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FRAC-WECO
Flux-based Risk Assessment of the impact of Contaminants
on Water resources and ECOsystems
Programme: La Science pour un Développement Durable
Programma: Wetenschap voor een Duurzame Ontwikkeling

Deliverable D12

Methodology for integration of process studies and development of a decision support tool

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1. Introduction

The objective of FRAC-WECO is to develop an integrated methodology contributing to a more comprehensive risk assessment of contaminated sites on water resources and ecosystems. The project combines on the one hand process studies contributing to a more comprehensive assessment and modelling of water and contaminant fluxes at various scales (local and catchment) and of biogeochemical properties and toxicity of contaminants, on the other hand impact studies such as risk assessment methodologies so as to propose management tools and indicators for ranking contaminated sites in terms of risks and costs.

The originality of the approach relies mainly on two aspects: i) a risk evaluation based on the calculation of contaminant fluxes between the source (contaminant emitter) and the receptor(s); ii) the use of the DPSIR approach as a general framework for coupling the physical and socio-economic components of the analysis. To develop that methodology, various skills, tools and concepts are provided and developed by the different research groups involved in the project and it is the sum and the integration of these components that will allow reaching the final objectives.

It is thus necessary to define an integration schema from the beginning of the project, to guarantee the complementarity and compatibility of the various research efforts. Integration concerns on the one hand the physical component of the analysis for which the various process-based researches should contribute to the global objective of the project, being able to assess contaminant fluxes between the Source and the Receptor. On the other hand, integration should also contribute to make compatible the physical and socio-economic compounds of the project.

The Integration methodology is described in the following chapters of this deliverable. First, the physical and socio-economic components of the studied system under investigation are described. At this level, a combined DPSIR-SPR approach is used to present in a summarized way the causal chain corresponding to the studied system. This will subsequently form the basis of the integration methodology. Second, the various elements considered for moving from the system analysis to decision support are detailed: DPSIR indicators, modelling concepts and socio-economic tools. Conclusions and perspectives are finally drawn.

2. Description of the studied system

Risk assessment of contaminants is a wide and very "popular" topic for research and applications. It may encompass almost any kind of contaminants (point versus diffuse, accidental versus periodic or continuous, existing versus potential…), any kind of driving vectors (water, air…) and any kind of receptors (human beings, terrestrial and aquatic ecosystems, natural resources…). Although it is expected to obtain results and tools that are as generic as possible, the objectives of FRAC-WECO have been limited to a reasonable set of situations, given the means and possibilities offered within the consortium. The objective here is to describe as accurately as possible the domain of investigation of FRAC-WECO and its limits.

2.1. Physical component and SPR approach

The physical system corresponds to the underground medium and the water it contains, starting from the land surface down to any "impervious" layer that limits the continuity of the groundwater system, vertically or laterally. It also integrates the buffer zone between groundwater and surface water and surface water itself to the extend it interacts with groundwater.

Water is the main vector of the mobility of contaminants in this system. In the upper underground layers, water saturation is likely to be variable and less than or equal to 100% (unsaturated zone). The groundwater system corresponds to the deeper underground layers saturated with water (saturated zone), below the phreatic surface. Contaminants were originally emitted at the land surface and they have more or less penetrated in the underground, by infiltration or because of land reorganization. They are nowadays located at various depths, depending on the physico-chemical properties that drive their more or less important mobility in the underground.

As stated in the proposal, the project will in priority focus on the impact of existing sources of contamination (historic pollution) on water resources and associated ecosystems. This can be conceptualized using the Source – Pathway – Receptor approach (SPR). The SPR approach is commonly used in risk assessment studies for conceptualizing and describing the processes underlying the mechanisms of environmental risk (CLARINET 2002). The SPR approach, as applied to the physical system considered here, is illustrated in Figure 1 and described hereafter.

Source

The <u>*Source*</u> is the emitter of contaminants in the environment. FRAC-WECO will mostly focus on point sources of contamination, keeping in mind the fact that diffuse contamination issues are also likely to be part of the analysis.

