# Comparison of continuous and event-based simulation for UPM studies

*Paul Dempsey, Claire Brown WRc*

## 1 Introduction

Many UPM studies have met difficulties in dealing adequately with long draindown times and the combined impacts caused by intermittent and continuous discharges. Seasonally varying baseflows caused by inflow and rain-induced infiltration can also create difficulties in chosing appropriate model parameters. In addition, river flows are usually handled as statistical distributions with no correlation to rainfall – an assumption that can be pessimistic.

Most of these issues can be addressed by using integrated modelling procedures with long term continuous simulation but it is not clear when these more sophisticated procedures are worthwhile.

This paper describes these issues and seeks to provide some measure of their significance by comparing the results from continuous and event-based simulations in one case study. Results are compared for different assumptions relating to rainfall selection, rain-induced infiltration, and river flow distributions.

## 2 Continuous simulation modelling

A number of issues need careful consideration for continuous simulation modelling. These are discussed here, together with a description of how they are handled in SIMPOL3. SIMPOL3 is a WRc modular modelling package which is regularly used for a range of environmental applications (e.g. diffuse pollution, highway runoff, bathing water compliance and UPM). For UPM applications, different modules are available for sewer subcatchments, trunk mains, treatment works and river reaches. Networks of modules are created to represent complete sewer/river catchments and simulations are carried out in continuous mode over multi-year periods to help identify and optimise solutions. To date SIMPOL3 has been used in about ten UPM studies with catchment populations ranging from 5000 to 2 million.

***Catchment wetness***
In urban hydrology models, UCWI and API30 are used as measures of catchment wetness. Rainfall processing software such as STORMPAC v3 can produce continuous hourly series of UCWI and API30 values for given rainfall series and specific catchment details. SIMPOL3 acquires these hourly values, with the hourly rainfall, from an external file.

***Runoff***
The New UK (variable PR) runoff model allows for changing catchment wetness during a storm by updating the API30 value. In principle, the variable PR model can readily be programmed for continuous simulation. This is implemented in SIMPOL3 together with a simple potential evaporation model to allow for the drying of interception storage.

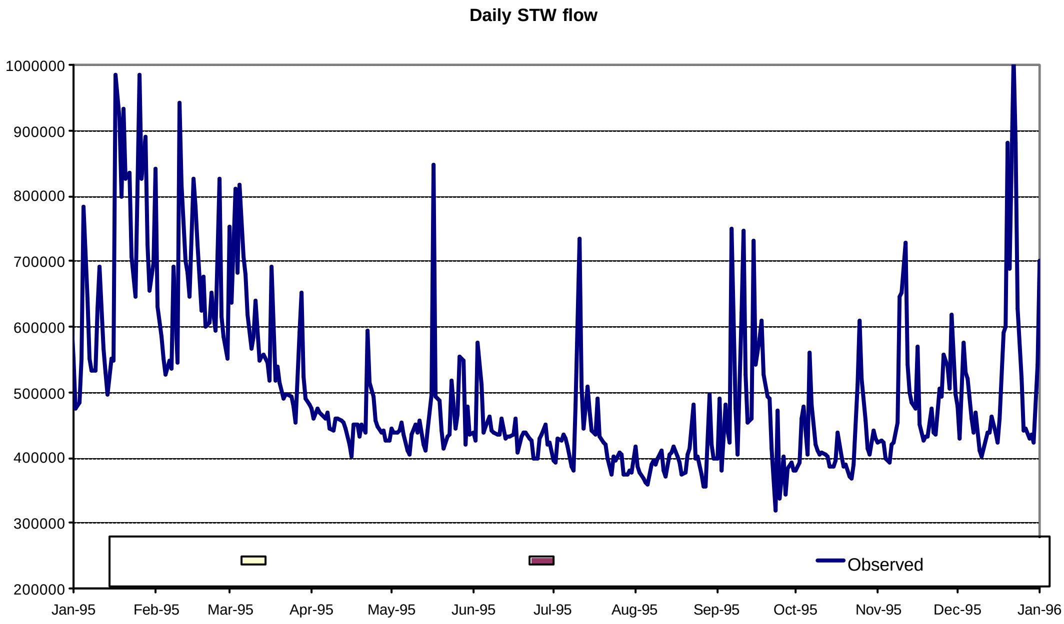
The Wallingford (fixed PR) runoff model is designed to be used with single events using a fixed UCWI value throughout an event. As such it does not lend itself readily for use in continuous simulation. In SIMPOL3 a pragmatic compromise is used to implement the fixed PR model for continuous simulation. UCWI values are read in from the external rainfall file each hour but the value used in the runoff equation is only changed every 6 hours. This maintains, to some degree, the ‘fixed PR’ concept, upon which the model was developed, but also allows for catchment wetness to vary in a sensible fashion over long simulation periods.

