# Handling future uncertainties in urban drainage planning using flexible systems - The COFAS Method

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## Abstract

Urban drainage systems are influenced by numerous future drivers, which affect the performance as well as the costs of the systems. A review of different future drivers for urban drainage systems carried out earlier in SWITCH Scholes et al. 2006) illustrates, that no sufficient predictions for the long operational life span of the systems are possible. Therefore, one should consider flexibility as a decision criterion for urban drainage systems. This identified need led to the development of the COFAS method, which enables the flexibility of different BMP options to be identified and compared Sieker et. al. 2008). The method is based on classical utility value analysis UVA) using a hierarchy of indicators for environmental, economic and social aspects Peters et al. 2005). To overcome the difficulty of comparing alternatives regarding different aspects, the assessment for an indicator e.g. cost, emissions or water quality parameter) is standardized by using so-called utility functions. While the classical UVA approach is using only one aggregated system value to compare different scenarios, the COFAS method involves applying statistical methods to the level of variation associated with the utility values under different conditions. A user-friendly software tool for COFAS has been developed which is the core of Deliverable 2.1.4. The deliverable also contains example files a tutorial, and scientific background. Software and deliverable document are available for download on the SWITCH website.

**Keywords:** uncertainties, flexibility, urban drainage, SUDS, COFAS, multi criteria analysis

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## 1. Introduction – Flexibility in urban drainage planning

Cities and Villages are dynamic systems. Especially larger urban agglomerations are ever changing regarding size and structure. Urban areas are also constantly interacting with their environments through expansion, consumption of natural resources, production of pollutants, etc.

The Ruhr-area for example had half a million inhabitants before the industrialisation. Fifty years later 6 million people lived in the same area and the environment had changed totally: heavy air pollution, surface sealing and the conversion of natural rivers into open sewer channels were only some the consequences. In the last decade, the population has shrunken again by several percent caused by the decline of the heavy industry. Until 2015, a drop of 7% has been forecasted. First seen as a bad development, this structural change nowadays leads to high quality jobs, better life standard and a healthier environment. The revitalised river Emscher is a symbol for this process Figure 1).

Figure 1: River Emscher around 1890, 1960 and 2000.

Similar stories are known from all over the world, e.g. from Middle England, Detroit in Michigan or the former communist countries in Eastern Europe. They show very clearly that development not always means growth, although most of the so-called mega-cities like Beijing; Mexico City or Lagos are today in a process of rapid expansion.

It is well known that urban development has a strong impact on the water cycle:

- Increase of flood peaks and volume,
- Decrease of base flow,
- Hydraulic stress and morphological damages,
- Water pollution,

are usually mentioned as typical accompaniments of urbanization, although not the urbanization itself is causing these negative impacts but the way that we usually cope with the runoff from the urban areas. Traditionally, stormwater is discharged as quickly as possible to the next receiving water by pipe systems or open ditches. Negative effects are compensated – if at all – by end of pipe facilities like retention ponds or clarifiers. In recent years, alternative strategies targeting the causes are becoming more popular. These best management practices BMP) – also called 'SUDs ' or LIDs - provide the same drainage comfort as traditional sewer systems but also sustain the urban water cycle and control pollution at the source.

It is obvious that changes in the urban development "urban dynamics") have an influence on design and operation of urban stormwater management systems USWMS) – traditional or

source control approach. For example, an increase of sealed surfaces due to urban sprawl is causing more runoff. For this higher hydraulic load sewers have to be enlarged or new BMPs have to be built. Another example is the higher pollution of road runoff caused by a higher traffic load.

Beside of urban dynamics, stormwater management systems will be affected by climate change. Global warming is a fact today, but a prediction of the extension of the effects on USWMS is difficult because of several reasons:

- Predictions of global warming are based on socio-economic scenarios. Even the best climate model is only an “if-then” prediction.
- Linkage of global warming and change of precipitation pattern has uncertainties.
- Design of USWMS asks for local precipitation with high resolution in time, while the common climate models have a global or regional scale.

Summarized, climate change will have an effect on stormwater management in the future, but is not possible to quantify this effect today. The same applies to many other drivers that may have an influence on USWMS in the future. Figure  shows a mind-map of socio economic environmental drivers and their interactions.

