

Insights gained from four component hydrograph separation

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ABSTRACT

Traditional hydrograph separation techniques split an observed storm hydrograph into two main components representing 'storm runoff' and 'baseflow'. In this paper a new separation technique is described which makes an initial split into two main components, quickflow and slowflow, which are each then subsequently split into two further subcomponents. The resulting procedure is termed the 'four component hydrograph separation technique'. Various ways of recombining these four subcomponents to build up a curve that represents the observed storm hydrograph are possible, of which two ways are examined in further detail. If it is assumed that the four component separation technique provides a promising representation of an observed storm hydrograph, these two ways allow theoretical and practical insights to be gained into four existing hydrograph separation techniques. A conclusion, common to all four, is that much more care is required in naming the flow lines separating out each of the suggested subcomponents making up the observed storm hydrograph. This paper also emphasises the key role played by the slowflow storm runoff subcomponent, which has not been given sufficient prominence in existing event-based models in the past. A procedure for estimating each of the four subcomponents is illustrated for an observed event.

Key words | component, four, hydrograph, insights, separation

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INTRODUCTION

Many advances in rainfall-runoff modelling have been made in recent years by aiming to relate the gross rainfall input directly to the total streamflow (Beven 2001), rather than relating the effective rainfall to the storm runoff. This circumvents the initial problem posed (NERC 1975) of having to estimate rather poorly-defined storm runoff and baseflow components prior to unit hydrograph identification. Hydrograph separation is embraced within the procedure, with dominant quick and slow response components of modelled streamflow found as follow-on byproducts of the identification (Littlewood 2009).

A non-linear filter mechanism is applied to the gross rainfall to determine the effective rainfall (Whitehead *et al.* 1979), which is then related to the total streamflow by a suitable linear transfer function (Young 1975, 1984). Examples are the

IHACRES model (Jakeman *et al.* 1990, 1993; Jakeman & Hornberger 1993) and the bilinear power model of Young & Beven (1991, 1994), which are very similar in their modelling of the routing component but differ in their approach to modelling the catchment nonlinearity (Beven 2001). Evaluation of these models suggests that a parallel transfer function structure is appropriate (Figure 1), with a proportion of the runoff being routed through a fast pathway and the remainder through a slow pathway (Beven 2001).

The aim of this present paper is to apply these advances more fully to event-based models, in particular to the routing component. The parallel structure of fast and slow responses has been adopted, but each of these responses has been represented by a non-linear conceptual reservoir, thus avoiding the linear system constraint inherent in the linear transfer

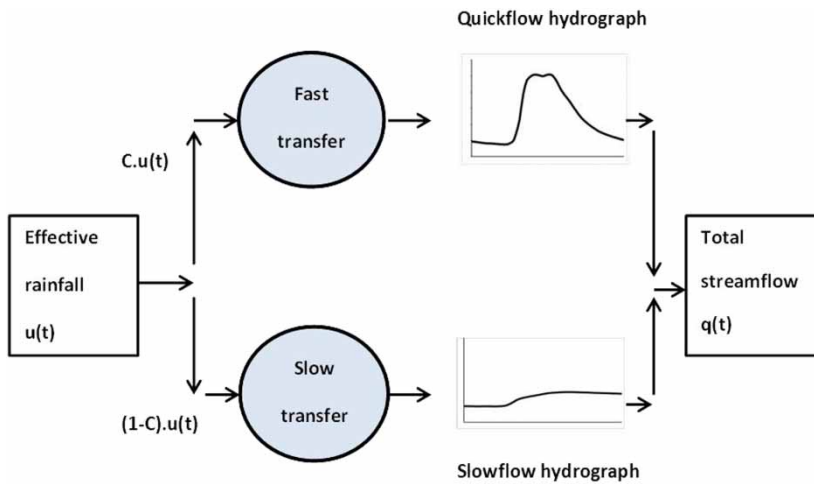


Figure 1 | Parallel transfer function routing structure.

function model. The resulting four component hydrograph separation technique is examined to see what insights, both theoretical and practical, are gained into the hydrograph separation techniques of previous event-based models described in the literature:

- (i) General Separation (GS) model (Reed *et al.* 1975; Beven 1991)
- (ii) Flood Studies Report (FSR) model (NERC 1975)
- (iii) Revitalised Flood Hydrograph (ReFH) model (Kjeldsen 2007)
- (iv) Reservoir Inflow Sequence (RIS) model (Mandeville 2004).

These advances have only been partially reflected in recent versions of event-based models used to analyse a single observed storm hydrograph. For example, the ReFH rainfall-runoff model (Kjeldsen 2007) was introduced to supersede the then 32-year-old FSR model (NERC 1975). However it still involves an initial separation of the observed hydrograph into two components called the ‘direct runoff hydrograph’ and ‘baseflow’. A revised version of the unit hydrograph is used to relate the effective rainfall to this ‘direct storm runoff’. A linear conceptual reservoir is introduced to model the baseflow, which is an important improvement over the FSR technique. However, because a proportion of the shape of the output from the quick response component (the direct runoff hydrograph) is used to represent the format of the input to the slow response component, the overall routing structure of

the ReFH model does not conform to that of a parallel linear transfer function, which is one of the foremost advances mentioned previously.

This paper does not directly address the major issue of comparing continuous simulation with event-based models. Both approaches have their own strengths and weaknesses. Rather than dismissing one or the other, it is felt there is merit in taking forward both approaches in parallel. Comparison between the results obtained from each separate approach serves to stimulate the advancement of the other. For example, in this paper adopting the routing structure of a parallel transfer function, used in certain leading continuous simulation models, and applying the concept to four event-based models, allows some useful insights about the latter to be gained.

In the alternative direction, there may well be cases where advances in event-based models could lead to some useful insights about corresponding continuous simulation models. For example, it appears feasible to identify the split between quickflow and slowflow contributions during pre-event and post-event recession periods using the RIS event-based model (Mandeville 2004). This method is based on examining the gradients abstracted from the observed streamflow data alone, without any additional supporting rainfall data. While some continuous simulation models, such as IHACRES, can accomplish the same task, they need both streamflow and corresponding rainfall as input data (Littlewood & Jakeman 1991).