Further details of these runoff models are given in past WaPUG papers – eg Allitt Autumn 2003.

### *Rain-induced infiltration*

Elevated winter baseflows are a common feature of many sewer systems and are caused by increased infiltration/inflows due to higher water tables – see Figure 1. For continuous simulation modelling it is important to be able to allow for this effect. Rain-induced infiltration is represented in SIMPOL3 using an adaptation of a model first described by WRc in the mid 1970's. The model allows a timeseries of flows to be generated that combines seasonally variable groundwater infiltration and rainfall induced infiltration.

**Figure 1 A one-year plot of flows arriving at an STW - illustrating elevated baseflows following extended wet periods**



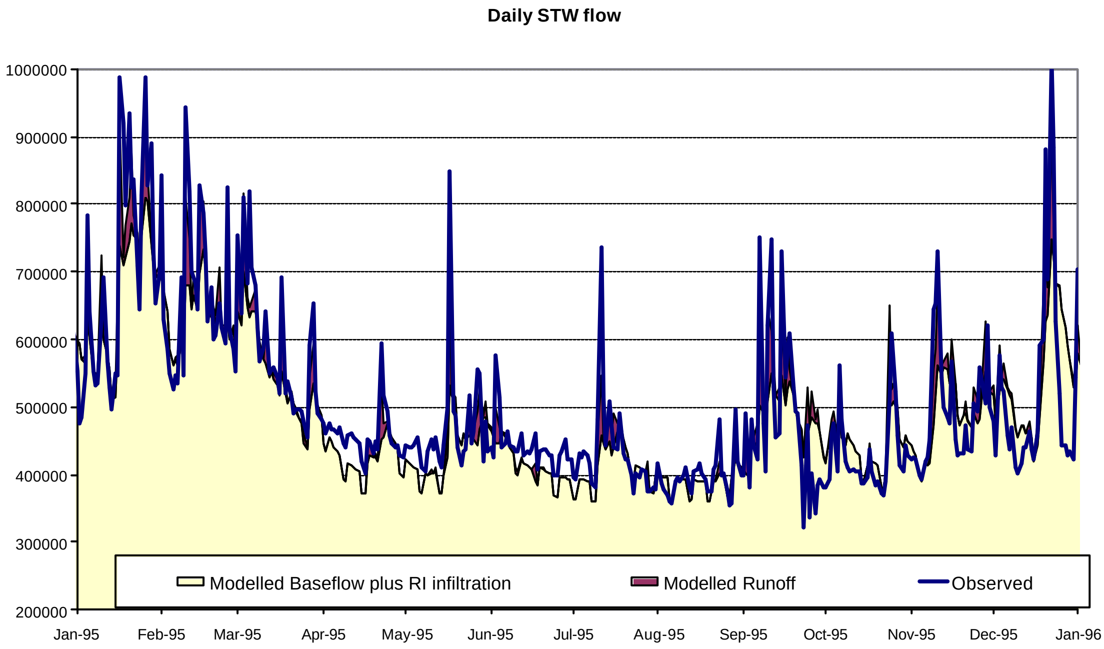

The model calculates rain induced infiltration (RII) in $m^3$/hr for each hour(n) using the following equation:

$$RII(n) = 10.F.S.A.i(n)$$

where
F is a dimensionless coefficient
A is the total catchment area (ha)
S is a dimensionless seasonal factor that accounts for soil moisture deficit, groundwater level and evaporation. This is recalculated each day and incorporates a calibration factor, B.
i(n) is the cumulative rain store and is recalculated each hour to reflect rainfall history. It includes an exponential decay function (with calibration factor H) which has a seasonal component.

Calibration of this model involves finding the best fit values for parameters B, S, H and F. This is illustrated in Figure 2 for the same observed data as in Figure 1. Ideally, long term flow records for varying rainfall histories are needed to obtain a reliable calibration.