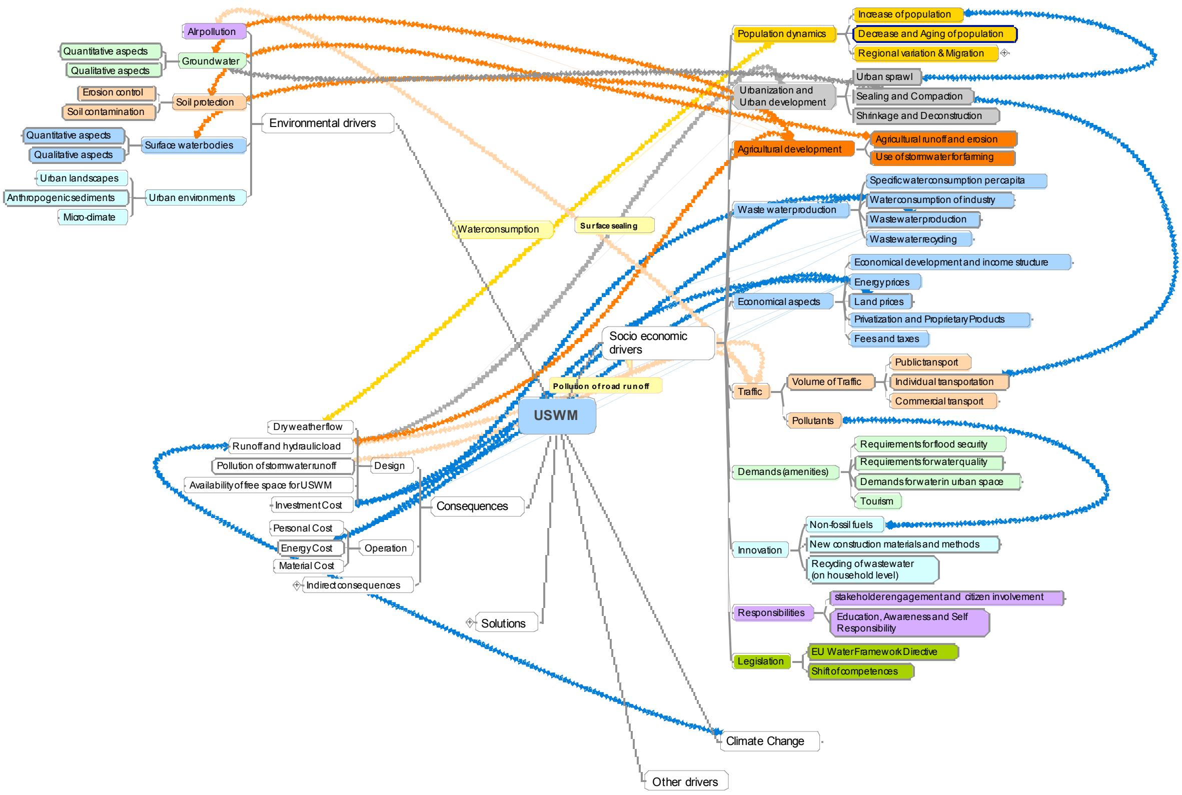


Figure 2: Overview chart of socio economic environmental drivers and their interactions (Scholes et al. 2006)

With having these influences in mind, strategies for design and operation of USWMS should consider future changes. This is in particular the case, because USWMS are usually long-term investments. Compared to other parts of a cities infrastructure like telecommunication or

power supply systems the average lifetime of a sewer system is relatively long. Major parts of an urban drainage system, for example the sewer system or retention tanks have a life cycle of more than 50 years. In Germany, tax deduction for concrete sewer pipes has to be done over approx. 80 years. Many sewers in the city centers are more than 100 years old. Nevertheless, the typical time horizon for an urban drainage master plan UDMP) is usually between 25-30 years. A review of several UDMPs in Germany (Sieker 2000) has shown that:

- Usually only an increase of urban area and water consumption is taken into account as future changes. Other possible drivers like changes in stormwater pollution, demands for higher security against flooding or new regulations are generally not considered.
- Even in cities where a decrease of population is already observed and future reduction is predicted, the urban drainage master plan still assumes an increase of surface sealing.
- Design storms are usually derived from historical recordings of rainfall. Future changes in rainfall pattern causes by climate change are not taken into account.
- Cost comparisons are done on the base of life cycle cost assessments. With this tool, long lasting alternatives are generally preferred. Flexibility and adaptiveness are not considered as decision criteria.

