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Integrating Blue-Green and Grey Infrastructure through an Adaptation Pathways Approach to Surface Water Flooding

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Statement (if applicable):
LK carried out the modelling work. Both authors contributed to design, analysis and interpretation of data. Both authors drafted and approved the manuscript.

Integrating Blue-Green and Grey Infrastructure through an Adaptation Pathways Approach to Surface Water Flooding

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Keywords: Flooding, Sustainable Drainage Systems, Adaptive planning, Adaptation Pathways, Multiple Benefits

1. Summary

A range of solutions to future flood risk are available ranging from Blue-Green Infrastructure (BGI) as commonly incorporated in Sustainable Drainage Systems (SuDS) and traditional grey infrastructure (e.g. pipe networks, storage tanks, flood walls). Each offers a different profile with respect to costs, flexibility of implementation and the ability to deliver a range of wider benefits beyond their flood protection function. An important question that must be addressed when considering these approaches is what is the most suitable mix of grey and blue-green solutions to urban flooding at any location and at any future time? This paper uses an adaptation pathways approach to compare a range of alternative options to deal with current and expected future flood risk in part of a South London Borough. Solutions considered separately and in combination include grey pipe expansion, bioretention cells, permeable pavements and storage ponds. A methodological framework combines a range of existing tools to develop, assess and characterise each pathway, including a Storm Water Management Model (SWMM), a SuDS opportunity selection tool, an adaptation pathway generator and the CIRIA BEST tool for monetising multiple benefits. Climate change is represented by the UK Water Industry Research method for establishing future rainfall intensities for sewer and BGI design. Results show combining future Blue-Green interventions with the existing Grey system are more efficient at dealing with flooding and maximising other benefits. This is true for both moderate and high emissions scenarios.

The relative contribution of each option's capital and operation and maintenance costs has implications on where the option is implemented as well as the rate of implementation. The monetisation of the multiple benefits associated with each pathway shows that their economic co-evaluation alongside infrastructure costs can change the preference for one pathway over another.

2. Introduction

Urban flood risk represents a growing threat to people, property and the operation of interdependent infrastructure systems in many cities. Driving this risk are climate induced changes to rainfall and increasingly rapid programmes of urban development [1], both of which are associated with considerable uncertainties about the future [2]. Solutions range from extensions of existing hard drainage systems, usually

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in the form of grey buried pipework and ancillary structures, to Sustainable Drainage Systems (SuDS) using varying forms of Blue-Green Infrastructure (BGI) incorporating vegetated surfaces to store and infiltrate excess stormwater at source. Blue-Green refers to Infrastructure that aims at restoring the naturally-oriented water cycle while contributing to amenity by bringing water management and green infrastructure together [3], while Grey infrastructure refers to human-engineered traditional approaches to water management such as pipes and hard surfaces [4].

The past tendency to construct grey pipe systems can lead to a technical lock-in and reduce flexibility to modify the system performance in the light of climate and development uncertainties. Blue-Green solutions can be more flexible and are often delivered at lower cost whilst generating a wide variety of benefits in addition to flood protection [5]. For this reason, an important question that must be addressed is what is the most suitable mix of grey and blue-green solutions to urban flooding at any location and at any future time? This is relevant to retrofit and new built environments that already require or will require in the future a flexible adaptation plan to climate change.

Principles of adaptive planning as described by Walker et al [6] are becoming more widely used to evaluate these approaches. Key elements of a sustainable adaptive plan are: the exploration of a wide variety of relevant uncertainties, connecting short-term targets to long-term goals over time, committing to short-term actions while keeping options open, and continuously monitoring the world and taking further actions when necessary. This allows unforeseen uncertainties to be addressed by adapting the system continuously to new circumstances as they develop. An approach to adaptive planning is the design of possible adaptation pathways which are valued and compared to a baseline pathway, so one option can be chosen for implementation which is suitable at the present time. Those alternative pathways that are not adopted now remain as possible solutions later if future pressures render current plans inadequate. Such systems are characterised as anti-fragile, as they incorporate possible designs that may improve performance in cases of high or deep uncertainty [7, 8].

To value such flexibility, a Real Options Analysis (ROA) has been recommended [9, 10] with an early example based on evaluating flood risk management for the Thamesmead area of the Thames Estuary reported by Woodward et al [11] in 2011, demonstrating substantial cost savings under future uncertainties when Real Options are used instead of more traditional, precautionary approaches. ROA assumes that future uncertainties can be sufficiently estimated as uncertainty is dynamic and with time there is more knowledge to inform decision-making [12, 13]. On the other hand, approaches such as Dynamic Adaptive Policy Planning (DAAP) accept that decision-making is made under conditions of deep uncertainty meaning that policy actions have an uncertain design life and will fail sooner or later [14]. For this reason, DAAP explores alternative sequence of decisions in the form of adaptation pathways for multiple futures and identifies the path dependency of different strategies [15]. Gersonius et al. [2] provide a comprehensive comparison of these two approaches and give recommendations as to which should be used and under what circumstances. Complementing these approaches, Robust Decision Making identifies measures that have little sensitivity to the source of uncertainty (i.e. different climate change scenarios) by trading off some optimality [16].

In the context of adaptation pathways, Hall et al [17] explored adaptation thresholds and pathways for tidal flood risk management in London based on the adaptation options identified by the Thames Estuary 2100 project [18]. These included improving the existing defences; providing tidal flood storage; building a new barrier; and creating a barrier with locks. TE2100 was one of the first major infrastructure projects to explicitly recognize and address the issue of the deep uncertainty in climate projections throughout the planning process [19]. Analysis showed the adaptation pathway that most cost-effectively and robustly maintains risk at a tolerable level involves moving the Thames Barrier 17 km towards the sea if mean sea level rises 2m above

present levels [17]. While experts are accustomed to adaptive planning concepts, working with stakeholders requires shifting their short-term thinking to anticipatory long-term thinking. This requires exploring multiple scenarios, assessing consent to and costs of different options, and identifying assessment criteria for the multiple pathways is needed [20]. Changing from one pathway to another has implications on the economic valuation of projects as this switch is accompanied by “transfer costs” as opposed to a linear infrastructure development following an Net Present Valuation; by extension minimising the cost of adjustment over time becomes an objective of adaptive planning [21].

Recent guidance by Water UK [22] on the Production of Drainage and Wastewater Management Plans recommends an adaptation pathway approach where longer term drivers of change are evident but uncertain, and the planning problem that results is complex and potentially significant. For example, managing surface water flows could involve an adaptation pathway approach that examines operational measures (real time weather and flow management) as an initial option with residual risks managed by a ‘green’ intervention as and when flow triggers indicate that thresholds are being exceeded.

Several authors have discussed approaches to uncertainty with respect to flood risk management, for example exploring adaptation pathways for sustainable water management in river deltas in the Netherlands [6, 23, 24], drainage policies to address flooding in Singapore [25] and real options based assessment of urban Blue-Green infrastructure on the Kent Ridge Campus of the National University of Singapore [26]. A similar real options approach has valued adaptation pathways for drainage improvements in a Korean Municipality with the benefits of delaying investment in several options for a period of time explored [27]. These studies do not incorporate a co-evaluation of the wider benefits provided by the blue-green pathways they assess, nor do they include an appraisal of flexibility and ease of implementation for each option.

However, multi-objective optimisation models have been reported for the design and operation of water distribution systems [28]. Radhakrishnan et al [29] have demonstrated a flexible planning process in Melbourne, Australia, showing a combination of rainwater tanks and flood-proofing of households to be the most effective strategy on the basis of maximising the benefit-cost ratio of adaptation measures. In this procedure the attributes of each adaptation measure are recorded qualitatively with respect to flexibility, ability to provide a secondary function, liveability and productivity criteria. Liu et al [30] use climate scenarios and evaluate real options for an area in London using 1D-2D flood modelling and cost benefits analysis. While they identify a set of BG options, the analysis does not explore how pipe upgrades can contribute to the solution nor how multiple benefits can have implications on the economic assessment.

Whilst adaptation pathways have been applied in real-world decision settings based on multiple scenarios these have been mainly for large, engineered infrastructure projects that manage floods, droughts and sea-level rise, such as for the Rhine delta, and for the Thames. Lawrence and Hasnoot [31] have raised the question whether such pathways applications are applicable at other scales and institutional settings, and suggest this is not yet fully tested.