There are two more areas on which this paper is not directly focused. First, it does not address the important task of identifying or predicting the volumes of effective rainfall which need to be routed through the parallel transfer function. However, identifying the correct storm runoff volumes in the first place, for quickflow and slowflow separately, is an integral consideration which these insights do address. Second, the paper does not seek to directly develop or justify any of the event-based models examined, or even the overall four component separation technique itself, as a stand-alone separation procedure. This paper concentrates on adopting the concept of the four component separation technique, and comparing it to the separation techniques used in four existing event-based models, to see what insights emerge, and whether the structures of those four models are amenable to any improvements.

STRUCTURE OF THE MODEL

The following routing system has been adopted to model a single observed storm hydrograph event. The parallel structure is composed of two main components, the quickflow hydrograph and the slowflow hydrograph, as shown in Figures 2 and 3, respectively, which are added together, for the same time ordinates, to represent the total streamflow (Figure 1).

By extending the pre-event quickflow recession curve, the quickflow hydrograph may be separated into two further subcomponents, as shown in Figure 2:

- QFP: the quickflow preceding runoff
- QFS: the quickflow storm runoff.

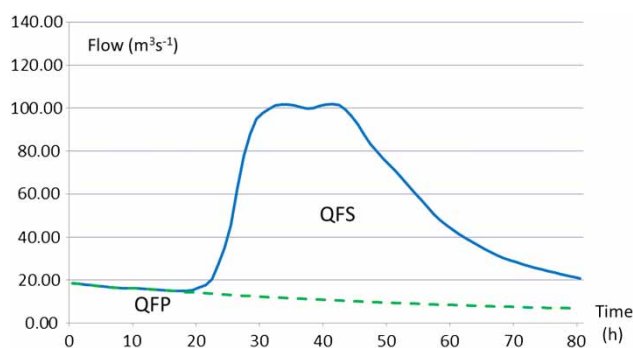


Figure 2 | The quickflow hydrograph component showing subcomponents QFP and QFS.

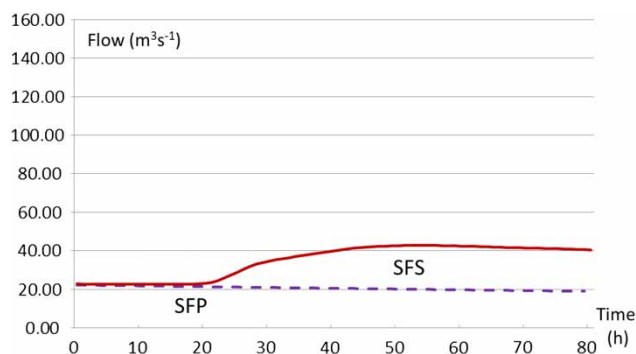


Figure 3 | The slowflow hydrograph component showing subcomponents SFP and SFS.

QFP is the quickflow hydrograph that would have occurred if the storm inflow had not taken place. QFS is the additional response due to the storm inflow; it is bounded by the extensions of the pre-event and post-event quickflow recession curves, that tend asymptotically to zero flow as values of time t become larger.

Similarly, by extending the pre-event slowflow recession curve, the slowflow hydrograph may be separated into two further subcomponents, as shown in Figure 3:

- SFP: the slowflow preceding runoff
- SFS: the slowflow storm runoff.

The resulting four subcomponents (QFP, QFS, SFP and SFS) form the basis of the so-called four component hydrograph separation technique.

In this section the observed storm hydrograph is first split into the two main components, the quickflow hydrograph (Figure 2) and the slowflow hydrograph (Figure 3). It is considered that these two quite different responses do physically exist and so can be identified, but the actual sources of water contributing to each component is still a matter of debate. These two components are then split into the subcomponents QFP, QFS, SFP and SFS. These four subcomponents are not thought to physically exist in general, except for the particular cases of QFP and SFP during the pre-event recession phase. Instead, they are put forward as concepts that will be employed to analyse the structures of some established event-based models.

Assumptions

The following three assumptions are adopted:

- (i) the pre-event and post-event quickflow recessions are formed of different portions of the same quickflow master recession curve;
- (ii) the pre-event and post-event slowflow recessions are formed of different portions of the same slowflow master recession curve;
- (iii) although the slowflow response is much more damped than that of quickflow, the inflow section of the slowflow hydrograph occurs during exactly the same period of time as the inflow section of the quickflow hydrograph, namely, starting a few ordinates prior to the time of minimum quickflow and finishing at the time ordinate of the inflection point on the quickflow hydrograph recession curve.

FIRST COMBINATION METHOD

The four subcomponents identified (QFP, QFS, SFP, and SFS) may be combined in at least two different ways, to build up a curve that represents the observed storm hydrograph. The first of these two methods is illustrated in Figure 4. Initially, the two subcomponents representing preceding runoff, SFP and QFP, are combined together to form a steadily declining flow component. Subsequently, the two storm runoff subcomponents, SFS and QFS, are added in sequence to this flow component, to reproduce the hydrograph shape.

The GS technique

Beven (1991), in his stimulating review of hydrograph separation, recommended that the majority of separation

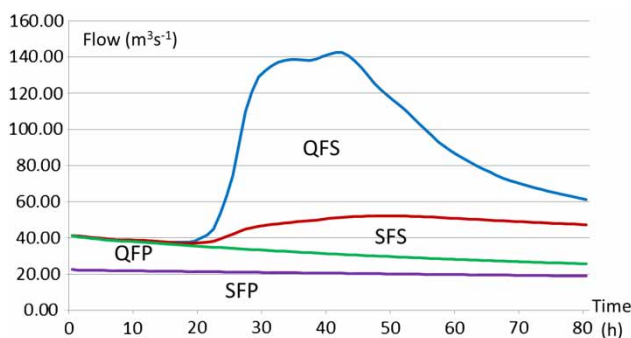


Figure 4 | The first method of combining the four subcomponents.

techniques available at that time should be avoided altogether, but did suggest that one method was theoretically defensible, although not much used by hydrologists in practice. This method will be entitled the GS technique, and is illustrated in Figure 5.

The method extends the pre-event observed recession until it eventually tends asymptotically to zero flow for higher values of time t . It relies on assuming that this extended recession represents the hydrograph that would have occurred if no storm inflow had happened. If this contribution is subtracted from the overall observed storm hydrograph, the remaining shape, as outlined by a solid line in Figure 5 and entitled the 'storm runoff', represents the contribution arising from the storm inflow alone.

