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Scientific Assistance towards a Probabilistic Formulation of Hydraulic Boundary Conditions

Synthetic events reference guide

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Scientific Assistance towards a Probabilistic Formulation of Hydraulic Boundary Conditions

Synthetic events reference guide

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Abstract

This report gives an overview of the workflow to generate synthetic events with known frequencies. The synthetic events are the result of the combination of unit profiles and extreme quantiles with known probabilities of occurrence. This report is the base for a software tool developed for synthetic events generation. Furthermore the general procedure for synthetic events generation is described for two particular cases

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1 Introduction

1.1 Scope of contract

Flanders Hydraulic Research (FHR) has commissioned IMDC NV to adapt its standardized methodology for rendering composite hydrographs, developed at KU Leuven (Willems 2001 & 2002), to recent evolution (e.g. climate change), updated data series (e.g. recent measurements) and diversifying applications (e.g. coastal zone, flood risk calculations,…).

The project team consists of Sarah Doorme (advisor), Gert Leyssen (jr. Eng.), Lorens Coorevits (jr. Eng.) and Joris Blanckaert (Sr. Eng. and project manager for IMDC). On behalf of FHR Eng. Fernando Pereira is in charge of the general supervision of the project. Eng. Toon Verwaest of FHR ministers scientific support towards coastal zone applications.

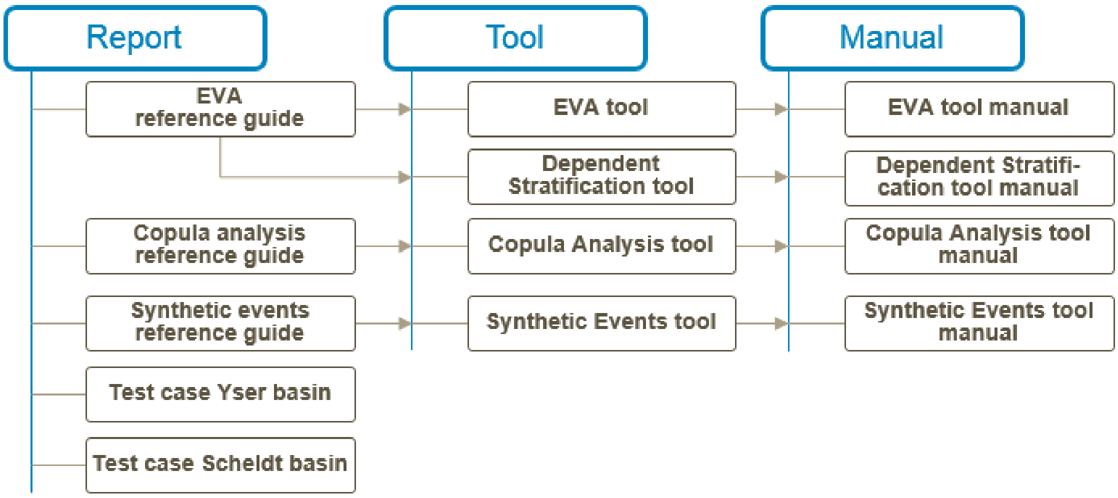
1.2 Overview

A new methodology is presented, which is based on extended literature review and expertise of the project team members. The methodology is described in a set of technical reports and is implemented in a suite of software tools for use in flood risk analysis and probabilistic design projects. The Graphical User Interfaces of the software tools are described in a set of manuals.

The new methodology is tested within two representative test cases, i.e. for the Yzer basin and the Scheldt basin (navigable waterways in Flanders). The test cases are described in two reports.

Figure 1-1 presents an overview of the reports, tools and manuals.

Figure 1-1: Overview of reports, tools and manuals



1.3 This report

This report provides an overview of the creation of unit profiles and synthetic events. A unit profile is a characteristic shape of an event based on events in observed or simulated time series, for example a rainfall runoff hydrograph, scaled between 0 and 1. A unit profile can be combined with synthetic quantiles to create extreme synthetic events with a set probability of occurrence. These synthetic evens can be used as design boundary conditions.

The approach to generate synthetic events is slightly different for different random variables. There are variables with one parameter, like storm surge, and variables with multiple parameters, like wind with wind speed and wind direction or hydrographs which are composed of base flow and runoff.

The second chapter provides an overview of the workflow to generate synthetic events composed of one parameter. The third chapter highlights the approach to generate respectively synthetic discharge hydrographs and synthetic wind events.

This report is used to create a software application which facilitates the creation of synthetic events (see Figure 1-1).

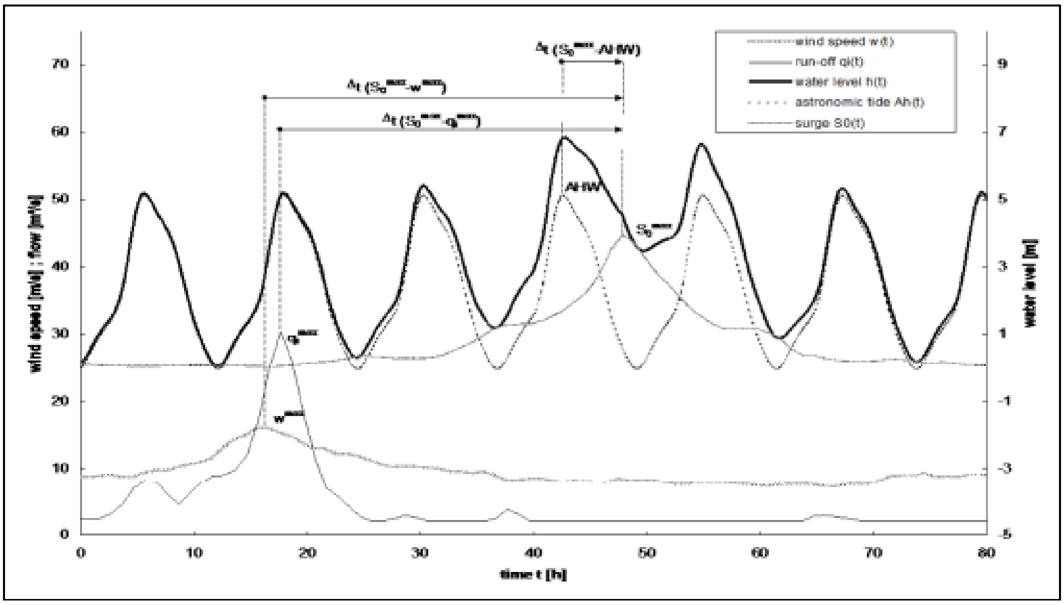
2 Synthetic events

Synthetic events are the combination of synthetic extremes drawn from an extreme value analysis and a normalized unit profile that's empirically deducted from the extreme events in the observed time series or generated on a theoretical basis. A normalized unit profile is scaled between 0 and 1. If it is empirically deducted, a standard deviation can be calculated. Multiplication of the normalized unit profile with the value of the synthetic extreme yields a synthetic event with a set probability of frequency of occurrence, which is calculated by means of the extreme value distribution.

A major advantage of this methodology is its flexibility. The number of primary and secondary variables can be changed from strictly univariate to fully multivariate. Furthermore a statistical uncertainty analysis can be performed without additional model computations, since the same set of synthetic storms is used, only the probabilities are modified.

Figure 2-1 displays a joint synthetic event with 3 main variables, consisting of a synthetic wind speed event, a synthetic hydrograph and a synthetic tidal profile derived from a synthetic storm surge in combination with a tidal profile. Time lags ⊠t between the main variables are taken into account as (conditional) secondary variables.

Figure 2-1: Joint synthetic storm wind-flow-storm surge



But the most appealing advantage is the focus on the probability of consequences. Synthetic storms do have a frequency per year, which is invariable, but there is no relation with the exceedance frequency (or return periods) of the corresponding consequences. This is especially convenient in fields where there is no clear causality between boundary condition and consequence. For instance a geotechnical dike failure can be caused by a storm "i", having a limited storm surge but a high wind speed from an unfavorable direction (hence major wind waves), and by a storm "j", with high storm surge but rather favorable wind direction.

Although it is possible to calculate the return period of the high water level of storm i and j, or the return period of their wind speed, which will probably be different, this is not of practical importance. The return period of the consequence, the dike failure, is of much greater importance, and is calculated by summation of the frequencies of storm i and j[1]. The methodology with synthetic events, generated by stratified sampling, has the mere advantage that it allows for determining a frequency distribution of the consequences – the considered failure modes – rather than assigning the statistical frequencies of the hydrodynamic load to the consequences (cfr. Composite hydrographs). Hence, this appears to be an appropriate methodology for risk analysis.

