). In the dry summer period RAFs gradually increased baseflow from baseline to ∼1.5–4% (April-Aug ’18; Fig. 7). RAFs generally caused small increases in recharge overall (<1%, all designs; Fig. 6), and this was generally in response to rainfall events up to ∼2.5–5%, otherwise it remained at baseline (Fig. 7).

Tree planting had at least twice the impact on lows flows, than of RAFs overall, but in the opposite direction (overall reductions 4–8%; Fig. 6). Flows gradually declined from ∼3–5% below baseline to ∼7–10% (April-Aug ’18) with only slight increases following rainfall events (Fig. 7a). The number of low flow days increased from baseline by between 11 and 25 days, and 7 consecutive low flow days by between 18 and 39 days (Table 3). Tree planting also had at least twice the impact of RAFs on recharge, again in the negative direction, reducing recharge 1.5–3% (Fig. 6). Event-based net reduction in recharge was represented by a delayed response compared to baseline (Fig. 7). There was less difference between NBS types for medium flows; all scenarios resulted in ∼1–4% reduction overall.

For RAF designs, larger changes were observed when double the volume was spread over greater areas (from RAFs_Ephem to RAFs_Throughout1), compared to additional increases in volume (RAFs_Throughout1 to RAFs_Throughout2). This applied to reductions in high and medium flows (differences of 4.9% then 2.9% and 1.5% then <1%), and increases in low flows and recharge (differences of 1.3% then <1% and <1% then <1%) (Table 3, Fig. 6). This was also observed in the reduction of the mean number of low flow days (by 8 days, then by 1 day) and those occurring 7 days in a row (by 10 days, then by 1 day) (Table 3).

For tree planting designs, an increase in area of planting (10/12 to 30hectares), led to two to three times the reduction of medium flows (reduced by ∼1 to 4%), low flows (reduced by ∼4% to 8%) as well as recharge (reduced by 1.7% to 3%) (Table 3, Fig. 6). Area size of planting increased effects up to the Q_{50}, but made less of a difference to the Q_{10}, with change in effect less than 1%. The effect of location of planting was less obvious, but riparian planting reduced medium and low flows slightly less than infiltrations strips, and recharge slightly more. Riparian planting was marginally more effective than tree planting over the full area of free-draining soils and infiltration strips at reducing the Q_{10} (for all, difference <1%).

NBS cost-benefit analysis

The study period hydroclimate was considered reflective of conditions which may occur in the next 25 years in the Scottish Highlands,