This paper tests the concepts above by applying an adaptation pathways approach at the smaller scale of an urban sub-catchment. Specifically, it is applied to the urban drainage network of a South London Borough sub-catchment that is currently under flood risk and where a mix of blue-green and grey options are possible to manage it. To the best of our knowledge, this is the first time that different blue-green and grey measures are combined at this scale to form pathways for long-term adaptive planning. Thus, the paper aims to answer two overarching questions:

(a) “What is the right mix of blue green and grey infrastructure at any given time and location?” This is addressed through an adaptation pathways approach. By extension, the second question arises as to

(b) “How do multiple benefits affect the choice of preferred pathway?”

Whilst recognising the importance of a standard cost-benefit approach to appraising the effectiveness of reducing flood damage, the following discussion focuses on a comparison of infrastructure costs to the wider monetised multiple benefits accrued through each option, as a new means of comparing between different adaptation pathways, bringing together a number of existing tools for this purpose.

3. Methodology

3.1 Adaptation Framework

Figure 1 presents a methodological framework that is designed to: (a) identify future flood locations, review possible intervention options (within the constraints of the study area), create and evaluate the hydraulic performance of constrained adaptation pathways (Steps 1-4) and (b) assess the implementation and wider benefits of each pathway (Step 5). Through monitoring of climate change evolution and of each option’s performance, the framework allows for the iterative re-assessment of the pathways (steps 6) as new climate information emerges. Performance thresholds for each pathway can be expressed in a variety of ways; for example directly as exceeding the level of flood protection within service delivery targets [22] or as a limitation on the associated damage cost and loss of business revenue, as used by Radhakrishnan et al. [29]. A parallel analysis (not considered here) could be used to explore the impact of future urban development on required flood mitigation measures.

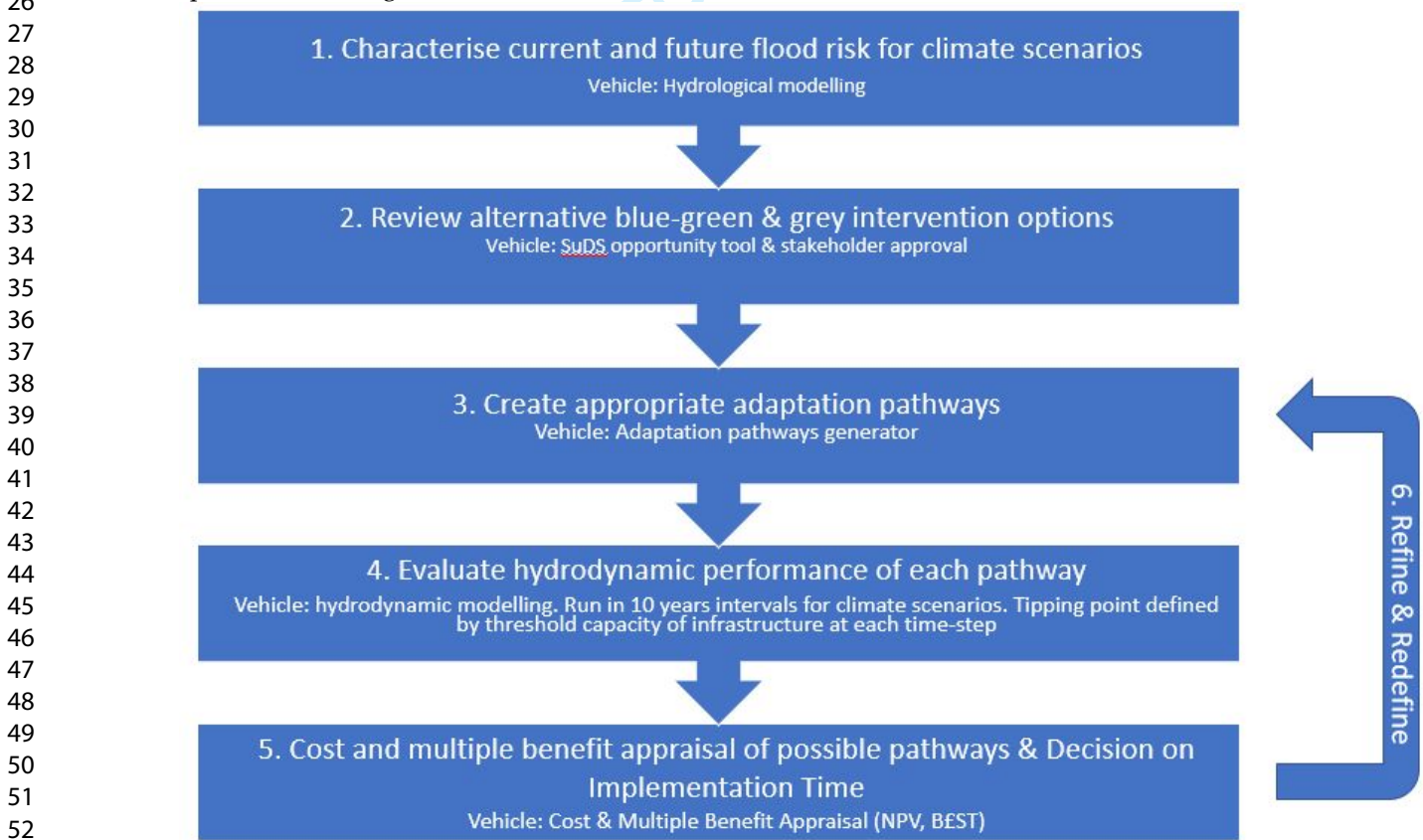


Figure 1. Framework to identify possible adaptation intervention options and the options’ combination in assessed pathways using cost and multiple benefits appraisal.

3.2 Representing climate change impacts on design storms

The timing of the implementation of flood mitigation infrastructure will depend on the rate of climate change, such that a shorter interval between each adaptation is expected for a high emissions scenario (e.g. representative concentration pathway RCP 8.5 [32]). Conversely, when a moderate rate of climate change is anticipated, as for the central RCP 4.5 scenario, a slower increase in estimated flooding would allow adaptation interventions to be separated by longer periods. In this study the impacts of these two scenarios are explored, and five planning and investment phases are specified between 2020 and 2070, (see section 4). A low emissions scenario shows negligible impact on design storm (no impact until 2050 [33]) and is therefore less relevant in terms of adaptive planning.

Summer period design storms were used to run the hydraulic simulations. Future design storms are modelled using the prediction of UKWIR [33, 34] and the uplifts, i.e. climate change impact on design storms, are specific for the area of London. This is based on estimates of rainfall intensity change using a climate analogue approach and a very high resolution (1.5 km) climate model developed by the UK Met Office [33]. Table 1 presents the correction factors that are applied to derive future design storm profiles.

3.3 Hydraulic Modelling

Hydraulic modelling is performed using SWMM5.1 [35] which is a dynamic rainfall-runoff simulation tool. The model was developed using a range of publicly available information as well as data from the water utility company and the lead local flood authority [36]. In the present application it is used to simulate single events and assess runoff quantities. The generated runoff from the design storm is then routed through the network of existing pipes and manholes, and adjustments made to incorporate the effect of differing SuDs interventions.

SWMM tracks the quantity of runoff generated within each drainage area and reports the flow rate and depth of water in each pipe or manhole throughout the simulation period, which is comprised of multiple time steps. While the model built for this study successfully reproduces known flooding in locations where historic reported flooding has occurred, no monitored flow data exists to improve the model calibration. Moreover, errors were detected in the pipe data provided and subsequently corrected by the authors to ensure the most realistic representation of the existing system. Despite the lack of more refined model validation, the results are consistent and considered adequate to demonstrate the methodology of Blue/Green and Grey drainage infrastructure integration. Further modelling would be required to confirm each flood location and establish the flow pathways likely to occur. Nevertheless, the results are considered viable for the illustrative purposes of the further methods described in this paper.

3.4 SuDs Opportunity Mapping Tool

Initial screening and appraisal of options is performed using the GIS-based environment of the "SuDS Opportunity Mapping Tool" [37] developed for the Greater London Authority. The tool identifies possible options given physical constraints (e.g. the minimum and maximum drainage area required for each option). Examples of options considered include green roofs, raingardens, surface attenuation ponds and tree pits. It is noted that the tool does not perform overland or in-pipe routing. The latter is modelled in SWMM as described above. Once the possible options have been defined, they can be prioritised within the mapping tool based on the total cost required to attenuate a volume of water calculated for a specific rainfall event (in the form of £/litre attenuated by each option). As not all constraints or stakeholder preferences are considered by the tool, further elaboration and detailed design of each option may be required.

