A case study demonstrating how the groundwater infiltration model can be used to represent slow response using the Ludlow Model

Abstract

Atkins carried out a DAP for Ludlow for Severn Trent Water during the previous AMP. As part of this study a short term flow survey was carried out. Recorded flows at some flow monitors showed evidence of slow response, which can be described as an attenuated response occurring slightly after the main peak flow. This leads to a longer tail to the observed hydrographs than would otherwise be seen from just contributing impermeable areas. An InfoWorks model was developed at the time of the DAP and verified against the flow survey results. The observed slow response was effectively calibrated in the model by adding additional Wallingford surface impermeable areas with a high Runoff Routing Value of 40 (Scenario 1). These gave a reasonably good degree of match to the observed response.

For this paper it has been tested whether it is possible to produce a similar slow response using the New UK runoff surfaces (Scenario 2) or the groundwater infiltration model (Scenario 3). Results showed that New UK surfaces set to pervious runoff could not replicate the effect without adding unrealistic amounts of pervious area. The groundwater model (scenario 3) did reproduce the existing modelled response in terms of the peak flow and the rising limb part of the hydrograph. However, the groundwater model produced a slightly steeper rising limb and flatter tail to the slow response.

Introduction

The town of Ludlow is located 30 miles west of Birmingham and 30 miles north of Hereford near the Welsh borders in East Shropshire. It is a historic market town, largely developed during the Middle Ages. The town has a population of approximately 11,700. Atkins carried out a DAP for Ludlow under the framework agreement during the previous AMP period. A flow survey was carried out consisting of 26 flow monitors, 4 depth monitors and 8 rain gauges. The survey extended from December 2002 to March 2003, covering a period of 14 weeks. The survey was extended beyond the standard 6 week period in order to capture suitable rainfall events. Eventually 3 storms were selected for verification, each of which passed the criteria outlined in the WaPUG code of practice apart from some spatial variation in the rainfall. The spatial variation was attributable to the fact that two of the rain gauges were located in villages approximately 5km from Ludlow that contribute flows into the main part of the catchment.

Existing Model Verification (Scenario 1)

During the verification process it became apparent, at a number of flow monitor locations, that although observed peak flows were well matched by the model there was an under prediction of total volume. This was due to a higher flow being recorded by the monitor for some time after the peak than was being simulated by the model. This is typically referred to as slow response. The slow response could arise from a number of sources. Terry and Margetts (2004) describe how a partially blocked drain or road gulley can give rise to an attenuated runoff hydrograph. The same authors describe how additional impermeable areas, that may be relatively remote from the sewer network, can become active and contribute flows into the sewer network once a sufficiently high depth of rainfall occurs to overcome depression storage. These areas would also tend to produce a more attenuated hydrograph compared to typical paved and roof areas. Other possibilities are that the slow response could arise from runoff from permeable surfaces or from some form of groundwater infiltration. It is likely to be relatively difficult to pinpoint the exact source of any slow response area for each specific case, even if an observer were to be present on site at the time of a rainfall event. The probable scenario is that only potential sources can be highlighted for each location.

At the time that the Ludlow DAP was completed it was found that the observed slow response could be replicated in the model by the addition of extra amounts of impermeable areas using Wallingford runoff surfaces with a high Runoff Routing Value of 40. This value was selected to best match the observed response. The value of 40 gives a more attenuated runoff hydrograph than for standard paved and roof surfaces that are usually represented in the model with routing values of 1 and 4 respectively. The existing verification represents Scenario 1. Figure 1 shows the improved verification achieved at one of the monitors, for one event.

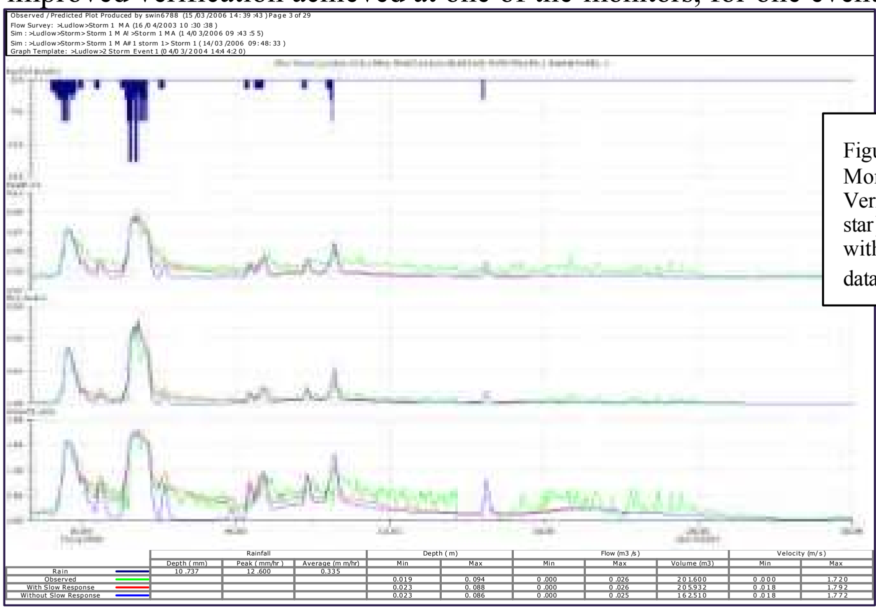


Figure 1: Storm 1 Monitor 03: Original Verification (blue with star), Re-verification (red with circle), flow survey data (green with square)