Using the first method (Figure 4) of combining the four subcomponents as a background drop, the volume of runoff under the extended pre-event recession curve is identified as the sum of the SFP and QFP subcomponents (Figure 5). This combination represents the flow that would occur if there was no storm inflow, so supports the assumptions made in the GS technique. More importantly, the runoff volume, outlined by a solid line in Figure 5 and lying between the extensions of the pre-event and post-event observed hydrograph recession curves, is the sum of the QFS and SFS subcomponents:

$$\text{'storm runoff'} = \text{QFS} + \text{SFS} \quad (1)$$

This quantity represents the overall runoff response due to the storm inflow. In his 1991 review, Beven assumed that this volume was identical to just the quickflow storm runoff

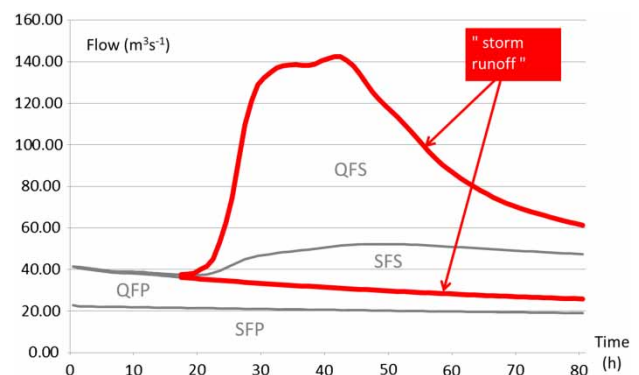


Figure 5 | The GS technique applied to an observed storm hydrograph.

QFS alone, but Equation (1) demonstrates that it is actually a combination of both quickflow and slowflow. If this GS technique was adopted as an analysis method, it would consequently require an additional step to separate out the storm runoff into its constituent quickflow and slowflow sub-components QFS and SFS, so the technique is incomplete.

Reed *et al.* (1975) had earlier applied this GS technique to individual storm events, dividing the observed hydrograph into 'underlying flow' and 'runoff due to the storm'; the latter portion was not assumed to represent just quickflow. For an event occurring after a relatively dry spell, the underlying flow is approximated by the outflow from a linear conceptual reservoir. The runoff due to the storm is not assumed to cease at some arbitrary finite time ordinate, but is modelled by using a response function which possesses an infinitely long tail.

The authors even demonstrated how their technique can be applied to a sequence of multiple storm events. They claimed that continuous prediction with the model is, in principle, quite feasible, and in practice applied a computer program to examine the model response to a series of synthetic peaks.

The FSR separation technique

This technique is described in detail in NERC (1975) as part of the overall unit hydrograph method adopted in the FSR, and is illustrated in Figure 6. It divides the observed storm

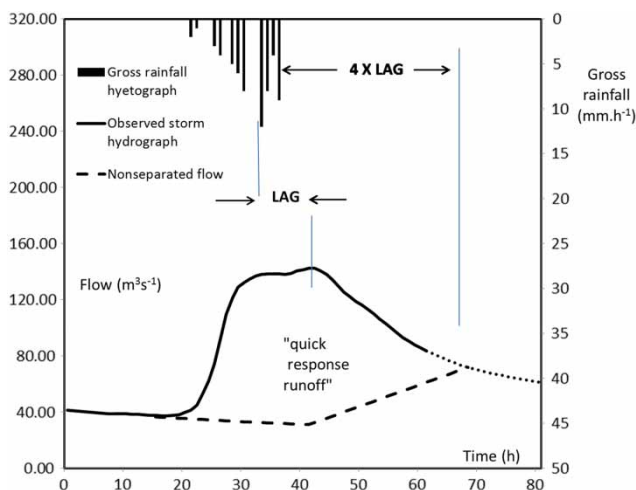


Figure 6 | The use of the LAG parameter during the FSR separation technique.

hydrograph into two main parts, the 'quick response runoff' and the 'nonseparated flow'. Essentially, the pre-event observed recession curve is extended until the time ordinate coincident with the observed peak flow is reached. From this point a straight separation line is drawn to reach the post-event observed recession curve, extended if necessary, at the ordinate which occurs at $4 \times \text{LAG}$ after the end time of the gross rainfall hyetograph. LAG is the time interval between the ordinates of the centroid of the gross rainfall hyetograph and the observed hydrograph peak flow.

A direct comparison between the four component and FSR separation techniques is illustrated in Figure 7. It is noted that the adopted process of extending the observed recession curve from the time ordinate at the start of the rising portion of the storm hydrograph seems sensible, as this will exclude contributions from both the QFP and SFP sub-components. Preferably this process should be continued further, after the time ordinate corresponding to the peak hydrograph flow is reached.

However, the major concern is that the quick response runoff, identified by the FSR technique, is a combination of a proportion of each of the QFS and SFS sub-components:

$$\text{'quick response runoff'} = \alpha \cdot \text{QFS} + \beta \cdot \text{SFS} \quad (2)$$

where α and β are dimensionless constants. The long tail of the QFS subcomponent, for higher values of time t , is not included in this quick response runoff, leading to inaccurate estimates of the latter quantity. It also includes the early part of the SFS subcomponent, which it should not. It seems likely that the proportions α and β would vary from

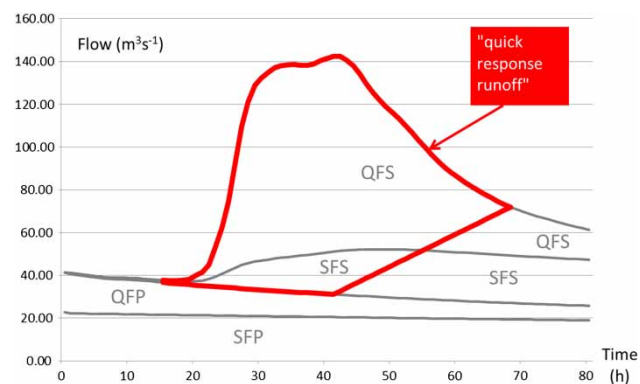


Figure 7 | The FSR separation technique applied to an observed storm hydrograph.

one storm event to another, and from one catchment to another, so are fairly arbitrary. The aim of the FSR technique is to ensure that the quick response runoff volume is equal to just that of QFS, i.e., $\alpha = 1$ and $\beta = 0$; but it appears that this scenario would only be approached if the SFS contribution was minimal, and even then α would be far from the ideal value of 1. Therefore, if it is assumed that the four component technique provides a promising representation of an observed storm hydrograph, it follows that the FSR technique leads to an estimate of quick response runoff that is unsound, because it is found to be a combination of arbitrary proportions of QFS and SFS, rather than equal to just the whole of QFS on its own.

