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# Rainfall, Runoff and Infiltration Re-visited

## Introduction

The flow variations in sewers have been modelled for several years with a comparatively high degree of accuracy as far as the diurnal variations and responses to climatic conditions are concerned. However, until comparatively recently the variations in flow due to fluctuations in groundwater levels, soil storage capacity and wetness of the catchment have only been modelled in basic terms. For the past decade it has been possible to use runoff models that respond to the increasing wetness of the pervious surfaces in a catchment during a storm event. However, due to the absence of suitable initial wetness parameters to use with synthetic design storms this runoff model has not been widely used. This runoff model first released in 1991 is still referred to as the 'New' UK Runoff Model; perhaps the time has now come to revise this name.

In the days of WASSP and WALLRUS most modellers were familiar with the limitations of the runoff models in use and various techniques were developed to ensure that the model parameters stayed with certain limits within which the runoff routines were sufficiently robust. With the introduction of Hydroworks and Infoworks many of the techniques (or fudges) have fallen out of use with many of the younger generation of modellers falling into the same traps, which their elder colleagues fell into ten years before.

Over the past few years there has been an increasing need to simulate long periods with simulations of a period of several months is not now uncommon. Some of the runoff routines previously used are not suitable for such extended simulation periods; chiefly because of the way in which the interaction of rainfall and the soil storage is simulated.

The purpose of this paper is to review the techniques that are available nowadays for simulating rainfall, runoff and infiltration. Some of the techniques are only suitable for certain limited applications whilst others can be more universally applied. This paper will also explore the suitability of the different techniques for different applications.

Before considering the different techniques available and their suitability it is useful to review the physical processes which occur that we are trying to replicate.

## The Physical Processes

The Water Cycle requires no explanation here. It can be considered to start with evaporation from the sea creating clouds of water vapour which then move over land and deposit their water load as rain. In some parts of the UK it rains considerably more than in other parts due to a number of factors including topography, altitude, prevailing winds and the distance from the sea. The rainfall lands on the ground where some of it is immediately lost (the "Initial Losses") due to evaporation (especially off warm surfaces), wetting of surface layers or dust, absorption into shallow surface layers and the filling of shallow depression storage (from which it later evaporates).

If the rainfall exceeds the initial losses a proportion of the rainfall creates runoff whilst the remainder soaks into the ground and contributes to the soil storage. The proportion that is directed to runoff depends upon a number of factors but the chief one is the nature of the surface. An impermeable surface such as roads or roofs cause a high proportion of the rainfall to contribute to the runoff whilst a recently ploughed field may create no runoff with all of the rain soaking into the soil.

The degree of wetness of the surfaces varies throughout the period of the storm. Impermeable surfaces tend to become fully saturated very quickly and thereafter all of the rainfall is turned into runoff though some of that runoff may go to permeable areas and may not enter any drainage network. Once these impermeable surfaces have been wetted the percentage runoff does not vary greatly.

Permeable surfaces react differently. As the storm progresses the upper layers of the soil become wetter and wetter and when the rainfall exceeds the rate at which it can soak into the ground the rainfall is turned into runoff and when the rainfall intensity drops below the soakage rate the runoff ceases even though rainfall may still continue. Therefore the percentage runoff varies throughout the duration of the storm.

Runoff from impermeable surfaces is routed via guttering, rainwater pipes and gullies into the sewerage system. The extent of impermeable surfaces that drain to sewerage networks varies considerably depending on a number of factors. Areas that have good soakage characteristics frequently have roofs and paved surfaces connected to soakaways. In many areas the roads and roofs drain directly into the sewerage systems. This is not always the case with footpaths, especially where there is a grass verge inbetween the footway and the road – in these cases the impermeable surfaces may drain to permeable areas. Therefore most sewers with any impermeable surfaces connected, exhibit a quick response to rainfall with a peak flow occurring a short time after the peak rainfall.

Rainfall, which soaks into the ground, is directed into the 'soil storage reservoir' but when the soil reaches a certain saturation threshold (the percolation threshold) water starts to percolate downwards. A proportion of this percolation flow might infiltrate directly into the sewer network whilst the remainder penetrates deeper into the groundwater storage reservoir. The infiltration flows into the sewers are therefore not dependant upon the groundwater table rising up to above the invert level of the pipelines.