Figure 1: Improved Verification at Flow Monitor 3 for Storm Event 1 by adding slow response

The process of adding additional slow response areas to the model in this way is essentially a calibration exercise. The source of the slow response area has not been specifically identified but additional areas are added to the model to reflect the observed flows. The approach used reflects the rationale described in the Terry and Margetts paper discussed above, i.e. that the additional flow arises from some impermeable source that was not included in the original area take off for some reason and which produces a more attenuated response.

Re-verification using New UK (Scenario 2)

The New UK runoff model has come into wide use in recent years to calibrate additional permeable areas to match the sort of slow response discussed above (Osborne 2000). The advantage of the New UK approach is that it accounts for the increasing wetness of permeable surfaces, and hence increased runoff, as a storm increases. However, numerous authors (Margetts, 2002; Allitt, 2002; Squibbs, 2003; Squibbs and Jack, 2003; Terry and Margetts, 2003) have reported on the problems of applying New UK under design conditions.

An analysis was carried out to see if the slow response element of the recorded flows in Ludlow could be re-verified (in reality re-calibrated) using the New UK model. In order to do this a model was created simply containing three of the typical dummy/additional subcatchments that had been added to the Ludlow model containing additional impermeable area. These subcatchments had initially been used to model the flows in Scenario 1. The contributing area was altered from 'impervious' to 'pervious' and New UK was specified as the runoff volume type in place of Wallingford surfaces. Appropriate API30 values were calculated for the three verification events and applied to the contributing rainfall. Simulations were carried out with the same amount of contributing area but with New UK permeable surfaces in place of Scenario 1. This now represents Scenario 2.

Results showed that New UK runoff for Scenario 2 was substantially lower than Scenario 1. The predicted shape of the two runoff hydrographs was also different, see Figure 2.

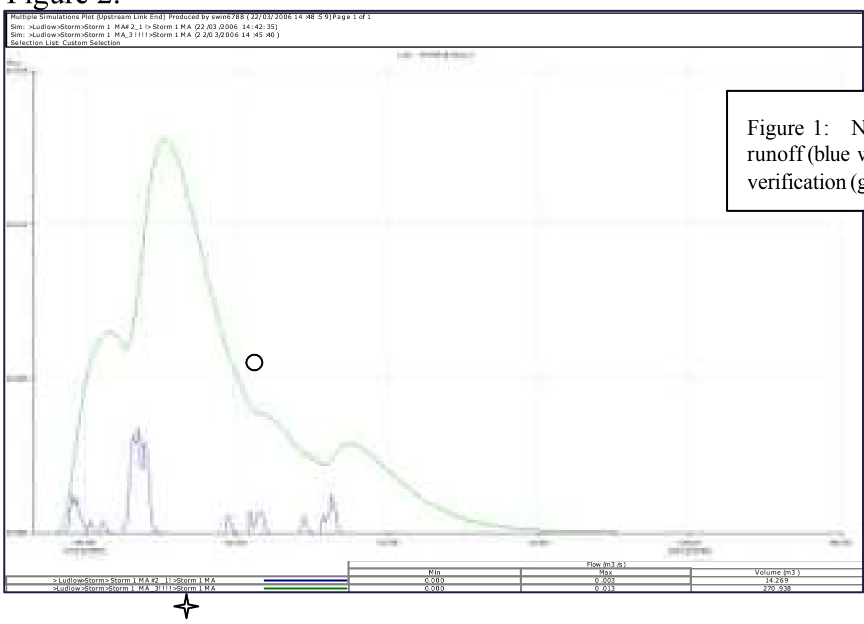


Figure 1: New UK pervious runoff (blue with star), Original verification (green with circle)

Figure 2: Predicted Runoff from New UK permeable surfaces and Wallingford impermeable surfaces with a high routing factor

The amount of slow response area originally added to the Ludlow model for verification varied between 0.5ha to 3.5ha at different monitor sites. The New UK permeable runoff volume was only around 1/20th of the slow response in the original verification. Thus, to get the same response using New UK would require 20 times the original amount of area. This was felt to be an unreasonably large amount to add. Thus, it was concluded that in this case the slow response observed in the flow survey was unlikely to be permeable runoff. Therefore, it was deduced that it must be attenuated impermeable runoff, as it was originally modelled, or groundwater infiltration. In consequence, the groundwater infiltration model within InfoWorks was tested to see if it could reproduce the observed effect.