2.1 Workflow

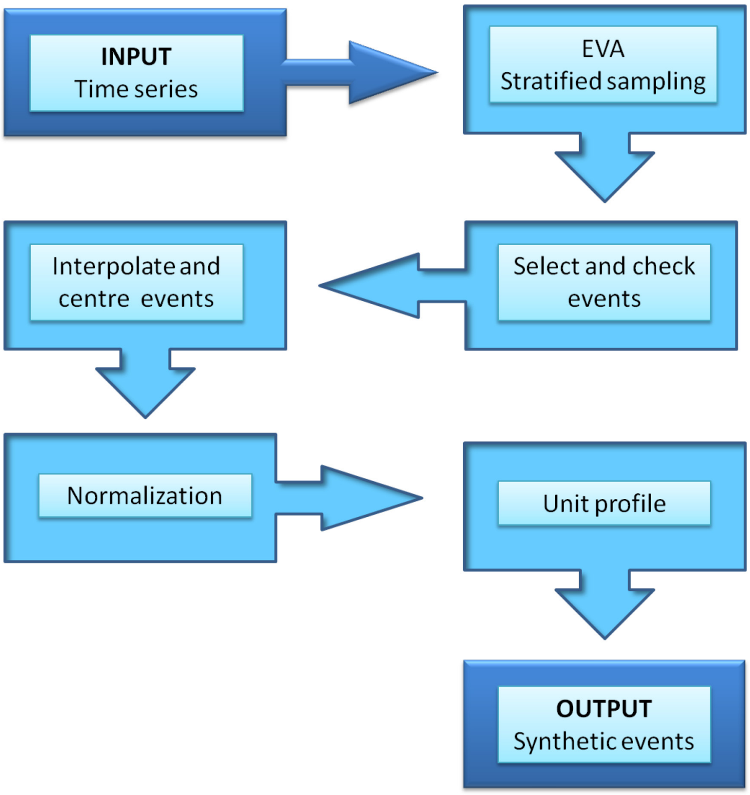
The creation of univariate synthetic events consists of 3 steps:

- Extreme value analysis (see EVA reference Guide; Figure 1-1)
    - POT selection or Block maxima selection (for each main variable)
    - Fitting of an extreme value distribution by maximum likelihood and in case of a multivariate distribution fit of a Copula analysis (see Copula Analysis reference Guide; Figure 1-1) to transform the univariate distributions to a multivariate one.
    - Stratified sampling to generate synthetic extremes with a known frequency
- Unit events (for every main variable)
    - Select events by considering the data in a certain time frame around the extremes and check the events
    - Interpolate the events to time series with a constant time step (t=0 on extreme values)
    - Normalize the events.
    - Calculate the mean normalized event (unit profile) + standard deviation based on the highest events
- Synthetic events
    - Combine unit profile(s) with extreme quantiles

The workflow is schematized in Figure 2-2.

[1] It is important to make a clear distinction between frequency (occurrences in number per time interval) and exceedance frequency (exceedances in number per time interval). Exceedance frequency is the reciprocal of return period.

Figure 2-2: General workflow of the synthetic event procedure



2.2 Extreme value analysis

2.2.1 POT or Block maxima selection

POT, peak over threshold, selection is the identification of local independent maxima above a certain threshold u. The inter-event level factor (IELF) and time interval guarantee the independence of the POT values. The minimal variable value between 2 POT values has to be lower than the inter-event level, which is determined by the product of the IELF and the value of the lowest POT of the two. The time interval is the minimal time between two POT values. A block maximum is the maximal value in a certain time period, e.g. yearly maxima.

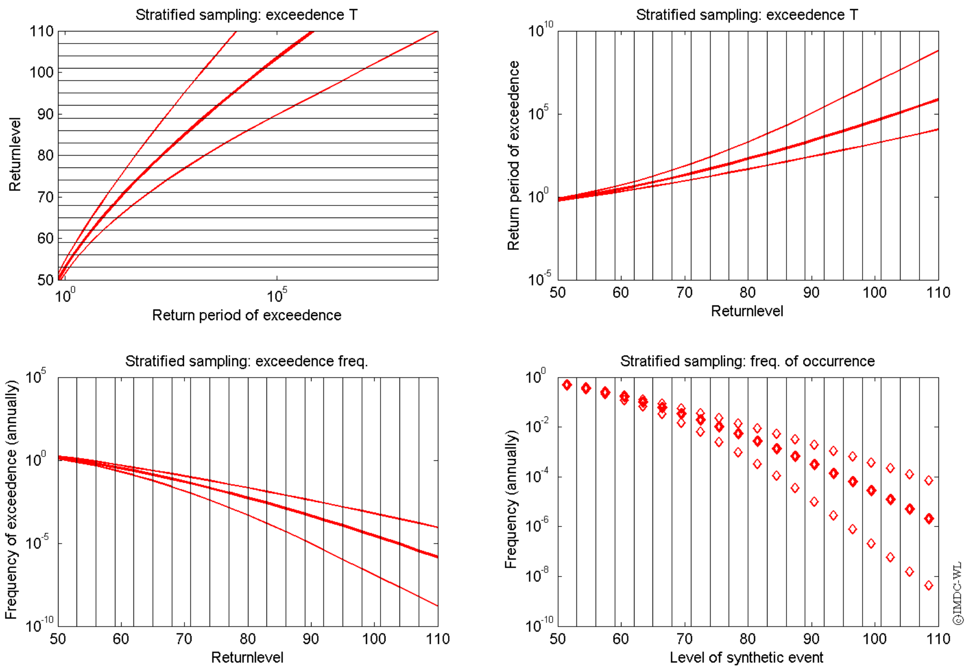
2.2.2 Fitting of the extreme value distribution

The methodology to fit an extreme value distribution through a selection of extreme values is covered in the EVA reference guide (see Figure 1-1).

2.2.3 Stratified sampling

Stratified sampling is a sampling method where the amount of samples can be controlled. It is a statistical technique where the main population is divided into homogeneous subdomains, or (hyper)cubes. In this case the extremes are divided into a number of subdomains and the extreme value distribution is discretized so the frequency of occurrence of every subdomain is known. Each subdomain will be represented by its mean value. The subdomains should not be too wide in order to achieve a good representation of the entire domain. On the other hand the number of subdomains is proportional to the number of simulations. Hence it should be limited to keep the computational time under control. An illustration of the stratification of a univariate distribution based on the return level-return period plot is visualized in Figure 2-3. The domain is subdivided into fixed classes with a fixed width of the return level. The frequency of each subdomain is calculated and linked with the mean value of each subdomain.

Figure 2-3: Stratification of the return level-return period plot



This *stratification* procedure can also be applied to a multivariate population. The d-variate uniform population ($[0, 1]^d$) will be subdivided in elementary d-hypercubes, each of which having its own probability. Each elementary hypercube is being represented by a synthetic event with a certain probability of occurrence (frequency) calculated by the multivariate distribution. It is important to note that the number of synthetic extremes increases exponentially with the number of dimensions of the multivariate distribution.

2.3 Unit profile

The unit profile is calculated for all the main variables in the steps described below.

2.3.1 Select event

The events are chosen by selecting data in a time frame around each extreme value. This frame is dependent on the variable and the duration of the event and has to be determined by manual inspection and expert judgment. In most cases the time frame will be asymmetric around the maximum. The time frame, before and after the maximum, has to be wide enough to include the longest events.

2.3.2 Interpolate and center events

The time step and time frame of all the selected events have to be equal because of the normalization procedure. This can be accomplished by linear interpolation of the existing data points to a time series with fixed time step and a time frame with time zero at the POT value.

2.3.3 Check of the events

The selected events have to be checked both for possible measurement errors and for their specific behavior. It is important that every time frame contains only one event. A wide time frame can contain multiple events where only the event corresponding to the extreme value is desirable.

2.3.4 Normalize events

The events are scaled by dividing every value by the maximal value of the event. Hence normalized events with a peak value of 1 at time zero are obtained.

