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APPLICATION OF 1D AND 2D NUMERICAL MODELS FOR ASSESSING AND VISUALIZING EFFECTIVENESS OF NATURAL FLOOD MANAGEMENT MEASURES

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Natural Flood Management (NFM) techniques that include alteration, restoration or use of landscape features, have emerged as a novel way of reducing flood hazard. We applied a modelling framework to assess the effectiveness of storage ponds as a NFM measure in a rural catchment located in NE Scotland. The modelling framework consists of a combination of 1-D (for storage modelling) and 2-D (flow routing and flood inundation) hydraulic models. The models were used to estimate the impact of temporarily storing water to address flooding issues at the local area. A single pond of 27,000 m^3 will attenuate a median flow event (1 in 2 year) by ~9% and also prevent downstream flooding. However, based on stakeholders' feedback, large ponds would not be feasible owing to relatively high costs and requirement of additional safety measures. Hence a network of smaller ponds would be the preferred solution. We found that a smaller pond of 9,500 m3 would attenuate the median flow by ~3%. This indicates the potential of several smaller ponds to collectively reduce flood risk which is the next phase of work to be investigated.

BACKGROUND

Natural Flood Management (NFM) is currently being promoted as a sustainable catchment-scale approach to managing flood risk in the UK NFM is generally defined as the alteration, enhancement, restoration or utilisation of natural landscape features and characteristics as a way of reducing flood risk [17]. NFM includes a range of measures and techniques that aim to work with natural hydrological and morphological processes to store and attenuate the flood water within the catchment. By targeting hydrological flow pathways at source, such as overland flow, field drain and ditch function, a significant component of the runoff generation can be managed in turn reducing soil nutrient losses [20]. NFM also includes measures such as woodland creation and management, land management techniques (both soil and drain management and modification), working within and on the banks of the channel (e.g. re-meandering and woody debris), runoff management techniques and coastal NFM measures.

NFM measures have been implemented in the UK especially after the Pitt review of the 2007 floods. In Scotland, the Flood Risk Management Act (Scotland) 2009 is the main policy driver for the implementation of NFM. While NFM benefits are widely known at the local scale, their effectiveness at catchment scale is still relatively unknown In addition, identifying the impact of NFM measures on runoff and flood risk at the local scale independent of other factors is difficult [7].

Spatially explicit hydrodynamic flood modelling approach is one useful method that can be used for identifying key vulnerable areas and assessing flood risks at different temporal-spatial scales. A key strength of these models is that they are able to provide time-series information about the onset, duration and passing of a flow event [22]. The recent increased availability of distributed remote sensing data has allowed considerable progress in the field-scale application and testing of a wide variety of 2D flood inundation models [12],[18]. Light Detection and Ranging (LiDAR) data, for example, provide a wealth of topographic information that is widely used in floodplain mapping [5], [9],[10]. In this study, we aim to apply a novel approach to assess how upstream flows can be temporarily stored and flows attenuated by introducing small flood storage ponds in the upstream reaches that will contribute to flood reduction downstream. The local stakeholder's feedback and the NFM principles are taken into account while assessing the potential for these measures.

STUDY AREA

The Tarland Burn (74 km^2), a sub-catchment of the River Dee catchment (2105 km^2) - is located in Aberdeenshire, north-east Scotland (Figure 1). The annual average rainfall within the catchment is ~800 mm. Soils are predominantly freely draining humus-iron podzols (Countesswells series) and freely draining brown forest soils (Tarves series) [11]. The catchment spans an elevation ranging from 109m to 700m (Figure 1). The land use is typical for many agricultural regions of Northeast Scotland and also a typical of an East Coast tributary running through mixed farming country [3]. The major land uses are arable (25%), plantation forestry (19%), improved and unimproved grassland (36 and 10% respectively), heather moorland (8%) and mixed/broadleaved woodland (2%) [6].