The InfoWorks Groundwater Infiltration Model

Infiltration is often modelled as a constant base flow that does not vary during or between simulations. The relatively recently introduced groundwater infiltration model in InfoWorks gives the option to represent infiltration more realistically as a temporally varying quantity. This model is not widely used as yet, possibly due to the fact that it initially appears to be relatively complex compared with the relatively more widely used and understood approach of adding extra Wallingford or New UK slow response runoff surfaces. There is also a lack of understanding of how to generate appropriate design parameters once the model has been successfully calibrated against recorded events. Despite this, some success has been reported in the use of the model (for example Zhong 2005).

The model uses a dual reservoir approach to represent infiltration from two key sources:

1) Rainfall-induced infiltration which results from soil water infiltrating directly into the sewer network. This has an effect on flow within hours or days of the storm.

2) A proportion of rainfall percolates deeper into the groundwater reservoir and in the weeks or months following the storm the groundwater level may be sufficiently high to cause groundwater *infiltration*.

For re-verification of the Ludlow model it is only necessary to consider infiltration of type 1) i.e. rainfall induced infiltration that occurs within a few hours of the storm.

In order to set up the groundwater model, contributing pervious areas are specified with a groundwater profile. A number of parameters are then calibrated in order to match the slow response as required. The key parameters to calibrate are: the percolation percentage infiltrating, the percolation threshold and the percolation coefficient. A description of the effect of each of these parameters is given in InfoWorks help and is not repeated here. A groundwater profile is also required, the initial soil saturation and initial groundwater level are specified in this file.

Re-verification using the Groundwater Infiltration Model (Scenario 3)

As was the case with assessment of the New UK model, testing was carried out on a model containing just three of the slow response subcatchments from the verification of the Ludlow model. The groundwater infiltration model was tested to see if it could reproduce the slow response hydrographs from these subcatchments as generated during the original verification (Scenario 1).

In the model containing just three subcatchments the runoff volume model was left as Wallingford but the surface type was amended from impervious to pervious to allow rainfall to permeate downwards into the soil store. This then produces infiltration to the sewer network when the percolation threshold is exceeded. The amount of contributing area was then calibrated alongside the various parameters in the groundwater module until the best degree of fit to the original added slow response was obtained. This is Scenario 3. It should be noted that the total flow into the sewer network arises from the infiltration generated by the groundwater module plus runoff from the permeable surfaces.

One point to note is that there is a difference in the results obtained if the whole of the flow survey is simulated than if the three individual verification events alone are run in the traditional way. This is partly because the depression storage is already filled by the earliest rainfall when simulating the whole flow survey period. When running individual events the initial part of the rainfall will be taken up by filling the depression storage and so less runoff and groundwater infiltration is produced.

Evaporation also has a different effect when simulating individual storms as opposed to the whole flow survey period, as this has the effect of lowering the soil store depth during dry periods. Thus, when rainfall occurs after a dry period, the initial part of the storm is taken up in raising the soil store level back to the percolation threshold before any groundwater infiltration to the sewer system occurs. Therefore, it is necessary to simulate the whole flow survey period (rather than individual storms) when using the groundwater model to accurately represent the effect of evaporation during dry periods. Simulating the whole flow survey period can lead to large simulation times and sizeable results files being generated. It also takes InfoWorks a considerable amount of time to plot the flow survey versus model results graph when the whole flow survey period has been simulated.

The evaporation rate could potentially be one of the factors calibrated against the flow survey results to obtain the desired slow response effect. A standard evaporation rate of 2mm/day has been used here to demonstrate its effect on the infiltration module results.

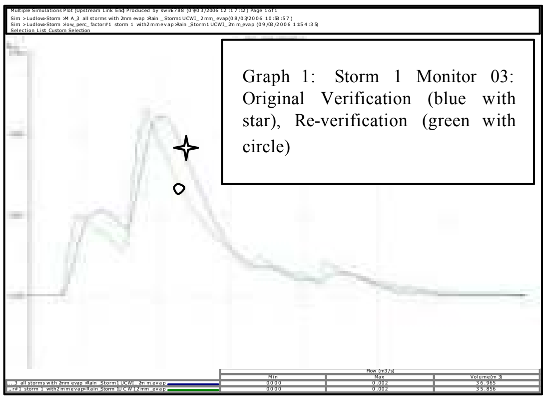
Since there is an UCWI value which is specific to each verification event it is necessary to use sub-events within the rainfall profile so that the correct local UCWI values are applied to each part of the rainfall when simulating the entire flow survey period. This ensures that the runoff generated part of the flow is correctly calculated.