2.3.5 Unity profile

The mean value for each of the event time steps yields the unit profile. The number of normalized events used in this calculation should be high enough to take the variation into account and small enough to be a good representation of the evolution of the highest events. To take the natural variation around this mean unit profile (Y_{m_u}) into account the standard deviation is calculated for every time step:

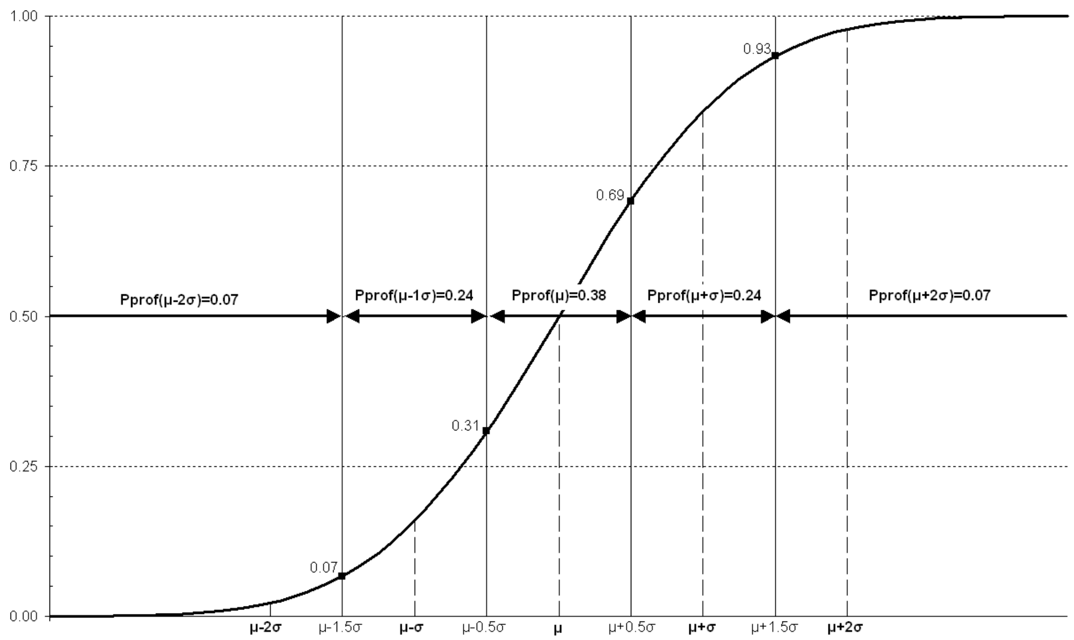
$$Y_{m\_u} = \frac{\sum_{i=1}^{n} Y}{n}$$

$$std\_Y = \sqrt{\frac{\sum_{i=1}^{n} \left(Y - Y_{m\_u}\right)^2}{n-1}}$$

This results in five unit events with a known probability under the assumption of a normal distribution (Figure 2-4):

- μ-2σ: the mean unit event minus twice the standard deviation
- μ- σ: the mean unit event minus the standard deviation
- μ: the mean unit event
- μ+ σ: the mean unit event plus the standard deviation
- μ+2 σ: the mean unit event plus twice the standard deviation

Figure 2-4: Probability of the five unit profiles under the normal distribution assumption



2.4 Synthetic events

A synthetic event is the combination of the unit profile and the extreme quantiles with a known probability. So every synthetic extreme will result in 5 curves which have a total probability equal to the probability of the extreme quantile. The probability of each profile is the probability of the corresponding extreme quantile multiplied by the probability of the profile.

In case of multiple main variables each extreme quantile consists of a set of values for the main variables with a joint probability. The values of secondary variables are derived from the primary values. The combination of primary and secondary variables is case dependent and will be further explained in the test cases (see Figure 1-1).

3 Particular cases

The procedure described in chapter 2 is the general procedure. Some particular cases can be identified where a slightly adapted procedure is necessary. This is usually the case if a primary variable consists of two or more components.

The procedures described below are written for a univariate case to improve the readability, but they can be extended to a case with multiple main variables.

3.1 Discharge

A discharge event or hydrograph gives the rate of flow (discharge) versus time at a specific point in a river or channel. The rate of flow is typically expressed in cubic meters per second. From a conceptual point of view, a stream hydrograph is commonly considered to include at least a base flow component and a direct flow component. The former represents the relatively steady contribution to stream discharge from groundwater flow, while the latter represents the additional stream flow contributed by surface runoff, typically as a result of a rainfall event. The shape of a discharge event depends on various factors like the topography of the river, the geology of the basin and the rainfall event. This case will focus on the creation of synthetic hydrographs for the Belgian rivers. The methodology to create extreme synthetic discharge events has already successfully been applied in IMDC (2008).

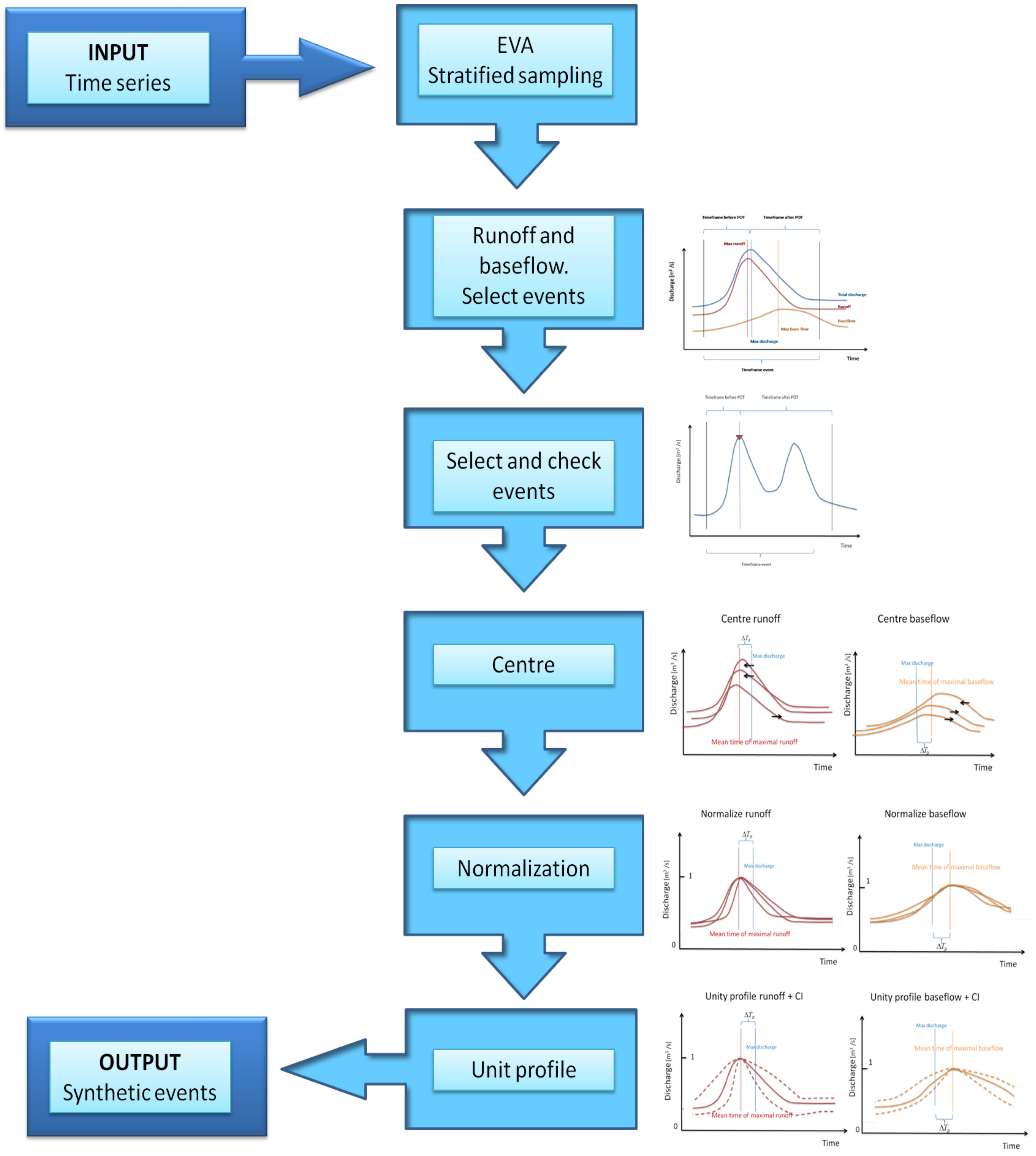
3.1.1 Workflow

To obtain a synthetic discharge event which is composed of base flow and runoff the following steps are necessary:

- Extreme value analysis (see EVA reference Guide; Figure 1-1)
  - POT or Block maxima selection
  - Fitting of an extreme value distribution by maximum likelihood
  - Stratified sampling to generate synthetic extremes with a known frequency
- Unit events
  - Calculate runoff and base flow for the entire time series
  - Select and check event by taking the data of a certain time frame around the extremes
  - Centralize runoff and base flow maxima
  - Normalize the runoff and the base flow of the selected events so their maximum is equal to 1.
  - Calculate the mean normalized event (unit event) and standard deviation that is representative for the highest events
- Create synthetic events
  - Combine unit hydrograph with the synthetic extremes

The workflow is schematized in Figure 3-1.

