Validating a rapid assessment framework for screening surface water flood risk

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Abstract

This research evaluates performance of a rapid assessment framework for screening surface water flood risk in urban catchments. Recent advances in modelling have developed fast and computationally efficient cellular automata frameworks which demonstrate promising utility for increasing available evidence to support surface water management, however, questions remain regarding trade-offs between accuracy and speed for practical application. This study evaluates performance of a rapid assessment framework by comparing results with outputs from an industry standard hydrodynamic model using a case study of St Neots in Cambridgeshire, UK. Results from the case study show that the rapid assessment framework is able to identify and prioritise areas of flood risk and outputs flood depths which correlate above 97% with the industry standard approach. In theory, this finding supports a simplified representation of catchments using cellular automata, and in practice presents an opportunity to apply the framework to develop evidence to support detailed modelling.

Introduction

Flood management is an established component of UK environmental policy, however, there is an emerging recognition that a historic focus on fluvial and coastal flooding has left a gap in managing urban surface water (Pitt, 2008). Recent reports estimate annual surface water flood damages in the United Kingdom between 0.25 and 0.5 billion GBP (EWA, 2009; DEFRA, 2012), and predict this to rise to between 0.5 and 1 billion GBP over the next 50 years (Committee on Climate Change A.S.C., 2012). Studies estimate that UK surface water flooding now constitutes up to 40% of national annual flood damages (Douglas et al., 2010). Managing surface water flooding is of national strategic importance and is amongst the hazards prioritised in the UK Climate Change Risk Assessment, National Risk Register and National Flood Resilience Review (DEFRA, 2012; Committee on Climate Change, 2015; 2017; HM Government, 2016).

The magnitude and likelihood of future flood damage is predicted to escalate as a result of increasing precipitation intensity, expanding urban areas and a reliance on aging urban drainage infrastructure (Barker, 2007; Wheater and Evans, 2009; IPCC, 2014; Ana and Bauwens, 2010). UK flood policy has identified this risk and legislated towards identifying and managing hazards (Pitt, 2008; DCLG, 2010; HM Government, 2010). One mechanism for achieving this is implementation of Surface Water Management Plans (SWMP) as set out in the PPS25 and detailed in DEFRA technical guidance (DCLG, 2010; DEFRA, 2010). SWMP's are investigations designed to outline long term solutions to manage surface water across local authority jurisdictions and develop a strategy for partnership working across organisations operating within this boundary. Application of plans typically involves large scale strategic risk assessments, followed by focused studies in areas defined as vulnerable to flood hazards. A key objective of this process is to identify possible interventions which can be applied to alleviate flood risks.

Investigating flood risk in urban catchments is typically carried out using detailed 2D hydraulic modelling coupled with 1D pipe networks, of which many software packages are available (Elliott and Trowsdale, 2007; Hunter et al., 2008). These approaches are detailed, but solution of the complex governing equations leads to a computationally demanding analysis which can restrict the number of simulations achievable in a given timeframe, scope or budget. This potential restriction is of particular significance when considering the need for studies to consider
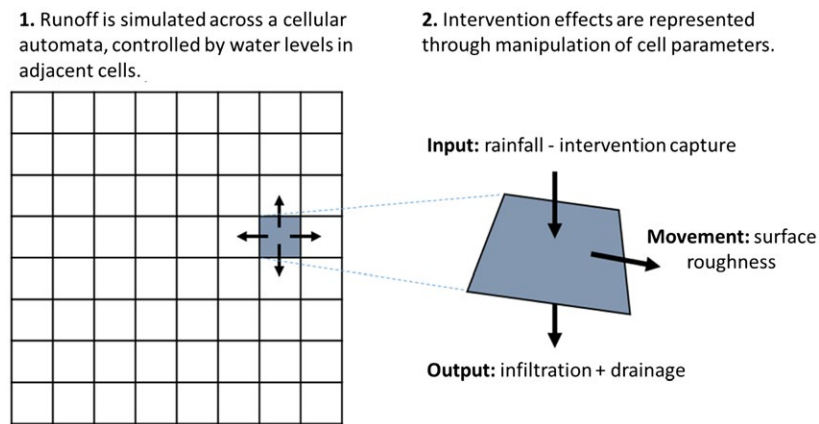
Fig. 1. CADDIES modelling across a regular grid, with parameters describing water input, output and runoff speed specified at a cell by cell resolution (Webber, Fu, *et al*., 2018a).

a wide range of scenarios and intervention opportunities to evidence the strategic direction of future work (House of Commons, 2016). Historic approaches recognise the trade-off between physical representations and computational cost (Dottori *et al*., 2013) and have applied simplified screening methodologies to steer further detailed design. These approaches tend to include qualitative or semi-quantitative approaches, such as multicriteria decision making, GIS analysis, stakeholder engagement and scoring potential options. (Ellis *et al*., 2004; Makropoulos *et al*., 2008; 2007; Young *et al*., 2010). This provides fast guidance, but is at the expense of simulating flood dynamics.

Research advances have developed new surface water flooding models which apply simplified governing equations alongside machine learning techniques, such as cellular automata, to quickly model urban runoff, therefore simulating surface water flood dynamics at lower computational cost relative to conventional techniques (Ghimire *et al*., 2013; Guidolin *et al*., 2016; University of Exeter, 2017). Recent research has applied these simplified flood models to create rapid surface water assessment frameworks which are capable of fast analysis of urban flooding using easy to access data, simplified representations of cities and computationally efficient cellular automata flood models (Webber, Fu, *et al*., 2018a; Webber, Gibson, *et al*., 2018b). These approaches offer advantages of quickly screening flood risks through simulating many possible strategies and future scenarios. Recent literature has demonstrated their potential for urban surface water management (Webber, Fu, *et al*., 2018a; Webber, Gibson, *et al*., 2018b), however questions remain regarding comparing the performance of these new approaches relative to existing methods.

This research aims to validate the utility of a fast flood assessment framework (Webber, Gibson, *et al*., 2018b)

by comparing the approach with an industry standard flood model, representing established professional engineering practice. Past research has compared the underlying flood model used in the rapid assessment framework, 'CADDIES', with 'Infoworks Integrated Catchment Management' (ICM) to compare performance routing 2D runoff, but a gap remains regarding validating the approach against a model including a 1D pipe network (Gibson *et al*., 2016).

Methods

Overview

The utility of the rapid assessment framework is examined through three questions, representing scenarios with increasing levels of detail: Can the framework consistently prioritise areas of flood risk for a no sewer scenario? Can the framework consistently prioritise areas of flood risk for a drainage system scenario? Is the approach suitable for modelling interventions in an urban catchment? These questions are answered through comparing the rapid assessment framework with a published surface water management plan, undertaken by Arcadis, using industry standard hydrodynamic modelling.