When the groundwater reaches a certain level the water will start to flow through the ground towards rivers, streams and the sea. Where sewers are constructed below the level of the groundwater there can be continuously infiltration into these sewers at any points of defect where the pipelines are not adequately sealed.

Infiltration flows into sewers can therefore either be constant (with slight variations) or they can be in response to rainfall. For simplicity these two different types are termed "Groundwater Infiltration" (GI) and "Rainfall Induced Infiltration" (RII). To complicate matters further, in coastal areas there can also be a groundwater response to tide levels. This variation in groundwater levels causes a variation in the infiltration rates into the sewers and it is best to still consider this as "groundwater infiltration" though it will now have a cyclic variation rather than remain constant.

Flows in sewers therefore stem from a combination of sources:-

- Domestic foul flows
- Commercial foul flows
- Trade Effluent discharges
- Groundwater Infiltration
- Impermeable Runoff
- Permeable Runoff
- Rainfall Responsive Infiltration

## Rainfall

A major step forward with the modelling of rainfall was made when the 'Wallingford Procedure'[1] was introduced in 1983. Much of the pioneering work was undertaken in the development of the "Flood Studies Report". The derivation of the parameters needed to generate realistic synthetic rainfall profiles for any point in the UK is a simple exercise using four maps of the UK with the relevant parameters plotted.

Since the introduction of the Wallingford Procedure and the early versions of WASSP and WALLRUS the modelling community has embraced the simplicity of the approach which allowed design storms to be generated very quickly and appropriate catchment wetness indexes also determined very quickly. There were however a number of problems with the methods used for the generation of the rainfall profiles which caused the design storms to not adequately match the local variations which occurred with rainfall.

In 1999 the "Flood Estimation Handbook"[2] was published with a CD-ROM[3] that allowed rainfall depths to be generated far more quickly and with greater accuracy, taking account of local variations. The Author presented a paper[4] at the 2001 Spring Meeting about the use of FEH rainfall in modelling.

Modelling using FEH rainfall is gaining greater acceptance in the industry though in many areas the regulatory framework is tending to inhibit greater use.

## Runoff

Rainfall runoff modelling is extremely complex and has been the subject of much academic research over past decades and indeed is continuing today in many establishments around the world.

The software produced by Wallingford Software contains a variety of different runoff models which can be used. The variety of models available can be daunting and it is not surprising that many modellers do not fully understand all of the models available. The more commonly ones used are reviewed in the section below and are also summarised in Table 1 below:-

| Model | Application | Comments | Suitability |
|---|---|---|---|
| Fixed Percentage Runoff | Can be applied individually to all surface types within a drainage area. | Simply insert a percentage for the runoff from each surface type. | Suitable for all catchments where a good estimate of the runoff percentages can be made. |
| Constant PR Model<br>aka Wallingford Procedure<br>aka Standard Runoff | This is the DEFAULT model in all Wallingford Software products. MUST be used to represent all surfaces within a drainage area. | Needs to be used with care and observing the limitations of this model.<br><br>Uses UCWI values to set initial conditions which then remain throughout storm. | Suitable for all urban catchments in the UK.<br><br>Design values of UCWI are readily available. |
| Variable PR Model<br>aka New UK Runoff Model | This model only applies to permeable surfaces and must be applied to all the permeable surfaces in a drainage area. | Impermeable surfaces use a fixed percentage runoff. Permeable surfaces use this model and the runoff varies with increasing or decreasing wetness.<br><br>Uses API30 values for catchment wetness which are updated throughout the storm. | Suitable for all urban catchments in the UK.<br><br>No definitive values of API30 yet available for design storms. |
| SCS Method<br>(USA Soil Conservation Service Model) | Can be applied individually to all surface types within a drainage area or mixed with fixed percentage runoff. | Principally a rural catchment model. | Essentially only suitable for wholly or predominantly rural catchments but can also be used to model a rural catchment draining into an urban catchment. |
| Green-Ampt | Can be applied to individual surfaces. | An infiltration model for pervious and semi-pervious surfaces. | Suitable for rural surfaces and pervious surfaces within a catchment. Associated in the US with the SWMM runoff routing model. |
| Horton | Can be applied to individual surfaces. | An infiltration model for pervious and semi-pervious surfaces. | Suitable for rural surfaces and pervious surfaces within a catchment. Usually associated with the Desbordes or SWMM runoff routing models. |
| Constant Infiltration (ConstInf) | Can be applied to individual surfaces. | The ConstInf model allows a constant infiltration to be set from the surface into groundwater. This is effectively a loss to the system but if the storage capability is exceeded a fixed runoff occurs. | |