Figure 3-1: Workflow for synthetic discharge events



3.1.2 Extreme value analysis with stratification

The extreme value analysis is identical to the procedure described in §2.2.

3.1.3 Unit profile

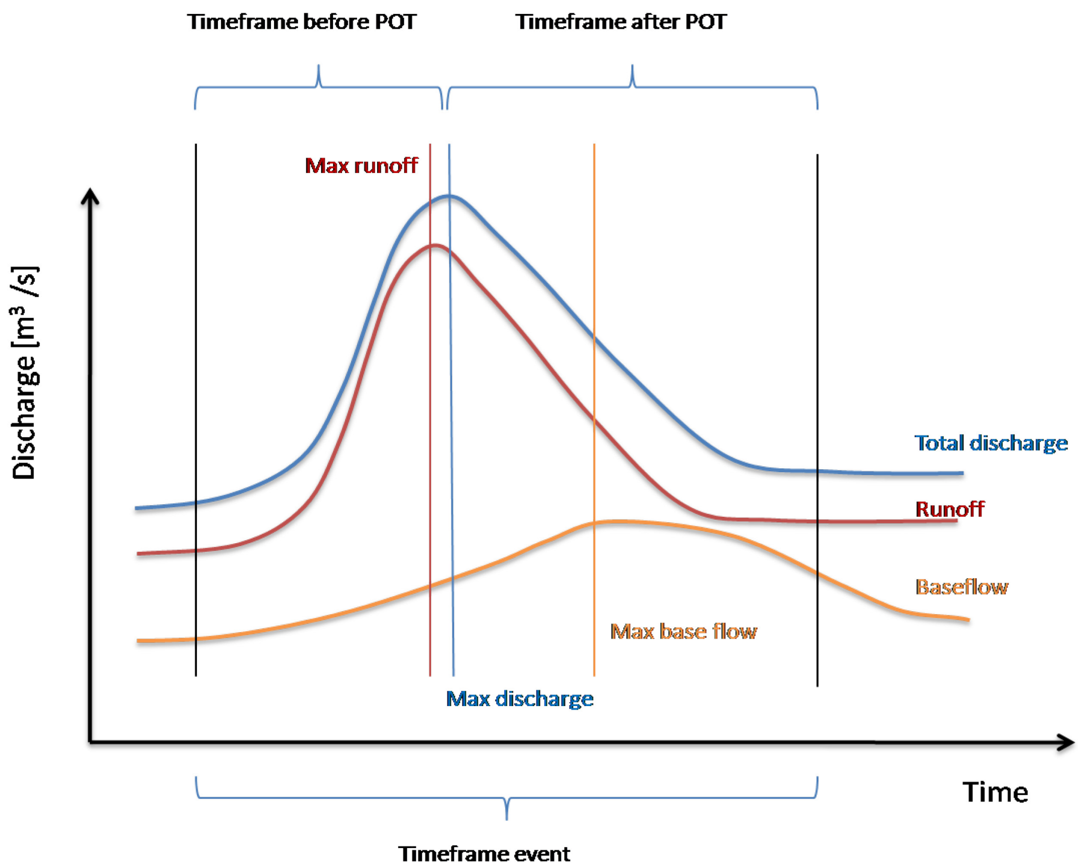
Calculation of the runoff and base flow and select events

The total discharge is the sum of the runoff and the base flow. This base flow can be calculated by the procedure described in Eckhardt (2005).

$$Q_b(t) = \frac{(1 - BFI) * \alpha * Q_b(t-1) + (1-\alpha) * BFI * Q(t)}{1 - \alpha * BFI}$$

With α the recession constant and BFI the base flow index with default values of respectively 0,99 and 0,35. This technique assumes a measured time series of the total discharge without gaps. Interruptions or missing values will lead to errors because the value at time step t is based on the value at the previous time step. The runoff can be calculated by subtracting the base flow from the total flow (Figure 3-2).

Figure 3-2: Theoretical hydrograph



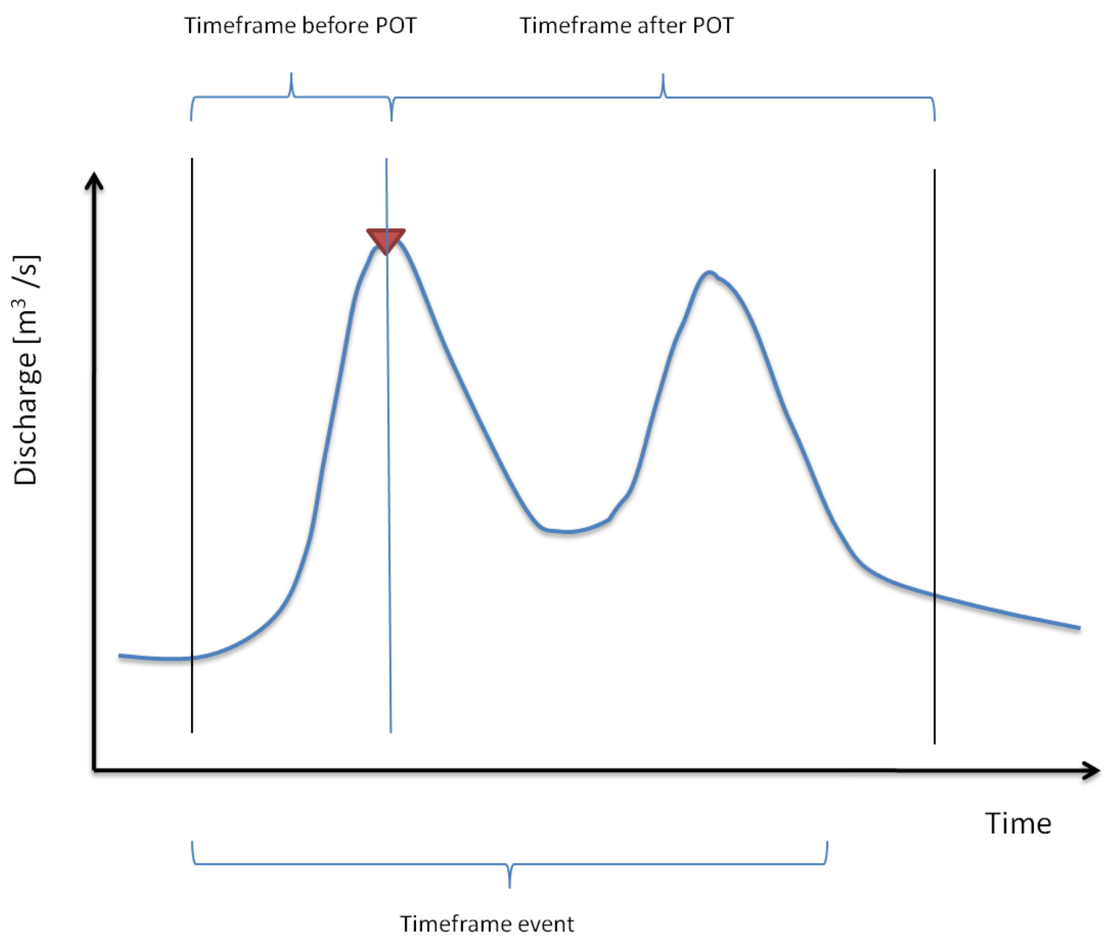
The events are chosen by selecting data in a time frame around each extreme value. This frame is dependent on the river profile and has to be determined based on the shape of the highest hygrographs (manual inspection and expert judgment).