Research investigated performance of the rapid analysis framework by comparing outputs with ICM simulations which form the basis of the St Neots SWMP (Arcadis, 2012). This section outlines the data, processes and assumptions required to setup both models. In certain circumstances differences between model architectures has prevented an identical application between both approaches, where this is the case it is specified within the methodology.

Full details of the rapid surface water flood assessment framework examined are published in Webber, Fu, *et al*.

(2018a) and Webber, Gibson, *et al.* (2018b). The framework applies a computationally efficient cellular automata 2D model ('CADDIES') to route the movement of above-ground surface water across a regular grid (Ghimire *et al.*, 2013; Guidolin *et al.*, 2016). Runoff flow rate between grid cells is controlled by Manning's equation, which utilises parameters describing gradient (controlled via cell elevation), surface roughness, water inflow and water outflow in each cell (Fig. 1). The model only represents the above-ground 2D system and does not directly simulate the 1D underground (piped) system. Instead, an allowance for pipes removing runoff from the surface is represented through adjusting outflow rates in cells, which effectively removes runoff from the simulation at a set rate. Rainfall is applied directly to each cell in the grid as a water input. The model architecture and rapid assessment framework are aimed at fast simulation speed through increased computational efficiency, and the utility of this is intended for screening urban catchments to direct further detailed analysis using industry standard models.

Analysis has been carried out based on three scenarios, with each scenario requiring a more detailed representation of the catchment. Scenario One, 'no sewers', represents the catchment with no functioning of the existing surface water drainage system. Scenario Two, 'surface water drainage', includes the existing surface water drainage system, with pipe locations and sizes based on data used in the St Neots SWMP (Arcadis, 2012). Scenario Three, 'intervention', includes the existing surface water system plus additional flood management interventions assessed in the St Neots SWMP. These scenarios facilitate a performance comparison across a range of conditions
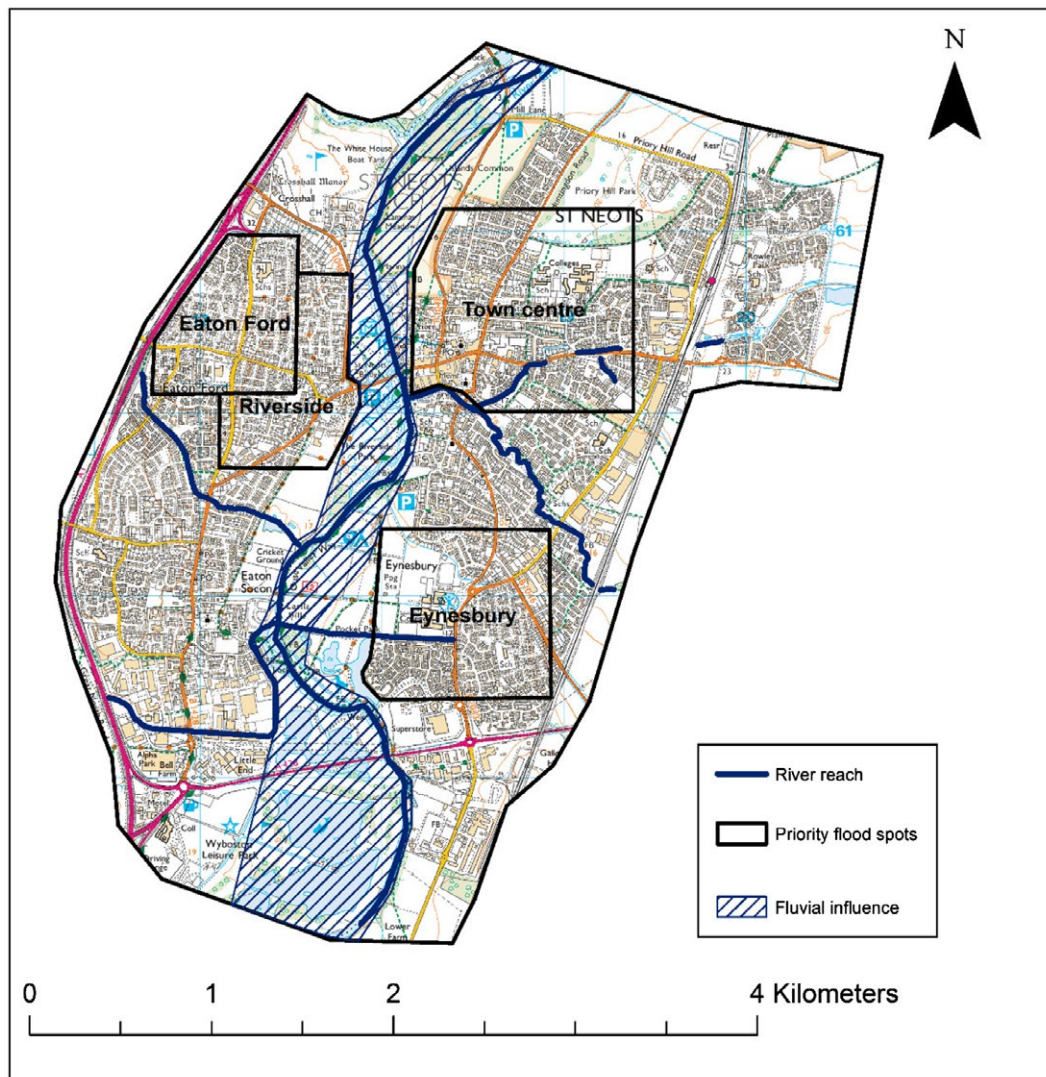

Fig. 2. St Neots model extent, with priority flood spots highlighted.

which gradually increase in complexity. The full detail of these scenarios is described later in the paper.

Characterising study area and rainfall

Study area

St Neots is the largest town in Cambridgeshire, UK, with a population of 28 000. The town is situated on flat terrain which acts as the flood plain for the Great Ouse River and its tributaries. The study area is approximately 9.5 km² and is defined by the urban extent of the town, which includes suburbs and surrounding road system (Fig. 2). The area has a history of flooding, including fluvial flooding surrounding the river and surface water flooding in the urban area. St Neots is prioritised in the Cambridgeshire County SWMP because of the number of properties and key infrastructure at risk from surface water flooding, identified using multicriteria analysis (Arcadis, 2012).

Representing the catchment using ICM

Infoworks Integrated Catchment Management is an industry standard flood modelling software package which provides an integrated simulation of rainfall, overland runoff, the pipe network and watercourses. This section details the approach used to represent St Neots within this model structure. Full details from this modelling study have been published as part of the St Neots SWMP (Arcadis, 2012).