Receptors

From the very beginning of the project, it has been agreed that the potential receptors for which FRAC-WECO should develop risk assessment tools are water resources and associated ecosystems. This excludes from the direct analysis human health problems and terrestrial ecosystems degradation.

The identified receptors are thus:

- Groundwater as a resource (***<u>Receptor 1a</u>*** in Figure 1), abstracted groundwater (***<u>Receptor 1b</u>***) and groundwater ecosystems (***<u>Receptor 1c</u>****,* provided that they can be identified);
- Surface water as a resource impacted by the discharge of groundwater (***<u>Receptor 2a</u>***), abstracted surface water (***<u>Receptor 2b</u>***) and surface water aquatic ecosystems (***<u>Receptor 2c</u>***).

Pathway

Knowing the sources and receptors considered the following pathways can be identified:

- ***<u>Pathway 1</u>***: the unsaturated zone between the Source and the groundwater table: this constitutes the whole pathway for risk assessment of the groundwater resource and a part of the pathway for risk assessment of groundwater abstraction points, of surface water and of aquatic ecosystems;
- ***<u>Pathway 2</u>***: groundwater flow paths as a complementary pathway to the unsaturated zone for risk assessment of groundwater abstraction points, of surface water and of aquatic ecosystems;
- ***<u>Pathway 3</u>***: surface water flow paths through runoff, which can also drives dissolved contaminants and contaminants attached to suspended matters; however, this component is not specifically covered within the FRAC-WECO project.

Along these flow paths, we need to identify the relevant processes for assessing the fate of contaminants from the Source to the various Receptors, i.e. contaminant mobility (advection, diffusion and hydrodynamic dispersion), contaminant retardation and reaction (sorption – desorption, biodegradation, biotransformation…). Contaminant dispersion in the environment through volatilization is provisionally excluded from the analysis framework, at least in terms of risk assessment.

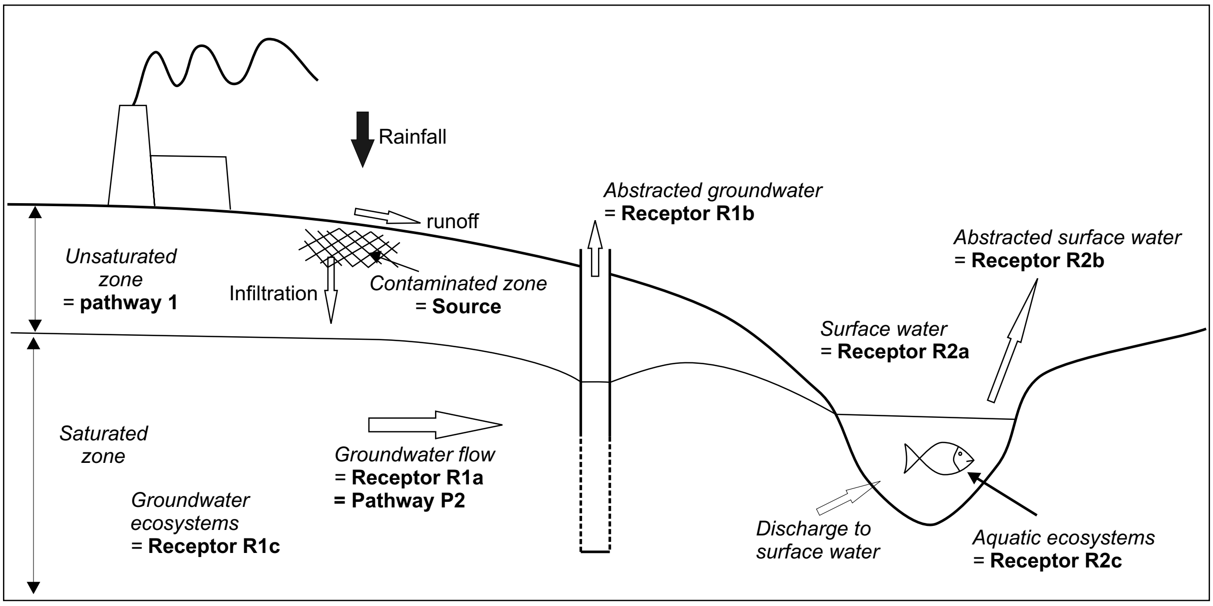

Figure 1. Source – Pathway – Receptor analysis of the physical system under investigation