3.5 Visualisation of adaptation pathways

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The description of the adaptation pathways follows the approach that was originally presented by Haasnoot et al. [23], where tipping points are identified to signify the need to change to a different policy or intervention at a specific point in time. A conceptual example of the approach is presented in Figure 2. The tipping points occur at the times when desired performance thresholds are exceeded (note the scale of the map is not linear). Once a threshold is exceeded, the pathways can combine actions or be treated sequentially. In Figure 2, they follow a sequential order.

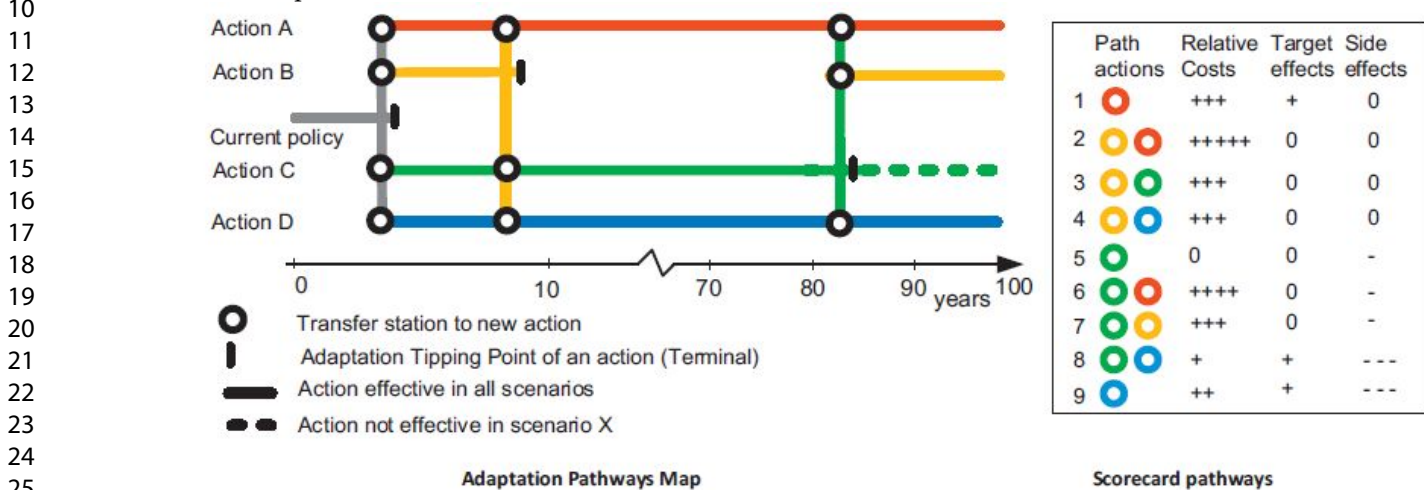


Figure 2. Example of an adaptation pathways map and the associated scorecard presenting the costs and benefits of the 9 possible pathways [15]

3.6 Cost estimations

Representative capital and O&M costs for pipe upgrades were adapted from Starkl [38] and US EPA [39] respectively. Capital costs for bioretention cells, permeable pavements were adapted from Royal Haskoning as used in the London study of Liu [30]. Capital costs for the retention pond were adapted from Stovin et al [40] and are in agreement with those estimated using the HR Wallingford SuDS cost calculator [41]. Overhead costs are not included. Ratios of Capital over O&M costs of Blue-Green infrastructure were adapted from Houle et al. [42]. The CIRIA Benefits Evaluation of SuDS Tool (BEST) tool [43] is used to assess and monetise relevant multiple benefits arising from Blue-Green infrastructure interventions. The tool initially uses a broad screening and qualitative assessment to identify the benefits to evaluate further. It uses a common approach to value benefits but structures the outputs for the user within two common frameworks: an ecosystems services or capitals account. The capital-based approach has been added in 2019 to reflect the growing use of natural and other capitals to enable the output to be in ‘common language’ used by professionals. Options are compared with a baseline (pipe system) and the key drivers and impacts are first defined qualitatively. Subsequently, the benefits’ present value is computed using the tool’s library values. A sensitivity analysis can be performed to account for the uncertainty in both the quantity and value of the benefit generated.

While a conventional cost-benefit analysis typically looks at the Capital and Operation & Maintenance (O&M) costs of different infrastructure options, as well as the flood damage avoided at different return periods, to calculate a benefit-to-cost ratio based on annualised average flood losses [44], this work compares the implementation costs of each pathways and a quantification of the wider benefits that can be achieved through a long-term adaptation plan. As different interventions are introduced at different times along a pathway, their Present Value (PV) will depend on the moment when the transition happens. The later an option is implemented, the lower its PV will be due to the application of a discount rate (in this study it is set at 0.035 as recommended by HM Treasury [45]). An inflation rate is applied as ignoring it would lead to an

underestimation of PV (set at 0.02). The concept of PV applies also to the multiple benefits which are considered in the monetary assessment of the pathway. However, as the multiple benefits of blue/green infrastructure are time dependent themselves (e.g. a tree requires time to grow in a tree pit), this lag in service delivery needs to be accounted for by using a growth curve, where relevant. In this study, this has implications on CO₂ sequestration (see Results). An inflation rate does not apply to the value of these wider benefits [43].

4. Case study area

The study area is primarily a residential area of terraced houses in a South London Borough which is planned to experience further urbanisation. Figure 3 presents the subcatchment under study which includes a proportion of high flood risk areas. The subcatchment covers an area of 0.97 km² and, in this case, is separated into different drainage areas upstream and downstream of major junctions in the sewer system. Flooding is observed particularly at the downstream sections of the subcatchment, upstream of the outfall to a local river (drainage area 5). The interaction between the outfall and the river is not modelled in the present study to isolate the effect of surface flooding; undisturbed discharge is, therefore, assumed. In this case study, when the present option does not prevent flooding from a 1 in 5-year storm, as indicated by the nodes and spill volumes shown in Figure 3, the next adaptation option is activated. This return period was selected as (i) SuDS are effective at flood mitigation in frequent disruptive events [46]; (ii) the outfall on the river is submerged for events greater than 1 in 5 years (as the present paper focuses solely on pluvial flooding and capacity effects of the existing drainage system, it models events where no back-flow is expected) and (iii) this paper deals with a retrofit environment where a 1 in 5-year event constitutes already a flood risk at several locations. Design storms for a new development area would typically be of a higher return. A more detailed 1D-2D model can later be developed to value infrastructure and flood damage costs avoided under other return periods.

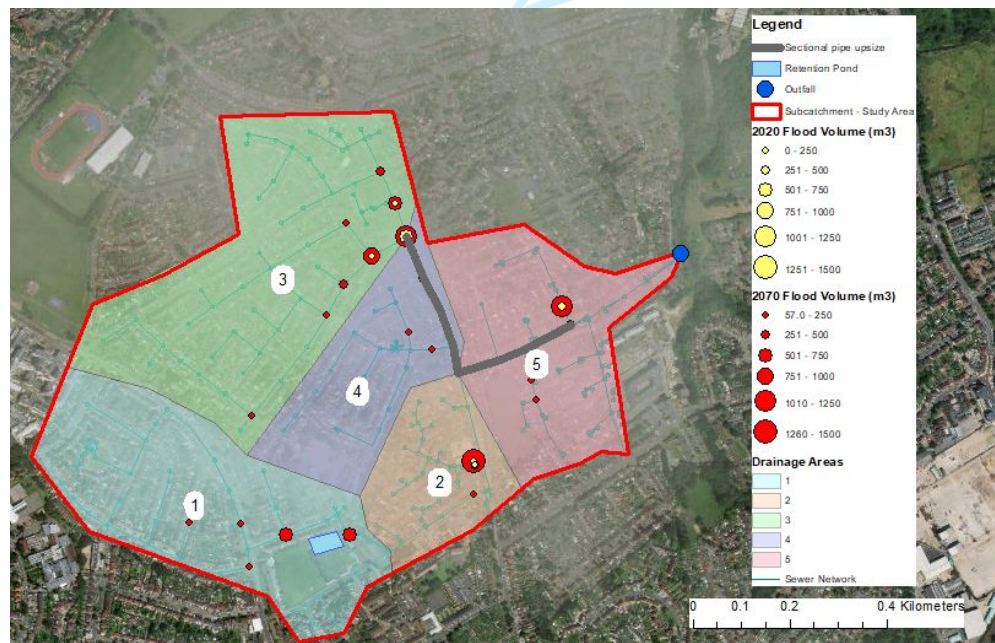


Figure 3. Nodes under flood risk in 2020 and 2070. Symbol size reflects flood volume m³. Drainage areas have been delineated based on the criticality of junctions. Implementation locations for the retention pond and the pipe upsize under two of the possible adaptation pathways.