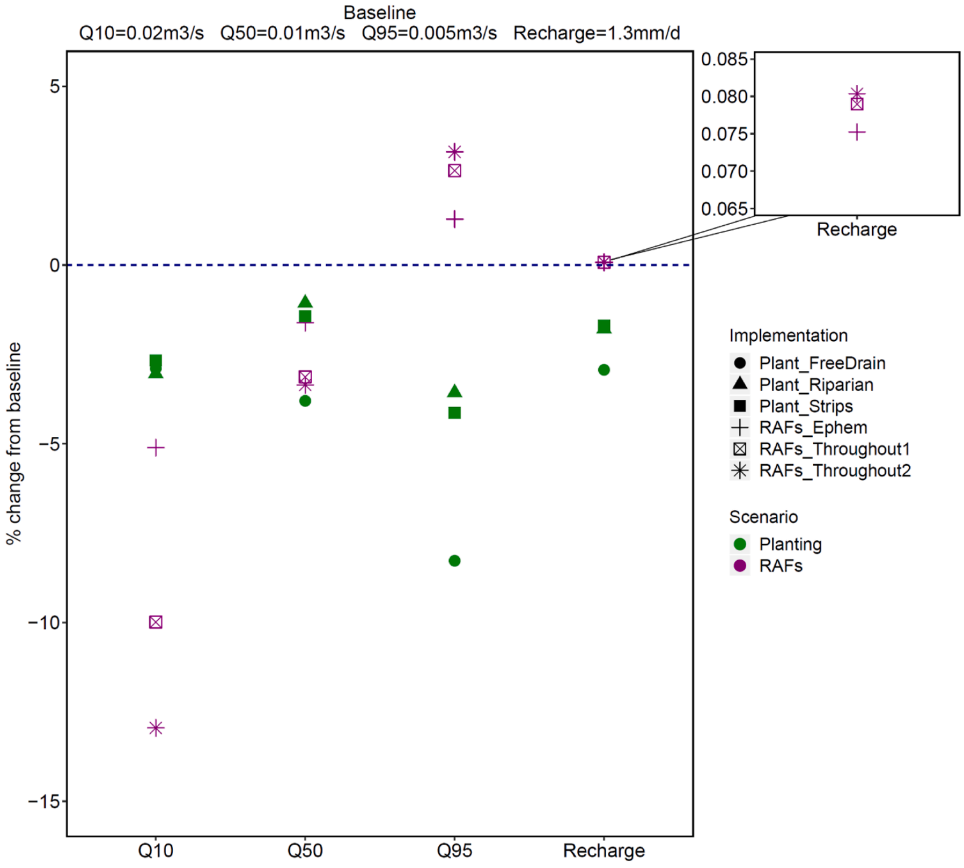

Fig. 6. Full modelling period summary scatter plot of Q_{10}, Q_{50}, Q_{95} and recharge for tree planting and Runoff Attenuation Features (RAFs) scenarios, showing mean % change from baseline for 20 parameter sets (for which the direction of change was consistent for the majority). Zoom plot shows RAFs mean% change from baseline recharge.

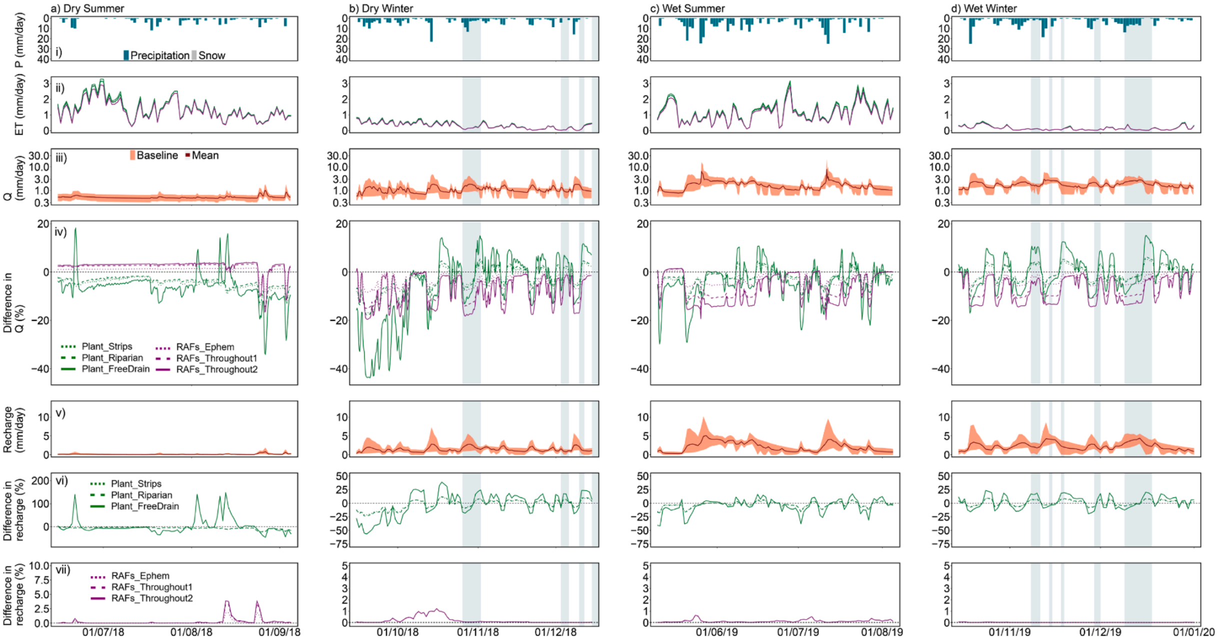

Fig. 7. Contrasting conditions (a) Dry summer (b) Dry winter (c) Wet summer (d) Wet winter, with (i) Precipitation and snow (ii) mean catchment ET for each Nature Based Solution (NBS) scenario including tree planting and Runoff Attenuation Features (RAFs); (iii) mean baseline discharge with uncertainty band from 20 parameter sets, (iv)% difference from mean baseline discharge for each NBS scenario; (v) baseline recharge with uncertainty band for 20 parameter sets; and% difference in recharge from mean baseline for (vi) planting scenarios and (vii) RAF scenarios. Note difference in axes for difference in recharge between (a), and (b), (c) and (d).