**Figure 2 Application of Rain-induced infiltration model to explain baseflow variations**




### *Emptying of storage tanks*

An important reason for continuous simulation modelling is to take account of 'back-to-back' storms which may affect the emptying of storage tanks. Off-line storage tanks need specific rules to control how and when they can be emptied. In SIMPOL3, the emptying of tanks can be controlled by local rules (e.g. based on flow rates in the main sewer downstream of the tank) or by remote rules (e.g. based on water levels in other tanks within the system).

### *Sediment build-up*

Sewer sediments represent important stores of polluting matter that can be mobilised during storm events. Sewer flow quality models will typically be set up to start event simulations with full sediment stores. For continuous simulation, a mechanism is needed to allow depleted sediment stores to become replenished during dry weather periods. SIMPOL3 does this by assuming that a fixed, small percentage of the mass of pollutant in the sewer system is deposited in each hourly timestep until the store is full, after which no further deposition occurs. The percentage deposited is variable for different subcatchments but is typically set to take about 5-10 days to refill an empty store.

### *WwTW effluent flow and quality*

In assessing the impact of intermittent discharges on watercourses it is necessary to make allowance for the concurrent discharge of treated effluents which affect the same river reaches. Treated effluents will continue to impact on river water quality during dry periods and this should also be taken into account in assessing compliance with standards. In SIMPOL3, the flows discharged by WwTWs are calculated from the simulated works input flows (from the sewer system and from storm tank returns) and thus take full account of the catchment hydrology and tank emptying sequences.

SIMPOL3 provides two options for representing the quality of these WwTWs effluent flows. One is to define statistical distributions for each determinand. These distributions are defined by 5 parameters (Annual Mean, Seasonal Amplitude, Seasonal Offset, Standard Deviation and Distribution Type). The first three parameters are used to generate a mean quality each day based on the assumption that the mean quality will have a sinusoidal distribution over a year. A Monte Carlo procedure is then used to randomly select a specific daily value based on this mean (using the Standard Deviation and Distribution Type).

The second option involves a more detailed representation of the actual WwTWs processes in terms of settlement and biological process equations. The parameters for these equations need to be calibrated against simulation results from a detailed treatment model (e.g. STOAT). Once calibrated, the SIMPOL3 treatment module can represent more realistically how effluent quality varies in response to variations in inlet flows, loads and temperatures.

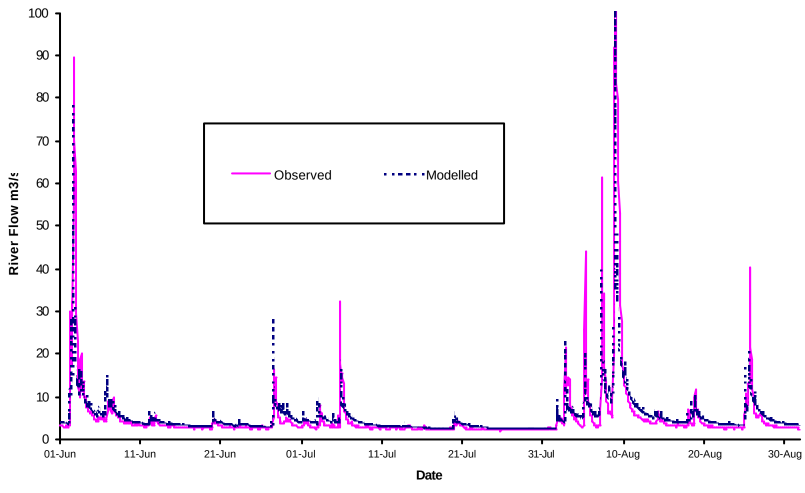
***River hydrology and runoff quality***

Wastewater system discharges must be mixed with suitable river flows (and quality) in order to estimate impacts and assess compliance with river quality standards. River flows are important not only for dilution but also for an accurate representation of the downstream river hydraulics which will affect river processes (e.g. reaeration).

For event-based simulation it is normal to define river flows (and quality) in terms of statistical distributions – and to select flows at random from these distributions. The dstributions can have seasonal components and can also include correlations in relation to event (rainfall) size.

