Integrated Catchment Modelling
- a Case Study

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1. Synopsis

This integrated catchment modelling case study is based on some recent modelling work undertaken by Richard Allitt Associates in the Brighton catchment. It provides an example of Integrated Urban Drainage where the conventional sewerage modelling is integrated with detailed modelling of a highway drainage system which normally drains to soakaways but at times of intense rainfall contributes significant flows into the combined sewer network. This phenomenon was first noticed during model verification when for one storm there was an unexpected additional flow of over 500 l/s found at one flow monitor site.

This paper summarises the investigations and the modelling undertaken to locate the additional inflows. An area normally drained to soakaways was located and the individual soakaways were modelled as SUDS nodes with limited soakage potential and the road gullies were defined with their own inlet characteristics (head-discharge relationships) in accordance with the Highways Agency publication "Spacing of Road Gullies". This modelling has enabled the overland flows to be modelled with an acceptable level of confidence, albeit with only one big rainfall event to verify them against.

The paper also discusses how this integrated approach can be used to better simulate flooding mechanisms where highway runoff is a factor and also to evaluate the relative proportions of the flow which come from each source.

2. Introduction

Richard Allitt Associates were commissioned by Southern Water in July 2005 to construct and verify a new Infoworks model of the Brighton & Hove catchment which has a population of nearly 260,000 and covers an urban area of some 4,000ha. The specification for the model building was to build a Type III model suitable for identification of all the hydraulic problems and also so that preliminary designs for solutions can be developed with confidence. In view of these requirements a high density of flow monitors were used in the project. The project was also used as a pilot study for the use of a high quality Digital Terrain Model (DTM) which has been the subject of a paper[1] presented at the Spring 2006 WaPUG meeting and at the Infoworks 2006 International User Conference.

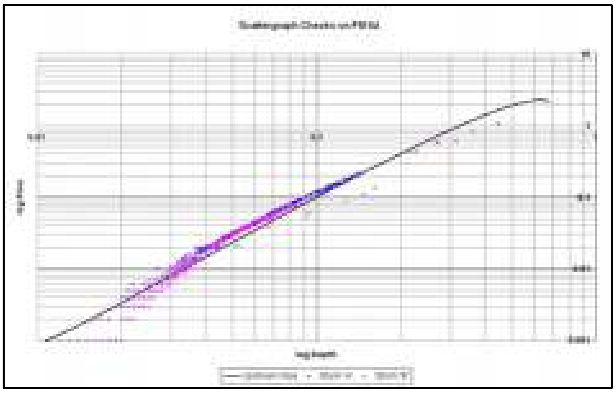
The City of Brighton & Hove is located on the south coast of England and the topography and the geology of the Brighton & Hove catchment is dominated by the South Downs which are formed of chalk with some overlying clay and alluvium in the dry river valleys.

The topography in the catchment is variable because of the proximity of the South Downs and the catchment has a maximum elevation of about 180m OD dropping down to a lowest elevation of about 5m OD.

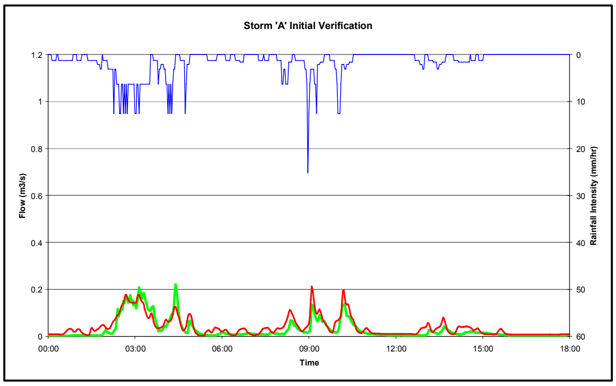
The drainage system for Brighton and Hove is generally separate in the higher areas where surface runoff is mostly drained to soakaways into the chalk, whilst in the lower lying areas in the older parts of the city the surface runoff is drained to combined sewers. The layout of the sewer network is dendritic in the upper areas and looped in the flatter coastal areas.