The catchment area was specified by a polygon delimiting the surface water catchment. This area is contained by the A1 to the west and a railway line to the East (Arcadis, 2014). Elevation was represented using an irregular triangular mesh generated using 2m resolution LiDAR data. The elevation of each triangle is set as the mean of the levels at each corner of the feature. The mesh was generated using the ICM mesh building function. Buildings were included within the landscape as voids within this mesh. This approach forces runoff to flow around the building thresholds. All rainfall landing on voids was specified directly into the surface water drainage system. Roads were included in the elevation model through a 100 mm reduction in elevation to account for kerb heights. This method was intended to ensure runoff would follow the road network before spilling onto other urban areas.

Land use was classified through application of a uniform roughness coefficient applied across the entire domain. The SWMP describes sensitivity analysis and determines a suitable surface Manning's roughness coefficient of 0.045 (Arcadis, 2012). The SWMP initially aimed to use variable

roughness based on OS Mastermap land use types, however, initial studies indicated a significant increase in processing and simulation time. Separation into urban and rural land use values was also discarded because of the 'minimal impact on the flood extent' (Arcadis, 2012).

An infiltration rate of 2.5 mm/h was applied across the entire domain, based on available local information (Arcadis, 2012). As with variable roughness, sensitivity analysis regarding this value is described in the SWMP.

Design rainfall was derived using Intensity–Duration–Frequency rainfall catchment descriptors from the FEH (Centre for Ecology and Hydrology, 1999). Rainfall was represented using a series of design rainfall hyetographs representing rainfall in a 5, 3.3, 2.5, 1 and 0.5% annual exceedance probability (AEP) events. Rainfall durations examined included 0.5, 1, 2, 4, 8 and 16 h events. The 2-h rainfall was found to generate most significant flooding across all AEP events.

The Revitalised Flood Hydrograph (ReFH) method was used to estimate the fluvial flows and levels for the modelled watercourses. On the River Great Ouse, the estimated 1 in 5 annual probability fluvial flood flows and levels were applied as the upstream and downstream boundary conditions respectively for all the ICM simulations, in order to reflect the longer catchment response time in the river prior to reaching St Neots. However for the remaining modelled tributaries in the ICM model, the estimated flood flow hydrographs (with 2 h storm duration) were applied as the upstream boundary condition for the respective annual probability flood event.

Representing the catchment in CADDIES

The CADDIES model was set up to replicate as closely as possible the assumptions and approach applied using the ICM model. Elevation was included using the same 2 m resolution LiDAR DTM which underpinned the ICM approach. CADDIES applies runoff routing across a regular grid mesh and so the irregular triangular mesh applied in ICM could not be included within the model. Instead the elevation was input directly using the input DTM, reducing the preprocessing time required to generate the 2D mesh. Buildings were included within the elevation input file through application of a 1 m threshold level for all structures in the catchment. Thresholds were defined using the same OS Mastermap land use layer used to specify building locations in ICM. Raising the threshold of the structure replicated the ICM approach through forcing runoff to flow around the structure. Road elevation was included using the same 2 m resolution elevation model applied in the ICM approach.

Very small scale features smaller than the 2 m DTM resolution were not explicitly included as a result of data

unavailability and the intention of the study to replicate the previously published work for a strategic scale case study. These features are known to influence the extent of surface flooding (Fewtrell *et al*., 2011; Dottori *et al*., 2013). Both ICM and CADDIES are capable of including these through application of very fine resolution data or editing input DTM's to specify these features.

The effects of land use were replicated through application of the same assumption to apply a constant uniform infiltration and roughness parameter across the entire catchment. Rainfall was also applied using the same input hyetographs applied in the ICM model.

The scope of the CADDIES model is limited to the risk of surface water flooding to urban areas, and as such the watercourses were not included within the model.

Representing intervention scenarios

Representing the 'no sewer' scenario

The no sewer scenario represents a total failure of the surface water drainage system. For this scenario the catchment was represented as described above, with no additional interventions applied to the catchment.

Representing the 'surface drainage' scenario

In ICM the urban surface water network was simulated using a detailed 1D model which represented pipe layout, diameters and invert levels. Runoff enters the surface water system through catchments specified to each pipe and leaves the system at outfalls located along watercourses running through the urban area. Certain buildings
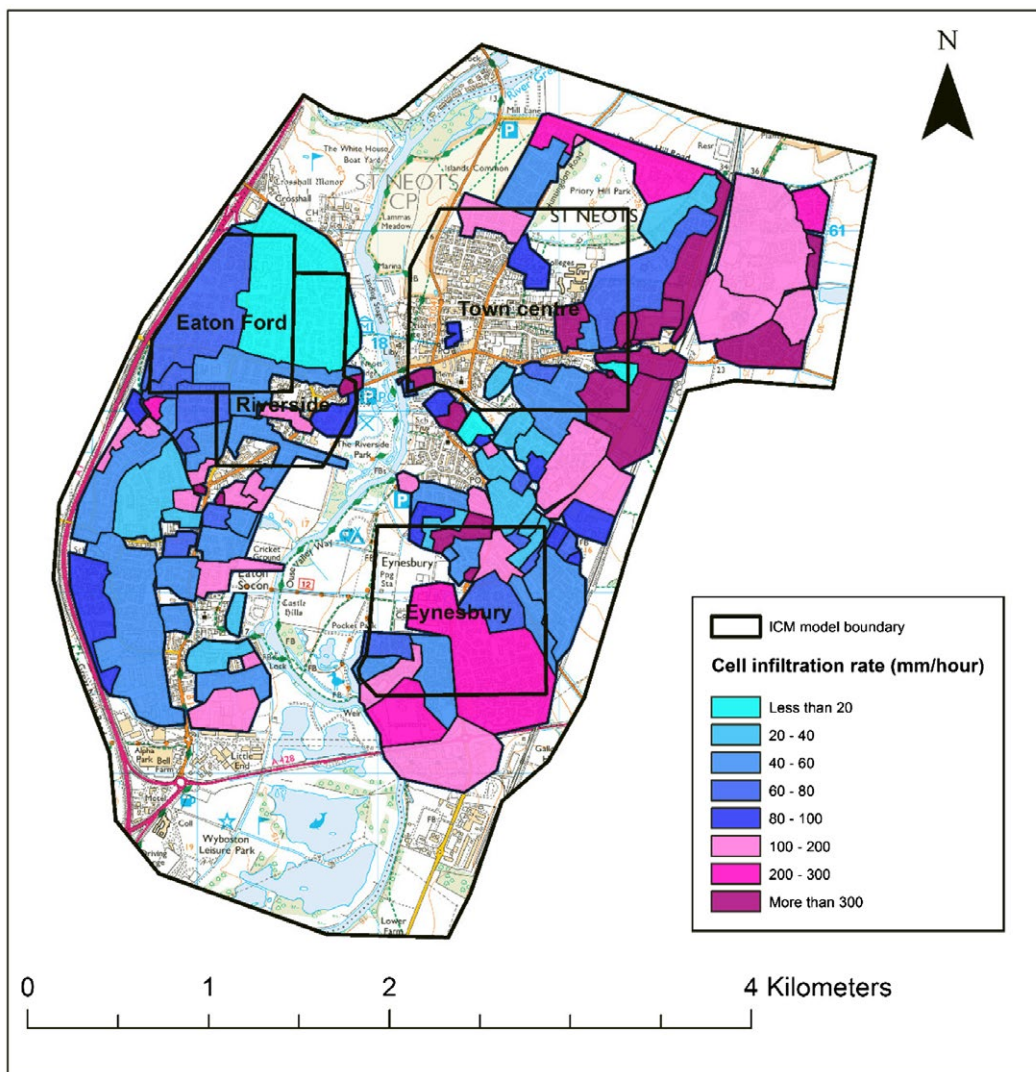