For continuous simulation models it is more typical to use rainfall timeseries to generate river flows directly. In SIMPOL3 hydrologically effective rainfall (HER) is calculated from the applied rainfall assuming a seasonal sinusoidal model for potential evaporation and a two tank soil moisture deficit (SMD) model. The HER is then routed through non-linear soil and groundwater stores, using the Base Flow Index (BFI) to apportion flows through the latter store.

**Figure 3 Example of calibrated SIMPOL3 model prediction of river flows**



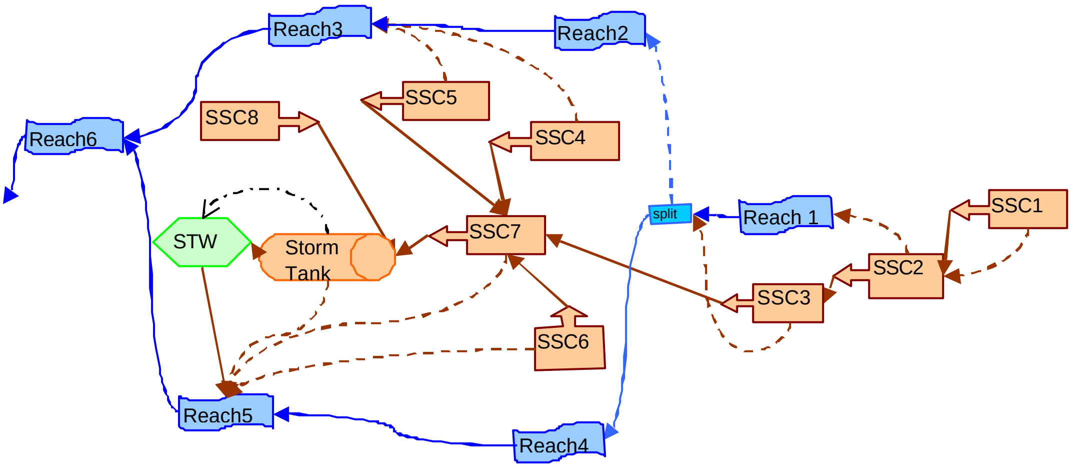

Each river reach has its own subcatchment, each of which can have different applied rainfall series – this allows spatial patterns in rainfall to be taken into account. An example of river flows generated by SIMPOL3 are shown in Figure 3.

The quality of runoff from the soil store is defined by 5-parameter statistical distributions (as described earlier). Impermeable area runoff can also be defined within river reach subcatchments to represent highways and surface water drainage systems which are not part of the combined sewer system. Runoff from these areas is calculated using urban hydrology models as described earlier.

## 3 Exploration of issues

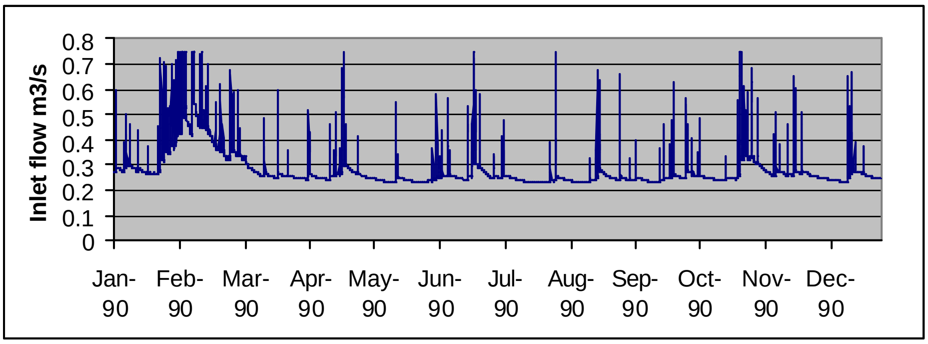
An existing SIMPOL3 model, from a completed UPM study, has been used to help explore the significance of some of these issues. The model layout is illustrated in Figure 4. It involves 8 sewer subcatchments, a storm tank, treatment works and 6 river reaches. For this exploration, the focus was limited to the storm tank and its impact upon the downstream river reach (Reach5) only.

**Figure 4 SIMPOL3 network of sewer/river catchments used to compare simulation methods**




For this catchment, flow survey data suggested that winter baseflows were typically 30-50% higher than summer baseflows due to RII. The RII model in SIMPOL3 was adjusted to produce this pattern, as illustrated by the modelled flow hydrograph shown in Figure 5.