In most cases the time frame will be asymmetric around the maximum of the hydrograph because a typical hydrogram has a steep rising limb and a less steep recession limb (Figure 3-2). The timeframe, before and after the maximum, has to be wide enough to include the longest hydrographs. The time step and time frame of all selected events have to be equal because of the averaging in the standardization procedure. This can be accomplished by linear interpolation of the existing data points to a time series with fixed time step and a time frame with time zero at the POT value.

Hydrograph check

It is important to select only one hydrograph, but the entire hydrogram, in each event. The time range of some hydrographs can be so short, for example summer events that several independent hydrographs can occur in one chosen time frame. The winter events on the other hand contain multiple peaks where the second or third peak possibly causes the worst flooding because all the storage areas are filled during the first peak (Figure 3-3). A manual check of the time frame of all the events is an important step in the analysis. A user friendly application for this step is developed in the software application.

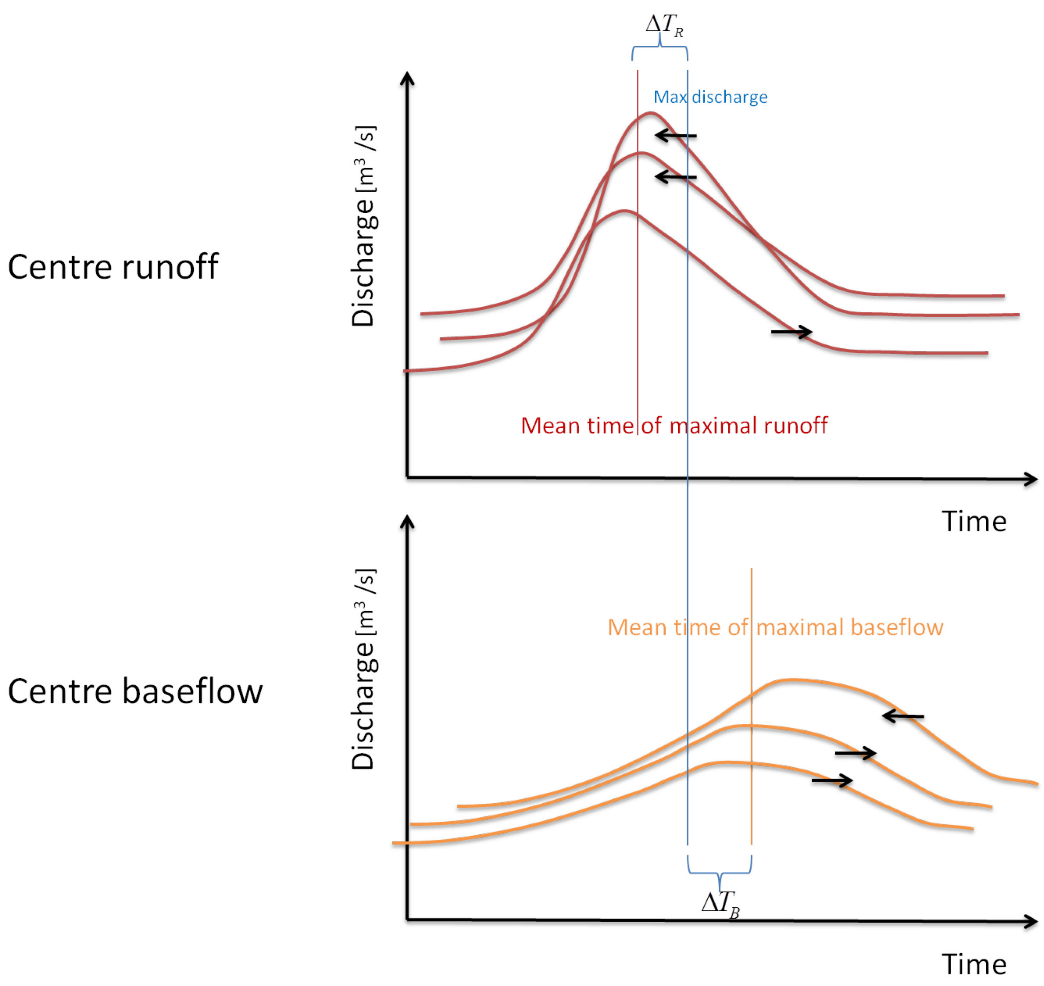
Figure 3-3: Double hydrogram



Centralize

The discharge of each event can be considered to consist of runoff flow and base flow. The maximum of the runoff is generally reached before the total discharge maximum while the maximum of the base flow is reached afterwards. The time difference between the maximum of each runoff hydrograph and the POT of the total discharge is different for each event. The mean difference will be used to centralize the maxima of the runoff (Figure 3-4). This way all the maxima of the runoff events will be on the same time step so a standardized runoff profile can be calculated. The maxima of the base flow are generally reached after the total discharge maximum but the time difference depends on the event. Again the mean difference is used to centralize the base flow events (Figure 3-4). The different events can have different time frames, based on the manual selection. The normalization procedure on the other hand allows only one timeframe. The broadest time frame is used for the analysis, while the values for the shorter events are given by a linear interpolation between the first or last value and the minimum in de missing time period.

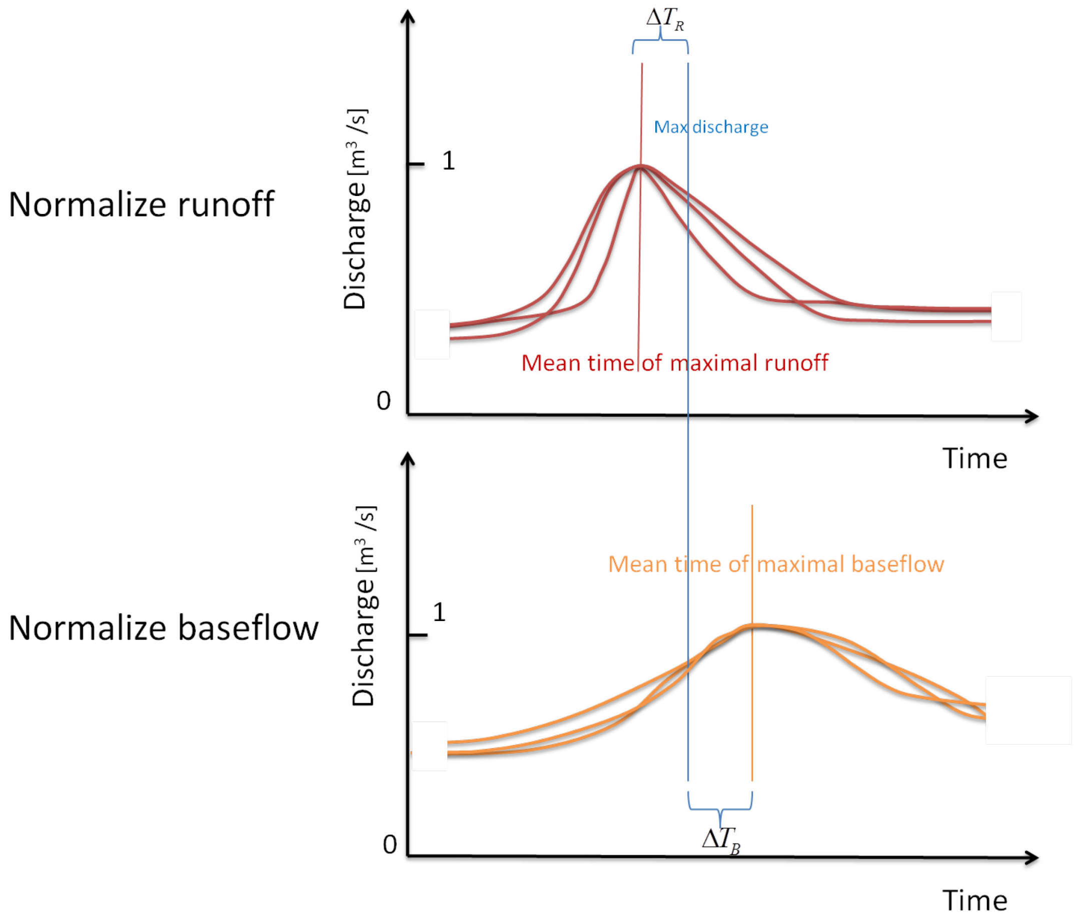
Figure 3-4: Centre procedure for the runoff and base flow



Normalization

Once the events are selected the runoff and the base flow can be normalized by dividing by, respectively, the maximal runoff and base flow. This way every event has the same weight in the calculation of the unit profile (Figure 3-5).