Deficiencies in the FSR separation technique have been acknowledged for many years. In its defence, it should be repeated that the technique was originally established for undertaking systematic engineering hydrology applications under a tight schedule, at a moment in time prior to the rapid development of rainfall-runoff models over the last 40 years. It did not have the luxury of the generous time available under an applied research project. As such, it is a simplification of reality, specifying only two arbitrarily defined components of observed streamflow, prior to identification of the unit hydrograph for quick response runoff.

The IHACRES model is an example of a continuous simulation rainfall-runoff model that was first introduced in 1990 and which has since been refined and applied to many different sets of hydrometeorological data over the last 25 years (Littlewood 2008). That paper lists a number of general advantages that the IHACRES approach provides in comparison to the FSR separation technique, including:

- (i) low flows modelled;
- (ii) ability for continuous streamflow simulation;
- (iii) no prior hydrograph separation required;
- (iv) automatic hydrograph separation;
- (v) no smoothing of the unit hydrograph shape required.

In contrast, the aim of Figure 7 is more specific, namely, to illustrate in what way the separation lines used in the FSR technique are deficient and lead to unreliable components, and how they could possibly be improved. It highlights the problems caused by restricting the number of separated components to just two, and argues that the use of four

subcomponents provides a much more flexible approach to dividing up the observed streamflow hydrograph.

One other point of interest concerns the extension of the pre-event observed recession curve. Figure 7 shows that this extension is composed of the flow formed by the combination of the subcomponents QFP and SFP. These, in turn, form the extensions of the pre-event recessions of the main quickflow and slowflow hydrograph components. During the analysis of observed storm events undertaken during the Flood Studies Report (NERC 1975), three different conceptual models were explored to provide a method to extend the pre-event observed hydrograph recession: a single linear reservoir, a non-linear reservoir and a set of two linear reservoirs in parallel. The third model was found to be best at matching the extended recessions. This result gives some credence to support the combined use of the two subcomponents QFP and SFP to represent the extension of the pre-event observed recession curve shown in Figure 7.

SECOND COMBINATION METHOD

The four subcomponents may be combined under a second method, as illustrated in Figure 8, which has some slight differences when compared to the first method shown in Figure 4. As a foundation, the two subcomponents SFP and SFS are combined to make up the slowflow hydrograph component. Next the two quickflow subcomponents QFP and QFS are added on top of this slowflow hydrograph component to define the observed storm hydrograph. The flow line forming the upper limit of the QFP subcomponent in

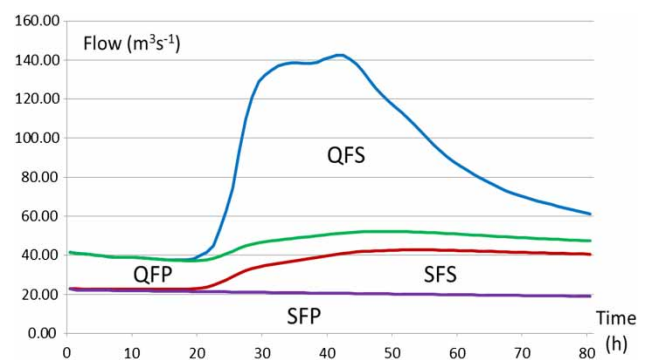


Figure 8 | The second method of combining the four subcomponents.

Figure 8 follows exactly the same values as the flow line in Figure 4, forming the upper limit of the SFS subcomponent.

Note that, at the time ordinate at the end of the observed hydrograph post-event recession, before it is extended the total flow value is composed of four different flow contributions arising from the subcomponents SFP, SFS, QFP and QFS. This emphasises the complexity of trying to separate out the various different components, and may account for some of the myriad methods of hydrograph separation proposed in the past.

New terminology

The second method of combining the four subcomponents provides an opportunity to suggest a possible terminology that may lead to clarification during general discussion regarding hydrograph separation. There are a number of different flow lines arising from the technique, and it is important to be clear about which particular lines are being discussed. In Figure 9, two of the most important flow lines are shown with suggested titles attached. The line forming the upper bound of the two subcomponents, SFP and SFS, represents the main slowflow hydrograph component, so this flow line will be called the slowflow separation line. The other line, which starts with the pre-event observed hydrograph recession curve and then traces the lower bound of the quickflow storm runoff subcomponent, QFS, will be termed the nonseparated flow line. This latter terminology broadly follows that developed during the FSR separation technique described in NERC (1975), as this line encompasses all the remaining runoff other than that of QFS itself without being too specific about its constituent components.

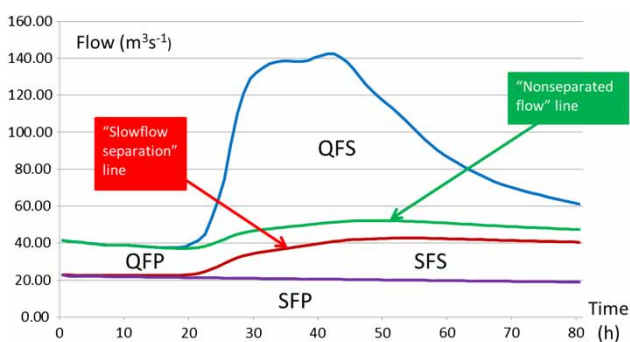


Figure 9 | Suggested terminology for distinguishing between different flow lines.

The ReFH separation technique

This separation technique, described by Kjeldsen (2007), forms one of the key improvements introduced during the development of the ReFH rainfall–runoff model. It is illustrated in Figure 10. In essence, the final ordinates of the post-event recession curve of the observed storm hydrograph are used to identify the characteristics of a linear conceptual reservoir that can be used to model the ‘baseflow’. The inflow which is selected to enter this reservoir is assumed to be a proportion of the storm hydrograph runoff, and this proportion is adjusted so that the ‘baseflow separation line’, which is chosen to commence at the first flow ordinate of the observed storm hydrograph, will also coincide with the final portion of the observed post-event recession curve. The resulting separated runoff, contained between the observed storm hydrograph and this baseflow separation line is termed the ‘direct runoff hydrograph’.