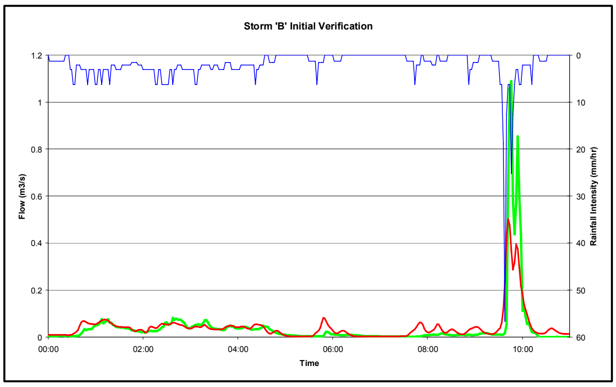
3. Flow Survey and Model Verification

An extensive flow survey comprising 121 flow monitors and 19 raingauges was undertaken in order to verify the model. A very high standard of verification was achieved at most flow monitor locations and the historical verification gave a very good correlation to reported flooding. There were one or two exceptions to this and one of these was Flow Monitor No 64 which was located in a 675mm dia branch sewer running down the side of a valley to join the larger main spine sewer in the valley bottom. This monitor was fully operational for two of the four storms used for verification. These two storms were both 10 hours duration with between 23mm and 27mm of rainfall which made both storms between 1 in 1 year and 1 in 2 year return period though with significantly different profiles and different peak intensities. These two storms were considerably in excess of the minimum WaPUG criteria. The scattergraph for this flow monitor showed a very good data consistency and also that the data matched extremely well with the Colebrooke White theoretical line. There was no reason to suspect that any of the measured data was incorrect; indeed to the contrary all the information supported the data being of above average quality.



The initial storm verification (see hydrographs below) for the model at FM64 showed a good match for Storm ‘A’ but for Storm ‘B’ with higher rainfall intensities the model seriously under-predicted the peak flows. The observed peak flow was 1,090 l/s whilst the simulated flow was only 502 l/s. There was therefore a shortfall of over 500 l/s.





It was clear from these initial verification hydrographs that when there was higher intensity rainfall there was a considerably greater flow in the system which could only be caused by additional areas contributing runoff. Clearly in periods of lesser intensity these additional areas do not normally contribute runoff. It was only the storm with peak intensities in excess of 25mm/hr (or even higher) that caused these additional areas to contribute runoff.

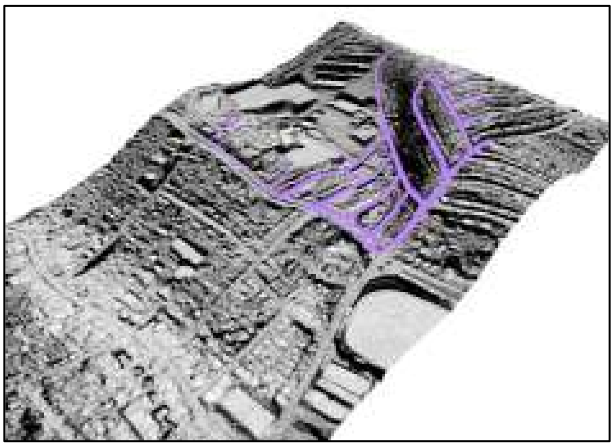
4. Highway Drainage & Supergulley

The catchment area upstream of FM64 was re-examined to assess whether there were any additional areas which could contribute flows under certain conditions, but not under normal conditions. It was found that there was a ‘supergulley’ connected to the sewer a short distance upstream of the flow monitor. Supergulleys are (probably) unique to Brighton & Hove and are installed by the Highway Authority to minimise the consequences of flooding due to highway runoff. There are a number of ‘supergulleys’ installed in the Brighton & Hove catchment but it had not been appreciated that there was one installed in this sub-catchment.