Figure 3-5: Normalized runoff and base flow



Unit profile

For each time step the scalar mean over all the normalized runoff and base flow events yields the unit runoff and base flow event. The standard deviation in combination with the assumption of normality around the unit profile yields confidence intervals around each unit profile. The mean unit profile for the runoff (Q_{R_u}) and base flow (Q_{B_u}) can be calculated for every time step (Figure 3-6):

$$Q_{R\_u} = \frac{\sum_{i=1}^{n} Q_{R\_i}}{n} \quad Q_{B\_u} = \frac{\sum_{i=1}^{n} Q_{B\_i}}{n}$$

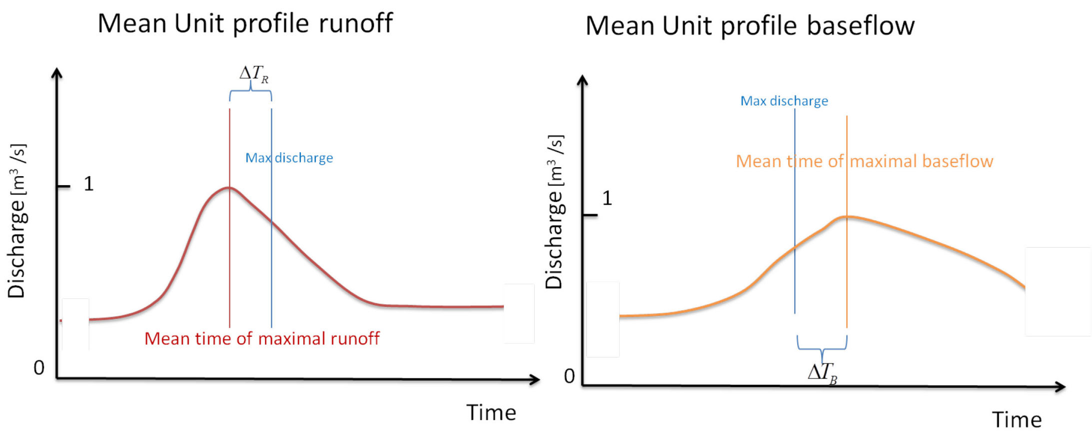
The runoff and the base flow will be recombined to form a total hydrograph. The combination of the runoff and base flow standard deviation will however result in a non-zero standard deviation on the maximum discharge. This causes problems in the creation of the synthetic events.

Another approach is to use the standard deviation of the total discharge events. This standard deviation also contains the natural deviation around the mean unit profile. Because of the specialized recomposition of the total discharge, based on the runoff, base flow and extreme quantile, the standard deviation can only be combined with the discharge after its recomposition. The total discharge standard deviation is given for every time step by:

$$std\_Q = \sqrt{\frac{\sum_{i=1}^{n}(Q_i - Q_u)^2}{n-1}}$$

Where Q_i is the total discharge of event i and Q_u the mean unit profile.

Figure 3-6: Mean unit profile



3.1.4 Synthetic events (hydrographs)

A synthetic event is the combination of the unit profile and the extreme quantile with a known probability. In case of hydrographs there are two unit profiles, runoff and base flow, which both contribute to the total hydrograph. The maximal value of this total hydrograph is given by the extreme quantiles. For each time step (t) the total discharge (Q) is given by the sum of the base flow unit profile ($Q_{u,b}$ multiplied by the maximal base flow ($Q_{b,max}$) and the runoff unit profile ($Q_{u,r}$) multiplied by the quantile ($Q_{s,max}$) minus 'a'.

$$Q(t) = Q_{u,b}(t) * Q_{b,max} + Q_{u,r}(t) * (Q_{s,max} - a)$$

$Q_{b,max}$ is a function of $Q_{s,max}$ found by a simple linear fit through the POT values and their corresponding base flow maxima (Figure 3-7). The parameter 'a' is found by iteration so the maximum of the total discharge is equal to the considered extreme value. This gives the mean profile. Under the assumption that variance of the unit profile of runoff discharge follows the normally distributed, the mean and standard deviation of the total discharge of every extreme quantile is (std_Q_{eq}):

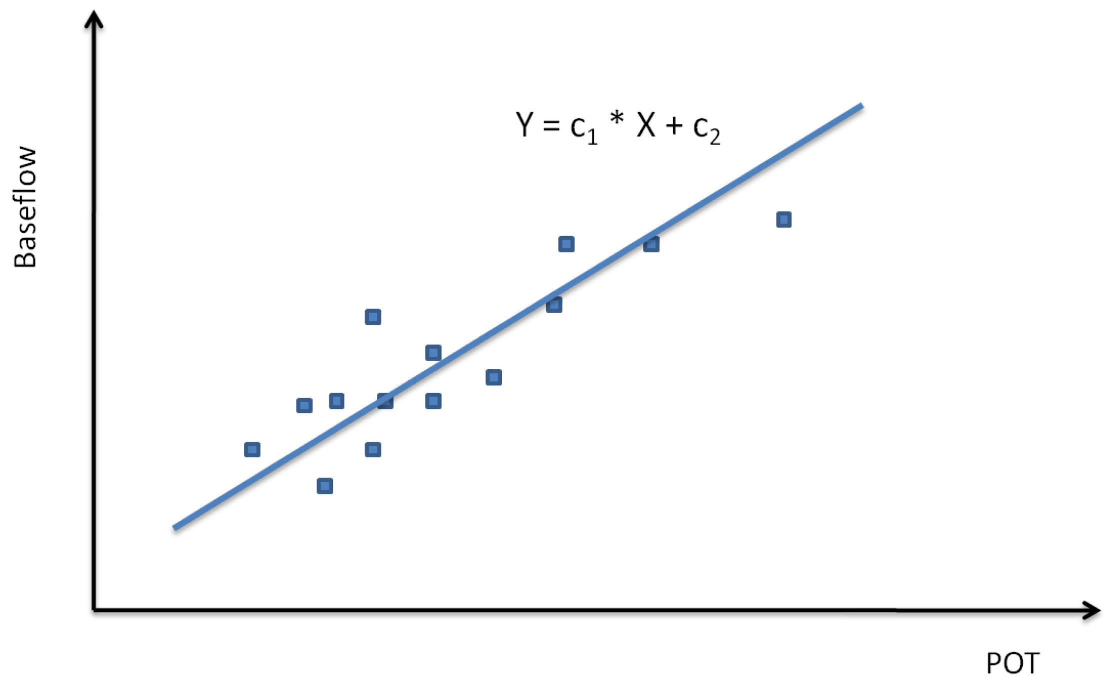
$$std\_Q_{eq} = std\_Q_{u,r} * Q_{s,max}$$

This results in 5 profiles for the total discharge:

- μ-2σ: the mean synthetic event minus twice the standard deviation
- μ- σ: the mean synthetic event minus the standard deviation
- μ: the mean synthetic event
- μ+ σ: the mean synthetic event plus the standard deviation
- μ+2 σ: the mean synthetic event plus twice the standard deviation

The value of the synthetic event has to be higher than the base flow. So in case μ- σ ορ μ- 2σ is less than the base flow, the base flow is used.

Figure 3-7: Relationship between the POT and the base flow



3.2 Wind events

Wind is in some cases a primary variable with minor importance. If one researches the impact of storm surge, wind and the driving depression will generate the surge but the focus will be only on these wind events that generate and therefore occur at the same time as a surge event. In this case only a subset of all the wind events is used in the analysis. In other cases like wave modeling or windmills load research all the wind events are included in the analysis.