Several negative examples of this common practice can be observed in East Germany. Just after the fall of the iron curtain in the early nineties, most of the East German cities set up new urban drainage master plans. With the euphoria of that time, enormous growth rates had been assumed. The consequences are over-sized drainage systems and treatment plants resulting in very high wastewater tariffs.

An ideal UDMP would have tried to base future scenarios for the socio-economic development on expert knowledge. If a prediction of the socio-economic development is unclear or if scepticism is politically not opportune which was the case in East Germany in the early nineties) than take flexibility and adaptiveness as decision criteria into account.

## 2. Flexibility in System Theory

From a system perspective each system is part of a hierarchy where systems of higher levels are made up of subsystems from lower levels, but not in the sense of a top-down sequence of authoritative control. Rather semi-autonomous levels are shaped from the interactions among a set of variables that share similar speeds. Each level communicates a small set of information or quantity of material to the next level. In this sight the flexibility of a system depends on its capacity of adaptation and its resilience in recovering from perturbations. Therefore resilience of a system refers to the ability to maintain structure and self-organization of the subsystems of each level, if the whole system is confronted with external stress (Holling 2001).

Renewal and readjustment are essential elements of this process. Renewal in components helps a system to persist. Therefore, for a system to be sustainable, its subsystems must have the possibility to go through renewal cycles. As long as the system can adapt in this way, it is sustainable. Since every process of adaptation is only a temporary solution to changing conditions, it is of high importance to maintain diversity within the system. Diversity represents a repertoire of alternative options and increases the possibility that altered conditions can be successfully met. The consequence of implementing big infrastructure is that high sunk costs make systems extremely inflexible (Tillman et al. 2005), one way to

avoid this scenario and implement diversity, is through small scale modular design. In this way diversity:

- Avoids dissipation that comes along with the link-up of processes
- Enables adaptation to regional conditions special environmental requirements, different social acceptance of technologies, etc.)

Small scale modular diversity exponentially increases the amount of possible configurations that can be achieved from a given set of inputs. This increases the flexibility of a system and provides for the characteristics of a complex adaptive system. The system is equipped with internal degrees of freedom and distributed control. As a result, it has a higher resilience in relation to both: socio-economic and natural environment. This allows diversity to contribute to long term stability through adaptive flexibility. Special regional conditions can more efficiently be met by choosing exactly that measure for each special issue that fulfils the spatial profile appropriately. This approach allows for using the best practices to fulfil different criteria. In reference to classical value analysis that adds achievement of criteria of a certain measure in total, the aggregated value of a system made of different small scale modular components replaces a value of greater homogeneity because low accomplishments in different criteria that might occur in a large scale system can be bypassed in a system consisting of small scale modular subsystems, in choosing a measure meeting the special requirement profile. In this way the homogeneity of value of a certain measure symbolizes the adaptive flexibility of a system.

## 3. Utility Value Analysis

Utility value analysis is a classical method in multi-criteria assessment MCA) (Peters et al. 2005). To overcome the difficulty of comparing alternatives regarding different aspects, the assessment for an indicator e.g. cost, emissions or water quality parameter) is standardized by using so called utility functions Figure ).