For the choice of storm hydrograph runoff on which this inflow depends, a different procedure is used between analysis of an observed event and simulation of a design event. During analysis, the observed storm hydrograph is adopted for this storm hydrograph runoff, while during design the estimated direct runoff hydrograph is used.

The four component hydrograph separation technique certainly supports the introduction of a conceptual reservoir to represent the slowflow component of the observed hydrograph. In this respect, the ReFH technique used to determine the direct runoff hydrograph has much greater justification than the FSR technique, which does not include such a conceptual reservoir; it is consequently a

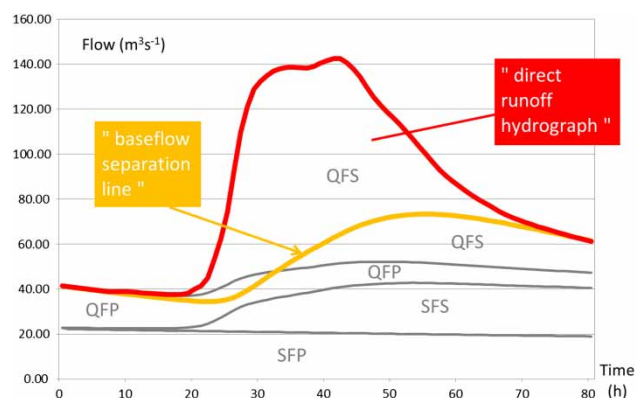


Figure 10 | The ReFH separation technique applied to an observed storm hydrograph.

considerable improvement. Well before the development of the ReFH technique in 2007, the idea of a linear conceptual reservoir to represent the dominant slowflow response in continuous simulation models had been demonstrated for the IHACRES model by Littlewood & Jakeman (1991). Littlewood (2008) extended the range of this idea to the case of a single observed storm hydrograph by applying the IHACRES model to an event drawn from the river Lossie record at Torwinny in Scotland.

However, Figure 10 shows that there are important differences between the ReFH and four component separation techniques. The baseflow separation line adopted in the ReFH technique broadly follows the nonseparated flow line described in the previous section, rather than the lower down slowflow separation line (Figure 9). As the outflow from the ReFH linear conceptual reservoir closely resembles that from a slowflow system, it would seem more appropriate that it does not start from the first flow ordinate of the observed hydrograph, but rather from some smaller flow value instead, such as the initial ordinate of the SFP subcomponent. It should also preferably finish at a lower flow value than that of the observed post-event recession curve.

It appears that the ReFH technique assumes that the contributing flow from the QFP subcomponent is zero; under this scenario, the nonseparated flow and slowflow separation lines would coincide (Figure 9). While QFP may well be small, or even negligible, for summer storm events which occur after a long dry spell, it is suggested that this is not the case for the vast majority of storm events occurring during the remaining months of the year.

The RIS separation technique

This separation technique is described by Mandeville (2004), and illustrated in Figure 11. The first step of the technique is to estimate the slowflow separation line shown in Figure 9, in order to split the observed storm hydrograph into its two main constituents, namely the slowflow hydrograph component (Figure 3) and the quickflow hydrograph component (Figure 2).

An analysis method involving gradients of the observed storm hydrograph is used to determine the slowflow hydrograph component for the pre-event and post-event recession

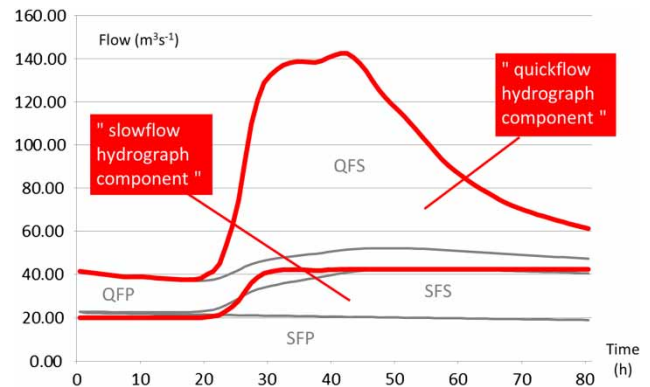


Figure 11 | The RIS separation technique applied to an observed storm hydrograph.

periods, respectively. This method assumes that the slowflows during the pre-event recession period are constant, which is a reasonable approximation of the slowly decaying slowflow values actually occurring. Similarly, it assumes constant slowflow values during the post-event recession period, although normally this latter flow rate is found to be higher than that found during the pre-event recession period.

However, this particular analysis method, involving gradients of the observed storm hydrograph, is only valid for those periods during which the observed storm hydrograph is in recession; outside of these periods it cannot be employed. Therefore it is necessary to adopt a practical method, which has little theoretical justification, for interpolating the central portion of this slowflow hydrograph component. It can be seen from Figure 11 that the match between the estimated and theoretical slowflow hydrograph components is poor during this intervening period, and this is an area of the RIS technique that needs strengthening.

Once this slowflow hydrograph component has been estimated, it may be subtracted from the observed storm hydrograph, and the resulting quickflow hydrograph component $Q(t)$ is analysed by the second step of the RIS technique, as shown in Figure 12.

This procedure exploits the properties of the pre-event and post-event recessions both forming portions of the same quickflow master recession curve, which is the first of three assumptions listed earlier. Initially, a Recession Gradient Function $m_r\{Q(t)\}$ is identified, which relates the gradient $(dQ/dt)_r$, found for a typical point on the quickflow recession, to its corresponding flow value $Q(t)$. For example,

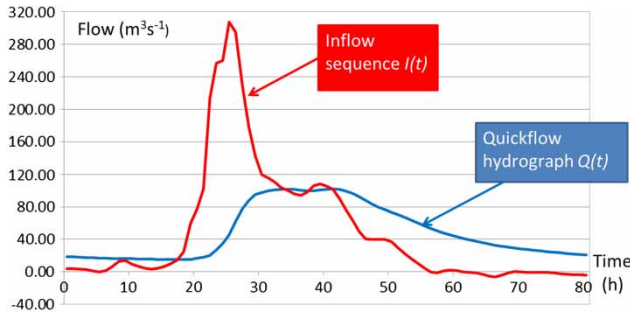


Figure 12 | The inflow sequence $I(t)$ obtained from applying the RIS formula to a typical quickflow hydrograph $Q(t)$.