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In the present study, adaptation refers to dealing with existing flood problems but also accounting for future climate up to 2070. The impact of urbanisation is not explored in this study, but the same methodology can be applied for a slow or rapid development scenario.

The information used in this study and its sources are presented in Table 2.

5. Results

Step 1: Current and Future Flooding

The subcatchment under study is divided into 5 drainage areas. The subcatchment comprises of 260 nodes, each with their corresponding contributing areas. Based on the hydraulic modelling results, seven nodes flood at present (2020) for the selected storm return period (Figure 3). With regards to the high emissions scenario, by 2070 this increases to 24 nodes flooding with a fourfold increase in flood volume.

This first assessment allows a long-term dynamic view of climate change impacts which supports the formulation of an adaptive, rather than a static time and location-specific solution that ignores catchment scale interactions. Table 3 shows the spatial and temporal distribution of flooding based on the current configuration of the drainage network and represents a baseline “do-nothing” scenario. Drainage area 3 is at greatest risk, with initial interventions also required in parts of drainage areas 2 and 5.

Step 2: Selecting Interventions and assessing performance

The options identified from the feasible intervention options which have been tested, are as follows:

- (i) bioretention cells (BCs),
- (ii) permeable pavements (PPs),
- (iii) pipe expansion
- (iv) SuDS retention pond

An initial assessment of their performance is carried out for each option independently. The options are constrained by physical limitations. BCs and PPs are limited to a maximum of 7% and 18% available land cover respectively. Their typical design is described in CIRIA [47] and this determines their attenuation capacity.

Table 4 shows the impact of a grey pipe expansion strategy. When considering a high emissions scenario, this strategy reduces the number of flooded nodes compared to the do-nothing strategy but is only fully effective over the short term until 2030 and only for the upstream sections of the network. Flooding continues to be experienced in drainage area 5 and, so, such a solution must also work in conjunction with some form of source control. Furthermore, increasing pipe sizes alone is initially successful, but by the end of the planning period it only reduces the total flood volume by 21% compared to the “do-nothing” option (Tables 3 and 4). When considering a central emissions scenario, a similar effect is observed with regards to flooding in drainage area 5. The solution reduces the total flood volume by 27% compared to the “do-nothing” option (Table 3), i.e. is marginally more effective than in the high emissions scenario.

Both BCs and PPs are considered to capture (up to) 80% of runoff from impervious areas and 50% from pervious areas. The difference reflects the fact that there is typically more control over pre-engineered areas. Interventions are implemented in the drainage areas upstream of the manholes predicted by the model to flood, with any excess runoff flowing to the immediately downstream drainage area. A minimum land cover

of 20 m² and 50 m² is assumed for each BC and PP unit respectively, such that the former are more flexible in terms of installation. Given the above constraints, BCs can manage all runoff generated by the 2050 storm event for the high emissions scenario. After that point in time, flooding is observed at nodes located in drainage areas 3 and 5. With regards to PPs, they can provide adequate control to manage flood risk until 2030, however, to be effective after that point, they would need to be combined with other measures. The sequence of options described here is summarised in the formulation of the adaptation pathways of Figure 4 (see following section). In contrast to the high emissions scenario, the viability of BCs is extended to 2070 when considering the central emissions scenario.

Land availability and topography in the upstream part of the subcatchment (drainage area 1) allows the possibility of introducing a storage facility installation in the form of a surface attenuation pond. The installation can cover about a quarter of the open area. In the absence of any other supporting BG or Grey schemes (e.g. BCs or pipe upsizing), the installation is effective in reducing flood volume in drainage area 1 by 93% and 72% for the target years 2050 and 2070 respectively (high emissions scenario).

Step 3 & 4: Viable adaptation pathways

As a very large number of option combinations can be conceived, the following criteria were used to guide the formulation of intervention pathways and narrow down their number used in the study:

1. *The intervention implementation rate at the individual drainage areas matches the increase in future flood volume as a result of increased rainfall intensity.* Different times of introducing an intervention are modelled to study the effectiveness of each of the feasible options.
2. *Given that source control can have a positive impact downstream, intervention implementation is prioritised in the upstream drainage areas.* For example, interventions in drainage area 3 will have a positive and sufficient flood control impact on drainage area 4 until a particular future point in time. Once runoff contributions within drainage area 4 increase to result in flooding, further interventions will be required for this drainage area (either by increasing conveyance capacity or runoff attenuation).
3. *A combination of options might be the most suitable approach within some drainage areas and for certain periods of time.* For instance, a combination of pipe upgrades and Bioretention Cell (BC) interventions is examined as shown in pathways 4 and 5 (see Figure 4).
4. *Implementing today an option not yet needed can be cost-efficient.* The implementation of a retention pond in 2020 results in no flooding in drainage area 1 until the year 2060 for the high emissions scenario. However, flooding is observed upstream of the pond after 2060 and this requires the installation of BC interventions upstream of those nodes. It is, therefore, appropriate to assess these two interventions in combination. Intervening earlier upstream results in a (marginally) smaller capacity for the retention pond scheme today. As a result, this approach also serves to provide a range of other multiple benefits sooner. This approach is followed under pathway 3.
5. *Physical characteristics constrain the options available.* As shown in Figure 3, while drainage area 1 offers the opportunity for a range of options due to land availability, this does not apply for drainage area 3. As flooding occurs only near the outlet of drainage area 3, attenuation storage could have been particularly cost-effective. Unlike drainage area 1, physical constraints preclude installing a retention pond to drainage area 3.
6. *Grey infrastructure upgrades (pipe upsizing) increase conveyance but offer limited additional storage.* Pipe diameter upsizing is required for all pipes downstream of the manhole of interest to avoid forming flow bottlenecks. A series of pipe upgrades were tested by increasing nominal diameters. An increase by more than two nominal sizes appeared to have minimal additional benefit in this study. Increasing pipe size upstream in the subcatchment to solve localised flooding transferred the problem downstream (in-pipe storage

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volumes are relatively limited to counter this effect in this small area). Increasing conveyance can potentially reduce the time of concentration from upstream sections of the catchment and, thus, synchronise flows, increase peak flow and reduce time to peak.

Taking the above into consideration, the following systematic procedure was followed. Initially, the effectiveness of each option alone was established for every 10-year interval. It was recorded whether it offered satisfactory service in each drainage area and if not, what was the required additional infrastructural capacity. Grey options were complemented with BG options when service was not delivered any more. Similarly, when BG options reached capacity, they were then complemented by an alternative BG option or a Grey option. Flood risk assessment for an entire pathway is carried out by sequentially including each option and then identifying the tipping point for it (i.e when performance thresholds are exceeded). When the next option is implemented in the model, a new tipping point is identified. Pathway maps represents the tipping points for the complete subcatchment and not for each drainage area, i.e. one drainage area might not have reached its tipping point when others have (see Results).

The adaptation pathways diagram in Figure 4 presents effective combinations of intervention options that can be implemented to manage flood risk for the planning horizon of 50 years. A total of five pathways are deemed viable based on the modelling assessment. The timing of each intervention option differs in each pathway and between scenarios. Options already implemented but that might reach their capacity at a predicted future time continue to operate and contribute to flood control, in combination with new interventions from that time onward. The following list describes the viable pathways under the high emissions scenario:

1. BCs are a viable solution until 2050, followed by a parallel installation of BCs and PPs.
2. PPs are a viable solution until 2030, followed by a parallel installation of PPs and BCs.
3. BCs are installed until 2025, followed by (a) a parallel implementation of BCs and Pond Storage until 2053, and (b) finally a parallel implementation of BCs and PPs. Attenuation storage continues to contribute to flood control for the entire planning horizon, but its installation has been completed. Its continuous maintenance is required to meet service delivery targets. Practically, as the introduction of the pond is in the very near future, its construction is timed together with the implementation of BCs in drainage area 1 as shown in Figure 5 and discussed above (early implementation of an option).
4. BCs (viable until 2050), are followed by a parallel implementation of localised Pipe upgrades and PPs.
5. Implementation of large-scale Pipe upgrades with parallel BC installations. It is noted that the upgrades cover a larger part of the network than those of Pathway 4.