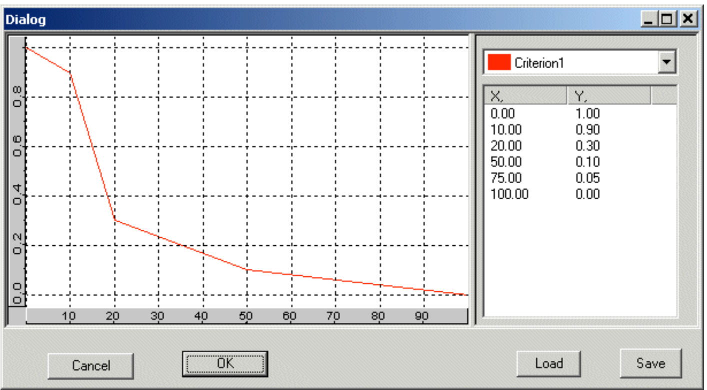


Figure 3: Example for a utility function

By adding up the utility values, weighted for each indicator, different alternatives can be compared. A typical result is shown in Figure . Formerly criticized as a nontransparent, academic method, this type of MCA is nowadays seen as a useful tool for group decision making (Sieker et al. 2005). The same principle is for example used in consumer magazines to compare different products. Also some decision support systems are using this concept (Ellis et al. 2005). By using modern software tools, it is possible to quickly change weighting factors or utility functions, carry out sensitivity analysis and to present the result is transparent way.

Nevertheless, the flexibility of a system to adapt to future changes is not considered with the classical UVA. Only one aggregated system value is used to compare different scenarios.

And introducing “flexibility” as another indicator is a very subjective way to assess adaptability.