Supergulleys (as shown in the previous photograph) have very large waterway openings and generally measure 1.35m wide by 0.675m deep with a 300mm or 450mm dia outgoing pipe. The size of these supergulleys are such that pedestrian barriers are required around them to protect members of the public. These supergulleys can take very large quantities of water off the highway.

Most of the 'supergulleys' have been installed for many years with Brighton & Hove Council only installing them as a responsive or reactive measure and only with the agreement of Southern Water. In most cases the 'supergullies' are at the downstream end of roads or networks of roads which are drained on a combined basis; they just bring the same highway runoff water into the system as would normally contribute but they overcome problems associated with leaves and litter obstructing conventional gullies.

The sub-catchment area upstream of FM64 is the only known area where the 'supergulley' brings additional runoff flows into the sewers as most of the upstream catchment is drained to soakaways. It was considered likely that what was happening in this sub-catchment was that during rainfall of up to moderate intensity the conventional road gulleys (which drain to individual soakaways) were capable of dealing with all of the highway runoff and in these storms there was only a small area directly draining to the 'supergulley'. However, in more intense storms the conventional road gulleys were unable to remove all the highway runoff with the consequence that some flow continued past each gulley, either because the soakage capacity of the soakaway was exceeded or because the capacity of the gulley gratings[2] was exceeded, and the cumulative effect meant that towards the bottom of the contributing road network there were very large overland flows arriving at the 'supergulley' which was then efficient in discharging them into the combined sewer.



The extent of the road network which could potentially contribute runoff in these circumstances was determined by an examination of the digital terrain model. It was found that there was an extensive network of about 3.4km of roads which could potentially contribute flows from an area of over 40,000m^2.

There are also some large school playing field areas within the catchment and it is possible that under certain conditions there could be runoff from these fields which could contribute to the flows along the streets. However, it is unlikely that this was the case with verification Storm 'B' as the runoff was too rapid and peaked which is typical of impermeable runoff rather than permeable runoff which would normally be flatter.

5. Modelling Objectives

It is clear that with additional impermeable areas contributing runoff during intense storms it was important that the modelling should be able to replicate this so that the simulations of more extreme design storms could be as accurate as possible.

The challenge in terms of modelling was to attempt to replicate what actually occurs and specifically to arrange the model such that the overland flow routes are included but so that during smaller storms there is no flow along the overland flow routes and thus no additional flows.

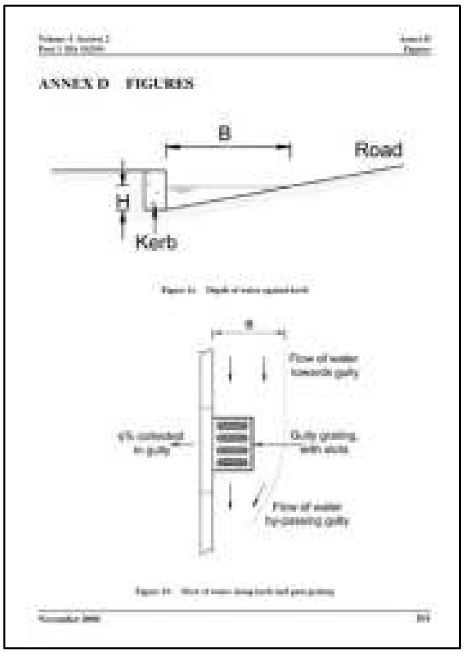
It was unclear at this stage whether the governing factor in the highway runoff was the soakage capacity of the soakaways at each of the road gullies or whether it was the actual capacity of the road gulley gratings. It was therefore decided that the best course of action would be to model both of these aspects and to then undertake a sensitivity analysis such that each aspect in turn could be investigated to assess whether it was the governing factor.