## Fixed Percentage Runoff Model

This model, as the name suggests, is simply based on each surface type having a fixed percentage runoff. For example paved surfaces might be allocated an 80% runoff and roofs might be allocated a 90% runoff. It is difficult to know what percentages should be used and there is little advice currently available. This is the simplest runoff model to use but because of the difficulties of determining suitable percentages it is rarely used.

## Constant Percentage Runoff Model – (Wallingford Procedure Runoff Model)

When the Wallingford Procedure was first released in 1983 We were introduced to the "Percentage Runoff Equation" (or PR Equation):-

$$PR = (0.829 \times PIMP) + (25 \times SOIL) + (0.078 \times UCWI) - (20.7)$$

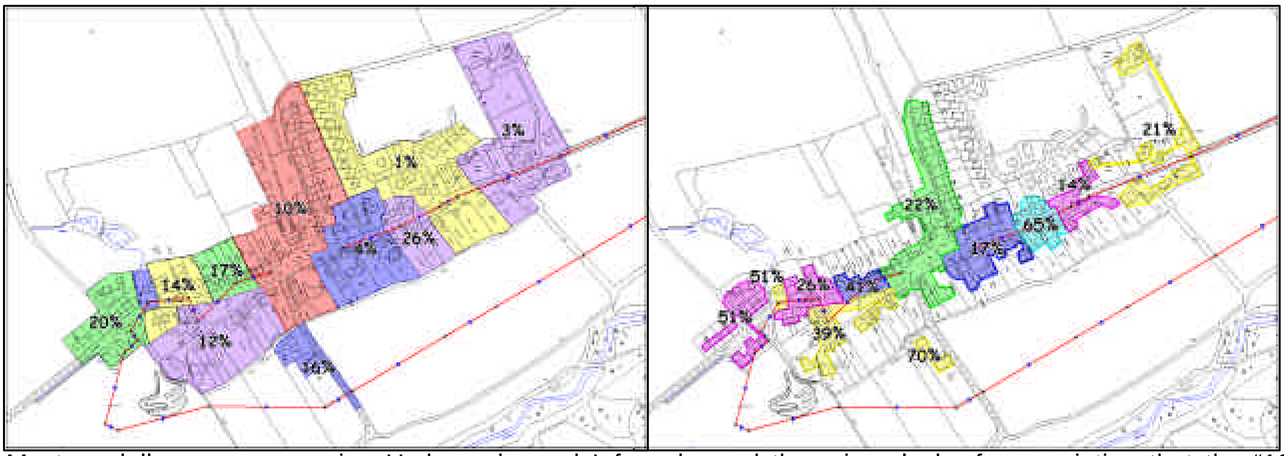
This equation was the result of regression analyses carried out on data from 510 storm events from 17 different catchments. This was based on a statistical approach and the equation explained 58% of the variation in the data with a standard error of 10.3%. In WaPUG User Note No 9[5] Ron Chapman explains the PR Equation and concludes that the PR Equation has many limitations and users must be aware of these if they wish to obtain realistic results. He goes on to state that users should make the effort to understand the significance of the parameters used. With low values of PIMP, SOIL or UCWI unreasonably low or even negative values of PR can be created. To overcome this the software sets a lower limit of 20% and an upper limit of 100%. With typical summer UCWI values it is necessary for the PIMP value to be generally be in excess of 40% for the PR value from the equation to be above the minimum 20%.