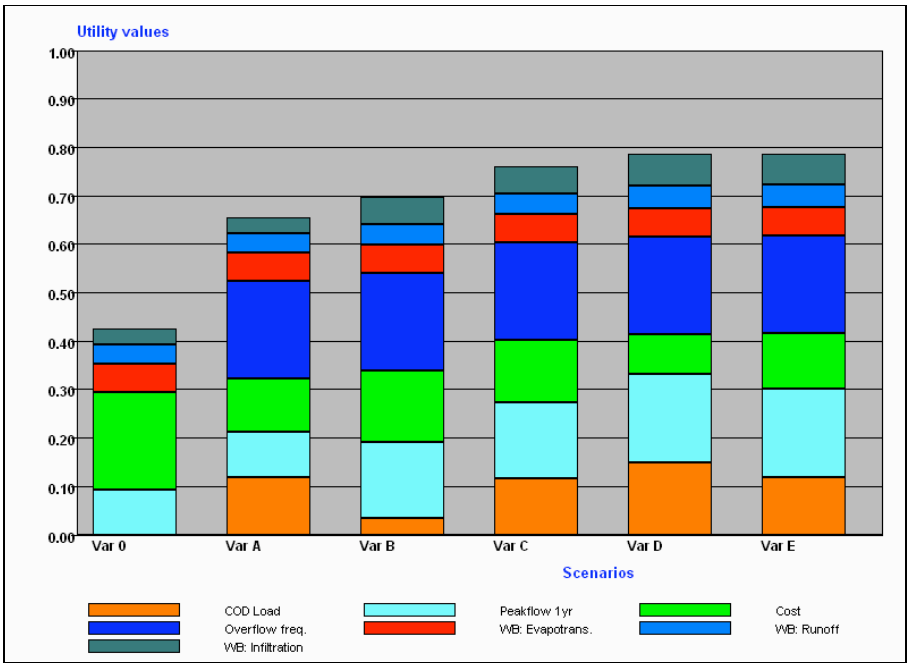


Figure 4: Result of a utility value analysis

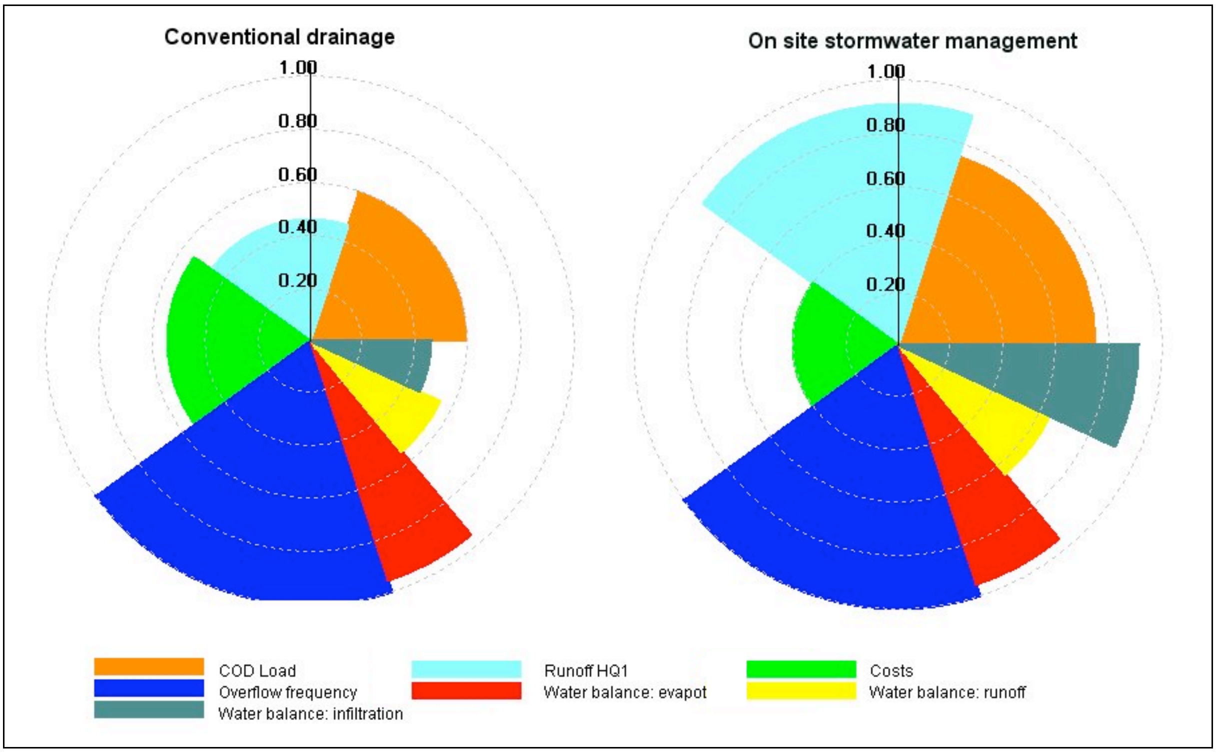


Figure 5: Sector diagram for weighted utility values

# 4. The COFAS method

While the classical UVA approach is using only one aggregated system value to compare different scenarios, the COFAS method COFAS: Comparing the Flexibility of Alternative Solutions) involves applying statistical methods to the level of variation associated with the utility values under different conditions.

A useful way to visualize this variation is in a sector diagram see Figure 5). In this diagrammatic, the radius of a sector represents the utility value while the aperture angle shows the weighting factor. In the example shown in Figure 5, it is clear that the variation in the utility values associated with the conventional drainage solution left-hand chart) is greater than those associated with an on-site stormwater management solution right-hand chart). This type of chart can be created with the COFAS-Software presented in this deliverable.

In order to measure the variation of the utility values the “internal homogeneity” Hom is introduced. It is calculated from the weighted standard deviation of the partial) utility values. Different authors use slightly different methods to calculate the internal homogeneity compare Helm et al. (2007) and Schlottmann et al. (2007). In the COFAS-tool the internal homogeneity is calculated according to the following equations:

$$Hom = \begin{cases} 1 - \dfrac{\sigma}{tUV} & where\ \sigma \le tUV \\ 0 & where\ \sigma > tUV \end{cases}$$

$$\sigma = \sqrt{\sum_{i=1}^{n} w_i \left(pUV_i - tUV\right)^2}$$

| | |
|---|---|
| Hom | Internal homogeneity |
| tUV | Total utility value weighted mean of the partial utility values) |
| pUV | Partial utility value utility value of one criterion) |
| σ | Standard deviation of the partial utility values |
| n | Number of criteria = number of partial utility values |
| $w_i$ | Weighting factor for criterion i $\sum_{i=1}^{n} w_i = 1$) |
| i | Index for partial utility values |

Hom = 0 means minimum homogeneity, e.g. 50% of the criteria have the partial) utility value 0 and the other 50% have the utility value 1. Hom = 1 means maximum homogeneity, i.e. the partial) utility values of all criteria are equal. Combining the internal homogeneity Hom) and the total utility value tUV) results in the development of a “multi-dimensional Degree of Target Achievement dDTA)” value (Helm et al. 2009; Schlottmann et al. 2007).

$$dDTA = \sqrt{tUV \cdot Hom}$$

A comparison of alternatives utilizing dDTA values has the advantage that it avoids the potential drawback of a highly negative aspect of a solution e.g. water pollution) being compensated for by a highly positive attribute e.g. flooding).