6. Modelling Overland Flow Routes

The overland flow routes were modelled as open rectangular channels generally 150mm deep by 500mm, 1,000mm , 2,000mm or 3,000mm wide depending on how far down the network they are located. The positions of modelled nodes (manholes) were selected on a subjective basis based on a reasonable number of road gullies upstream of each one. Inbetween the modelled manholes there were a number of 'break' nodes included at significant changes in the vertical alignment of the channels. The cover levels and invert levels were determined directly from the DTM.

7. Modelling the Soakaways and Road Gulleys

The principal nodes in the overland flow channels were modelled as SUDS structures with the depths and plan areas set to be equivalent to the size and soakage perimeters of the soakaways at the road gulleys. The soakage rates needed to be estimated and these were used as the main variable. The flood type used in conjunction with each of the modelled nodes was the 'gulley' flood type which requires a head-discharge relationship to be established. The Highways Agency design standard HA 102/00 "Spacing of Road Gullies" and the Technical Notes "Representation of Gullies[3]" and "Definition of Hydraulic Capacity of Gullies for InfoWorks CS[4]" were used to determine suitable head-discharge relationships depending on the longitudinal gradient of the road (which was determined from the DTM).

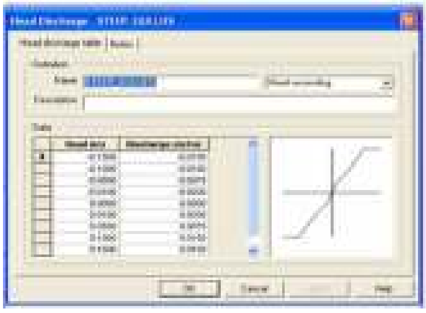


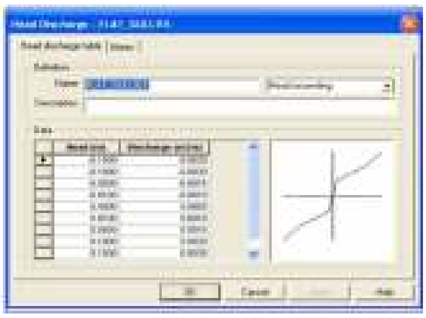
The calculation of appropriate head-discharge characteristics for road gulleys is particularly complex because the efficiency of the individual road gulley is dependent upon numerous factors including longitudinal road gradient, road crossfall gradient, channel roughness, grating bar coefficient, area of waterway slots, grating area and waterway area as a percentage of the grating area. The diagram to the right (reproduced from "Spacing of Road Gullies[2]") illustrates the basic principle that there is a flow of water towards the gulley and depending on the efficiency of the gulley some of the water is collected by the gulley and some water by-passes the gully. It is clear that the width of the flow of water approaching the gulley and the width of the gulley are crucial factors determining what flow by-passes the gulley. Obviously with steeper longitudinal road gradients and steeper road crossfall gradients the width of the water flow approaching the gulley is less than with flatter gradients. It also follows that with progressively higher return period the flows approaching the gulley increase and once the width of the gulley has been exceeded the flow of water by-passing the gulley increases. Thus the efficiency of the gulley decreases as the flow increases.

The other important aspect with road gulley performance is the capacity of the pipe connecting the individual gulley to the main sewer or in this case study the capacity of the soakaway. Guidance from "Spacing of Road Gullies[2]" is that on steeper roads where the gulley efficiency is far higher (because the width of the approaching water flow is narrower) the governing factor can be the capacity of the pipe from the gulley to the sewer and there is a recommendation that a maximum flow of between 10 l/s and 15 l/s should be assumed.

There are of course other factors which can influence the performance of road gullies including the distance between the gulley grating and the kerb, the degree of maintenance, the extent of blinding with leaves or litter, any drop kerbs and local variations in road levels (see photo). To take account of all the factors which influence each individual gulley would be far too time-consuming and clearly a more simplified and standardised approach is needed.

Most of the road gulleys in the study area were in steep roads but some were located where the road gradients flattened out. The gulleys were therefore categorised as 'steep gullies' or 'flat gullies' and appropriate head discharge relationships were derived as illustrated below.