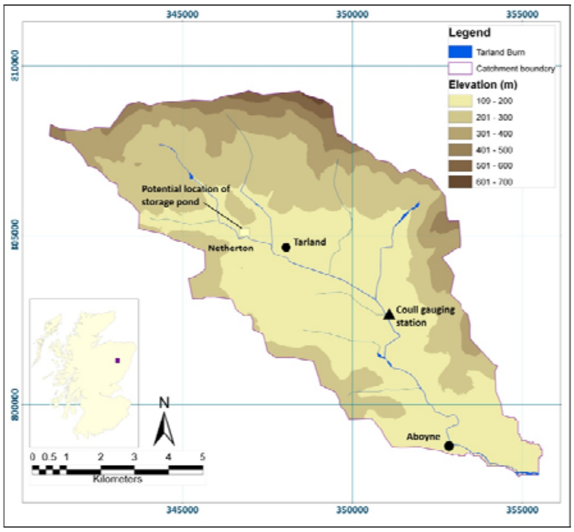

Figure 1. The study area of Tarland Burn catchment (derived from Ordnance Survey 10m DTM, reproduced by permission of Ordnance Survey)

There is a historical legacy of land improvement and intensification of land management. The Tarland Burn and its tributaries have been extensively deepened and straightened to drain the surrounding floodplain and wetlands for the benefit of agriculture [1]. The isolation of the natural floodplain and removal of wetland 'storage' zones that used to dominate the lower valley bottom may have led to an increase in flood risk recently.

The two main settlements in the catchment are Tarland and Aboyne with a population of ~700 and ~2,600 respectively [16]. In both areas several private dwellings and public roads were flooded over the last 15 years [1]. Also some commercial premises were flooded in Aboyne. There were several flood events that occurred in April 2000, October 2002, December 2005, March 2006 and most recently in July 2009 and May 2010 [1]. The flood of October 2002, an event of a magnitude equivalent to a median flood (1 in 2 year), caused significant impact on the local roads of Tarland posing high risk to several houses adjacent to the Tarland Burn (Figure 5B). In order to address the flooding issues in Tarland a previous study found that there was a potential for a range of NFM measures in this catchment [1]. These included wetlands, online and off-line storage ponds, riparian management and tree planting. However, many buffer strips have been installed primarily for diffuse pollution management [6].

METHODOLOGY

Hydrology

As the catchment had limited rainfall and flow records, design events were estimated using UK's Flood Estimation Handbook (FEH) statistical rainfall runoff model (available in ISIS version 3.4 as a FEH rainfall runoff method boundary, FEHBDY) based on a set of catchment descriptors parameters [13]. WINFAP-FEH 3 Design flood modelling software was used for flood frequency analysis [19]. It should be noted that the design flow hydrographs developed by this method can be inaccurate if the parameter estimation is based solely on catchment descriptors. Hence, in order to address the uncertainty issues to some degrees, some representative observed rainfall-runoff events recorded at Coull Bridge gauging (~50 km^2, Figure 1) station were selected and used for the calibration of the model. The monitoring network in the catchment has recently been improved with a new flow gauging established near the pond site at Netherton which enables improved modelling analysis in the future.

Estimating storage volume

The location of the pond was determined based on consultations with the landowner taking on comments from previous studies [14] coupled with other factors such as the site's topographical condition. The flood storage involves creating a small earthen bund to form a storage pond in the floodplain to temporarily hold water and an outlet structure (a simple broad-crested weir) to release water downstream (Figure 2). Computation of pond areas and storage volumes was done using a Digital Elevation Model (DEM) derived from 1m LiDAR using MapInfo. We selected ISIS to estimate water storage and route the flow downstream. ISIS is a one-dimensional hydraulic model that models a pond as a storage reservoir defined by a set of water depths and corresponding reservoir surface areas.

Flood inundation modelling

A 2D grid-based model (TUFLOW, BMT WBM, Build 2011) was applied to develop a flood inundation map. TUFLOW is a computational hydrodynamic model used to simulate the flow of water along channels and across surfaces. Full details about the model can be found at http://www.tuflow.com. Essentially the model solves the shallow water equations to model 2D flows [23]. The approach adopted includes modelling of the channel as a 1D network nested within the 2D domain representing the floodplain. The catchment was divided into a network of small grids and cells. A 5m cell was considered appropriate considering the size of the channel and computational time (2 seconds) required to run the model. A ground DEM was then developed using the LiDAR data of 1m resolution by transferring elevations to the centre of each cell. The channel roughness or bed resistance values (e.g. Manning’s n) were assigned based on the current land use as suggested in the literatures [8].