with current projections suggesting changes in seasonal rainfall patterns, less snowfall, higher intensity of rainfall in winter, and hotter, drier summers [85]. Therefore, the results based on these conditions provide a plausible indication of NBS impacts so were used as an estimate for the 25-year CBA. Comparison between the NBS types shows that despite RAFs costing around half that of planting (RAFs_Throughout2 £0.05 m vs Plant_FreeDrain £0.11 m), RAF impacts on the Q_{95}_7days were around three times more positive. The low cost of RAFs and high benefit for an additional day of distillery production (Table 4, Fig. 8) meant even the minimum estimate would result in a positive NPV (smallest RAFs_Ephem scenario, over 25 years NPV=£5 m). Increasing both RAF area and volume (from RAFs_Ephem to RAFs_Throughout1) was beneficial, but further increases in volume were not necessarily worth the investment (RAFs_Throughout1 to RAFs_Throughout2), resulting in less additional benefit.

For tree planting scenarios there was greater uncertainty associated with potential impact, but all ranges suggested negative NPV (Fig. 8). Planted area increase from 10/12hectares to 30hectares correlated with declining NPV, although riparian planting was slightly less negative than strips despite its slightly larger planted area.

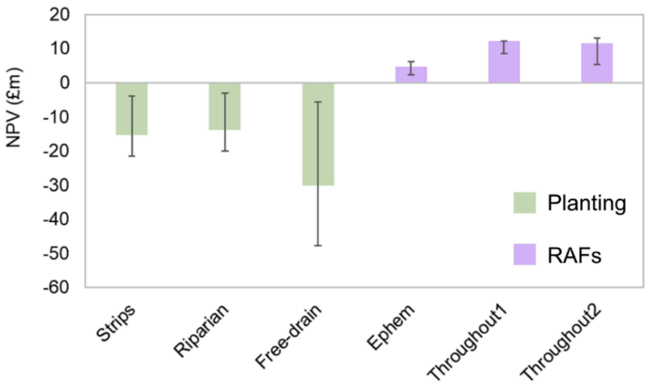

Fig. 8. Cost-benefit analysis for 25-year time period showing Net Present Value (NPV) in £million for Nature Based Solution (NBS) scenarios for tree planting and Runoff Attenuation Features (RAFs), with error bars showing maximum and minimum estimates based on parameter ranges.

Table 4
Summary of Nature Based Solution (NBS) scenarios for tree planting and Runoff Attenuation Features (RAFs), key results and cost-benefit analysis for 25-year period, summarised as Costs, Benefits and Net Present Values (PV).

Scenario	Q_{95}_7day (days)			PV Cost (£m)	PV Benefit (£m)			PV Net (£m)		
	min	mean	max	mean	min	mean	max	min	mean	max
Observed		7								
Baseline	15	32	46							
Planting										
Plant_Strips	20	52	74	0.04	−22	−15	−4	−22	−15	−4
Plant_Riparian	19	50	72	0.04	−20	−14	−3	−20	−14	−3
Plant_FreeDrain	22	71	108	0.11	−48	−30	−5	−48	−30	−6
RAFs										
RAFs_Ephem	7	26	43	0.01	2	5	6	2	5	6
RAFs_Throughout1	4	16	30	0.02	8	12	12	8	12	12
RAFs_Throughout2	0	15	39	0.05	5	11	13	5	11	13

Discussion

This study found that RAFs but not trees could increase low flows, reducing the impacts of drought, with positive cost-benefits. This adds to previous work in temperate regions which has focussed on NBS effectiveness and the cost-benefits for reduction of flood damage. Exploring the effects of NBS design as well as type was shown to be important to ensure optimum NBS implementation and management of water resources for stakeholders (e.g., the whisky industry). This combination of hydrological modelling with indices could be applied to assess the impacts of NBS in other contexts e.g., water quality, as well as being directly relevant to low flow management for the distillery. More broadly, we have demonstrated the importance of comparing NBS for both high and low flow management and applying this within cost-benefit analysis, to encourage informed implementation of NBS.

The long-term context and future mitigation potential of NBS

Although relatively simple, use of the long term SSFI with climate change projection trends provided a reasonable baseline from which NBS effects in the next 25 years could be estimated to inform the cost-benefit analysis [2,4,86]. This was justified given the extreme nature of the drought captured within the monitoring period, highlighted by the SSFI [54]. A reasonable alternative to inclusion of full climate change projections within the model, this avoided adding further uncertainty to the results. Results from this study therefore represent a relatively rare example of the potential impacts of NBS through two years of extreme conditions, which could provide much needed insights into the required scale of NBS for mitigation of similar, or more extreme conditions likely to occur more frequently in future with climate change [4].