The overall runoff from a contributing area (to a single node) is quite complex with individual runoffs from the different surface types depending on the individual areas of each surface type and weighting factors with pervious areas only having 10% of the weighting of impermeable surfaces. This means that all surfaces (even permeable ones) produce runoff provided that the rainfall is in excess of the initial losses.

The essential point of the Constant PR Model is that the percentage runoff (PR) remains constant throughout the simulation period and is set from the initial conditions. In the earlier days when WASSP was still in use the PR equation was applied across the whole catchment but advances when WALLRUS was released applied the PR equation to each individual contributing area. The PR equation uses the UCWI (Urban Catchment Wetness Index) which for verification storms is individually calculated using data from the Met Office and the precipitation over the previous 5 days.

In spite of the quite severe limitations of the PR equation the Constant PR Model (Wallingford Procedure Model) has achieved remarkable success with many hundreds of models which were satisfactorily verified. A key factor in the success of this runoff model was the advice in 1989 from the WaPUG Committee to use the "10 metre rule" (see WaPUG User Note 21[6]). The use of the 10 metre rule had the effect of keeping the minimum PIMP values above about 40%. Another factor in the success of the Fixed PR model was the readily available values of UCWI for use with synthetic design storms.

The two diagrams overleaf illustrate on the left the drainage areas for a village without using the 10 metre rule and following property boundaries. The diagram on the right has drainage areas defined using the 10 metre rule. The percentages quoted for each drainage area are those derived from the PR Equation (before overriding with the minimum values set by the software). The differences are readily apparent.




Most modellers are now using Hydroworks and Infoworks and there is a lack of appreciation that the "10 metre rule" should still be applied if the Constant PR Model is used as there have been no changes to the PR equation or its validity since the days of WASSP and WALLRUS. It is unfortunate that the 10 metre rule has fallen into disuse and this will lead to problems in some catchments.

## New UK Runoff Model – (Variable PR)

The "New UK Runoff Model" was first introduced in 1993 by Wallingford Software was intended to overcome the problems which the Fixed PR model gave with longer duration storms. The Variable PR model is effectively only applied to the pervious areas and the runoff from the impermeable surfaces is a fixed percentage defined by the user. The Variable PR model updates the percentage runoff at each major timestep in accordance with the increasing wetness of the catchment.

The New UK Runoff Model is explained by Martin Osborne in WaPUG User Note 28[7] and it can be seen from this that a key factor is the precipitation over the previous 30 days as defined with the API (Antecedent Precipitation Index). The API value is updated throughout the simulation event. The formula for $API_{30}$ is:-