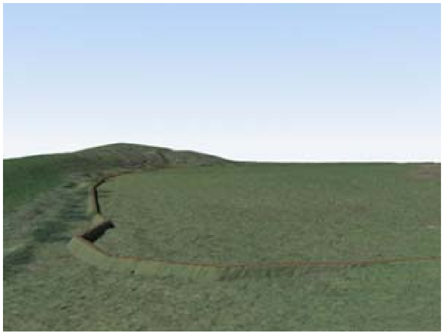

Figure 2. A 3D model created using Visual Nature Studio software, representing the intercepting bund of the proposed pond.

RESULTS

Modelling of a historical flood event

The flood event of October 2002 was modelled which affected many residential properties along the Burnside Road, Tarland village (Figure 3). The flood inundation map for this event indicates that the channel overtopped its right bank that led to the Burnside Road being completely inundated as evident from the photograph taken at the time of the event (Figure 3B). This suggests that the model was able to simulate this particular flood event reasonably well.

Assessment of storage requirement to prevent downstream flooding

Several scenario models were developed considering a range of flow events of different return periods. It was practical to analyse the storage requirement to prevent relatively frequent flood events (index flood with 1 in 2 year probability of occurrence) like the historical floods occurred in Tarland. It was found that a storage capacity of ~27,000 m^3 would be required to prevent the local flooding of this scale. The storage would attenuate the flow significantly with a reduction of the peak flow by ~9% (Figure 4). The flood inundation map of the 1 in 2 year flow event showed that even though a small area to the west of the village would be under flooding, much of the area along the Burnside Road where the October 2002 flood occurred would remain safe from flooding (Figure 5).

Figure 3. Bottom: Flood inundation map of October 2002 event. Top: (A) Normal conditions, (B) Flood conditions (Map reproduced by permission of Ordnance Survey).

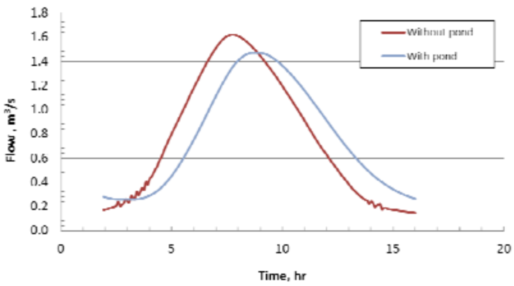

Figure 4. Flow attenuation as a result of a 27,000 m^3 storage pond. The hydrographs correspond to the main channel immediately downstream of the proposed site of Netherton (Figure 1).

Figure 5. Flood inundation map of 1 in 2 year flow event with the storage pond at Netherton upstream of Tarland (Map reproduced by permission of Ordnance Survey).

Assessment of flow attenuation by smaller ponds

In order to assess the flow attenuation by smaller measures, which is the key interest of the stakeholders and fits with the NFM remits, the modelling framework was used to estimate flow from a range of ponds with a capacity of ~1,000 m^3 to 9,500 m^3. It is worth noting that any storage scheme below 10,000 m^3 will not be triggered by the Reservoirs (Scotland) Act as discussed earlier. Flow hydrographs corresponding to both 'with' and 'without' pond are compared for a set of storage against the extreme flow condition (1 in 100 year) as shown in Figure 6. It indicates an increasing flow attenuation (i.e. increase in time lag and decrease in peak flow) with the increase in storage capacity of the pond as expected. Figure 6 indicates that a storage pond of ~5,200 m^3 would reduce the peak flow by ~1%. Similarly, a bigger pond with 9,500 m^3 storage would reduce the peak flow by ~2.5%.