Simulation of water storage, flow pathways and hydrological indices

Identification of the potential effects of NBS can be challenging given they are effective over different temporal and spatial scales [29], particularly if model uncertainty is high. Here model uncertainty was limited, given that model setup was informed by empirical data. Specifically, these data were collected through extreme conditions [38] and revealed the ephemeral or perennial nature [39], and timing of runoff sources, which helped inform model representation of the variation in soil moisture and confirm presence or activation of flow pathways in the modelled catchment [23]. In addition, the effects of NBS were assessed using hydrological indices, avoiding difficulties of assessment over different temporal or spatial scales. Model uncertainty was considered by reporting results as mean percentage changes from the baseline. Each scenario carried the same level of uncertainty, and the majority of parameter sets resulted in the same direction of change, so that this could be interpreted with confidence.

The role of type and design of NBS scenarios on hydrological indices and through contrasting hydro-climatic conditions

Both NBS types were able to reduce high flows, although RAFs were more effective than tree planting (Table 3, Fig. 6). In addition, the design, specifically greater area and volumes of RAFs, increased the effects, as in other studies [11,87,88]. For design of planting scenarios, although area was important for flows up to the Q_{50}, it made little difference for the Q_{10} (<1% between scenarios) which agrees with other findings [89,90]. In fact, the location, specifically riparian planting, had marginally more of an impact on the highest of flows (Q_{10}). With limited availability of soil water storage during largest events, the increase in hydraulic roughness close to the stream network, thus interception of flow pathways or slowing flows when overbank flow was initiated, likely explained why riparian planting had more of an effect than the other planting designs [33,91].

The time-variable effects of NBS demonstrated that both types and designs should be specific to the local water management priorities in the catchment. For planting to be implemented over larger areas meant greater available sub-surface storage to reduce peaks in flow (from 17.5 to 40%). However, as found elsewhere (e.g. Soulsby et al., [92]) this varied with antecedent conditions; in wetter conditions (consecutive events, highest flows most likely) peaks were only reduced by ~5–10%. For RAFs, increased volumes over greater areas meant greater capacity to reduce both large and consecutive peaks in all conditions but only to a maximum of ~7–20%. These effects will however depend on local soils, geology and climate, affecting infiltration, percolation and evaporation rate [93,94].

The results highlighted the potential for RAFs to mitigate low flow periods. However, the effects here were relatively small compared to Norbury et al. [21] for which willow-engineered log jams in the North of England increased baseflow by 27.1%, and Somers et al. [95] for infiltration channels in Peru increased recharge 3.5%. The location, therefore, soils, geology and position (affecting infiltration and percolation rate [31,96–98]) and the design, specifically volumes and spread of storage, likely explain these differences. These differences highlight why more studies are needed in varied locations to understand variability in impacts and optimise choice of NBS type and design for specific catchment conditions. However, although effects were relatively small here, they should not be dismissed, as the cost-benefits for RAFs were positive.

Simulation of NBS scenarios through contrasting hydro-climatic conditions helped identify how the different water fluxes changed for the different types of NBS. Whilst planting scenarios appeared to increase sub-surface storage and retention of event water, the short retention time meant this had little impact on low flows compared to planting-associated increases in ET and water use [49]. Planting scenarios therefore reduced streamflow and recharge below baseline, which could be problematic in catchments where water yield was of concern. Although RAFs retained water on the surface for long enough to allow infiltration, transfer to deeper storage zones via slower flow pathways meant streamflow was raised above baseline and steadily increased, suggesting these processes were more significant than evaporation. This may not be the case in other sites with higher evaporation rates or potentially in future with climate change-induced air temperature increases [93,94], highlighting the importance of testing scenarios at different sites through contrasting hydro-climatic conditions to avoid unintended negative effects.

Although results suggested planting would reduce low flows and recharge, as found elsewhere [49,90,99], the impacts may have differed with alternative designs; species, age or distribution [100]. Model representations of tree planting are also often limited, specifically by temporal changes as a tree canopy develops e.g. interception, recharge and infiltration, but also early stages of planting and tree growth; compaction of soils, declines in water quality and higher water use [100–102]. The long-term effects of riparian trees may be particularly important [103], if management encouraged fallen branches to create woody debris dams, resulting in positive outcomes associated with Plant_Riparian and RAFs_Ephem. Given climate change and carbon mitigation strategies [104] where tree planting has been highlighted as a major solution, such scenario results could inform management approaches. This suggests assessment of NBS should be conducted on high and low flows, as well as short and long-term impacts before implementation [105].