The discharges for the steeper roads were a lot higher than for the flatter roads and were capped at 15 l/s.

The other factor which then governs how the model simulates the flow of water removed off the road by the gulleys is the number of gulleys included at each node within the model. This variable was the second variable used in the final verification and the sensitivity analysis.

8. Sensitivity Analysis

The next stage in the investigations was to undertake a sensitivity analysis to determine whether it is the capacity of the soakaways or the capacity of the gulley gratings which was the governing factor.

For the first model simulations the number of gulleys was set at the correct value and the soakage rate from the manholes was set at an unrealistically high value such that the gulley capacity was the governing factor.

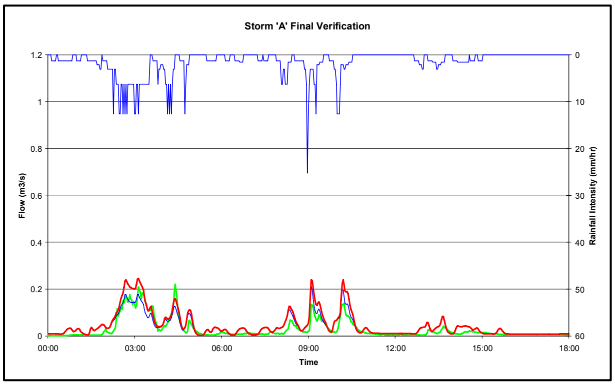
The second set of model simulations had the number of gulleys set at an unrealistically high value and a more appropriate value for the soakage rate was used so that the soakage rate became to governing factor.

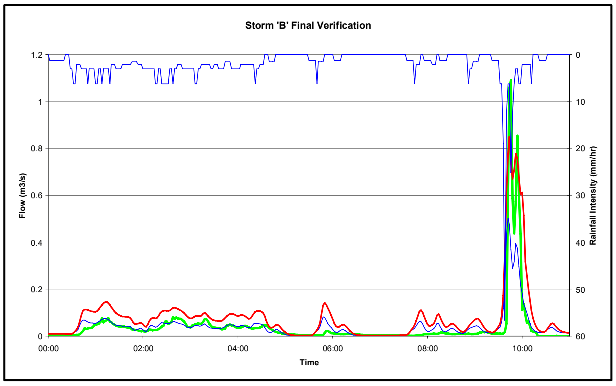
The results of these simulations showed an almost identical pattern so that it was not possible to differentiate which of the two factors was the governing one. Both sets of results showed a slight increase in flows for Storm 'A' and a more substantial increase in flows for Storm 'B'. It is possible that with more storms it might have been possible to refine the sensitivity analysis such that the relative dependence of the two factors could have been identified.

9. Final Verification

As neither of the factors could be identified as the governing factor the model used for the final verification was revised such that the values used for the number of gulleys and the soakage rate were both realistic.

The final verification which was achieved, whilst not wholly predicting the full peak flow for Storm 'B' was a substantial improvement when compared to the initial verification. However, the model also simulated some overland flow during Storm 'A' such that the standard of verification for Storm 'A' dropped slightly though it remained within acceptable limits. The final verification plots are shown below.





The observed data is shown with the green line, the initial verification with the thin blue line and the final verification with the thicker red line.

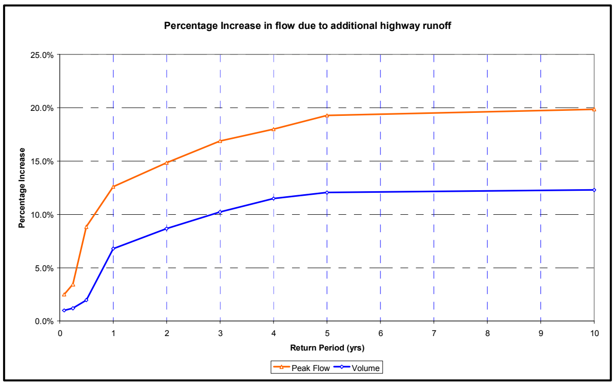
It can be seen that for Storm 'A' the flows have increased throughout the simulation though the final verification remains within acceptable limits. For Storm 'B' the simulated peak flows are now far higher and are approaching the observed values; however the flows in the early part of the storm have also increased.