Fig. 3. Surface water sub-catchments and corresponding outflow rates used in CADDIES.

are also specified to drain to soakaways, this is modelled through removing rainfall which falls on these cells.

The largest difference between the CADDIES framework and ICM was in the representation of the surface water sewer network. CADDIES does not include a 1D pipe system and so runoff captured by the surface water system was represented through adjusting the outflow rate within cells, effectively removing water from the simulation at a set rate (Figs. 1 and 3). Adjustments to outflow rates were made on a sub-catchment basis, defined based on the locations of the surface water system from the ICM model. It was assumed that the peak flow rate in each sub-catchment was set by the flow rate in the corresponding trunk sewer. GIS screening was applied to identify the trunk sewer for each surface water sub-catchment. The peak flow rate for each trunk sewer was calculated using the Colebrook White module in ICM. This rate was then averaged and applied across each cell in the associated sub-catchment. The methodology for this conversion is presented in Appendix A and a sensitivity analysis is presented in Appendix B. The outflow drainage rate was capped at 300 mm/h to avoid model instabilities generated by very high rates, typically generated where small catchments fed into culverts.

Representing the 'intervention scenario'

The intervention scenario corresponds to 'Option Combination C2' as specified in the St Neots SWMP (2012). This option includes small scale engineering options at strategic locations within the catchment, corresponding to priority flood spots (PFS) identified in the earlier scenarios. Interventions included changes to kerb heights, road elevation and construction of swales in areas of flooding. These interventions were represented in ICM and CADDIES through changes to elevation models reflecting the planned interventions.

Simulation

CADDIES simulations were undertaken using an 'Nvidia Tesla K20c' (2496 CUDA cores). CADDIES increases simulation speed whilst maintaining accuracy through application of an adaptive time step. The time step decreases towards a minimum as velocity increases, thus enabling the simulation to capture flow dynamics of fast moving runoff whilst stepping quickly through periods of low flow. Smaller time steps are more accurate, but result in a trade-off with simulation speed (Gibson *et al.*, 2016). This simulation applied a minimum step of 0.01 s.

Analysing model performance

Mean difference in peak depth per cell

Model performance was assessed through analysis of variation in flood depths between both modelling approaches. Performance was assessed in relation to the entire catchment (this included areas of fluvial flooding) and to PFS, identified within the SWMP (Arcadis, 2014). Peak flood depth outputs from both models were transformed into an identical '.tif' format (a regular grid) using GIS and then variation was examined on a cell by cell basis. Differences between models were evaluated through analysis of the mean depth and standard deviation between corresponding model cells, constituting a comparison of absolute differences between cells.

Flood/no flood correlation

In addition to assessing the absolute difference in flood depth it is also important for screening tools to reach similar conclusions, therefore a further metric, described as 'flood/no flood' (F/NF) correlation was applied. F/NF correlation classifies the flood depth in each cell as either a flood or no flood, based on a flood threshold level of 30 cm (Environment Agency, 2013). All cells over this threshold are classified as a flood, all cells below it are classified as a no flood outcome. All cells in both models were classified and then compared to generate a percentage agreement ('F/NF correlation') between model outcomes for each scenario.

Results

Mean difference in peak depth per cell

Full results regarding mean differences in peak flood depth per cell between CADDIES and ICM are presented in Appendix C. Positive values indicate that CADDIES was on average shallower than ICM and negative values indicate CADDIES output a deeper peak depth per cell. The mean difference in peak depth per cell for the entire study area and across all AEP's was between 5 and 6 cm, with a standard deviation between 22 and 24 cm. It should be noted that the 'entire study area' includes the watercourses (Fig. 2) which are not specifically modelled in CADDIES. Focusing analysis on the PFS (Fig. 2) demonstrated mean cell differences of less than 2 cm, with standard deviations between 5 and 12 cm across all AEP's.

All scenarios demonstrated consistent peak depths per cells between models. Model variance is approximately 1–2 cm with consistent performance across AEP's. The distribution of variation in mean flood depth shows a consistent trend across all scenarios (Fig. 4). Differences in flooding are predominantly observed around the fluvial flood zones of the River Great Ouse and its tributaries, with other smaller differences observed around building outlines and topographical features.