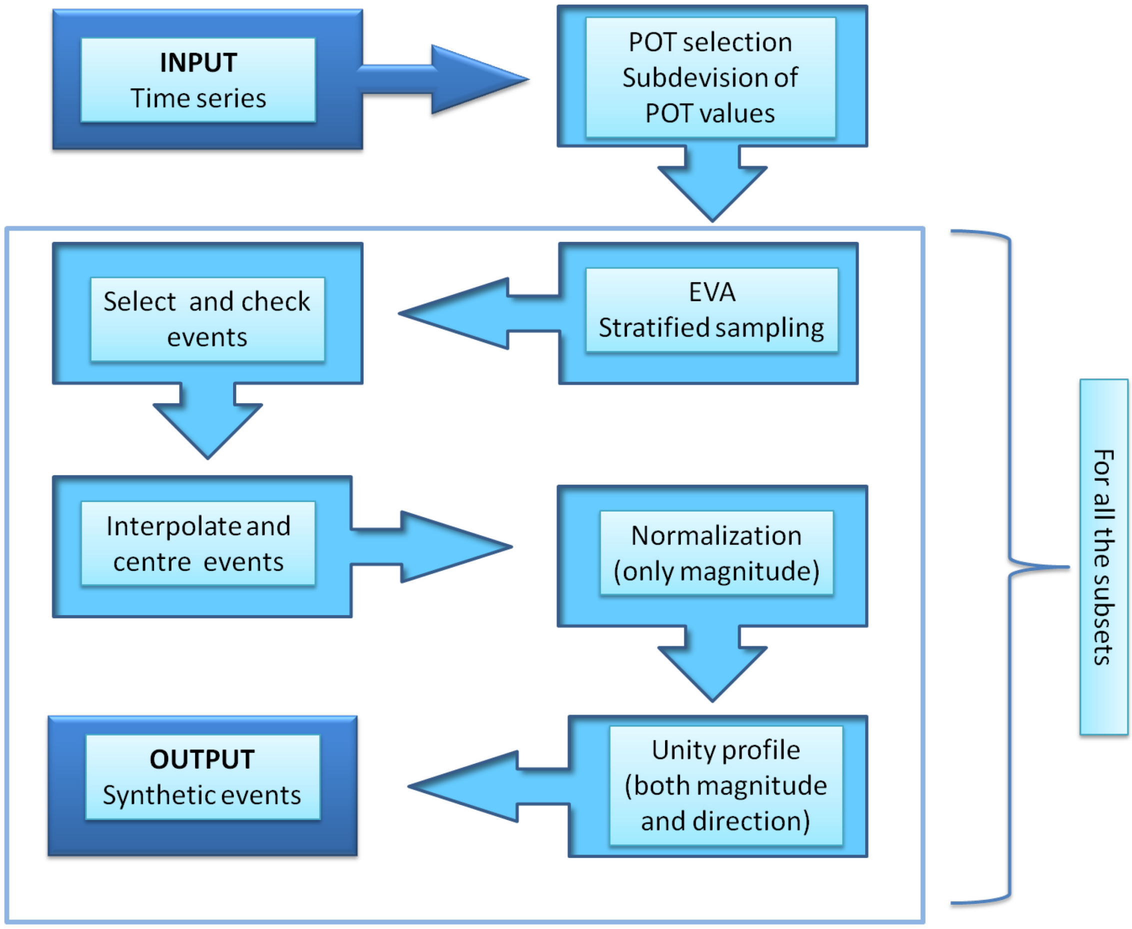
A second complexity of wind is that it consists of a magnitude and a direction. The common approach is to subdivide the wind events into discrete direction intervals based on the direction at the moment of the highest wind speed. The behaviour between the direction intervals are in most cases significantly different. The entire analysis for synthetic events is performed for every direction interval. A validation with the omnidirectional extreme value analysis is recommended.

3.2.1 Workflow

- Extreme value analysis (see EVA reference Guide; Figure 1-1)
    - POT or block maxima selection
    - Subdividing the extreme values if necessary (ex. direction + surge event). The following steps will be performed for all the subsets.
    - Fitting of an extreme value distribution by maximum likelihood
    - Stratified sampling to generate synthetic extremes with a known frequency
- Unit events
    - Select and check event by taking the data of a certain time frame around the extremes
    - Interpolate events to time series with a constant time step (t=0 on extreme values), i.e. both magnitude and direction
    - Normalize the magnitude of the events
    - Calculate the mean normalized event (unit profile) and standard deviation of both the magnitude and the direction that is representative for the highest events. This gives wind events with a time varying magnitude and direction
- Create synthetic events
    - Combine unit profile with synthetic extremes

The workflow is schematized in Figure 3-8.

Figure 3-8: workflow synthetic wind events



3.2.2 Extreme value analysis

POT or block maxima selection

See §2.2.1.

Subdividing of the extreme values

The extreme values are subdivided into 16 wind directions with a width of 22.5 °. The next steps will be performed for all the subsets. The extreme wind values can be divided into even smaller subdivisions based on the main variable under investigation. In a surge impact assessment it is recommended to take only the wind extremes which generate a significant surge into account.

Fitting of the extreme value distribution

The methodology to fit an extreme value distribution through a selection of extreme values is extensively covered in the EVA reference Guide (see Figure 1-1). A distribution is fitted through the extreme values of each wind direction.

Stratified sampling

The stratified sampling procedure is identical to the procedure described in § 2.2.3.

3.2.3 Unit profile

Select and check events

The events are chosen by selecting data in a time frame around each extreme value. This frame is depending on the variable and the duration of the event and has to be determined based by visual inspection and expert judgment. In most cases the time frame will be asymmetric around the maximum. The time frame, before and after the maximum, has to be wide enough to include the longest events.

The events have to be checked for measurement errors and time frame. It is important that every time frame contains only one event. A wide time frame can contain multiple events where only the event corresponding to the extreme value is desired.

Interpolate and center events

The time step and time frame of all the selected events have to be equal because of the averaging in the normalization procedure. This can be accomplished by linear interpolation off the existing data points to a time series with fixed time step and a time frame with time zero at the POT value.

Normalize events

The events are made uniform by dividing every magnitude value by the magnitude of the POT value. The directions are kept. This way the standardized wind events with a wind speed of 1 m/s at the peak value and the original directional variation are created.

Unit profile

The wind speed of a normalized synthetic wind event is calculated as a scalar mean over all the standardized wind speeds for every time step. The time frame of the real events is shifted so the POT value corresponds to time zero. So for each time step:

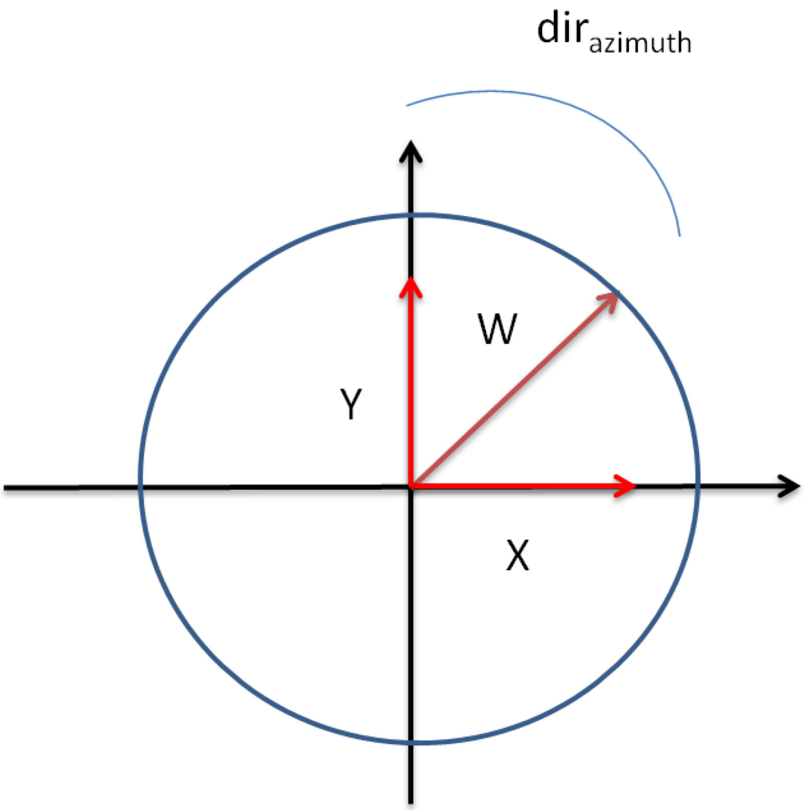
$$W = \frac{\sum_{\mathrm{i}=1}^{\mathrm{n}} \mathrm{W_i}}{\mathrm{n}}$$

With W the average wind speed [m/s] and n the number of events.

The time varying wind direction of a synthetic event is calculated for every time step by scaling the magnitude of the wind vector to 1 (=W). The x and y components of the wind vector are calculated by (see Figure 3-9):

$$W_x = W * cos(360° - [dir_{azimuth} - 90°]) \quad with\ W = 1$$
$$W_y = W * sin(360° - [dir_{azimuth} - 90°]) \quad with\ W = 1$$

Figure 3-9: scaled wind vector with X and Y components



The scalar mean W_x and W_y values of all the events are used to recompose the synthetic wind direction. The scaling gives every event the same weight in the averaging.