For the central emissions scenario, the tipping points along the same pathways are deferred as the options become viable for longer. For this reason, as seen in Figure 4, the final intervention option/step along pathways 1, 2, 3, 4 becomes redundant, e.g. the pipe upgrade under pathway 4 is no longer required. With regards to Pathway 5, the options remain the same, however, the contribution of the upgraded sewer network in runoff control is more significant. As a result, the rate of implementation of BCs is lower (not visible on Figure 4 but reflected in the cost evaluation in step 5)

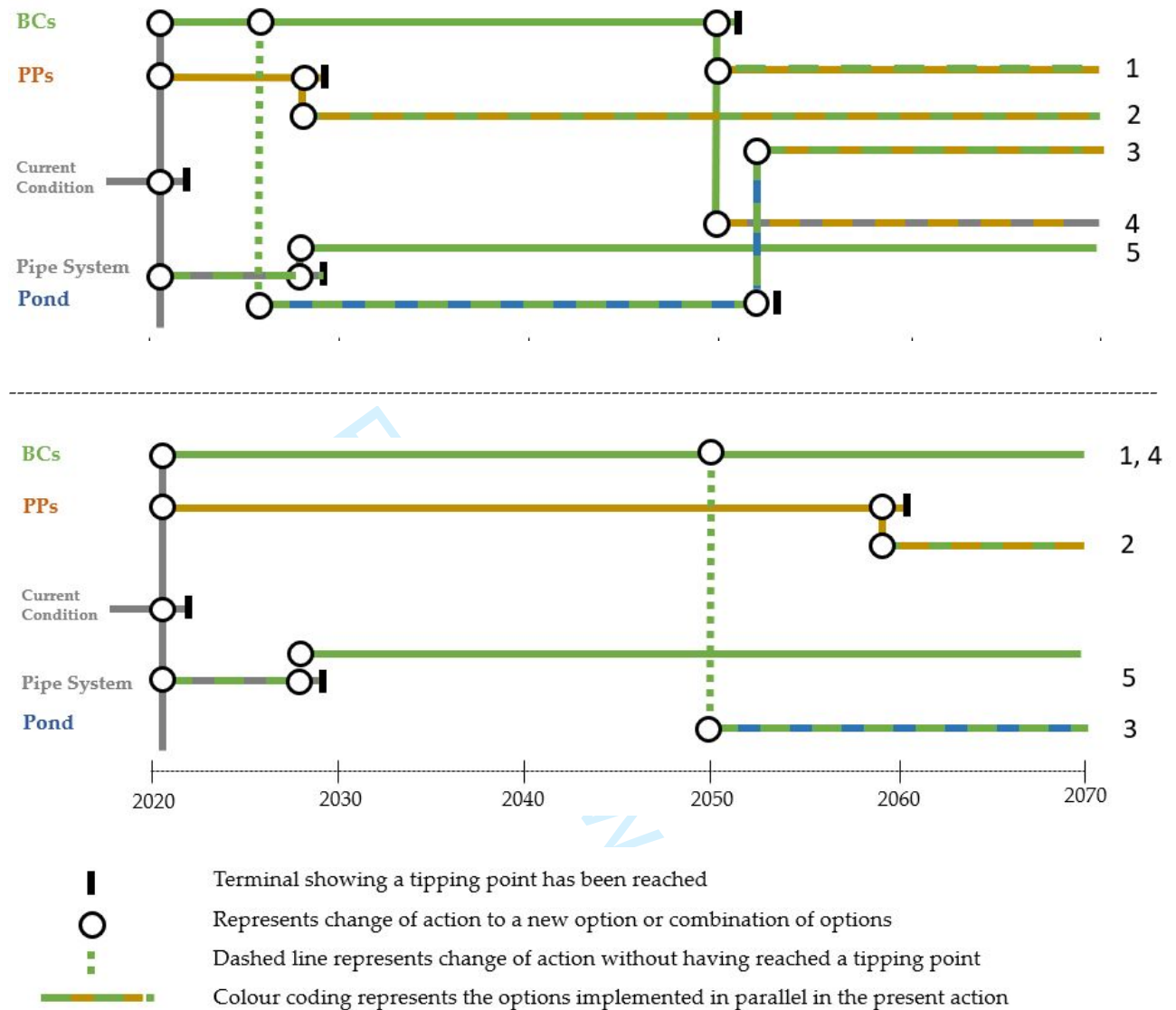


Figure 4. Adaptation Pathways formed by sequential and parallel intervention options implementation. Adaptation based on a high (top) and central (bottom) emissions scenario. The rates of implementation of each intervention option is different between different pathways that include them. Options already implemented in previous actions continue to contribute to flood control. Note the number of pathway steps are reduced in the central emission scenario.

Pathways 1, 2 and 3 are based solely on source control for both scenarios, using BG interventions only (PPs' are considered a BG measure). With regards to the high emissions scenario, Pathway 4 involves a small-scale pipe system upgrade (see Figure 3) implemented in 2050. The driver for this intervention is flooding at the upstream node (outlet of drainage area 3), despite the earlier introduction of BC installations. The increase in conveyance offered by this pipe upgrade is effective in dealing with the flooding caused in that location. However, it is noted that this solution increases flooding in two nodes of drainage area 5, as they are not able to discharge into the nodes along the central drainage path due to surcharging. This flooding is, in turn, dealt with by the targeted installation of a limited number of PPs. Under the central emissions scenario, the targeted pipe upgrades of pathway 4 are no longer required and, as a result, in this case pathway 4 is equivalent to

1
2
3
4 pathway 1. Pathway 5 involves the same interventions in both central and high emissions scenario but
5 implemented at different rates. The pipe upgrade is a one-off investment; hence it takes place within one
6 investment period (2020-2030). Moreover, it is identical between scenarios to avoid network constrictions.
7

8
9 Alternative combinations are not explored for further evaluation as they fail to deal with flooding up to the
10 end of the planning horizon, e.g. pipe upgrade combined with PPs does not provide enough flood control.
11 While other adaptation studies have identified trigger points when one option is no longer viable on its own
12 (e.g. BCs after 2050 in the high emissions scenario), the current work explores the need for interventions before
13 the trigger is activated. This is because certain options, like pond storage, can play a complementary role at an
14 earlier stage, i.e. before the trigger point has been reached and generate a range of wider benefits at an earlier
15 stage.
16

17 While Figure 4 presents the time when an unacceptable threshold in performance has been reached, Figure 5
18 expands this information indicating the timing of each asset intervention. As implementation needs to account
19 for lead times, the interventions are installed and valued at earlier points (i.e. at the beginning of each decade).
20 This is particularly true for pipe installation. While not all additional pipe hydraulic capacity is needed
21 initially (2020), the inflexibility of the option suggests that the target final dimension is used when the pipe is
22 installed. For this reason and given that flooded areas between 2030 and 2040 coincide, all pipe-interventions
23 take place at the outset of the pathway.
24

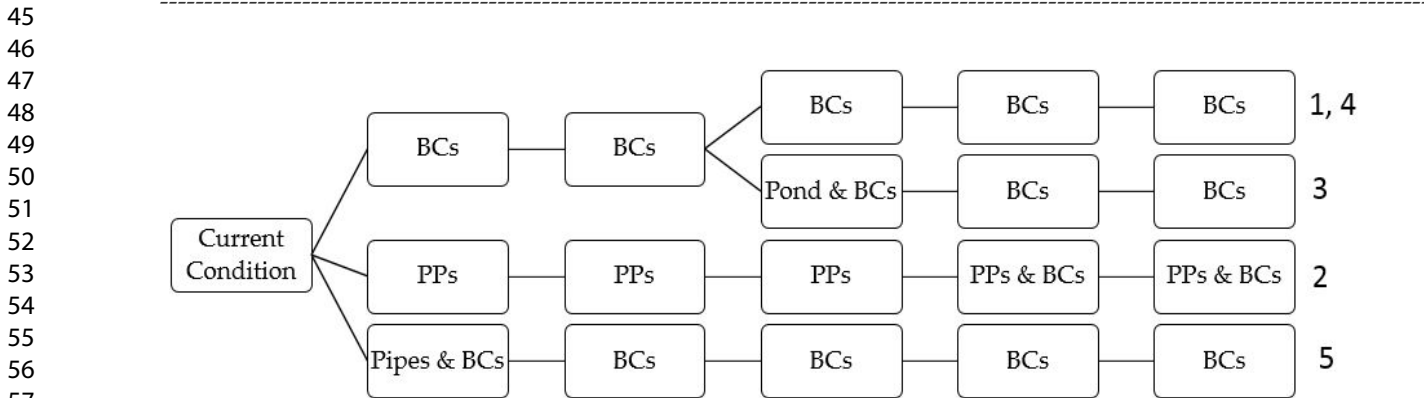
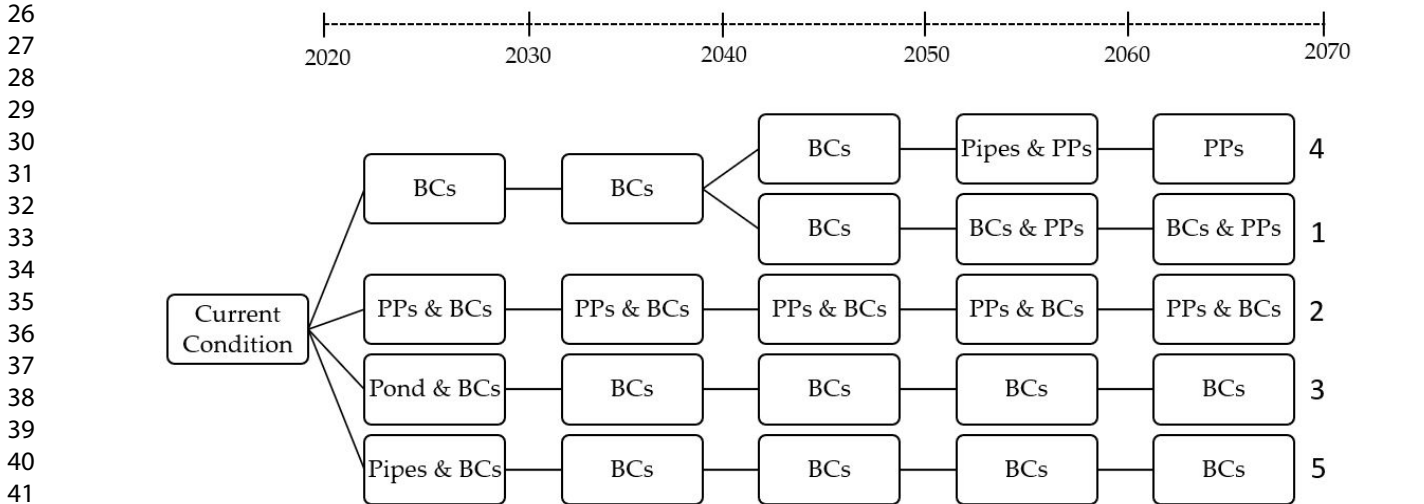