Differences across the floodplain are attributed to the rapid assessment framework not representing the fluvial system which is included within the ICM model (Fig. 2).
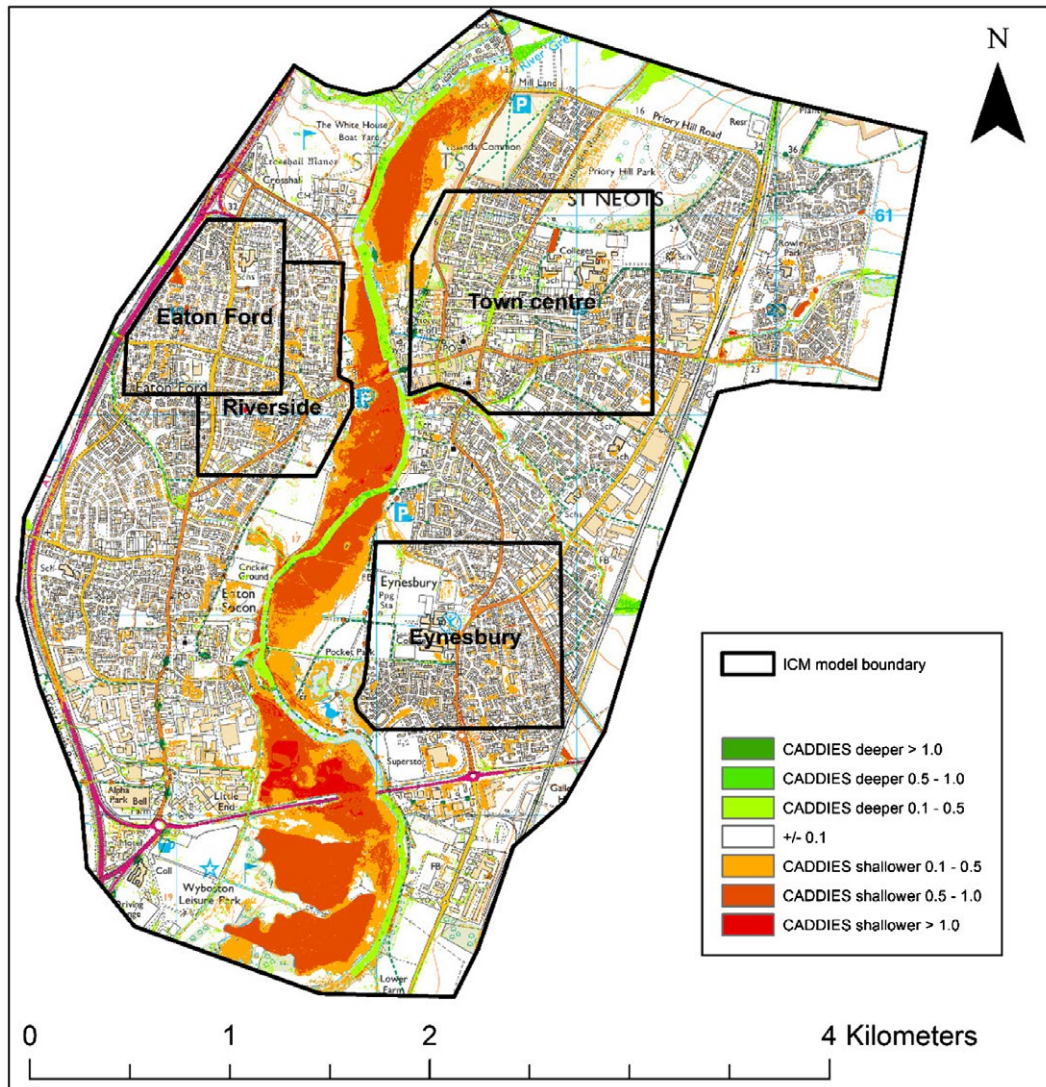
Fig. 4. Mean peak flood depth difference per cell for the intervention scenario during a 1% AEP, 2 h rainfall event.

This creates a model variation through three key mechanisms. Firstly, upstream input flow hydrographs add more water to the channel, floodplain and tributaries within St Neots, therefore increasing water depth on the fluvial flood plain, visible as red in Fig. 4. Secondly, ICM classifies the modelled 1D channels separately to the 2D urban domain, meaning that water located in the 1D channels is not registered as a flood output. CADDIES does register this as a flood output, observed through CADDIES results showing deeper flooding as green in Fig. 4 in the middle of the river channels. Thirdly, the surface water drainage system in ICM outflows to the river and floodplain, increasing depth in these areas relative to the simplified mechanism in CADDIES which removes water from the model, rather than transferring it.

Variation at the edge of buildings is attributed to differences representing structures between the two methods. In ICM the elevation mesh technique represents buildings as a void, whereas the rapid assessment framework applies an elevation uplift to represent structures. The elevation uplift can create areas of local ponding, and in the case of very deep water, also registers flood depths within a building. Representation as a void in ICM cannot register flood depth within the structure itself.

Flood/ No flood correlation

Full results for F/NF correlation across the entire study area and individual PFS are presented in Appendix D. Analysis indicates that models correlated at an average between
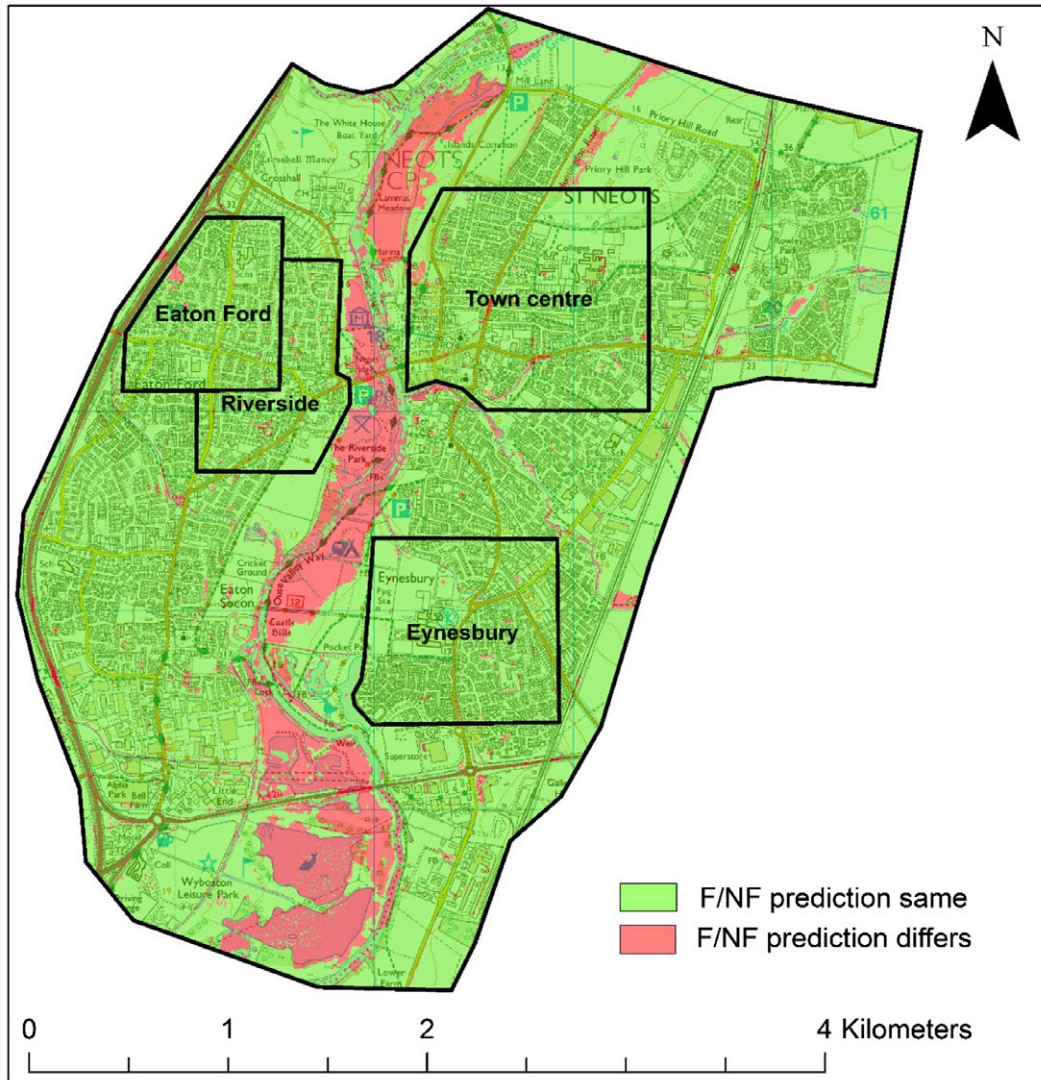
Fig. 5. F/NF correlation for the 'intervention' scenario during a 1% AEP, 2 h rainfall event.