Results of Re-Verification using the Groundwater Module

Reasonably good fits were obtained between the groundwater infiltration model (Scenario 3) and Scenario 1 for the overall shape of the hydrograph, the peak flow and the overall volume for the first of the three storms for each of the three monitor locations. Graphs 1 to 3 show the correlation between the hydrographs from the slow response in the original model and that produced by the groundwater model in the re-verified model for storm 1.

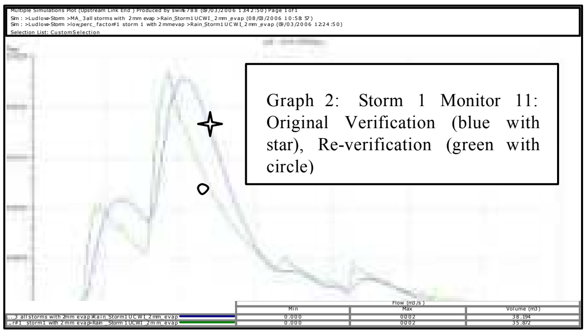
Monitor Number	Amount of impermeable area with Scenario 1 (ha)	Amount of permeable area in Scenario 3 (ha)
M03	0.5	0.4
M11	3.0	2.2
M16	0.5	0.4

Table 1 – Amount of area added used in original verification and in re-verification with groundwater module

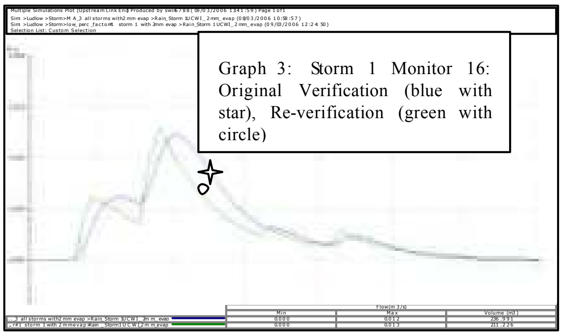


Graph 1: Storm 1 Monitor 03: Original Verification (blue with star), Re-verification (green with circle)

The major factors affecting the shape of the hydrograph in scenario 3 are the amount of contributing area and the percolation coefficient. The percolation coefficient has a comparable effect to the Wallingford routing factor in scenario 1. It determines the shape of the hydrograph produced. InfoWorks help recommends a value for the percolation coefficient between 0.1 and 10. Testing/calibration showed that the extreme lowest value of 0.1 produced the best match to scenario 1. However, there were some differences in the overall shape of the hydrograph produced.

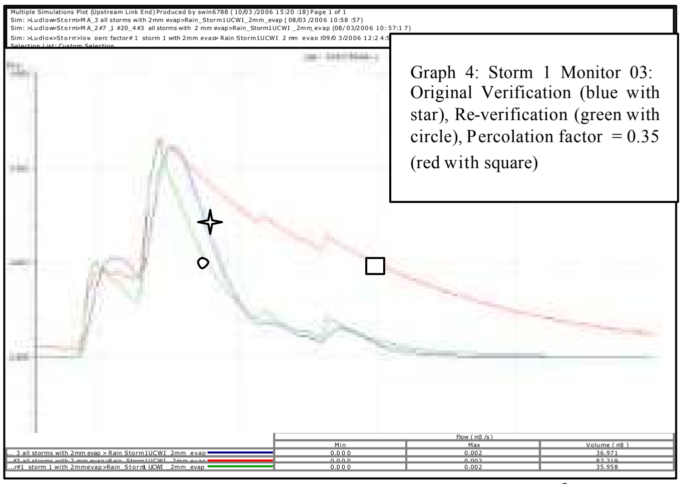


Graph 2: Storm 1 Monitor 11: Original Verification (blue with star), Re-verification (green with circle)



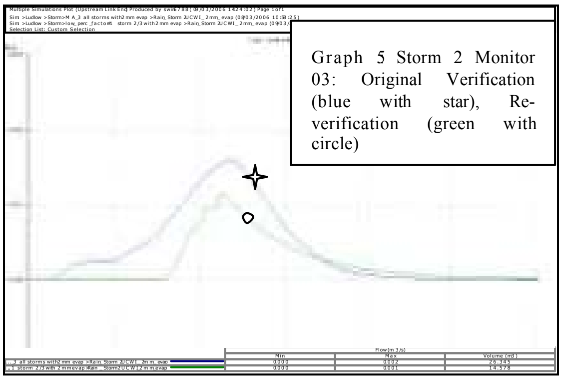
Graph 3: Storm 1 Monitor 16: Original Verification (blue with star), Re-verification (green with circle)

The hydrograph for scenario 3 tends to rise more steeply than scenario 1 in the rising limb. In addition, the recession part of the hydrograph for scenario 3 is shallower than scenario 1. Higher values of the percolation factor tend to have relatively little effect on the rising limb element of the hydrograph but produce a much flatter recession part which leads to an over prediction of volume. An example for a percolation factor of 0.35 is shown in Graph 4. This demonstrates the significant effect on the shape of the recession part of the hydrograph.