Figure 5. Implementation times for each infrastructure option under a high (top) and central (bottom) emissions scenario, based on the tipping points presented in Figure 4. Lead times have been considered.

Step 5 (a): Pathway Cost Evaluation

Costs are based on calculating PV's for the individual options that make up a pathway. Options contribute to the O&M cost of each pathway after their construction has been completed. For example, the PPs constructed before they reach their capacity in 2030 in pathway 2, will continue to require O&M until the end of the planning horizon, 2070 (see high emissions scenario). It is noted that PPs will require capital investment for replacement after 20 years (e.g. those installed in 2020 and 2030 will be replaced in 2040 and 2050 respectively). The later an option is implemented, the lower its maintenance costs will be as these are deferred to the future. The lead time for introducing an intervention is considered to be the 10-year interval before it is required.

Table 5 compares the Capital, O&M and Total PV of the five viable pathways for the high emissions scenario as calculated using the reference values described in section 3. BCs have relatively low capital costs but high O&M costs. The opposite is true for PPs. As a result, when comparing Pathways 1 and 2 where BCs and PPs are the principal measures respectively, the economic evaluation will depend on the relative contribution of the two cost categories. The contribution on Total Cost of PP replacement due to "end of life" outweighs the high O&M costs of BCs that apply to every year till the completion of the planning horizon. As a result, the economic evaluation of Pathway 1 is more favourable, despite both pathways making use of the same intervention options.

When considering the high emissions scenario, Pathway 3 involves the implementation of a retention pond from the outset. While the capital cost investment of the pond is low, the capital to O&M cost ratio is more favourable for the BCs. As a result, the overall cost of BC-intensive pathway 1 and pathway 3 is similar (within costing uncertainty). Under the central emissions scenario, the pond is implemented later (2050) and has also a smaller capacity and this results in a marginal PV reduction.

Moreover, pathways 1 and 4 share the same initial action, namely BCs implementation, until 2050 (high emissions scenario). After that moment, Pathway 4 combines PP installation with a targeted localised pipe upgrade intervention (564 m long, shown in Figure 3) that deals with conveyance issues at a specific part of the catchment. It also contains a limited installation of PPs that contribute only marginally to the total cost. Pipe installation has high capital investment costs but low O&M costs. In terms of total PV, the integration of BG and Grey drainage infrastructure appears to be equally cost-effective as the BG-alone Pathways 1 and 3 (considering costing uncertainty). Finally, Pathway 5 includes a large-scale pipe upgrade scheme (2,042 m). As shown in Table 5, this pathway is less cost-effective than pathway 4, which uses more targeted pipe solutions.

Figure 6 provides a comparison of PVs for different pathways in 10-year intervals (corresponding to a 10-year investment plan). For both the high and central emissions scenarios, the large-scale pipe upgrade solution of pathway 5 appears to have the highest initial costs, although expenditure declines after 2030. While a pipe upgrade appears to have comparable cost to other pathways under a high emission scenario (see Table 5), it significantly exceeds the cost of other pathways under the central scenario due to the high initial investment. It is therefore, a solution with possible future regret. In both possible futures, deferring the decision to spend now is sound investment planning. Pathways 1 and 3 appear equally flexible in this respect.

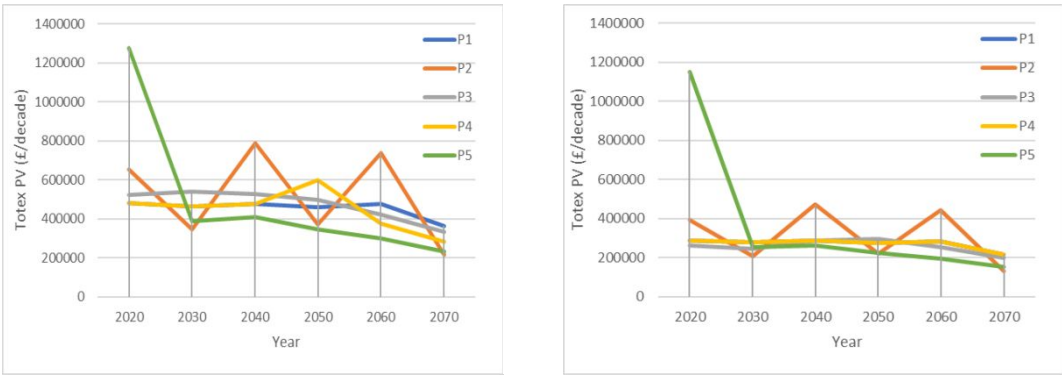


Figure 6. Total expenditure PV in decade intervals for a high (left) and central (right) emissions scenario. Note that while pathway P5 (pipe upgrade) has the lowest cost after 2030, it has very high initial capital investment for both scenarios. P2 involves renewal of PPs every 20 years which results in respective PV spikes. P1 and P3 reduce initial investment and support flexible adaptation.

Step 5 (b): Multiple Benefits Evaluation

A series of multiple benefits arise that are different for each pathway. Their monetised value allows offsetting against parts of the infrastructural costs and gives an indication of their socio-environmental significance, although these benefits are likely to accrue elsewhere than to the asset owner. While a long list of potential benefits have been identified [43], the most relevant for this study are considered to be the following:

- (i) BCs offer amenity, CO₂ sequestration and groundwater recharge opportunities;
- (ii) PPs contribute to groundwater recharge, while
- (iii) The retention pond planned under pathway 3 offers amenity, recreation, health benefits and educational opportunities.

While other benefits can potentially accrue, as for instance biodiversity benefits, their monetization is not always possible in practice. This is because BG options’ land use type does not correspond to the land use classification types utilised in B_{EST}, but also the scale of the interventions is too limited to allow for ecosystem connectivity. Similarly, as the prevailing ecological conditions of the pond would require a detailed study, the potential biodiversity benefits are not computed in this study.

Other benefits, such as air quality and water quality improvement, are potentially offered, although the potential benefit uplift offered by the pathways in this area is not significant [48]. Associated health and amenity benefits related to recreation are not considered to avoid value double counting [43]. The calculation of educational benefits from visits to the retention pond is based on B_{EST} conservative estimate (£16.57 per visit). The number of annual student visits is assumed equal to the local population of school children aged 6-15 [49].