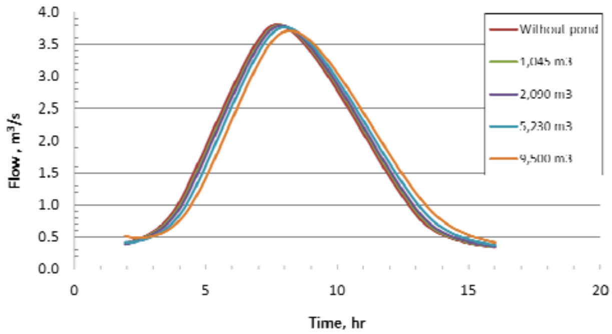

Figure 6. Flow attenuation by small-scale storage ponds

DISCUSSION

Uncertainty issues in modelling

The FEH methodology adopted in this study involves the use of a set of catchment data (catchment descriptors) which is mainly aimed at undertaking hydrological studies of ungauged sites. As such, there are several uncertainty issues with this technique. Flood magnitudes estimated from catchment descriptors are less accurate than flood peak data [15]. To address this issue, we checked and verified the flow estimates both from the catchment descriptors and peak flow data obtained from the Coull gauging station. We found a good match between the index flood estimates derived from the two methods. However, as the estimates of the index flood is based on the flood peak data of very limited period, care must be taken when up-scaling index flood especially for higher return period events which are typically longer than the record period. In addition, a range of sensitivity tests were performed in order to ascertain how uncertainties in model parameters impact on the robustness of the model output.

Stakeholder's feedback

A stakeholder consultation workshop organised at the catchment indicated that farmers were not very much concerned about very rare extreme events like the 1 in 200 year event for which a very large single flood retention basin may be required. Instead, they were more optimistic about having smaller schemes that would not necessarily be able to cope with such extreme events but could deal with more frequent and smaller events [4]. The farmers were aware of the fact that smaller ponds involve less cost both during construction as well as operation and maintenance. However, traditional large-scale engineering schemes involve higher costs and may not serve the principles of the NFM. In addition, a large storage pond (bigger than 10,000 m^3) would require additional safety measures under the legislations relevant to storage reservoirs. Hence, in line with the stakeholder's feedback and preferences, we mainly focused on smaller ponds and their potential for downstream flow attenuation to prevent flood risks in Tarland.

The flood inundation modelling indicated that a single storage pond up to 9,500 m^3 would not prevent local flooding in Tarland. However, given a reduction of ~2.5% in peak flow, we can argue that a combination of small-scale storage measures will have the potential to collectively attenuate the flow and reduce the downstream flood risk. Also, the pond would provide multiple benefits by trapping sediments. However, sediment build up can reduce the capacity and requires management. Building on these model outputs, we are currently developing a network model to examine the effects of small-scale storage schemes in multiple locations at a sub-catchment scale.

CONCLUSIONS

We developed a modelling framework for assessing the effectiveness of the storage ponds to alleviate flood risk in Tarland using a combination of 1D and 2D hydraulic models. First, the modelling framework was tested for a historical flood event which showed that the model simulated the flood event reasonably well. The framework was then applied to estimate the storage capacity required to prevent the flooding in Tarland. It was found that a single large storage pond of ~27,000 m^3 would be required to prevent a 1 in 2 year flood event. As the stakeholder's preference was in the smaller schemes as opposed to larger ones, the framework was used to estimate downstream flow attenuation by a range of smaller ponds. A storage pond of ~5,200 m^3 would reduce the peak flow by ~1%. Similarly, a bigger pond with 9,500 m^3 storage would reduce the peak flow by ~2.5%. This suggests that a combination of small-scale storage measures will have the potential to collectively attenuate the flow and with stakeholder's involvement they can be implemented as NFM to reduce the downstream flood risk. Further research will consider modelling of storage in multiple locations to assess the effectiveness in collective functioning at a sub-catchment scale.

REFERENCES

[1] Aberdeenshire Council, *Tarland burn catchment flood relief scheme, Aberdeenshire, Initial Environmental Assessment Report*, Aberdeenshire Council, (2007).

[2] Aberdeenshire Council, *Tarland Burn-Evaluation of potential demonstration project, Flood Storage Areas*, Aberdeenshire Council, *(*2011).

[3] AQUARIUS, *Farmers as water managers in a challenging climate, Tarland Baseline Report*, (2009).

[4] AQUARIUS, Farmers Workshop at Tarland catchment. Available online at: http://www.macaulay.ac.uk/aquarius/documents/FarmersWorkshopReport.pdf , (2010).

[5] Bates, P.D., "Remote sensing and flood inundation modelling", *Hydrological Processes*, Vol. 18, (2004), pp 2593-2597.