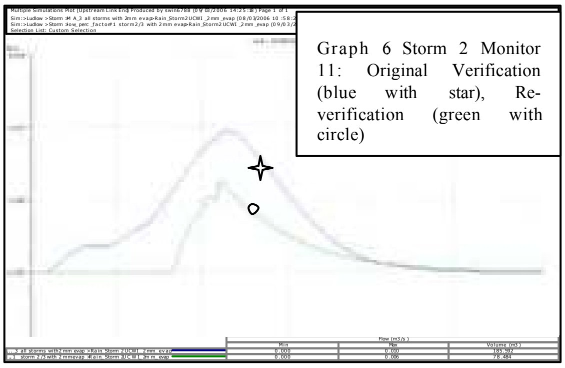


Graph 4: Storm 1 Monitor 03: Original Verification (blue with star), Re-verification (green with circle), Percolation factor = 0.35 (red with square)

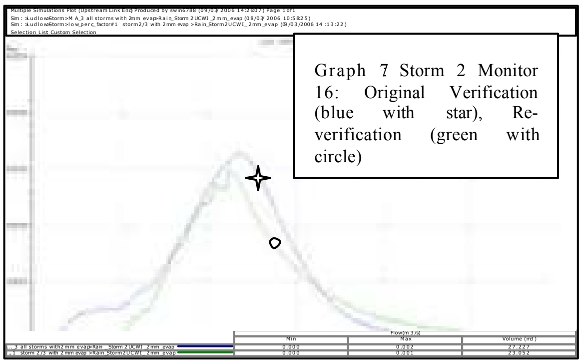
Storm one had an UCWI value of 167 and occurred within the first two weeks of the flow survey. Between storm one and storm two there was a period of approximately two months with relatively dry weather. Thus, when storm two occurred the UCWI value had declined to only 126. This has a different effect on the original verification compared with the re-verification with the groundwater module. With the original verification, the only effect is that the evaporation of 2mm/day reduces any rainfall to produce net rainfall. This only has an effect when there is incident rainfall. During the dry period there is, therefore, no direct influence from the evaporation. The main effect of the dry period is, therefore, that the UCWI value is lower for the second storm and consequently relatively less runoff is produced compared to an event with a higher UCWI.



Graph 5 Storm 2 Monitor 03: Original Verification (blue with star), Re-verification (green with circle)

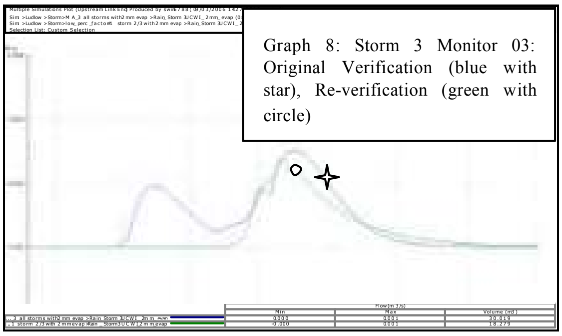


Graph 6 Storm 2 Monitor 11: Original Verification (blue with star), Re-verification (green with circle)

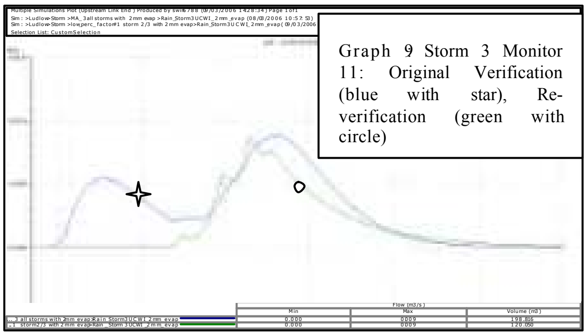


Graph 7 Storm 2 Monitor 16: Original Verification (blue with star), Re-verification (green with circle)

For the groundwater module the evaporation during the dry period has the additional effect of lowering the soil store depth. Thus, by the time the second verification event occurs the soil store depth is below the percolation threshold (the level at which infiltration to the sewer system occurs). As a result, the first part of the rainfall for the second event is taken up in raising the soil store depth to the percolation threshold. Thus, no infiltration is produced for the first part of the storm where, in the original verification, runoff to the sewer network was being generated. Consequently, less peak flow and less volume is generated for this storm by the groundwater module compared with the original model. The shapes of the hydrographs produced also differ more substantially than was the case with storm one. Graphs 5 to 7 show the correlation between the hydrographs from the slow response in the original model and that produced by the groundwater model in the re-verified model for storm 2. Graphs 8 to 10 show the correlation for storm 3.