88 and 89% across the entire study area. This includes the fluvial system, the limitations of which are discussed in the previous section. Analysis of PFS, where fluvial input is minimised, indicates model correlation between 93 and 99%. PFS with no watercourses, such as Eynesbury, demonstrated the highest average correlation. Models correlated more closely during lower magnitude events in all cases. The models demonstrated closer correlation during the surface water drainage and intervention scenarios (97–99%).

Fig. 5 presents distribution of model correlation by indicating F/NF correlation in green and variation in red. The figure presents a similar distribution to Fig. 4. Variation is focused around the river channels and several topographical features, including buildings and embankments.

Embankments which demonstrate variation in F/NF prediction are those which are served by culverts, represented by a 1D system and therefore not included within the CADDIES model. An example of this can be seen to the East of Eynesbury (Fig. 5) where the road embankment ponds water, resulting in a localised area of F/NF variation. This indicates a limitation of the fast assessment method.

Discussion

Is the rapid assessment approach suitable for screening a no sewer scenario?

The degree of utility of the rapid assessment framework to screen catchments in the no sewer scenario is

evaluated relative to three questions, each progressing to more nuanced level of application: Firstly, can the framework broadly replicate flood dynamics and identify PFS in the urban catchment? Secondly, does the framework correlate flood depths with industry standard techniques? And thirdly, are outcomes from application of the rapid assessment technique comparable to analysis using the industry standard approach?

During the no sewer scenario the rapid assessment framework replicates identification of the four PFS identified as part of the St Neots SWMP (2012). These regions are Eaton Ford, Eynesbury, Town Centre and Riverside. Only a minor variation in peak depths per cell of 0–2 cm $\pm$ standard deviation of 5–12 cm is observed in measurements across each of these flood spots during all AEP events. Outcomes from both approaches are likely to be very similar due to the 97.4% average F/NF correlation across all PFS and each of the AEP events. The 88% F/NF correlation observed across the whole catchment is likely to be mitigated in practice through initial catchment assessment to discount areas of fluvial interaction or where complex subsurface drainage features create localised anomalies.

The models demonstrate similar results and outcomes, providing evidence that the rapid assessment framework is acceptable for the purpose of screening flood hazards during the no sewer scenarios. However, it is emphasised that this comparison is between two models, and not recorded observations. Simplifications required for all models mean that neither approach should be considered an accurate representation of real life. In practice, models will always trade off simplifications in representation and limitations in data with accuracy, and should therefore be considered as tools for a specific application, in this case screening using readily available data. Flood model accuracy in highly complex urban environments is likely to be affected by many factors. Variation between models and urban flood findings can commonly be attributed to uncertainties, including inaccuracies in topographic surveys (Dottori *et al*., 2013); spatial resolution of elevation models missing permanent micro-topographical features, such as kerbs (Fewtrell *et al*., 2011), walls (Yu and Lane, 2006), ditches (Bates *et al*., 2006) and fences (Mignot *et al*., 2006); temporary microtopographical features such as cars (Dottori *et al*., 2013); landscapes altered by high energy flows (Dottori *et al*., 2013); flow interactions with buildings, which vary with height and inundation duration (Chen *et al*., 2012; Schubert and Sanders, 2012); uncertainties in statistical construction of temporal and spatial patterns of design rainfall (particularly for low probability events); changes to boundary conditions during storms (Bates, 2004; Masoero *et al*., 2013); and local short term irregularities, such as blocked or damaged drainage features (Neal *et al*., 2009).

Mean peak flood depth per cell and F/NF correlation provide a comparison of flood hazard across the catchment, but are sensitive to the size of the chosen domain and assess correlation between two models, rather than versus records. Many other model evaluation metrics are available, such as root mean squared error, Nash-Sutcliffe efficiency and mean error versus records (Neal *et al*., 2009).

Is the rapid assessment approach suitable for urban flood screening whilst including the sub-surface drainage system?

The primary limitation of the rapid assessment framework is considered to be the trade-off between representation of the 1D pipe system with a model architecture aimed at speed (Webber, Fu, *et al*., 2018a; Webber, Gibson, *et al*., 2018b). This study has identified that representing the pipe system using spatial variation in cell outflow rates across model sub-catchments demonstrates 98.5% F/NF correlation with the 1D network included in the ICM model. Both models screen the catchment and identify the areas at risk from surface water flooding. Within these catchments, models demonstrate a mean variation per cell of 0–2 cm with a standard deviation of 5–9 cm, alongside an average F/NF correlation of 98.5%. Correlation is similar across all return periods. The result of this correlation is that both modelling approaches are likely to result in similar outcomes for recommending further detailed modelling and prioritising areas of the catchment where interventions should be evaluated.

Representing sub-surface drainage using a simplified cell output rate appears an effective trade-off in areas where the water is removed; however, carries the limitation that water is not transferred to other regions where it may influence flooding, for example, outflows to watercourses. High-intensity short-term rainfall, responsible for the majority of urban surface water flooding, is unlikely to contribute significant amounts of volume to cause flooding in major watercourses, but this limitation should be considered carefully as the approach may not be suitable where small water courses, culverts or pipe full flow phenomenon such as surcharge are expected to contribute to surface water flood risk. This risk can be mitigated through initial analysis of flood risk such as evaluating flood histories, interviewing catchment stakeholders and reviewing previous studies in the area of investigation. These actions are typically recommended as part of strategic flood risk assessments.

As with the no sewer scenario, finding that the rapid assessment framework correlates with existing methodologies is caveated with the need to examine the spatial distribution of results to ensure action taken reflects the

strengths of the rapid assessment framework; namely, that the model is used to support further study in areas not influenced by fluvial flooding and that allowance has been made for significant sub-surface features.