2.2. Relations between socio-economic and physical components: DPSIR approach

To develop an integrated methodology to support decision making, a wide range of socio-economic, decisional and biophysical processes need to be investigated. Relations between physical and socio-economic components of the system should be well understood. A key step in the development of an integrated methodology is its conceptual phase: for this purpose the DPSIR methodology will be used as a general organizational framework for the project. The DPSIR methodology presents a chain of causal links between Driving forces/Drivers (economic sectors, human activities), Pressures (emissions, waste), States (physical, chemical and biological state of the resource) and Impacts on ecosystems, human health and natural resources (Kristensen 2004). This leads to Responses such as prioritization, target setting and indicators. Whereas the SPR framework is usually somewhat more restricted to the physical modelling of ecological risks, the socio-economic aspects of environmental problems are an integral part of the DPSIR framework that provides an important tool for achieving a common level of understanding and consensus between researchers, natural resource managers, policy makers and other stakeholders (Brouwer 2005).

In the framework of the FRAC-WECO project, the following sub-systems should be investigated.

Drivers

At the FRAC-WECO level, the objective is to focus on existing contamination issues. This means that the *Drivers* of the contamination issues are not directly considered as potential components of the analysis and preventive measures that would operate through the change of drivers' behaviour are not considered as potential responses. Research activities will thus focus on the P-S-I chain.

Pressures

Pressures are represented by the Sources of contaminants from where pollutants are emitted in the environment.

State

The *State* component is the aquatic system that includes ground- and surface water (as impacted by groundwater) characterized by their hydro(geo)logy, their bio(geo)chemistry and their ecology as affected by the emitted contaminants. As the project focuses on quality issues, changes of the state due to polluting pressures will mainly result in changes in biogeochemistry and ecology of aquatic systems. For instance, polluting pressures may lead to degradation of (i) groundwater resource quality as a whole (Receptor 1a) or at some abstraction points (pumping wells, Receptor 1b), (ii) surface water quality (Receptor 2a), particularly during recession periods when the groundwater base flow component of surface water is dominant and (iii) aquatic ecosystems (living in ground- and/or surface water, Receptor 1c and 2c respectively).

At this level, one needs to clarify the fact that surface water is included in the state of the project insofar as it is affected by the degradation of the discharging groundwater at the level of the studied contaminated site, not through a possible degradation of the surface water upstream from the studied contaminated site.

Impacts

Changes in the state of the aquatic system may lead to *Impacts*. Impacts are characterized as the change of goods and services provided by aquatic systems that lead to change in human welfare. The FRAC-WECO project will focus on the analysis of impacts due to groundwater quality degradation. Nevertheless, as mentioned before, if the surface water chemical and/or ecological status is affected due to groundwater discharge, impacts related to this degradation will also be taken into account (see Figure 2).

Impacts can be expressed in a monetary term and can be considered as the change of the total economic value of the aquatic systems due to the change of their state. The notion of total economic value will be used to provide a measure of the economic value of an environmental asset (OECD 2006):

- Any decrease in water status generally leads to *environmental damages* (negative impacts) that may be defined as the total economic costs (welfare loss) of the physical environmental damage to the water system (water body or river basin) as a result of the chemical and/or ecological state of the water system (Brouwer *et al.* 2007).
- Any improvement in water status (for instance after the implementation of remediation measures) leads to *environmental benefits* (positive impacts) that may be defined as the total economic value (welfare gain) of the physical environmental improvement of the water system as a result of the chemical and/or ecological state of the water system (or the reduction in damage costs) (Brouwer *et al.*, 2007).