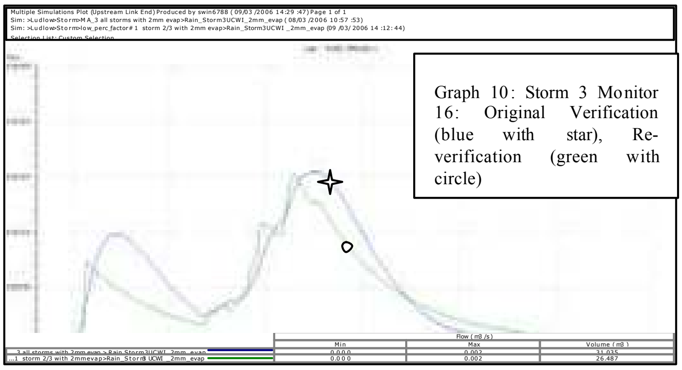


Graph 8: Storm 3 Monitor 03: Original Verification (blue with star), Re-verification (green with circle)



Graph 9 Storm 3 Monitor 11: Original Verification (blue with star), Re-verification (green with circle)

Again, there is a dry period between storm 2 and storm 3 although, in this case, the two events are less than seven days apart. Therefore, it can again be seen by comparison of the hydrographs produced for the original and re-verified model for storm 3 that there is a difference in the flow shapes produced. This is again due in part to the drop in level of the soil store during the intervening dry period.



Graph 10: Storm 3 Monitor 16: Original Verification (blue with star), Re-verification (green with circle)

Comments on Re-Verification with Groundwater Module

It should be noted that the groundwater module has been modelled with dummy subcatchments containing calibrated amounts of permeable area. The permeable area uses the standard parameters for a permeable surface using the Wallingford runoff model. The permeable surfaces produce runoff to the sewer network as well as permitting percolation into the soil store.

The permeable subcatchments have a PIMP of 0, since they are 100% permeable having no impermeable area. A PIMP value of 0 is below the range of applicability of the Wallingford runoff model. In addition, there exists the somewhat counter intuitive process of removing permeable areas from the model in accordance with the 10m rule and then adding them back into dummy subcatchments for the groundwater module.

Therefore, it may be advisable when using the groundwater model to utilise either New UK or fixed runoff for the permeable surfaces. However, there are well documented issues with running the New UK model in design mode. In addition, the fixed runoff model is relatively outdated and is only designed for impervious areas, or pervious areas where runoff does not vary significantly with antecedent conditions.

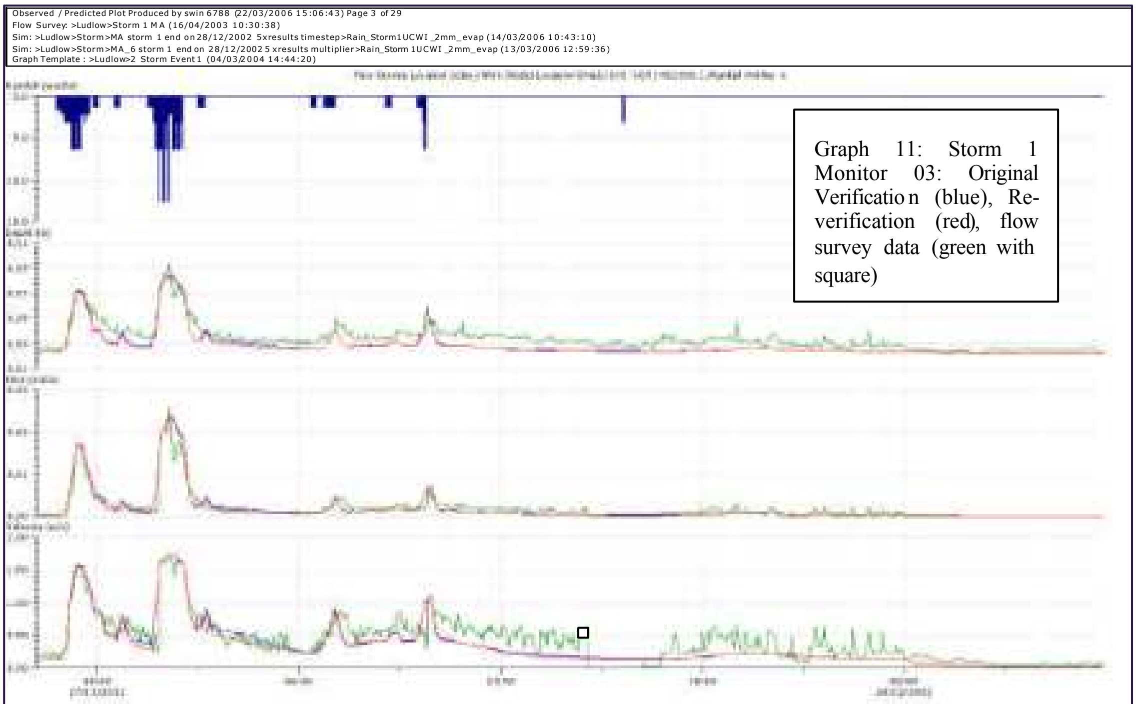
Although the phrase 'verification' has been used a more appropriate term would be 'calibration'. The process of replicating the attenuated response part of the hydrographs in the model in reality only involves incorporating additional factors to match the observed response. In the original verification this took the form of attenuated impermeable runoff and this exercise has shown that a relatively similar effect can be produced using the groundwater model. In each approach a number of factors (including the amount of contributing area to apply) are calibrated in order to produce the desired effect. Essentially the percolation coefficient in the groundwater module has the same effect as the routing factor in the Wallingford model in that it influences the shape of the hydrograph produced. The groundwater model also has additional factors such as the percolation threshold and the initial soil store depth that also need calibrating making it relatively more complex to use.