Is the approach suitable for modelling interventions in an urban catchment?

The most complicated scenario within this analysis is the inclusion of additional interventions alongside the existing drainage network. This scenario involves representing the land use, sub surface drainage and additional flood protection measures modelled using ICM. Both models identify PFS and correlate closely on mean peak flood depth (average 1 ± 8 cm) in cells and F/NF correlation (average 98.5%) within these regions. As discussed in previous sections, spatial analysis of differences attributes variation to watercourses and significant sub surface features such as culverts.

Close correlation between the two approaches supports application of the rapid assessment as a screening tool for examining an initial assessment of interventions in urban catchments (Webber, Fu, *et al.*, 2018a; Webber, Gibson, *et al.*, 2018b). The complexities of modelling runoff in urban catchments (Dottori *et al.*, 2013) alongside the high computational cost of 2D modelling (Elliott and Trowsdale, 2007; Hunter *et al.*, 2008; Emanuelsson *et al.*, 2014) have traditionally restricted the number of interventions which can be screened during design. Speed of analysis of the rapid assessment framework lends the utility of screening many interventions in a short space of time. Utility is supported through the application of simple data, such as elevation, land use mapping and rainfall events. This data is likely to be available in the initial stages of engineering projects and therefore provides an opportunity for decision makers to examine catchments during preliminary analysis and generate evidence to support the strategic direction and requirements for further detailed design. This is of particular advantage in the United Kingdom where recent government reports emphasise a requirement for strategic decisions in future flood risk management to be grounded in a robust and transparent evidence base (House of Commons, 2016).

General guidance

Analysis of the two models identifies that the advantages of the rapid assessment framework enable simulation of many scenarios and potential intervention strategies at a low computational and setup resource cost, and with comparable accuracy relative to other contemporary 2D simulation approaches. Automation of the approach can generate hundreds of scenarios and build an extensive set of 'what if' scenarios for preliminary decision support (Webber, Fu, *et al.*, 2018a; Webber, Gibson, *et al.*, 2018b). Simplification of several physical parameters, such as the sub-surface drainage system and watercourses, mean that this model should be applied only as an initial screening tool to direct and inform, rather than replace, detailed design models. However, this analysis does demonstrate that the performance of sub-surface drainage systems can be estimated to close correlation with 1D-2D models within the scope of urban surface water flooding. This is caveated with the understanding that the simplified representation will not simulate 1D flow phenomenon such pipe surcharge or blockage. It is therefore recommended that application of the rapid assessment framework should be supported with preliminary analysis to identify flood mechanisms in study areas and ensure that these align with the models strengths and are not associated with complex flow conditions in the sub-surface network or interactions with watercourses.

Practical utility of the rapid assessment framework can be summarised as suitable for initial catchment screening as part of developing evidence or enhancing communication and scenario exploration to aid decision support. As with all models, this provides a tool for a specific purpose and its uncertainties and limitations should be evaluated on a case by case basis (Blöschl, 2006; Dottori *et al.*, 2013).

Conclusions

The rapid assessment framework demonstrates close correlation with the ICM model applied for the St Neots SWMP. Major differences are attributed to variation in representation of the piped system, watercourses and structure thresholds. This study finds three main conclusions.

(1) The rapid assessment framework is a suitable tool for screening priority surface water flood spots in urban catchments.
(2) The framework demonstrates close correlation with ICM when evaluating surface water flood hazards within PFS. This finding applies to models constructed to multiple levels of detail, including without sewers (97.4%), inclusion of the sub-surface drainage system (98.5%) and addition of interventions to the catchment surface (98.5%).
(3) Application of the rapid assessment framework should be supported through preliminary analysis to ensure surface water flood hazard is not caused by interactions within local sub-surface drainage or river systems.

Comparison indicates that the rapid assessment framework is a promising tool for screening catchment flood risk which may add to urban drainage planning capabilities by responding to analysis speed and resource constraints. Future research should utilise framework speed towards analysis of many intervention strategies and scenarios within urban catchments, providing an opportunity to enhance evidence for strategic decision support.

Acknowledgements

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Appendix A: Process diagram for converting 1D drainage rates to 2D cell output rates

Identify unique surface water **drainage sub-catchments**

↓

Identify **trunk sewer** for each sub-catchment

↓

Calculate **trunk sewer peak flow** ('Q $_{sub}$' – m/s) for each sub-catchment

↓

Measure **sub-catchment area** ('A $_{sub}$' – m^2) and **cell area** ('A $_{cell}$' – m^2)

↓

Calculate a **cell outflow rate** (m^3/s) for each sub-catchment:

$$Cell\ outflow\ rate\ = A_{cell} \times \frac{Q_{sub}}{A_{sub}}$$
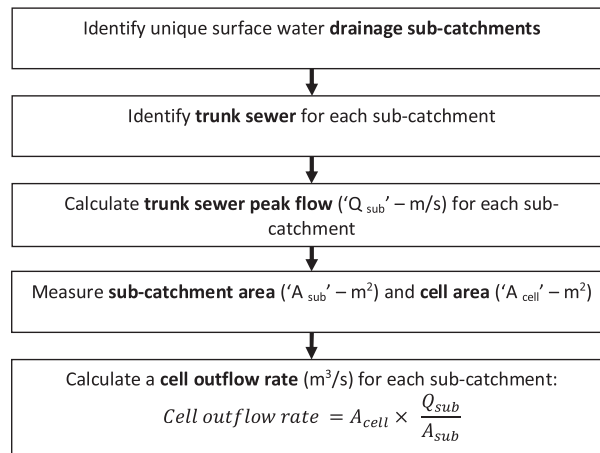
Where Q$_{sub}$ is trunk sewer peak flow (m/s), A$_{sub}$ is sub-catchment area (m^2) and A$_{cell}$ is cell area (m^2).

Fig. A1. Process for representing the surface water network in CADDIES using a cell outflow rate.