3.2.4 Synthetic events

A synthetic event is the combination of the unit profile and the extreme quantiles with a known probability. So every synthetic extreme quantile will result in 5 curves which have a total probability equal to the probability of the extreme. The probability of each profile is the probability of the corresponding extreme multiplied by the probability of the profile. An example of a synthetic wind event with time varying wind speed and wind direction is given in figure 3-10 and figure 3-11.

Figure 3-10: Synthetic wind events (X-Y visualisation)

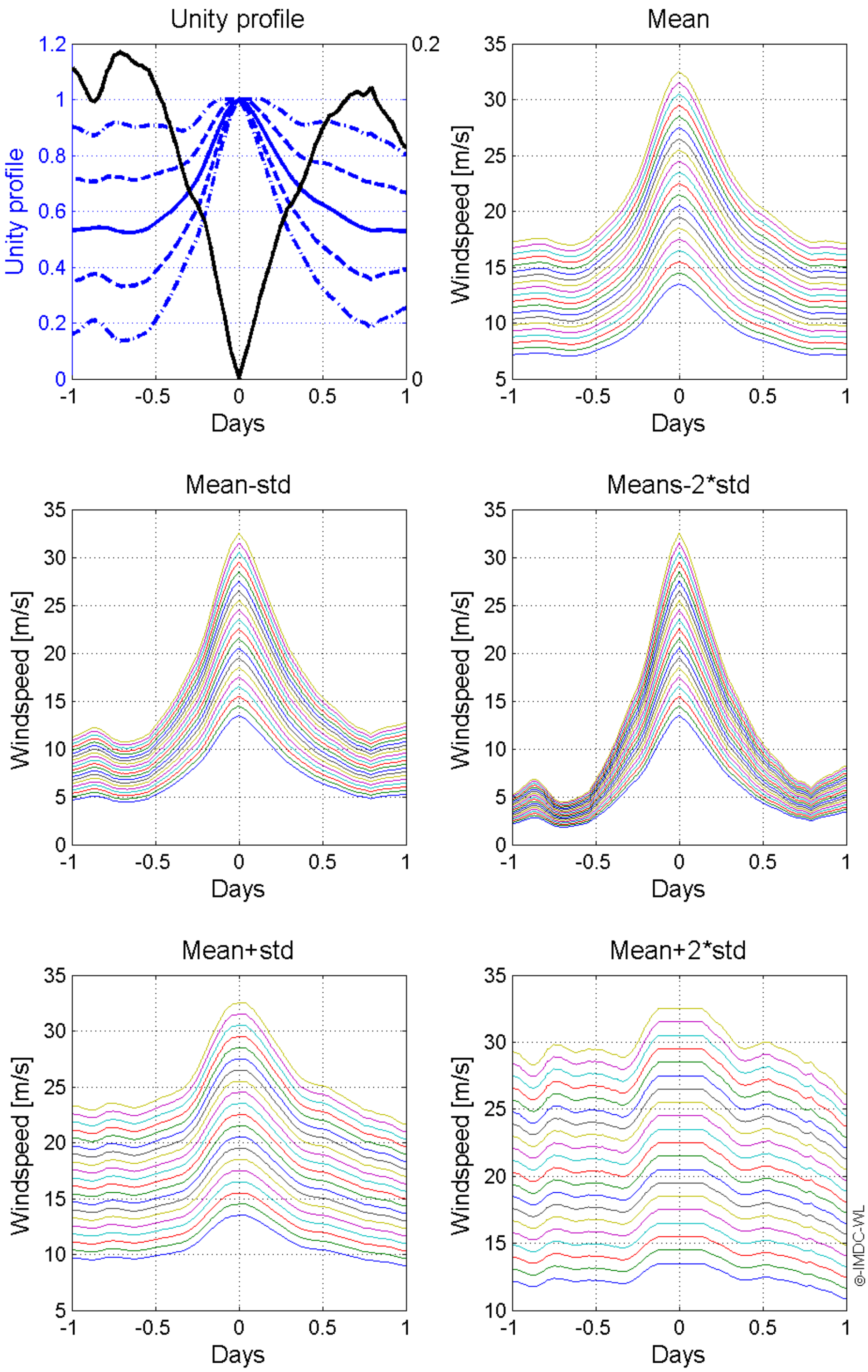
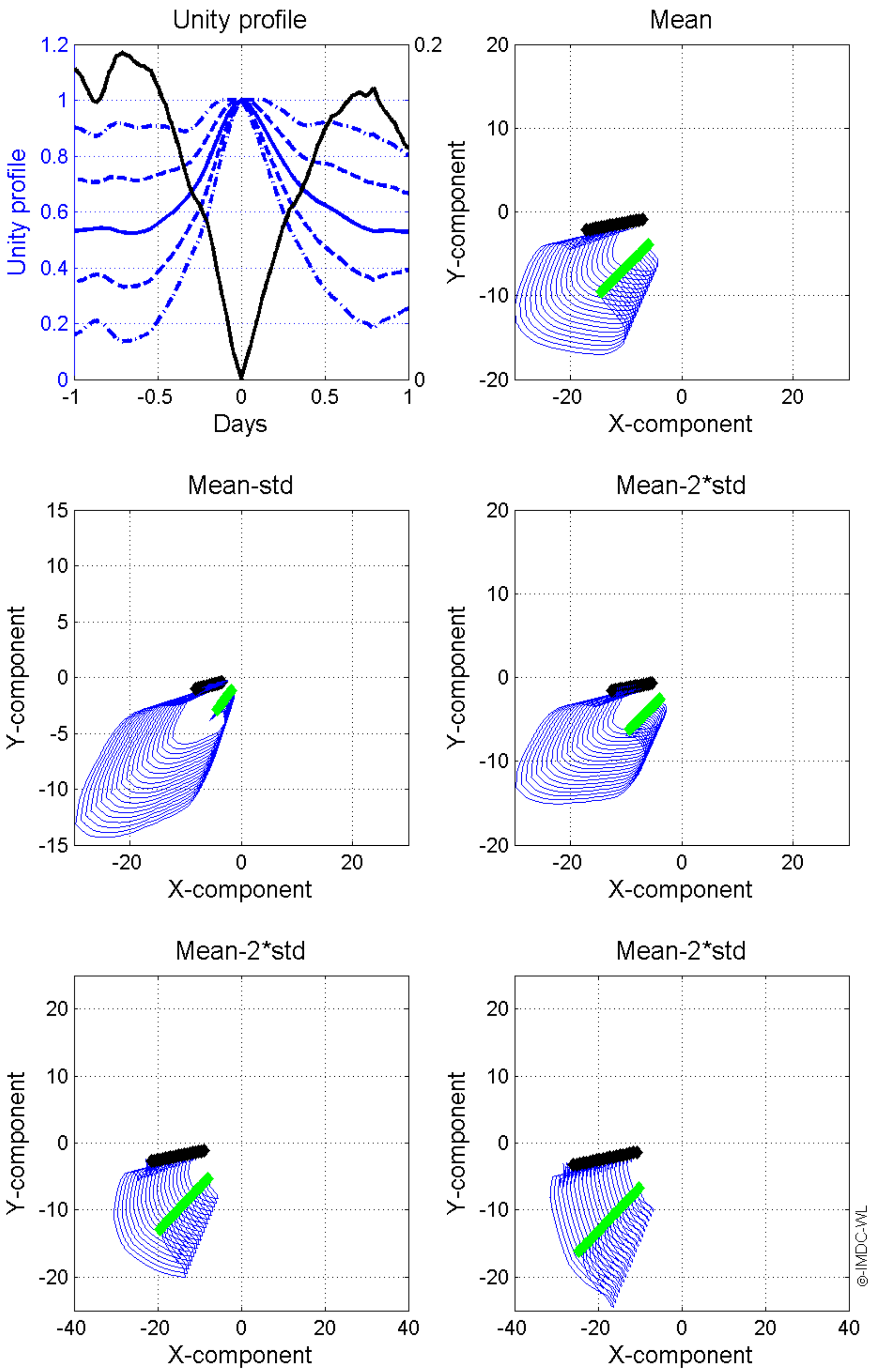


Figure 3-11: Synthetic wind events (X-Y visualisation)



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