$$API_{30} = \sum_{n=1}^{n=30} \left( P_{-n} \quad C_p^{n-0.5} \right)$$

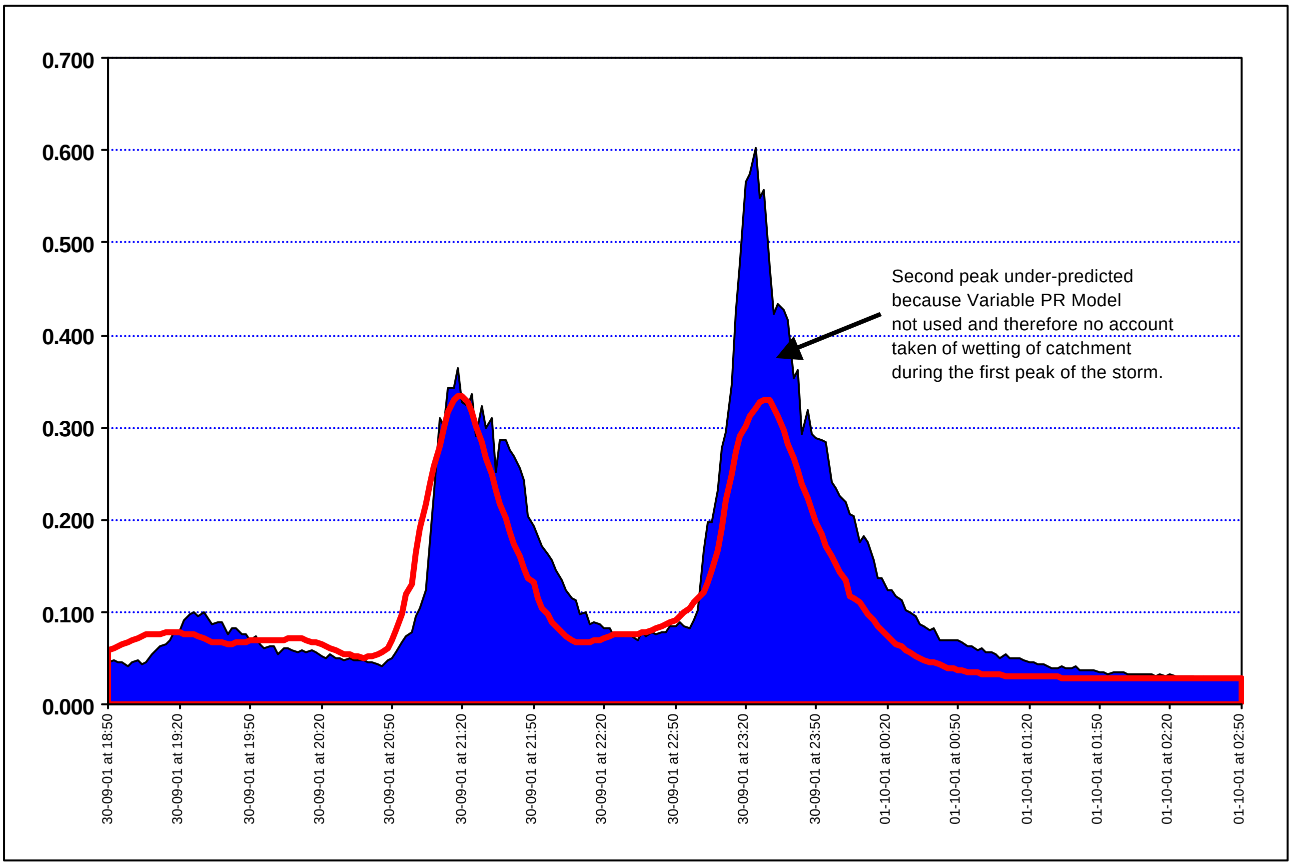
where
P-n is the effective rainfall (after allowances for evaporation) and
Cp is a decay constant based on soil class (0.1 for soil class 1 up to 0.99 for soil class 5)

As with other runoff models the user includes areas in the model representing the 3 surface types♣ (road, roof and pervious). The user also decides what proportion of the impermeable surfaces (roads and roofs) contribute runoff to the sewers; this is termed the 'effective impervious area factor' (IF) which can range typically from 0.45 for poor surfaces to 0.75 for good surfaces. This means that after initial losses are allowed for a fixed percentage of the rainfall (45% to 75% in the examples above) is turned into runoff. The remaining proportion of the impermeable surfaces (55% to 25%) is assumed within the model to drain to the pervious surfaces which have the Variable PR model applied.

Since the Variable PR model was introduced it has been used to infill the recession part of the hydrograph which is strictly rainfall induced infiltration rather than runoff. The main reason the Variable PR model was used in this way was because there was no alternative method available. There is now an alternative method available (the infiltration module in Infoworks) and perhaps the time is now right for the Variable PR model to be used as it was originally intended which is to model the runoff from permeable surfaces.

The hydrograph illustrated overleaf shows a verification plot in a Trunk Sewer where the Variable PR Model has <u>not</u> been applied. It can clearly be seen that the second peak is significantly under-predicted because the simulated runoff flows have not responded to the wetness of the catchment which increased after the first period of rainfall. This clearly demonstrates the need to apply the Variable PR Model.

♣ more than 3 surface types can now be modelled if necessary




The Variable PR method has gained little use (other than to provide a delayed response) principally because of the difficulties in using this runoff model in a design situation as there is currently no methodology available for determining suitable design values for the Antecedent Precipitation Index (API). This matter is discussed again later in this paper.

### Other Runoff Models

The other runoff models which are summarised in Table 1 are principally for use with rural catchments and could themselves be worthy of a separate paper. At the current time there is little literature available about the use of these models in the UK though the Author has undertaken several successful modelling studies in the UK using the SCS runoff model.