Cost-benefit analysis for NBS feasibility

Comparison of the NBS impacts on Q_{95}_1day and Q_{95}_7day revealed that RAFs improved water supplies during low flows, whereas tree planting did not. The CBA based on financial benefits specifically for enhancing water availability through low flows suggested RAFs should be recommended, and similar to previous studies [90,106], planting at this site would need to be carefully considered. With more frequent extreme periods in future with climate change, less opportunity for groundwater recharge [107] and more frequent drought conditions, RAF effects and cost-benefits could be even more significant. Developing understanding of how NBS approaches may be combined or scaled up to increase impact [29], could be crucial to ensure water availability through low flow periods in future, for the environment and industry [2].

Inclusion of environmental and social benefits would likely strengthen the NPV for RAFs given improvements to e.g. water quality and biodiversity [108], and for those same reasons tree planting, an initial negative NPV may become positive (as in Dittrich et al. [82]). Evaluated in this way, planting would have been recommended thus potentially worsening low flows and water yield for the distillery. Although difficult to include all benefits into a CBA [109], this study highlighted the importance of acknowledging the potential for well-designed NBS to mitigate both high and low flows, but also that results should be communicated to be of use to stakeholders (i.e. here, primarily focussing on water availability during low flows).

Within the CBA, there were uncertainties in the costs, estimates for maintenance e.g. sedimentation of RAFs, and differences between model baseline and observed values, however the overall conclusions were relatively certain given that one NBS type was positive and the other negative. For example, costs scaled for greater area/volumes of NBS were cross-checked, and within ranges reported elsewhere [18]. Although the model baseline Q_{95}_7day was higher than observed (32 and 7 respectively), use of the minimum model baseline values (15 days) provided the same overall conclusions. Finally, we recognise that the 25-year CBA involved extrapolating observations and simulations for a three-year period, which brings further uncertainty. However, given that the study period includes hydrological conditions at both the high and low flow extreme ends in a similarly long-term context (Fig. 4), we argue that 25 years is appropriate.

Wider applications

Although the model and CBA method (Q_{95}_7day index) were site-specific, both could be scaled up and applied across multiple catchments contributing to major rivers on which industry abstraction limits are based, especially given the Q_{95} is a widely used index for low flows [110–112]. This would aid determination of optimal locations and required scales of NBS for river basin-wide challenges. Although unlikely to change the outcome between the two NBS types, the methodology could be developed for longer-term cost-benefit analysis to also consider future climate projections [113]. Empirical evidence on the effects of RAFs and tree planting in different catchments would also improve understanding of their potential and optimal design in sites with different soils and geology, and how this may affect cost-benefit analysis to inform wider implementation and increase uptake.

Conclusion

The potential for Nature Based Solutions (NBS) to mitigate the impacts of more frequent flooding and droughts, as predicted with climate change, requires better understanding on effectiveness under varying hydro-climatological conditions. In particular, more knowledge is needed on how different types and design of NBS affect impacts on high and low flows and catchment water storage dynamics, and how this relates to the cost-benefits to improve implementation and increase industry uptake.

Successful implementation of a physically-based model combined with hydrological indices enabled comparison of the impacts of different types and design of NBS including Runoff Attenuation Features (RAFs) and tree planting. Both types of NBS reduced high to medium flows at the 1km^2 catchment scale. As well as more effective high flow reduction, RAFs increased low flows and groundwater recharge, whereas planting reduced them. The design of NBS affected the extent of impact; increases in RAFs storage volume over greater areas increased effects on high, low and medium flows and recharge, and although this mostly applied for increased planting areas, this was less important for the highest of flows. Contrasting hydro-climatological conditions revealed further type and design-related differences in water storage availability, retention and transfer, and therefore NBS' ability to enhance streamflow, or mitigate large or consecutive events. This provided insights into how NBS type and design may be essential for optimal performance but also to avoid negative effects for certain types of catchments with specific water management issues. Here, cost-benefit analysis focussed on water availability through low flows, which suggested RAFs up to a certain volume would be beneficial and cost-effective for the 25-year time period, whereas extensive planting may be less beneficial in this context over this time period.

Empirical data collected on different types and design of NBS in varied catchments would help provide more evidence on the potential impacts and develop guidelines for ensuring optimal design and cost-benefit of interventions. Combining different NBS approaches across different scales would also help to determine broader scale impacts and the potential for managing both high and low flows.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.nbsj.2023.100050.

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