Figure 7 shows the relative contribution of each benefit to the total multiple benefit PV for both scenarios, based on application of the CIRIA B_{EST} tool [43]. Groundwater recharge appears to be consistently a key benefit under all pathways since the case study area is water stressed and the SuDS design and local geology allow the benefit to be delivered. The contribution of CO₂ sequestration of BCs to the total benefit is limited as the option involves small and low types of vegetation. Moreover, the time it takes for shrubs to grow, was found to reduce their CO₂ sequestration PV contribution. Similarly, based on B_{EST}’s reference value, the monetization of amenity has a limited contribution to PV for pathways involving BC implementation. Pathway 5 which involves an extensive pipe upgrade is found to deliver the lowest multiple benefit PV. The

dominant benefits appear to be the educational and recreational value of the pond in pathway 3. It is worth noting that for all options, uncertainty relating (i) to the actual quantity of the benefit, and (ii) to the monetisation rate, can affect the PV of the pathways (a 75% confidence is applied for both uncertainty sources and is represented in Figure 6 through error bars).

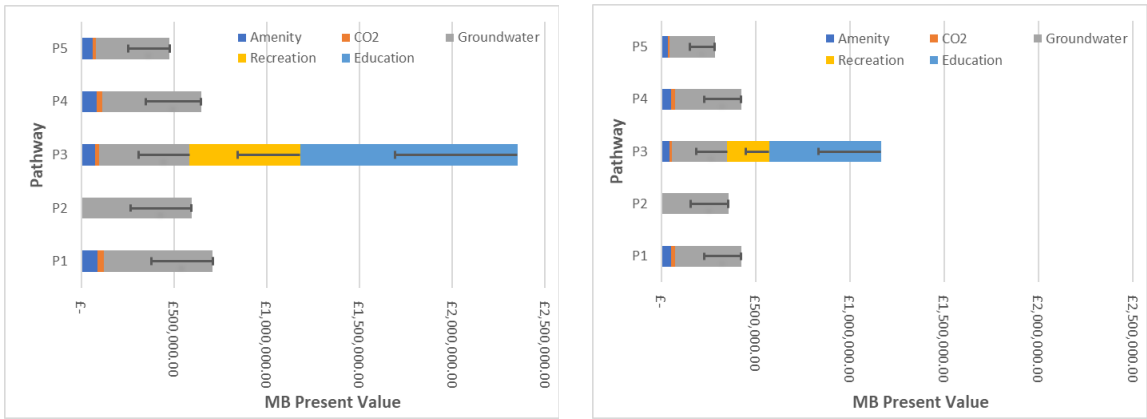


Figure 7. Distribution of maximum expected monetised multiple benefits of the different adaptation pathways for the high (left) and central (right) emissions scenarios. Error bars represent a 75% confidence interval in both the quantity and monetisation value of the benefit.

As interventions are implemented later (e.g. retention pond in P3) or at a slower rate (e.g. BCs in P1) for the central emissions scenario, there is a significant loss in multiple benefits delivery (see Figure 7). This becomes pertinent if costs and multiple benefits are co-valued, considering that the PV of multiple benefits which accrue to each pathway can potentially offset a considerable proportion of infrastructural cost. Avoided flood damage under the selected return period does not differ among pathways since the set performance threshold is commonly met. Co-valuation suggests that Pathway 3, which is a solely BG solution, is preferred under both scenarios as it offers a high degree of flexibility (represented by a uniform Totex PV, Figure 6) as well as significant multiple benefits delivery (Figures 7 and 8). As seen in Figure 8, changing the time of delivery of an infrastructure option alters both the multiple benefit and total expenditures which leads to variable ratios across scenarios and across pathways.

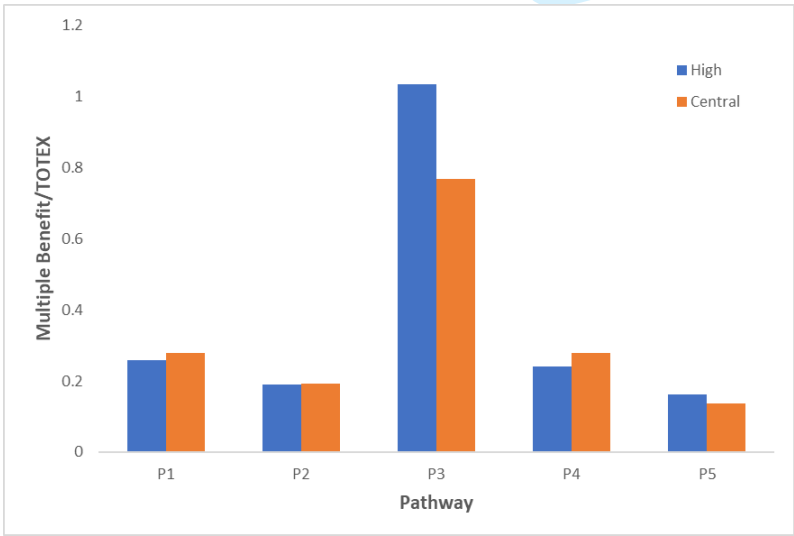


Figure 8. Multiple benefit to Total Expenditure Ratios for the high and central scenarios. Stakeholders will often value certain benefits with different associated weights, and therefore a multicriteria analysis would be needed to account for this. Moreover, co-valuation can affect the preference for one pathway over another (for example when comparing pathways 1 and 3).

6. Discussion

6.1 Summary of findings

Projected climate change impacts were shown to significantly increase flood risk in the subcatchment under study for a 1 in 5-year storm. Large areas of the network that are not under flood risk today are expected to flood within the next 50 years for the same return period event. In planning for flood risk management, the question “what is the right mix between green-blue and grey infrastructure” is pertinent. Developing an adaptation pathways approach, as demonstrated in this paper, provides a method for answering this.

The approach allows the structured definition and analysis of intervention options to deal with both current and future risk. Different grey and BGI options which are constrained by physical conditions (e.g. soil type, topography, land availability, invert level) apply to each drainage area, and modelling allows investigating interactions between these areas. While some upstream areas experience localised flooding, other areas flood as stormwater fluxes accumulates downstream (as shown at the outlets of drainage areas 1 and 3, or drainage 5 when considering the entire subcatchment).

The choice of solution will be different if the problem is seen in a narrow spatial scale (ignoring the wider catchment) or as part of a static problem. Furthermore, specific location constraints preclude specifying some options, and may limit the local significance of any potential wider benefits. Understanding the dynamic nature of rainfall intensification and flooding is key to choosing the right option, thus, the criteria outlined can help those interested in applying the approach to guide their intervention planning.

While individual options could not deliver long-term service on their own, their combination in pathways did. Pipe upsizing interventions were targeted to a specific area where flooding occurs, i.e. downstream of network convergences or bottlenecks (pathway 4) and were combined with a BG options. However, they were not preferred on the basis of the monetised benefits analysis. A large-scale pipe upgrade intervention appeared to be marginally less cost-effective when combined with diffuse source control using BG infrastructure.

When multiple BG options are technically feasible, the relative contribution of their Capital and O&M costs on the total PV needs to be carefully explored. The interplay between (i) the time of implementation and (ii) the two PV cost components can have significant economic implications due to the application of discounting. Similarly, pipe upgrades were shown to have high capital but low O&M costs.

Finally, unlike previous studies, this work showed that performance thresholds (trigger points) do not necessarily need to be met before introducing a new, in-parallel option. This is because certain options might not successfully eliminate flooding entirely but can be complementary in delaying a trigger point activation at certain drainage areas of a subcatchment. By implementing a complementary option, the rate of implementation of the principal intervention can be slowed down. This was shown in the case of the combined use of a retention pond and BCs for the high emissions scenario. In this respect, as shown in Step 5 of the adaptation framework (Figure 2), certain options are therefore deferred or brought forward (in the case,

the construction of bioretention cell can be brought forward to support the function of the retention pond). Future work will benefit from a real options analysis formalising the valuation of flexibility of an option's deferment or advancement [2, 11].

While traditional costing approaches are fundamental for planning flood control, they disregard the ability of blue-green infrastructure to deliver a range of multiple benefits. This study revealed that different options offer different benefits of varying value, which should be therefore considered. Each benefit's merit will strongly depend on local conditions. For instance, the contribution to groundwater recharge can be relatively important if the area under study is water stressed. On the other hand, other potential benefits might accrue but not considered important as the baseline condition is acceptable by stakeholders. Moreover, as pathways are developed in steps, the value of multiple benefits accumulates gradually. If the value of multiple benefits is significant then this might influence the decision of when to implement the option that delivers them, i.e. thinking beyond the flood risk regulation that is required. In the present study, most pathways had similar infrastructural cost PV, however pathway 3 delivered significant multiple benefits positive PV. The co-assessment of benefits can, therefore, potentially change the delivery order of the preferred options, the selected time of delivery and the choice of pathway. This ultimately lies in the relative weight attached to each cost and benefit component as part of the decision-making process by stakeholders [5].