**Figure 5 Typical annual sewage flow series predicted by the model**




***Methodology***

First, the continuous 10 year rainfall series was processed to provide three separate event-based series. Events were defined by the length of interevent period with no rainfall. Interevent periods of 2, 6 and 10 hours were used. Events with total rainfall depth of less than 3mm were ignored. Table 1 summarises the number of events created, by different duration categories.

**Table 1 Number of rainfall events in the different event series**

| Event duration (days) | No of rainfall events created from 10 year series – for interevent gaps of: | | |
|---|---|---|---|
| | 2hr | 6hr | 10hr |
| <1 | 1164 | 914 | 512 |
| 1-2 | 6 | 240 | 494 |
| 2-3 | - | 6 | 84 |
| 3-4 | - | - | 6 |
| >4 | - | - | 6 |
| All | 1170 | 160 | 1102 |

Then the model was run in continuous mode to assess 'current' performance for the storm tank (in terms of annual spill volumes) and for the river reach (Reach5) - in terms of compliance with 99%ile standards for an RE2 river. (In the main UPM study the model was used to check compliance in all the river reaches and for both the 99%ile standards and the Fundamental Intermittent Standards). In addition, full timeseries of sewer flow/quality arriving at the storm tank, and river flow/quality at the upstream end of Reach5, were output. These series were analysed to produce simple seasonal distributions that could be used for the event-based simulations (in place of the deterministic rain-induced infiltration and river hydrology models used in continuous simulation modelling).

The model was then set up to run in event-based mode (using the input distributions described above) and the performance was reassessed. In event-based mode, at the beginning of each event all storages are automatically re-set to empty and all sediment stores are reset to full.

The additional storm tank storage required to achieve compliance with river standards was derived for both continuous and event-based models.

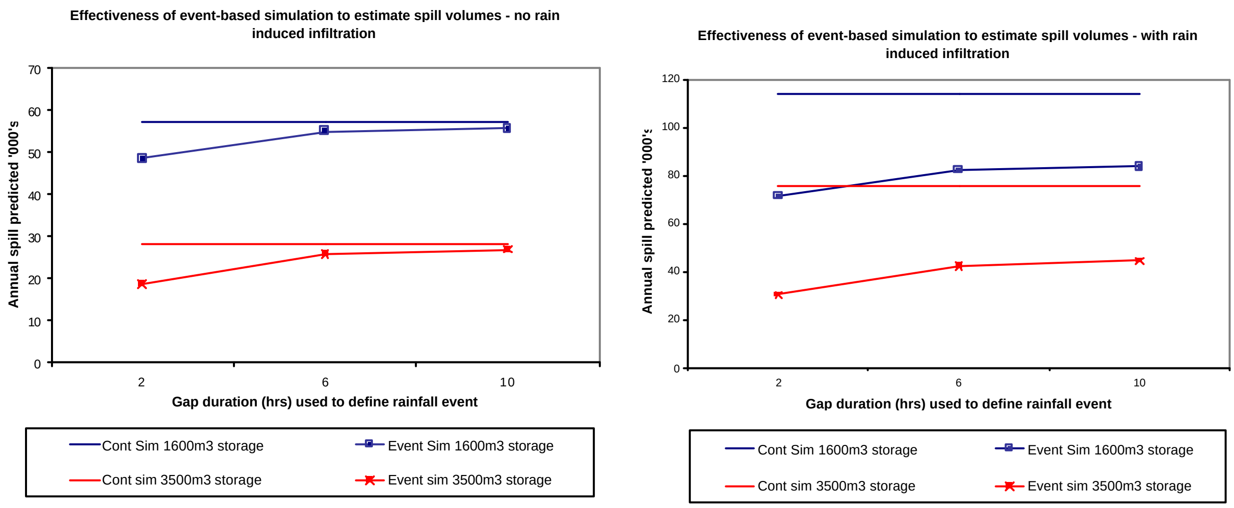
***Results***

*Simulation times*
Simulation times (for 10 year runs) were typically about 2 minutes in continuous mode and about 1 minute in event-based mode.

*Spill volumes*
The plots in Figure 6 illustrate the predicted annual spill volumes (for two different storage volumes). The results in the left hand graph are for constant baseflow (no RII modelled). In this situation, event-based simulation – using events defined by 6 or 10hr interevent gaps - gives results that are very similar to those for continuous simulation. However, using a 2hr gap to define events produces spill volumes which are underestimated. This can be readily explained by the fact that the draindown time for the 1600$m^3$ tank is about 8 hours. The percentage error is greater for the larger tank because the draindown time is longer.