A system with a high internal) homogeneity is more robust against future changes e.g. changing conditions associated with climate change, increasing urbanization etc.) then a system with a low internal) homogeneity, because it shows equally good performance against all criteria. Hence a variation of any of the boundary conditions would never lead to complete failure. In contrast a system with a low homogeneity may react very sensitively on changes of the boundary conditions, if the pressure on those criteria that already performed badly in status quo increases.

Thus comparing different alternatives using the sDTA leads to more robust solutions. Chapter 0 suggests, that systems which show a homogenous performance also provide a greater adaptive flexibility.

Flexibility (Changeability)

- Robustness:
  A System can cope with different boundary conditions without modifications.
- (Adaptive) Flexibility:
  A System can easily be adapted in order to cope with different boundary conditions.

Figure 6: Flexibility, Robustness, Adaptive flexibility

However, a comparison of alternatives by dDTA is still only based on information about the actual situation. To take into account the flexibility of alternatives regarding their ability to cope with future changes more soundly, an additional parameter exHom external homogeneity) is introduced to the previously developed approach. For each alternative solution, utility values were computed for different future scenarios. If the evaluation of the future scenarios includes an adaptation of the system, the external homogeneity measures adaptive) flexibility. If the system is not modified exHom measures robustness.)

The external homogeneity for an alternative is calculated from the standard deviation of the total) utility values for the different future scenarios according to the following equations:

$$exHom = \begin{cases} 1 - \dfrac{\sigma_{ex}}{mtUV} & where\ \sigma_{ex} \leq mtUV \\ 0 & where\ \sigma_{ex} > mtUV \end{cases}$$

$$\sigma_{ex} = \sqrt{\frac{1}{m}\sum_{j=1}^{m}\left(tUV_j - mtUV\right)^2}$$

$$mtUV = \frac{1}{m}\sum_{j=1}^{m} tUV_j$$

| | |
|---|---|
| exHom | External homogeneity |
| $tUV_i$ | Total utility value of the alternative for future scenario i |

mtUV Mean total utility value of the alternative over all future scenarios

$\sigma_{ex}$ Standard deviation of $tUV_i$

m Number of future scenarios

j Index for future scenarios

Combining the external homogeneity with the mean total utility value and the mean internal homogeneity leads to the “multi-dimensional, multi-variant Degree of Target Achievement dvDTA)” (Helm 2007).

$$dvDTA = \sqrt[3]{mUV \cdot m\,Hom \cdot exHom}$$

The COFAS-Software presented in this deliverable features the utility value analysis and the calculation of the internal homogeneity Hom). It provides numerous charts, including the sector diagram previously introduced. It also comes with a sensitivity analysis that again is supported by a chart. The COFAS-Software supports the calculation of exHom and dvDTA. The user will create one COFAS project for each future scenario. Then he can copy the result tables easily to an Excel-workbook that calculates exHom and dvDTA.

## 5. Example Kupferzell

The municipality Kupferzell in Southwest Germany Helm, 2007; Sieker et al. 2008) was analysed, to determine which type of urban drainage systems offer better flexibility options to cope with future uncertainties.