Appendix B: Drainage cell output rate sensitivity analysis

Table B1 Mean difference in peak depth per cell (m) between CADDIES and ICM whilst varying cell drainage output rates across the entire catchment in the 'surface water drainage' scenario

AEP (%)	A1 rate −50%	Appendix A rate calculation	A1 rate +50%
5.0	0.06 ± 0.22	0.07 ± 0.22	0.07 ± 0.22
3.3	0.06 ± 0.22	0.07 ± 0.22	0.07 ± 0.22
2.5	0.06 ± 0.22	0.07 ± 0.22	0.07 ± 0.22
1.0	0.06 ± 0.22	0.06 ± 0.22	0.06 ± 0.22
0.5	0.05 ± 0.23	0.06 ± 0.23	0.06 ± 0.23
Average	0.06 ± 0.22	0.06 ± 0.22	0.07 ± 0.22

Table B2 F/NF correlation (%) per cell between CADDIES and ICM whilst varying cell drainage output rates across the entire catchment in the 'surface water drainage' scenario

AEP (%)	A1 rate −50%	Appendix A rate calculation	A1 rate +50%
5.0	89.5	89.6	89.6
3.3	89.1	89.1	89.1
2.5	88.9	88.9	88.9
1.0	88.2	88.3	88.3
0.5	87.7	87.6	87.6
Average	88.7	88.7	88.7

Table B3 F/NF classification (%) outcomes (averaged across all AEP events) whilst varying cell drainage output rates across the entire catchment in the 'surface water drainage' scenario

Outcome		A1 rate −50%	Appendix A rate calculation	A1 rate +50%
ICM F	CAD F	1.0	0.8	0.8
ICM NF	CAD NF	87.7	87.9	88.0
ICM F	CAD NF	9.8	10.0	10.0
ICM NF	CAD F	1.5	1.3	1.3

Overall peak depth (Table A1) and FNF correlation (Table A2) per cell remains relatively consistent when adjusting the rate. However, when examined on an output scale (Table A3) a trade-off emerges where decreasing the output rate will lead to higher flood match outcomes at the expense of lower no flood match outcomes. Increasing the drainage rate has the opposite effect. As such the calculation rate applied in Appendix A is unmodified for this analysis.

Lower catchment wide F/NF correlation is attributed to the influence of fluvial flood mechanics (ICM F, CAD NF) and subsurface drainage features (ICM NF, CAD F). These issue are explored in detail within the paper.

Appendix C: Model comparison for mean difference in peak depth per cell between CADDIES and ICM (m)

Table C1 Model comparison for mean difference in peak depth per cell between CADDIES and ICM (m)

AEP(%)	Entire study area	Eaton Ford PFS	Eynesbury PFS	Riverside PFS	Town Centre PFS	All PFS
No sewer scenario						
5.0	0.05	−0.00	−0.01	−0.01	−0.01	−0.01
3.3	0.05	−0.00	−0.01	−0.01	−0.01	−0.01
2.5	0.05	−0.00	−0.01	−0.01	−0.01	−0.01
1.0	0.04	−0.00	−0.01	−0.01	−0.01	−0.01
0.5	0.04	−0.00	−0.02	−0.01	−0.01	−0.01
Average	0.05	0.00	−0.01	−0.01	−0.01	−0.01
Surface water drainage scenario						
5.0	0.07	0.01	0.01	0.01	0.00	0.01
3.3	0.07	0.01	0.01	0.01	0.00	0.01
2.5	0.07	0.01	0.02	0.01	0.00	0.01
1.0	0.06	0.02	0.02	0.01	0.00	0.01
0.5	0.06	0.02	0.02	0.01	0.00	0.01
Average	0.06	0.02	0.02	0.01	0.00	0.01
Intervention scenario						
5.0	0.07	0.01	0.01	0.01	0.00	0.01
3.3	0.07	0.01	0.01	0.01	0.00	0.01
2.5	0.06	0.02	0.02	0.01	0.00	0.01
1.0	0.07	0.02	0.02	0.01	0.00	0.01
0.5	0.06	0.02	0.02	0.01	0.00	0.01
Average	0.06	0.02	0.02	0.01	0.00	0.01

Table C2 Model standard deviation for mean difference in peak depth per cell between CADDIES and ICM (m)

AEP(%)	Entire study area	Eaton Ford PFS	Eynesbury PFS	Riverside PFS	Town Centre PFS	All PFS
No sewer scenario						
5.0	0.22	0.06	0.06	0.06	0.09	0.07
3.3	0.23	0.06	0.07	0.07	0.09	0.07
2.5	0.23	0.06	0.08	0.07	0.10	0.08
1.0	0.24	0.07	0.09	0.08	0.11	0.09
0.5	0.24	0.08	0.10	0.10	0.12	0.10
Average	0.23	0.06	0.08	0.08	0.10	0.08
Surface water drainage scenario						
5.0	0.22	0.05	0.06	0.06	0.06	0.06
3.3	0.22	0.05	0.06	0.06	0.07	0.06
2.5	0.22	0.06	0.06	0.06	0.07	0.06
1.0	0.22	0.08	0.07	0.07	0.08	0.07
0.5	0.23	0.09	0.08	0.07	0.09	0.08
Average	0.22	0.07	0.07	0.06	0.07	0.07
Intervention scenario						
5.0	0.22	0.05	0.06	0.07	0.07	0.06
3.3	0.22	0.06	0.06	0.07	0.07	0.07
2.5	0.22	0.07	0.07	0.08	0.08	0.07
1.0	0.23	0.09	0.08	0.08	0.09	0.09
0.5	0.23	0.10	0.09	0.08	0.09	0.09
Average	0.22	0.08	0.07	0.08	0.08	0.08

Appendix D: Model comparison for F/NF correlation (% of cells with the same F/NF classification using a 30 cm threshold)

Table D1 Model comparison for F/NF correlation (% of cells with the same F/NF classification using a 30 cm threshold)

AEP(%)	Entire study area	Eaton Ford PFS	Eynesbury PFS	Riverside PFS	Town Centre PFS	All PFS
No sewer scenario						
5.0	89.3	99.1	98.8	97.9	98.2	98.5
3.3	88.9	99.0	98.5	97.4	97.9	98.2
2.5	88.5	98.9	98.2	96.8	97.6	97.9
1.0	87.5	98.4	97.3	94.5	96.6	96.7
0.5	87.3	98.0	96.4	93.1	95.7	95.8
Average	88.3	98.7	97.8	95.9	97.2	97.4
Surface water drainage scenario						
5.0	89.6	99.4	99.6	99.1	98.7	99.2
3.3	89.1	99.1	99.5	99.0	98.4	99.0
2.5	88.9	98.8	99.5	98.8	98.2	98.8
1.0	88.3	98.2	98.9	98.0	97.5	98.2
0.5	87.6	97.4	98.2	96.8	96.6	97.2
Average	88.7	98.6	99.1	98.3	97.9	98.5
Intervention scenario						
5.0	89.6	99.2	99.5	98.7	98.7	99.0
3.3	89.2	98.9	99.4	98.5	98.4	98.8
2.5	89.2	98.7	99.3	98.4	98.4	98.7
1.0	88.1	98.1	98.9	98.3	97.7	98.2
0.5	87.7	98.1	98.2	97.7	96.9	97.7
Average	88.8	98.6	99.1	98.3	98.0	98.5