Whilst Storm 'B' gives a good indication that the model is now responding adequately to intense rainfall it would be desirable for the verification to have included more storms which exhibited this phenomenon; but that would require a considerably longer flow survey period in order to capture enough intense storms.

The model now provides a far more realistic simulation of the effects of intense storms (particularly design storms) and is therefore a far more effective tool for analysing flooding risk and designing flood alleviation schemes.

10. Whose Water Is It ?

Whilst the purpose of the integrated catchment modelling was simply to improve the representation given by the model, one spin off has been to be able to determine what proportion of the overall flow in the combined sewer is attributable to runoff from additional highway areas whose normal drainage system is unable to cope with intense storms. It is possible to check, using these techniques, whether the highway drainage is performing to the standard expected and to the normal highway design standards.



Different versions of the model can be run with and without the highway runoff component so that the differences which are attributable to the additional highway runoff can easily be determined.

When considering the responsibility for flooding and in particular the financial responsibility for alleviating flooding this procedure enables the costs to be apportioned. If a flood alleviation scheme were required on this particular sewer (which actually is not required in this case) then the modelling as illustrated by the graph to the left could support a dialogue with the highway authority for a contribution of up to 20%. A similar graph could be created at the location where a flood alleviation scheme is required.

11. Conclusions and Recommendations

The procedures discussed in this paper are relatively simple to implement though they are time consuming and should therefore only be used when there is a proven need for this level of sophistication in the modelling. Whilst in this particular case the highway area which contributes overland flows during intense storms is normally drained to soakaways the procedures are equally valid if the highways had been drained to a surface-water sewer, a highway drain or to an adjacent watercourse. In this particular case it was not possible to determine whether it was the gully capacity or the soakaway capacity which was the governing factor; in other cases where the only factor is the gulley capacity the modelling would be simpler.

The techniques described in this paper can be used to determine the apportionment of responsibility for flooding downstream and whilst this could perhaps be used to discuss financial contributions it would probably be better employed in assessing whether there is any scope for the highway authority to increase the number of road gulleys in the catchment or to make them operate more efficiently – in financial terms this would be probably be the most cost effective solution and it is something which the highway authority could implement themselves.

Drainage Engineers and Modellers may not be fully aware of the design guidance provided in respect of the design and spacing of road gullies and in particular what relatively low storm return periods most road gulley systems can deal with. It is recommended that all practising modellers should make themselves aware of the design guidance which can be found on the Highways Agency web site.

Whenever there is a combined sewer flooding in a valley or at the bottom of a hill it is recommended that the modeller dealing with the assessment of that problem fully considers the part which highway runoff can play and in particular whether additional areas contribute overland flows during intense rainfall. There may be a consequence that the flow survey period needs to be extended in order to capture more intense rainfall events. Failure to allow for these overland flows may result in schemes being implemented which only solve part of the problem.

12. Acknowledgements

The author wishes to thank Southern Water for permission to publish this paper. The views expressed by the author are his personal views and do not necessarily represent the views of Southern Water.

13. References

[1] Digital Terrain Models – the Technical and Financial Case, Allitt & Adams, WaPUG Spring Meeting, 2006.

[2] HA 102/00 Spacing of Road Gullies, (Design Manual for Roads and Bridges, Volume 4, Section 2, Part 3),Highways Agency, 2000.

[3] Representation of Gullies, Wallingford Software Technical Note, M Reeves, Infoworks CS Help, March 2005.

[4] Definition of Hydraulic Capacity of Gullies for InfoWorks CS, M Reeves, unpublished.