## Infiltration

It has been possible since the early days of WASSP to make allowances in the models for groundwater infiltration. This was originally applied globally as a figure for the whole catchment but then distributed equally along each metre of sewer. With increasing sophistication it has been possible for some time to model infiltration at specific locations, along certain sections of pipelines or as a distributed figure.

The latest version of Infoworks has greatly increased the number of ways in which infiltration can be modelled. In addition to the previous ways which are still available the modeller can now apply a time varying profile to groundwater infiltration flows, can simulate tidal variations in groundwater infiltration and perhaps most importantly can now model Rainfall Induced Infiltration.

### Rainfall Induced Infiltration

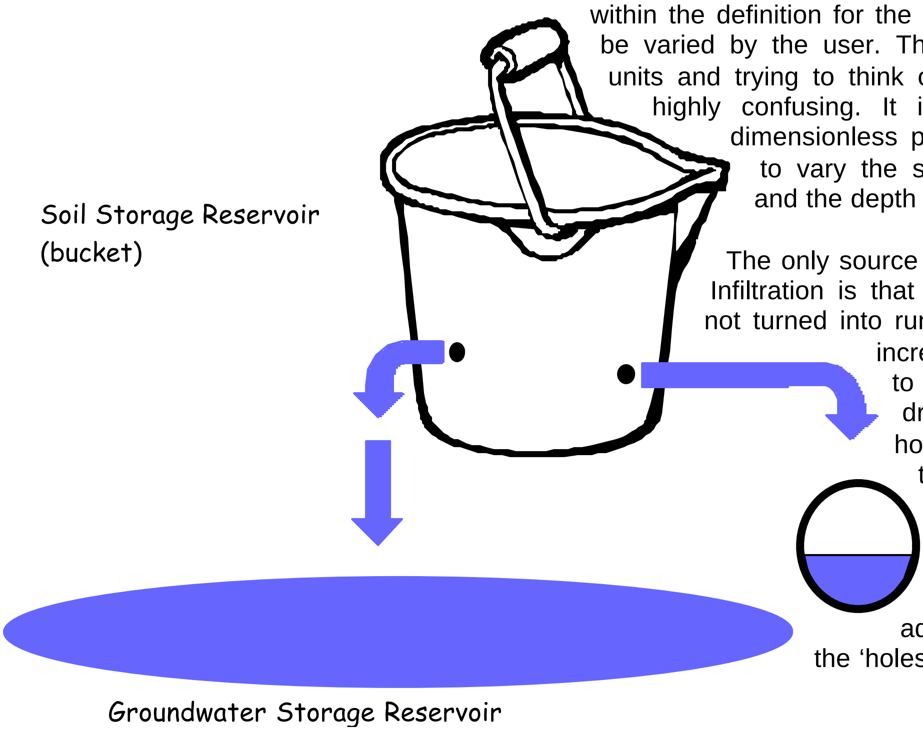
Rainfall Induced Infiltration (RII) is that infiltration which occurs in response to rainfall and is additional to the more constant groundwater infiltration. This phenomenon has long been recognised and is basically the remaining portion of the flow hydrograph which is not accounted for by foul flows, groundwater infiltration, impermeable runoff and permeable runoff. In the majority of catchments there is little or no rainfall induced infiltration but in those catchments which do experience RII there can be significant problems with, in some cases, the flows in sewers remaining high for several days after rainfall. The shape of a RII hydrograph will be unique to particular catchments and sub-catchments with the length of the hydrograph and the magnitude of the flows dependent on rainfall. The time to peak (ie the time between peak rainfall and peak flow) will tend to be reasonably constant but will to an extent be dependent on the preceding conditions.

Before the latest version of Infoworks the only way in which RII could be simulated was for a Modeller to use the Variable PR Model (New UK Runoff Model) with a very high routing coefficient of about 20 instead of 4. This approach gave an acceptable mimic of the flow conditions for verification storms but for any other storms, especially design storms the simulated flows became less and less reliable with increasing return period. The design of storage schemes using this approach were a particular problem and prudent modellers generally advised that models built in this way were not suitable for determining storage volumes.