The results on the right-hand graph are for variable baseflows (RII modelled). In this situation, the spill volumes are significantly underestimated by the event-based method, even when the 10hr interevent gap is used to define events. This is because the storm tank draindown times are considerably extended during periods of high baseflow and the complete emptying of the tank cannot be achieved within the event periods. The only way to correct for this is to define even longer events (using interevent gaps of, say, 15 or 20 hours). This produces such long events (some over 10 days long) that the method becomes little different from continuous simulation.

**Figure 6 Annual spill volumes predicted for different situations.**




*River impact*

The river impact results for the two methods are compared in Table 2. As might be expected, the failure rates are underestimated by the event-based simulation method (because of the smaller spill loads) and less extra storage is indicated. This underprediction of extra storage appears to be a direct reflection of the difficulty that event-based simulation has in handling RII flows (and their subsequent impact upon spill loads). This is illustrated by the results in Table 3 when RII is removed from both methods – predicted river impacts are similar and the same additional storage is indicated.

**Table 2 Failure rates (% of time) with existing storm tank storage (1600 $m^3$) – and extra storage ($m^3$) needed for compliance. With RII modelled.**

| River standard (99%ile) | Continuous simulation | Event-based simulation |
|---|---|---|
| Ammonia | 1.4 | 1.4 |
| BOD | 1.9 | 1.6 |
| Extra storage ($m^3$) needed to achieve compliance (i.e. <1% failure rate) | 2400 | 1400 |

**Table 3 Failure rates (% of time) with existing storm tank storage (1600 $m^3$) – and extra storage ($m^3$) needed for compliance. Without RII modelled.**

| River standard (99%ile) | Continuous simulation | Event-based simulation |
|---|---|---|
| Ammonia | 0.7 | 0.9 |
| BOD | 1.1 | 1.1 |
| Extra storage ($m^3$) needed to achieve compliance (i.e. <1% failure rate) | 300 | 300 |

A further analysis was carried out to compare the use of different river flow distributions when using the event-based simulation method. In the earlier runs a seasonally varying distribution (with different means and standard deviations each month) was used. This was chosen to agree as closely as possible with the flow regime generated by the continuous simulation method. More commonly, a single distribution would be used – either annual or summer only. The results for simulations using these distributions are compared with those for the seasonally varying flow distribution in Table 4.

**Table 4 Failure rates (% of time) with existing storm tank storage (1600 $m^3$) – and extra storage ($m^3$) needed for compliance. Using different upstream river flow distributions for event-based modelling.**

| River standard (99%ile) | River flow distribution used | | |
|---|---|---|---|
| | **Seasonal distribution** | **Annual distribution** | **Summer distribution** |
| Ammonia | 1.40 | 1.43 | 1.56 |
| BOD | 1.57 | 1.65 | 1.80 |
| Extra storage ($m^3$) needed to achieve compliance (i.e. <1% failure rate) | 1400 | 1600 | 1900 |

## 4 Conclusions

This limited exploration suggests that event-based simulation can give similar spill predictions to continuous simulation provided that events are defined with interevent gaps at least as long as the tank draindown times. However, it is clear that this requirement is difficult to meet for systems with significant rain-induced infiltration – in these cases, event-based simulation will substantially underestimate spill volumes and loads. This can lead to the underestimation of storage requirements to meet river standards – as illustrated by the case study presented here.

A well defined seasonal river flow distribution appears to work well for predicting river impacts (in terms of exceedances of BOD and ammonia thresholds) for event-based work with single discharges, giving similar results to that achieved by continuous hydrological modelling (for the same spill regime). However, for more complex systems where there is interaction between river reaches and multiple discharges, continuous hydrological modelling of river flows is likely to be advantageous.

The results also suggest that using an annual or summer-only river flow distribution for event-based simulation (rather than using a seasonal flow distribution) is likely to result in less cost effective solutions.

Finally, it is worth noting that the limitations of event-based simulation are most likely to be evident for schemes where annual performance is critical (e.g. where 99%ile river standards and annual spill frequency standards (shellfish waters) apply) and where large storage volumes are used. The limitations may be less evident for FIS compliance where summer performance is critical and rain-induced infiltration is less of an issue.