[6] Bergfur, J., Demars, B. O. L., Stutter, M. I., Langan, S. J. and Friberg, N., "The Tarland Catchment Initiative and its effect on stream water quality and macroinvertebrate indices", *Journal of Environmental Quality,* Vol. 41, (2012), pp 314-321.

[7] Blanc, J., Wright, G., Arthur, S., "Natural Flood Management knowledge system: Part 2- The effect of NFM features on the desynchronising of flood peaks at a catchment scale" CREW report. Available online at: http://www.crew.ac.uk/projects/capacity-building-research-projects, (2012).
[8] Chow, V.T., *Open-channel hydraulics*: New York, McGraw- Hill Book Co., (1959).
[9] Cobby, D.M., Mason, D. C. and Davenport, I. J., "Image processing of airborne scanning laser altimetry data for improved river flood modelling", *ISPRS Journal of Photogram. Remote Sensing*, Vol. 56- 2, (2001), pp 121-138.
[10] Di Baldassarre, G.D., Schumann, G., Bates, P.D., Freer, J.E. and Beven, K.J., "Flood-plain mapping: a critical discussion of deterministic and probabilistic approaches", *Hydrological Sciences Journal*, Vol. 55-3, (2010), pp 364-376.
[11] Dunn, S., Castellazzi, M., Shahgedanova et al., "Modelling scenarios of land use and climate change on diffuse pollution from agricultural nitrate", *Proc. British Hydrological Society Eleventh National Symposium, Hydrology for a changing world*, Dundee, (2012).
[12] Horritt, M.S. and Bates, P.D., "Evaluation of 1D and 2D numerical models for predicting river flood inundation", *Journal of Hydrology*, Vol. 268 (1-4), (2002), pp 87-99.
[13] Institute of Hydrology, "*Flood Estimation Handbook*", Centre for Ecology & Hydrology, Wallingford, UK, (2009).
[14] Matthews, K.B.; Blackstock, K.L.; Langan, S. et al., "Farmers as water managers in a changing climate – can we turn sustainability research into outcomes*?",Proc. International Environmental Modelling and Software Society (iEMSs). International Congress on Environmental Modelling and Software*, Ottawa, Canada, (2010).
[15] Robson, A.J.; Reed, D.W., "*Flood Estimation Handbook Vol 3: Statistical procedures for flood frequency estimation*", Institute of Hydrology, Wallingford, (1999).
[16] Scotland's Census, http://www.scotlandscensus.gov.uk/ods-web/home.html, (2011).
[17] Scottish Environment Protection Agency, "Natural Flood Management Position Statement: the role of SEPA in natural flood management". Available online at: http://www.sepa.org.uk/flooding.aspx, (2012).
[18] Siddique-E-Akbor, A.H.M., Hossain, F., Lee H. and Shum C.K., " Inter-comparison study of water level estimates derived from hydrodynamic-hydrologic model and satellite altimetry for a complex deltaic environment", *Remote Sensing Environment*, Vol. 115, (2011), pp 1522-1533.
[19] WHS, "*WINFAP-FEH 3 Design flood modelling software, User guide*", Wallingford HydroSolutions Ltd., (2009).
[20] Wilkinson, M.; Addy, S.; Ghimire, S. et al., "Natural flood risk management in flashy headwater catchments: managing runoff peaks, timing, water quality and sediment regimes", *proc. EGU General Assembly*, 7-12 April, Vienna, Austria, (2013).
[21] Wilkinson, M., Quinn, P., Ghimire, S. et al., "The use of Natural Flood Management to mitigate local flooding in the rural landscape". *Geophysical Research Abstracts*, Vol. 16, EGU2014-9878, (2014).
[22] Zerger, A., Wealands, S., "Beyond modelling: linking models with GIS for flood risk management", *Natural Hazards*, Vol. 33-2, (2004), pp 191-208.
[23] Zhou, J. G.; Causon, D. M.; Mingham, C. G. ; Ingram, D. M., "The Surface Gradient Method for the Treatment of Source Terms in the Shallow-Water Equations", *Journal of Computational Physics*, Vol. 168, (2001), pp 1-25.