The modelling of Rainfall Induced Infiltration is highly complex and whilst some parameters appear to have a degree of physical reality most of them are abstract and in some cases no units are quoted for the fields to be completed. Accordingly it is probably more realistic to consider modelling of RII to be a matter of calibration rather than verification but with sufficient storms and sufficiently long periods of reliable data it is possible to achieve a very high degree of confidence in the way in which this is modelled. This then gives confidence in the way in which the flows might be extrapolated with higher return period storms.

Modelling of RII is in its infancy and there is little guidance currently available. The current Help pages in Infoworks are of some help but it would be better if more detailed guidance and perhaps some case studies could be made available.

The mechanism for the way in which RII (and varying Groundwater Infiltration) is modelled can be likened to a bucket (to represent the soil storage) with two holes. One hole allows water to flow into the sewer and the other hole allows flow out of the bucket into the lower groundwater layer. There are a series of variables within the definition for the infiltration parameters which can be varied by the user. These generally do not have any units and trying to think of them as having units can be highly confusing. It is better to think of them as dimensionless parameters which allow the user to vary the sizes and positions of the holes and the depth of the bucket.




The only source of water for the Rainfall Induced Infiltration is that rainfall on the surface which is not turned into runoff. Therefore one technique to increase the volume of infiltration is to increase the surface areas draining to a node; this technique however can alter the way in which the runoff from permeable surfaces is modelled and therefore it is preferable to increase or decrease the volume of infiltration by adjusting the sizes and levels of the 'holes' in the bucket.

## Design Values of $API_{30}$

The Antecedent Precipitation Index (API) is used with the Variable PR Model to define the catchment wetness at the beginning of the storm. It is updated throughout the simulation at each major timestep and in this way varies the runoff from the permeable surfaces as they become wetter or drier.

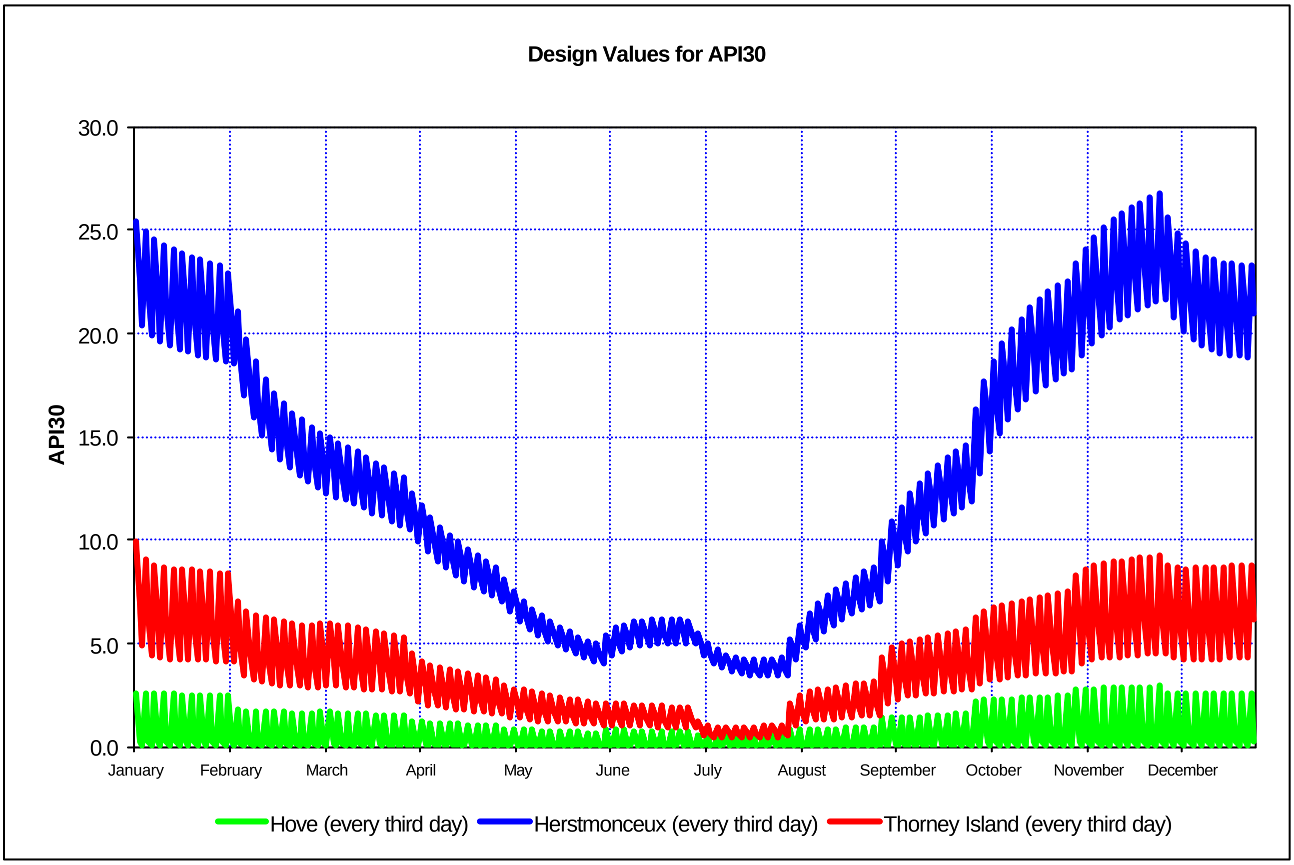
The lack of a methodology to determine suitable $API_{30}$ values for use with synthetic design storms has been a handicap for the past decade and has been responsible for the low usage of the Variable PR Model.