Which Verification Matched the Flow Survey to the Better Degree?

It has been shown that the groundwater model can be used to produce a slow response effect which is similar to that often generated with the Wallingford model with high routing factor. Good matches were generally obtained between the two approaches for the peak flow and overall volumes produced. However, the groundwater model produced a slightly flatter tail. Evaporation also has a more significant affect on the groundwater model, this leads to a difference in simulated hydrographs between the two approaches after any dry period. The question now arises as to which approach produces the best match to the flow survey data.

A series of simulations of the entire flow survey period were carried out, to see which of the two approaches produced the best quality verification. In all cases the difference between the verification hydrographs from Scenario 1 and Scenario 3 were virtually indistinguishable. In this instance the Wallingford runoff model (scenario 1) tends to produce very slightly more flow than the groundwater model (scenario 3). Since the model, on the whole, slightly under predicts compared with the flow survey data it can be said that the Wallingford approach produces very slightly better matches to the flow survey data. However, this is marginal.

A plot showing the virtually indistinguishable verification between the two approaches compared with the flow survey data is shown in graph 11.



Graph 11: Storm 1 Monitor 03: Original Verification (blue), Re-verification (red), flow survey data (green with square)

	Rainfall			Depth (m)		Flow (m3 /s)			Velocity (m/s)	
	Depth (mm)	Peak (mm/hr)	Average (mm/hr)	Min	Max	Min	Max	Volume (m3)	Min	Max
Rain	10.737	12.600	0.339							
Obs.				0.021	0.094	0.000	0.026	201.600	0.000	1.720
...in_Storm1UCWI _2mm_evap				0.023	0.083	0.000	0.023	187.476	0.018	1.737
...in_Storm1UCWI _2mm_evap				0.023	0.084	0.000	0.024	186.160	0.018	1.744

Design Simulations

There are some questions over the determination of design parameters for use with the groundwater module. The various parameters have been calibrated to suit the verification storms but are they applicable to larger summer or winter design storms? This is an area which potentially needs further investigation. Current advice from Wallingford is to use the same parameters used to verify the model in design storms. In this case study the Ludlow model was simulated with a 20 year design summer and winter storms and the results of the two models were compared. The results are shown in Table 2 and 3 below.

	Existing verified model – Scenario 1					
	M03		M11		M16	
	Peak (l/s)	Vol (m3)	Peak (l/s)	Vol (m3)	Peak (l/s)	Vol (m3)
20 year winter storm 120min dur'n	9.9	121	51.5	729	10.2	125
20 year winter storm 480min dur'n	9.9	183	55.5	1,098	10.3	189
20 year summer storm 120min dur'n	9.3	112	47.4	671	9.4	115
20 year summer storm 480min dur'n	9.6	168	52.5	1,009	9.9	174

Table 2 – Flows generated by the existing verified model (Scenario 1) for 20 year design storms

	Re-verified model with groundwater – Scenario 3					
	M03		M11		M16	
	Peak (l/s)	Vol (m3)	Peak (l/s)	Vol (m3)	Peak (l/s)	Vol (m3)
20 year winter storm 120min dur'n	9.7	115	53.1	632	9.7	115
20 year winter storm 480min dur'n	9	175	49.4	966	9	175
20 year summer storm 120min dur'n	9.3	111	51.4	614	9.3	111
20 year summer storm 480min dur'n	9.5	171	52.1	938	9.5	171

Table 3 – Flows generated by the re-verified model (Scenario 3) for 20 year design storms

A comparison of Scenarios 1 and 3 under design conditions shows that for monitors 3 and 16 both the peak flows and volumes are reasonably well matched between the two approaches. Scenario 1 is in general 2-5% higher in both peak flow and volume compared to Scenario 3.

Monitor 11 has much more contributing area than monitors 3 and 16. The degree of fit between the two approaches is not as close as the other two monitors. Volumes predicted by Scenario 3 are generally around 10% lower than scenario 1 for monitor 11. In addition, there is wider range of discrepancy in peak flow between the two scenarios. In some cases Scenario 1 is up to 10% higher than scenario 3 and in some cases it is up to 10% lower.