if flow rates are measured in units of $\text{mm}\cdot\text{h}^{-1}$, Mandeville (2004) found the Recession Gradient Function for storm events on catchment No. 61001, the Western Cleddau river at Prendergast Mill, to be:

$$(dQ/dt)_r = m_r\{Q(t)\} = -0.935[Q(t)]^{1.936} \text{ mm}\cdot\text{h}^{-2} \quad (3)$$

Next the RIS formula:

$$I(t) = Q(t)[1 + \{dQ/dt\}/(-m_r\{Q(t)\})] \quad (4)$$

is applied to the whole quickflow hydrograph $Q(t)$ to determine the corresponding inflow sequence $I(t)$. This inflow sequence (Figure 12) may be looked upon as that inflow which, when applied to a non-linear conceptual reservoir described by the given Recession Gradient Function, results in an outflow equivalent to the original quickflow hydrograph. Normally the inflow sequence $I(t)$ possesses an ordinate with zero flow value near both the start and finish times, and by summing the flow ordinates lying between these two ordinates the exact volume of runoff beneath the $I(t)$ sequence can be calculated. It can be demonstrated theoretically that the volume lying beneath this inflow sequence $I(t)$ is exactly equivalent to the required volume of the quickflow storm runoff subcomponent QFS. This means that it can be determined directly from the $I(t)$ inflow sequence without involving the complications inherent in measuring the QFS runoff volume under the tail of the asymptotic quickflow recession curve (Figure 2).

Although Equation (4) offers an exact theoretical solution, the RIS technique has also been found to be a viable practical procedure. It is currently being applied to

observed hydrographs for groups of storm events drawn from seven catchments spread around the United Kingdom; for example, results for 25 events, recorded on the Western Cleddau river at Prendergast Mill in western Wales, are described in Mandeville (2004). For five of these events, it has been found in practice that there are some difficulties in obtaining a realistic inflow sequence $I(t)$ when instability occurs near its maximum value, which highlights a second area of the RIS technique that needs strengthening.

The Recession Gradient Function $m_r\{Q(t)\}$ has been developed to identify the master quickflow recession curve, for both pre-event and post-event periods, for a particular catchment. Each catchment will normally have a different version of $m_r\{Q(t)\}$, although sometimes it is found that the same example fits two catchments located far away from each other. If expressed in the form of a simple power law it will possess two parameters, as shown in Equation (3). The Recession Gradient Function may form a useful new catchment descriptor, which in the future could be related to catchment characteristics by suitable regression equations.

A practical procedure for estimating the individual subcomponents

The question arises as to whether it is possible, in a practical case, to estimate the four flow subcomponents SFP, SFS, QFP and QFS, as shown in Figure 8, from relevant rainfall and streamflow data? A suitable procedure will now be described by considering the catchment No. 61001, the Western Cleddau river at Prendergast Mill, located in Wales, for which 25 storm events were available, the same data as those used in the Flood Studies Report (NERC 1975), with observed storm hydrographs recorded with hourly time intervals (Mandeville 2004).

The initial steps of the RIS technique will first be followed, by applying it to event No. 18 to identify the slowflow separation line (Figure 9). The first step is to identify the Recession Gradient Function $m_r\{Q(t)\}$ for the quickflow hydrograph, as shown in Equation (3). This involves a combined analysis of the observed hydrographs from all the 25 events available, which is described in Mandeville (2004). Ideally, the dates of these events should be selected to ensure that the events chosen represent both

the drier and wetter seasons of the year. Equation (3) may next be inverted to express the quickflow $Q(t)$ in terms of the gradient of the quickflow $(dQ/dt)_r$ during periods of recession:

$$Q(t) = (-[(dQ/dt)_r]/0.935)^{1/1.936} \\ = (-1.070(dQ/dt)_r)^{0.517} \text{ mm.h}^{-1} \quad (5)$$

If it is assumed that, during recession periods, the gradient of the slowflow dB/dt is very much smaller than the quickflow gradient dQ/dt , then the slowflow $B(t)$ may be estimated from

$$B(t) = q(t) - (-1.070(dq/dt))^{0.517} \quad (6)$$

where $q(t)$ is the observed streamflow, and dq/dt the gradient of the observed streamflow. In practice, some small oscillations are found in these resulting slowflow estimates, and a constant value is fitted through them. For example, for event No. 18, which took place on 28 September 1967, Table 1 shows pre-event and post-event slowflow estimates of 0.061 mm.h^{-1} and 0.175 mm.h^{-1} , respectively, occurring during the periods of recession.

However, Equation (6) is not valid for non-recession periods, and an interpolation technique is used to estimate $B(t)$ between the end of the pre-event recession and the start of the post-event recession. This technique makes use of the observed streamflow values to pro-rate the rising values of slowflow $B(t)$, but does not have any theoretical basis. The result of this analysis is the estimation of the slowflow separation line, which separates the observed streamflow for event No. 18 into the two main components, the quickflow and slowflow hydrographs (Figure 13). The quickflow hydrograph component is then found by subtracting the successive values at this slowflow separation line sequence from the observed streamflow.

The slowflow hydrograph encompasses the two subcomponents SFP and SFS. The first of these may be found by extending the initial constant value of pre-event slowflow all the way to the end time of the storm event. In the case of event No. 18, this value would be 0.061 mm.h^{-1} (Table 1). In reality, it is likely that this SFP flow value would decay slightly during the course of the event, but a

Table 1 | Significant flow values for event No. 18 on catchment No. 61001

Description	Units	Value
Catchment No.		61001
River name		Western Cleddau
Station name		Prendergast Mill
Catchment area	km ²	197.6
Event No.		18
Date of occurrence		28 Sep 1967
Pre-event slowflow	mm.h ⁻¹	0.061
Quickflow at end of pre-event recession	mm.h ⁻¹	0.083
Time ordinate at end of pre-event recession	h	3
Minimum observed flow	mm.h ⁻¹	0.128
Maximum observed flow	mm.h ⁻¹	0.795
Post-event slowflow	mm.h ⁻¹	0.175
Quickflow at start of post-event recession	mm.h ⁻¹	0.281
Time ordinate at start of post-event recession	h	23
Quickflow at end of post-event recession	mm.h ⁻¹	0.051
Time ordinate at end of post-event recession	h	41