Finally, comparing among different scenarios as opposed to a single scenario dynamic assessment can help identify no-regret options. For instance, while a pipe upgrade under pathway 5 appeared to have comparable cost to other pathways under a high emission scenario, it was shown that it significantly exceeded cost under the central scenario due to the high initial investment.

6.2 Limitations

The analysis identified the threshold over time (up to 2070) where no flooding takes place for the return period of interest if interventions are implemented. Therefore, the reference flood damage avoided is the same among all possible pathways and was ignored. However, it is common that CBAs' make use of Benefits/Cost Ratios, in which case the benefit value of avoided flood damage needs to be incorporated. The calculation of flood damage requires predicting flood depths. While SWMM is widely accepted as a practical open source tool for drainage planning, it does not allow this. A 2-D overland model coupled with 1D pipe flow would be required for this. Moreover, simulations would need to be performed for different return periods to calculate the increasing flood depth with return period. The damages can then be annualised for normalisation [44] and comparison among options/pathways. Finally, future work could look at incorporating ease of implementation criteria along with a quantitative assessment of flexibility dealing with uncertainty management. Such an approach has been recently incorporated in BEST to account for different levels of uncertainty [50].

7. Conclusions

The paper demonstrated how a step-wise methodology can be adopted to identify an appropriate mix of blue-green and grey infrastructure through time for a given location in the context of urban drainage. This involved the identification of options and their combination in pathways. These have then been compared on the basis of their infrastructure costs and their ability to deliver multiple benefits (assuming they are each capable of delivering the same levels of flood mitigation). The ability to move from one option or pathway to another as information becomes available with time and tipping points are met, demonstrates the value of flexible design. Finally, this work showed that there is a trade-off between deferring interventions until they are

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needed for flood risk regulation and delivery of multiple benefits associated with the interventions. This means that the pathway assessment process is critical to the outcomes of adaptive planning: when multiple benefits are taken into account, different interventions can be preferred as well as the time of their delivery might be brought forward. Finally, exploring scenarios that bound the problem uncertainty can help identify no-regret solutions.

Authors' Contributions

LK carried out the modelling work. Both authors contributed to design, analysis and interpretation of data. Both authors drafted and approved the manuscript.

Competing Interests

The authors declare that they have no competing interests.

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Disclaimer

The views expressed are those of the authors and so do not necessarily represent those of the wider consortium. Flood risk and intervention evaluations should not be considered accurate for the study area as modelling used for this work contains numerous assumptions and modifications in input data.

Associated Data

Associated research data can be downloaded from <https://doi.org/10.17863/CAM.47141>

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Tables

Table 1. Correction factors to account for impact of climate change on design storms for London, UK (adapted by interpolation from UKWIR [33])

Scenario	2030	2050	2070
Central Emissions Scenario	8%	13%	32%
High Emissions Scenario	21%	37%	54%

Table 2: Data sources and attributes

Parameter	Data Source	Attributes
Rainfall Input	CEH	Design Storms
Precipitation scale coefficients	UKWIR/Dale et al.	NA
LiDAR Data (DTM)	OS data/Edina	2 m resolution
Sewer Network	Thames Water	Detailed shapefile
Soil Classes	BGS	8 classes
Runoff Coefficients	LLFA model/Land Cover	NA
SuDS detailed design	Engineering Consultant (LLFA)	NA

Table 3. Spatial and temporal distribution of flooded nodes and corresponding volume under the “do-nothing” baseline scenario.

Scenario	Drainage Area	2020 (m3)	2030 (m3)	2040 (m3)	2050 (m3)	2060 (m3)	2070 (m3)
High Emissions	1	0	429	657	862	1131	1504
	2	440	1001	1181	1411	1609	1829
	3	963	1857	2259	2656	2803	3460
	4	166	378	470	548	683	861
	5	436	879	1038	1192	1412	1612
	Total Volume	2005	4544	5605	6669	7638	9266
	#flooded nodes	7	13	14	16	19	24
Central Emissions	1	0	125	165	228	429	741
	2	440	667	720	799	1001	1245
	3	963	1302	1389	1507	1857	2390
	4	166	234	249	269	378	500
	5	436	549	576	665	879	1096
	Total Volume	2005	2877	3099	3468	4544	5972
	#flooded nodes	7	8	8	9	13	14

Table 4. Number of flooded nodes in different sections of the network under a pipe upgrade scheme and their associated flood volume (with no other measures taken).

Scenario	Drainage Area	2020		2030		2040		2050		2060		2070	
		# nodes	m ³	# nodes	m ³	# nodes	m ³	# nodes	m ³	# nodes	m ³	# nodes	m ³
High Emissions	1	0	0	0	0	0	0	0	0	1	66	2	233
	2	0	0	2	456	2	769	2	0	2	9	2	7
	3	0	0	1	568	1	799	2	9	3	8	3	3
	4	0	0	1	233	1	311	1	382	1	439	2	571
	5	2	752	2	7	3	9	3	5	4	4	4	8
					296		395		500		607		731
	Total	2	752	6	4	7	8	8	6	11	6	13	2
Central Emissions	1	0	0	0	0	0	0	0	0	0	0	0	0
	2	0	0	1	87	1	109	2	200	2	456	2	899
	3	0	0	1	204	1	253	1	332	1	568	3	100
	4	0	0	1	108	1	129	1	159	1	233	1	340
	5	2	752	2	114	2	123	2	135	2	170	2	213
					8		4		8		7		6
	Total	2	752	5	154	5	172	6	204	6	296	8	437

Table 5. Cost evaluation of adaptation pathways

Pathway		Capital PV (£K)					Operational PV (£K)					PV (£K)
		BCs	PPs	Pipes	Pond	Total	BCs	PPs	Pipes	Pond	Total	Total
High Emissions	P1	735	8	0	0	743	1983	5	0	0	1987	2731
	P2	51	1858	0	0	1909	68	1140	0	0	1209	3118
	P3	578	0	0	70	649	1691	0	0	503	2194	2842
	P4	610	29	170	0	810	1843	11	19	0	1873	2682
	P5	449	0	957	0	1406	1329	0	218	0	1547	2953
Central Emissions	P1	441	0	0	0	441	1189	0	0	0	1189	1630
	P2	31	1115	0	0	1145	41	684	0	0	725	1870
	P3	347	0	0	31	378	1014	0	0	154	1168	1547
	P4	441	1189	0	0	1630	0	0	0	0	0	1630
	P5	269	0	957	0	1227	796	0	218	0	1014	2241

Table captions

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Table 1. Correction factors to account for impact of climate change on design storms for London, UK (adapted by interpolation from UKWIR [33])

Table 2: Data sources and attributes

Table 3. Spatial and temporal distribution of flooded nodes and corresponding volume under the “do-nothing” baseline scenario.

Table 4. Number of flooded nodes in different sections of the network under a pipe upgrade scheme and their associated flood volume (with no other measures taken).

Table 5. Cost evaluation of adaptation pathways

Figure captions

Figure 1. Framework to identify possible adaptation intervention options and the options’ combination in assessed pathways using cost and multiple benefits appraisal.

Figure 2. Example of an adaptation pathways map and the associated scorecard presenting the costs and benefits of the 9 possible pathways [15]

Figure 3. Nodes under flood risk in 2020 and 2070. Symbol size reflects flood volume m³. Drainage areas have been delineated based on the criticality of junctions. Implementation locations for the retention pond and the pipe upsize under two of the possible adaptation pathways.

Figure 4. Adaptation Pathways formed by sequential and parallel intervention options implementation. Adaptation based on a high (top) and central (bottom) emissions scenario. The rates of implementation of each intervention option is different between different pathways that include them. Options already implemented in previous actions continue to contribute to flood control. Note the number of pathway steps are reduced in the central emission scenario.

Figure 5. Implementation times for each infrastructure option under a high (top) and central (bottom) emissions scenario, based on the tipping points presented in Figure 4. Lead times have been considered.

Figure 6. Total expenditure PV in decade intervals for a high (left) and central (right) emissions scenario. Note that while pathway P5 (pipe upgrade) has the lowest cost after 2030, it has very high initial capital investment for both scenarios. P2 involves renewal of PPs every 20 years which results in respective PV spikes. P1 and P3 reduce initial investment and support flexible adaptation.

Figure 7. Distribution of maximum expected monetised multiple benefits of the different adaptation pathways for the high (left) and central (right) emissions scenarios. Error bars represent a 75% confidence interval in both the quantity and monetisation value of the benefit.

Figure 8. Multiple benefit to Total Expenditure Ratios for the high and central scenarios.

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