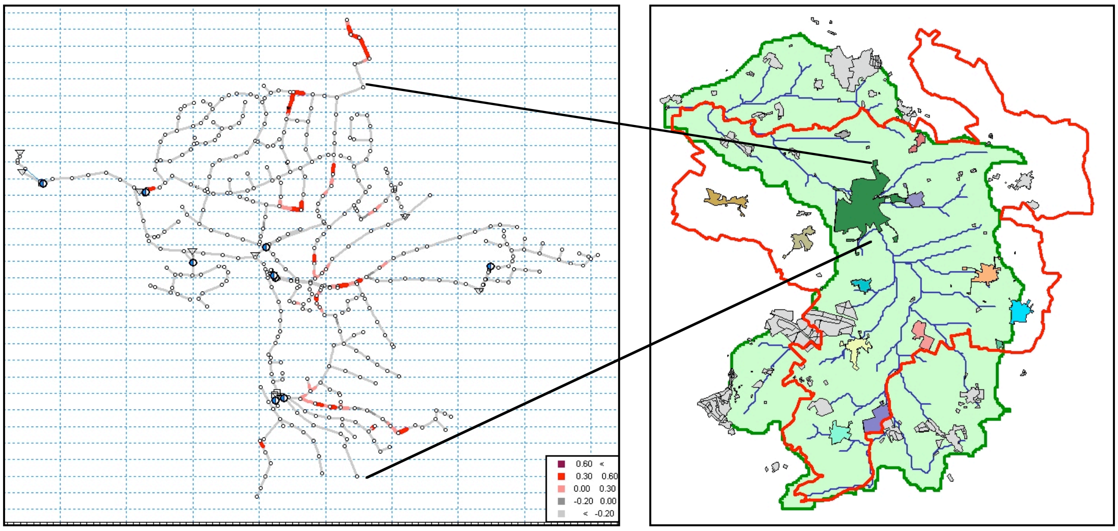

Figure 7: Mouse-model for the drainage system left), STORM-model for the catchment of the river Kupfer right)

The range of possible future developments is described as future scenarios for the year 2050. Tendencies of change in the environmental and socio-economic framework are identified through a literature survey. Four scenarios were developed: A linear scenario

extrapolation of the actual development), a loading case scenario combination of the results of a sensitivity analysis with plausible extremes for the boundary conditions), a growth-orientated scenario conditions for a individualistic and consumer-oriented society) and a conservational scenario conditions for a society with a focus on ecology and social engagement). The scenarios represent the required flexibility for urban drainage systems. System alternatives for the further development of the urban drainage system of Kupferzell are developed considering the existing drainage system as well as the future infrastructure for new development areas. The system alternatives represent four strategies based on different types of urban drainage systems:

- First, the continuation of the existing combined sewer system is intended.
- Second for expansions of the urban drainage system separated sewers are considered.
- Third, all additional urban drainage systems are realised as decentralised drainage systems.
- Fourth, an extended decentralised system is aspired with expansions are focused on infiltration, green roofs and rainwater utilisation as well as the disconnection of 20% of the paved surface from the existing combined sewer system.

For the system alternatives flexibility options for the adaptation on future alterations are identified. Considered flexibility options are the adaptation of the required retention volume, the upgrading and replacement of overloaded sewers and a staged design of the urban drainage system.

In a rainfall-runoff model the effects of the different future scenarios for the performance of the system alternatives are modelled. If an adaptation of the system on future alterations is required the flexibility options are implemented. The performance is ascertained based on a utility value analysis a classical method in multi-criteria assessment. In total 27 qualitative und quantitative indicators from the field of environment, society and economy were considered in order to take into account the requests of sustainability in performance.
There are 16 combinations of future scenarios and system alternatives with in total 432 single values. To produce meaningful results an aggregation to one value per system alternative is required. Therefore the COFAS-Method was applied, including the calculation and evaluation of internal homogeneity Hom), external homogeneity exHom) and "multi-dimensional, multi-variant Degree of Target Achievement" dvDTA). The COFAS-Software presented in this deliverable was not available at that time, so the application of the COFAS-Method had to be done manually using Excel.)

Finally the flexibility of the different system alternatives are compared. The results of the example Kupferzell illustrates, that for the further development of the urban drainage system, both decentralised alternatives offer a significant higher degree of flexibility and therefore are more easier to adapt to future changes than the both conventional system alternatives Sieker et al. 2008). Hence the implementation of decentralised sustainable urban drainage systems is a flexibility option. This result is congruent to general statements of the technical literature. So Sieker et al. 2007a; Schmitt, 2006; Sundberg, 2004) expect, that decentralised sustainable urban drainage systems offer a higher flexibility than conventional drainage systems.

## 6. Conclusions

The COFAS-method is a tool to compare the flexibility of alternative options e.g. for stormwater management) regarding their adaptiveness to future changes.

This flexibility is very important as it is not possible to exactly predict future change for most of the drivers relevant for stormwater management climate change, urban dynamics).

For the example Kupferzell is has been shown that decentralized solutions like stormwater infiltration are more flexible than conventional drainage systems. This seems to be a general fact; nevertheless it has to be proven in other applications.

## 7. The COFAS-Software and further documentation

Please visit http://www.switch.watsan.net/page/4748 to download the following:

COFAS-Software

Example files

Deliverable 2.1.4 document including a tutorial for the software and a scientific background on flexibility

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