A number of techniques have been attempted by others using stochastically generated data from Stormpac and this avenue looks promising.

The Author has taken a different approach and has tried to establish a methodology based on records of rainfall. Rainfall records were obtained for 3 sites (Thorney Island, Hove and Herstmonceux) in southern England. These have Soil types 3, 1 and 4 respectively. The data collected was only for the 11 years from 1990 to 2000 and an examination of the data and comparisons with long term average monthly rainfall figures showed that there was too much variation in the data for any meaningful conclusions to be reached. Discussions with Mathematicians advised that data from at least 30 years would be needed to be statistically valid.

The next step was to use the Long Term Monthly average rainfall (1961 to 1990) from these same sites, to assume that there was equal rain on each day of each month (to give the correct monthly total) and then to calculate the $API_{30}$ value for each day taking due account of evapotranspiration losses. It was found from these calculations that the evapotranspiration losses during the summer months (up to about 3 mm/day) exceeded the rainfall with the result that the $API_{30}$ values were zero for about 5 months of the year – this was considered to be incorrect.

On the basis that in southern England there are generally about 220 dry days per year the rainfall was assumed to only occur on every third day throughout the year but still giving the correct monthly totals. $API_{30}$ values calculated in this way appear to be far more promising and are illustrated below for the 3 sites studied.




The Met Office are now issuing Baseline Data for 5km x 5km grid squares throughout the UK and amongst other parameters which are available are Long Term Average monthly rainfall 1961 to 2000 (40 years), the number of rainy days each month with > 1mm of rain and the number of wet days per month with > 10mm of rain. This data looks very promising as the way forward in being able to determine reliable monthly $API_{30}$ values throughout the UK on 5km grids.

Obviously values obtained in this way will not be as cheap or as immediately available but they appear as though they will be far more accurate and more reliable than anything which has previously been available.

It is hoped that this will make it more acceptable to use the Variable PR Model as the principal runoff model.

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[1] The Wallingford Procedure: Design and analysis of urban storm drainage. Volume 1: Principles, methods and practice. *Hydraulics Research Ltd,* 1983

[2] Flood Estimation Handbook *CEH Institute of Hydrology,* 1999

[3] FEH CD-ROM 1999 *CEH Institute of Hydrology*, 1999

[4] Modelling FEH Storms *Richard Allitt*, WaPUG, Coventry, 2001

[5] WaPUG User Note No 9: The Percentage Runoff Equation *R. E. Chapman* 1996

[6] WaPUG User Note No 21: Runoff Equations and Catchment Data, *WaPUG Committee*, 1996

[7] WaPUG User Note No 28; A New Runoff Volume Model, *M P Osborne*, 1993