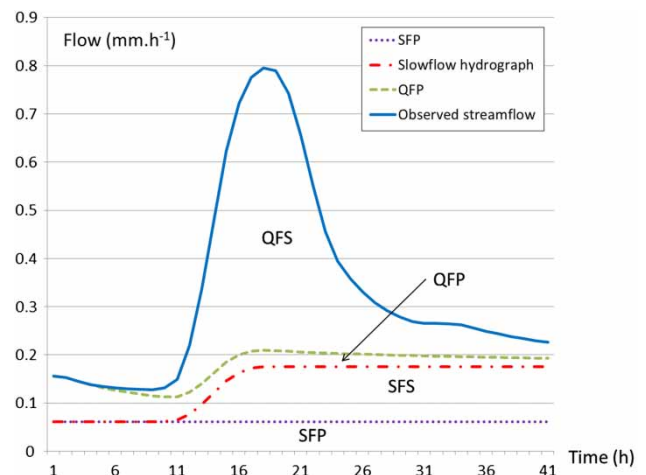


Figure 13 | A practical case study: estimation of the four subcomponents for event No. 18 from observed streamflow data for catchment No. 61001.

constant value provides a reasonable first approximation over the limited time period of the storm event. To determine the SFS subcomponent, the subcomponent SFP is

simply subtracted from the slowflow hydrograph found earlier (Figure 13). Table 1 shows that the post-event slowflow has a value of 0.175 mm.h^{-1} . Therefore the maximum flow value of SFS, taken alone, is given by $(0.175-0.061) = 0.114 \text{ mm.h}^{-1}$.

The quickflow hydrograph encompasses the two sub-components QFP and QFS (Figure 13). The first of these is found by determining how quickflow decays under pure recession. The Recession Gradient Function (Equation (3)) provides a method to do this, and, if integrated, can be rearranged to determine $Q(t)$ expressed in terms of time t

$$Q(t) = [1.068/(0.935t + 8.112)]^{1.068} \quad (7)$$

where the constant value 8.112 is determined from the quickflow value of 0.083 mm.h^{-1} at time $t = 3 \text{ h}$ at the end of the pre-event recession; this value of quickflow is found by subtracting the pre-event slowflow from the observed flow at that time ordinate. Equation (7) is then calculated for each time step from $t = 3$ to 41 h, to provide the complete subcomponent QFP (Figure 13). To determine the QFS sub-component, the subcomponent QFP is simply subtracted from the quickflow hydrograph component estimated earlier (Figure 13).

This procedure illustrates how the four sub-components SFP, SFS, QFP and QFS can be estimated, even though they remain as concepts and cannot be assigned physical reality, except possibly for the values of SFP and QFP during the pre-event recession. The most important aspect of the procedure is that these estimates are ultimately based on values of both the observed streamflow and the gradient of observed streamflow for the particular event No. 18, as well as a Recession Gradient Function of quickflow based on the observed streamflows of the whole group of 25 events. No observed rainfall data are required to complete this process.

DISCUSSION

The four component hydrograph separation technique facilitates the definition of various important flows in terms of suitable combinations of the various sub-components (Table 2). The terminology 'underlying flow' is adopted

Table 2 | Suggested revised definitions of the most important flows arising from hydrograph separation

Term	Definition	Four component interpretation
Underlying flow	The flow that would have occurred if the current storm event had not taken place	SFP + QFP
Slowflow hydrograph	The slowflow response resulting from a combination of the preceding storms and the current storm event	SFP + SFS
Nonseparated flow	The quickflow response to the preceding storms, added to the slowflow hydrograph OR	SFP + SFS + QFP
	The slowflow response to the current storm event, added to the underlying flow OR	SFP + QFP + SFS
	The quickflow response to the current storm event, subtracted from the overall observed streamflow hydrograph	(SFP + SFS + QFP + QFS) - QFS
Quickflow hydrograph	The quickflow response resulting from a combination of the preceding storms and the current storm event	QFP + QFS

directly from the analysis presented in Reed *et al.* (1975), while that of 'nonseparated flow' is based more loosely on the term mentioned in NERC (1975). These suggested definitions may be more exact than those presented previously in the standard event-based models described earlier. For example, historically the use of the word 'baseflow' is sometimes ambivalent. More often than not it is used to represent the nonseparated flow, but occasionally it is used to suggest the underlying flow (see, for example, Figure 2.5 in Beven (2001)).

The two terms 'slowflow hydrograph' and 'nonseparated flow' have been discussed earlier and illustrated in Figure 9 in the section on new terminology. The interpretation of 'underlying flow' as the combination of the two sub-components SFP and QFP seems intuitively sensible (Figure 4). These represent the slowflow and quickflow contributions that result from the size and time sequence of all storms that

occurred prior to the start of the current storm. The form of SFP and QFP are not affected by the size or timing of the current storm input. Although SFP and QFP may exist as separate physical entities during the period of the observed hydrograph pre-event recession, after the start ordinate of the current storm they are represented only as concepts, because they do not actually occur in practice.

The four component separation technique serves to highlight the relative importance of the SFS subcomponent (Figure 4). Some traditional event-based two component separation techniques tend to downplay its significance, with the GS technique ignoring it altogether, and the FSR technique only partly incorporating it. In the present approach, SFS is considered to be a key component. It represents the slowflow contribution arising from the current storm.

In terms of runoff volume, because of the more slowly converging upper and lower limits of SFS as time t increases, it may play a more important role than QFS, with its more quickly converging limits (Figure 4). In some catchments the total runoff volume contributed by SFS may exceed that contributed by QFS. No relevant results from analysis of event-based models are readily available to support this supposition, but corresponding continuous simulation models compare the volumes of the slowflow hydrograph (SFP + SFS) with those of the quickflow hydrograph (QFP + QFS) (Figure 8). For example, Young & Beven (1994) fitted their bilinear power law model to the CI6 catchment at Llyn Briane in Wales, and their final fit showed that 33.4% of the effective rainfall passed through the fast transfer component of the parallel linear transfer function, to give the quickflow hydrograph, and 66.6% through the slow transfer function, to give the slowflow hydrograph.

Although the main contributor to the size of the observed hydrograph peak remains the quickflow storm runoff subcomponent QFS, Figure 4 shows that SFS adds a definite, but modest, contribution to this peak flow ordinate. One reason for this is that, although the slowflow response is much more damped than that of quickflow, there is no lag of the slowflow response compared to that of quickflow, as mentioned previously in the third assumption. The inflow to the slowflow conceptual reservoir starts a few ordinates prior to the time of minimum quickflow, and finishes at the time ordinate of the inflection point on the quickflow hydrograph recession curve.