Overall, given the uncertainties in applying the groundwater model in design conditions, it is reassuring to see that the volume and peak flow matches between the two approaches are within 10%. This could be taken as evidence that some confidence can be applied to predictions from the groundwater model under design conditions (assuming that it is taken that scenario 1 produces reasonable results under design conditions). Further research on a wider range of models and conditions would be required to confirm this.

Summary

In this case study, a model was used which has been verified using Wallingford surfaces with high routing factor for the slow response element. Investigation showed that the slow response element in this case could not be replicated using New UK but a reasonable match was obtained using the groundwater model. The key points which should be noted are discussed below:

1) The groundwater model has two reservoirs. The first reservoir is used to represent a response within hours of an event. The second reservoir is used to replicate longer term/seasonal changes in groundwater inflows. In this case only the first 'soil store' reservoir has been used and the second 'ground store' reservoir has effectively been switched off.

2) In calibrating slow response using the groundwater module a number of factors need to be calibrated, more than when using the Wallingford model with high routing factor. This can make the process relatively complex. However the key factor to calibrate, along with the amount of contributing area, is the percolation coefficient. This coefficient mirrors the effect of the Wallingford routing factor. The percolation threshold can also have a marked effect on the magnitude of flow generated.

3) It is necessary to simulate the whole flow survey period (as oppose to individual storms) when using the groundwater model to accurately represent the effect of evaporation during dry periods. It is also necessary to use sub-events with local UCWI values so that the correct UCWI value is applied during each of the selected verification storms. Simulating the whole flow survey period can lead to large simulation times and sizeable results files being generated. It also takes InfoWorks a considerable amount of time to plot the flow survey versus model results graph when the whole flow survey period has been simulated. If using the second 'ground store' reservoir then simulating the whole flow survey period is crucial to allow movements in the groundwater level to be accurately simulated.

4) Evaporation has a more substantial effect on the groundwater model than on the Wallingford model. In this case this lead to relatively poorer matches between the two approaches for subsequent verification events caused by the effect of dry periods between the storms. The evaporation rate could potentially be one of the factors calibrated against the flow survey results to obtain the desired slow response effect. A standard evaporation rate of 2mm/day has been used here to demonstrate its effect on the infiltration module results.

5) In this case a good degree of fit was obtained between the groundwater infiltration and Wallingford runoff for slow response for the first storm event. The groundwater infiltration module tended to produce a slightly steeper rising limb shape to the hydrograph with a slightly shallower/flatter recession.

6) The groundwater module produced a virtually identical degree of fit to the flow survey data compared with the Wallingford runoff surfaces with high routing factor.

7) There are issues over generating design parameters for the groundwater module. A relatively large number of factors are calibrated in its use for verification, which is generally based on a relatively short period of flow

survey data. It is questionable whether these values can be said to be truly representative of conditions for running winter and summer design storms. For example the soil saturation, and groundwater level are likely to exhibit seasonal variations which will not be accounted for in calibrating the data against a single set of flow survey data.

8) Results from design simulations using a 20 year return period event showed good correlation between the groundwater infiltration and Wallingford runoff approaches. Winter and summer storms were tested with two different durations. The vast majority of matches between the two approaches for peak flow and volume were within 10% of each other.

9) When using the Wallingford model the 10m rule is applied and this removes permeable surfaces which may contribute to infiltration to the soil store which in tern leads to infiltration. Thus, permeable surfaces are added back into the model on dummy subcatchments when using the groundwater model. This creates a problem as the PIMP value of these subcatchments is 0 which is below the range of applicability of the Wallingford model (for modelling the runoff component from the permeable surfaces).

10) New UK or fixed runoff could be used to model the permeable surfaces for the groundwater model as they can cope with PIMP values of 0. However, both approaches have problems. An advantage of using New UK would be that the NAPI value is constantly calculated/updated throughout the simulation. This avoids the need to use sub events with appropriate UCWI values as described in point 3) of the summary.

11) The second 'ground store' reservoir could potentially be used to account for seasonal variations in infiltration due to variations in the ground store level. However, this would require substantially more flow survey data than is usually collected for a DAP. In addition, more verification effort would be required than is usually the case. Even then, if infiltration during one seasonal cycle were replicated it is questionable whether this could be said to truly representative of all summer and winter conditions for design simulations.

12) In some cases it may be possible to use permanent rain gauges and telemetry data from pumping stations to get long periods (years) of data. This can then be used to calibrate the infiltration in the model (from both the soil store and ground store) against the observed rainfall and pump run on times. This would give more confidence that the model is accurately reproducing long term conditions. It may then be possible to determine how the infiltration in the model would perform under a typical year of rainfall using a STORMPAC type analysis. However, the problem would remain over how to determine appropriate design parameters for, for example, a single 20 year return period event. The initial levels of the soil store and ground store relative to the percolation and infiltration thresholds would be key parameters in determining how much infiltration occurred during any design simulation.

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