This is in contrast to the FSR technique, where the average nonseparated flow was taken to represent the flow in the river before the event started and, to a lesser extent, the beginnings of the slow response from the event itself (NERC 1975). It was assumed that the slow response only started to occur some number of time intervals later than the start of the quickflow response, i.e., from the time ordinate corresponding to the peak of the observed storm hydrograph (Figure 6).

It was also assumed in the FSR procedure that the average nonseparated flow was broadly unvarying, and a constant value should be added to all ordinates of the design hydrograph, as in view of the almost trivial effect on the size of any design flood, nothing more complex could be justified (NERC 1975). However, the four component technique suggests that the size of SFS is dependent on the size of the current storm input, so it is variable, and if included in the nonseparated flow (Table 2) will no longer allow this latter function to be considered unvarying. Thus for a large design storm, the quickflow storm response QFS will be large, but SFS will also increase, to a more modest extent, so this latter increase needs to be incorporated into the final design hydrograph.

In contrast to the FSR technique, in the ReFH technique the baseflow contribution does directly increase for a larger direct runoff hydrograph because a proportion of the latter is taken as the inflow to the linear conceptual reservoir used to represent the baseflow routing structure.

CONCLUSIONS

During past discussions of event-based models, some confusion has arisen concerning the exact meaning of certain terms used, such as baseflow, nonseparated flow, and storm runoff. The same term may describe a different quantity for two separate models. The four component separation technique allows a suggested new terminology to be introduced, involving terms such as underlying flow, slowflow hydrograph, nonseparated flow and quickflow hydrograph. Each of these terms may then be defined exactly as a suitable combination of selected subcomponents.

The four component separation technique serves to highlight the relative importance of the slowflow storm runoff subcomponent SFS. This paper considers it a key component that has been either only partly incorporated

or even ignored altogether in some previous event-based models. While SFS normally provides only a modest contribution to the peak flow value of the observed storm hydrograph, it may, in some catchments, make a major contribution to the overall runoff volume resulting from the current storm event. As the size of SFS depends partly on the size of the current storm, and SFS forms part of the non-separated flow, the latter quantity cannot be assumed to be broadly unvarying, as proposed in NERC (1975), and consequently itself will increase for a larger storm event.

It is considered that under the four component separation technique the two main components identified, the quickflow and slowflow hydrographs, do physically exist, but the four subcomponents put forward exist only as concepts because they do not actually occur in practice. Despite this restriction, a procedure is outlined that demonstrates a way of estimating a time series of values for each of the four individual subcomponents, and is illustrated for a practical case study of a single historical event, observed on a catchment located in south-west Wales. The procedure described ultimately depends on only the streamflow data observed for a group of storm events occurring on the same catchment, and no corresponding rainfall data are required.

REFERENCES

- Beven, K. J. 1991 Hydrograph separation? In: *Proc. Brit. Hydrol. Soc. Third Nat. Hydrol. Symp.*, Southampton, UK, pp. 3.1–3.7.
- Beven, K. J. 2001 *Rainfall-Runoff Modelling: The Primer*. John Wiley & Sons Ltd, Chichester, UK.
- Jakeman, A. J. & Hornberger, G. M. 1993 How much complexity is warranted in a rainfall-runoff model? *Water Resour. Res.* **29** (8), 2637–2649.
- Jakeman, A. J., Littlewood, I. G. & Whitehead, P. G. 1990 Computation of the instantaneous unit hydrograph and identifiable component flows with application to two small upland catchments. *J. Hydrol.* **117**, 275–300.
- Jakeman, A. J., Littlewood, I. G. & Whitehead, P. G. 1993 An assessment of the dynamic response characteristics of streamflow in the Balquhiddy catchments. *J. Hydrol.* **145**, 337–355.
- Kjeldsen, T. R. 2007 *The Revitalised FSR/FEH Rainfall-Runoff Method*. Flood Estimation Handbook, Supplementary Report No. 1. Centre for Ecology and Hydrology, Wallingford, UK.
- Littlewood, I. G. 2008 Characterisation of river flow regimes for environmental and engineering hydrology: unit hydrographs for rainfall-streamflow modelling. *Folia Geographica: Series Geographica-Physica XXXIX*, 5–36.
- Littlewood, I. G. 2009 Progress with unit hydrograph-based rainfall-streamflow models for engineering and environmental hydrology. In: *Hydrological Extremes in Small Basins* (W. Chelmicki & J. Siwek, eds). UNESCO IHP-VII Technical Documents in Hydrology 84, Paris, France, pp. 117–122.
- Littlewood, I. G. & Jakeman, A. J. 1991 Hydrograph separation into dominant quick and slow flow components. In: *Proc. Brit. Hydrol. Soc. Third Nat. Hydrol. Symp.*, Southampton, UK, pp. 3.9–3.16.
- Mandeville, A. N. 2004 The reservoir inflow sequence (RIS) method of hydrograph analysis applied to a set of 25 flood events observed on a catchment located in western United Kingdom. In: *Proc. Brit. Hydrol. Soc. Int. Conf.*, London, UK, Vol. 1, pp. 171–179.
- NERC 1975 *Flood Studies Report*. Natural Environment Research Council, Swindon, UK, Vol. 1, pp. 388–390 and 425.
- Reed, D. W., Johnson, P. & Firth, J. M. 1975 A non-linear rainfall-runoff model, providing for variable lag time. *J. Hydrol.* **25**, 295–305.
- Whitehead, P. G., Young, P. C. & Hornberger, G. M. 1979 A systems model of streamflow and water quality in the Bedford-Ouse River. 1. Streamflow modelling. *Water Resour. Res.* **13**, 1155–1169.
- Young, P. C. 1975 Recursive approaches to time series analysis. *Bull. Instit. Math. Appl.* **10**, 209–224.
- Young, P. C. 1984 *Recursive Estimation and Time Series Analysis*. Springer-Verlag, Berlin, Germany.
- Young, P. C. & Beven, K. J. 1991 Computation of the instantaneous unit-hydrograph and identifiable component flows with application to two small upland catchments—comment. *J. Hydrol.* **129** (1–4), 389–396.
- Young, P. C. & Beven, K. J. 1994 Data-based mechanistic modelling and the rainfall-flow nonlinearity. *Environmetrics* **5** (3), 335–363.

First received 25 March 2015; accepted in revised form 26 January 2016. Available online 24 February 2016