Environmental (damage) Cost = –Δ Total Economic Value (TEV)

Environmental benefits = - Avoided Damage Costs = +Δ Total Economic Value (TEV)

Responses

From the assessment of impacts, or in application to the precautionary principle, decision-makers may have to determine appropriate *Responses*, in order to improve the state and mitigate the impacts (or to prevent future ones). It is important to stress that responses can target different parts of the DPSI system. As contamination is due to past industrial activities, Responses cannot address the Drivers directly. Pressures exerted on groundwater can be addressed for instance by soil excavation, which will decrease the existing stock of pollutants. The state of the groundwater can be improved by the treatment of contaminated groundwater. Impacts can be mitigated by supporting the installation of treatment systems for ensuring good quality drinking water.

2.3. Conceptual framework: a combined DPSIR – SPR approach

In the FRAC-WECO project, a combined DPSIR – SPR approach is proposed. To do so, the SPR conceptualization of the physical system will be integrated into the DPSIR framework.

Figure 2 illustrates the "conceptual model" corresponding to the FRAC-WECO project, the identification of the main Source, Pathways and Receptors concerned and the translation of these concepts into a simplified DPSIR flowchart. As expressed by this Figure, the project is composed on the one hand of process studies focusing on the physical system and aiming at linking the pressure and state components of this system using the SPR concept, on the other hand of a socio-economic component aiming at quantifying the impacts in terms of changes in human welfare, of the degradation of the state first (2 first years of the project: damage cost assessment) and its potential restoration next (two last years of the project: cost-benefit analysis of alternative management measures).

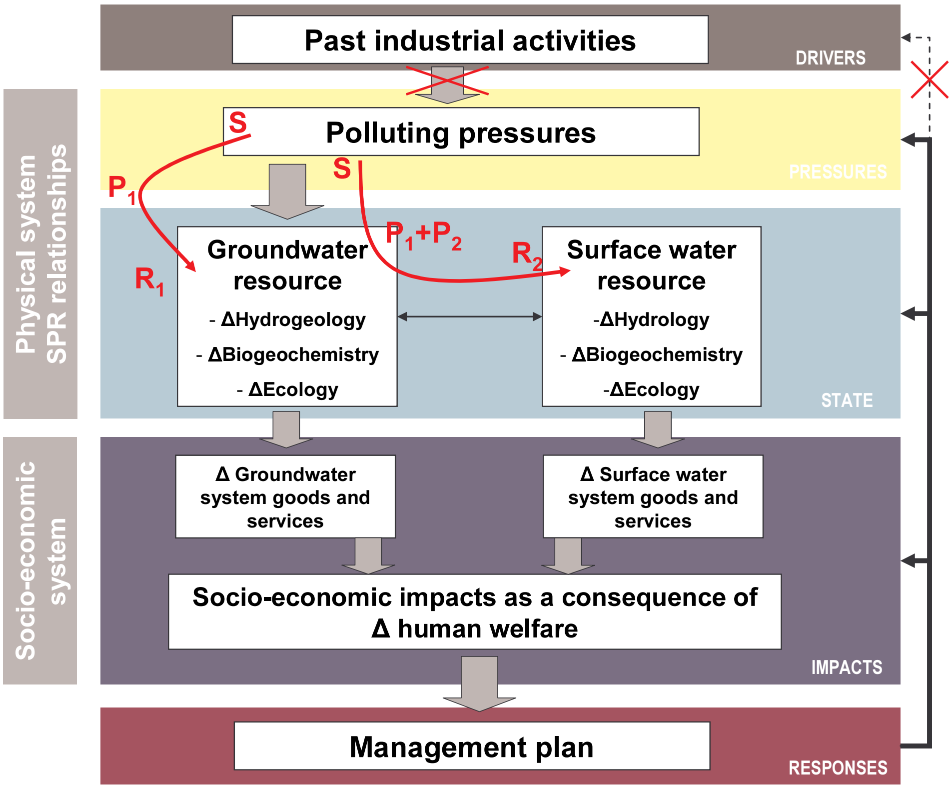

Figure 2. Integrated SPR- DPSIR flowchart corresponding to the FRAC-WECO project.

3. Decision support

The combined DPSIR-SPR approach provides a conceptual framework for a good understanding and structuring of the problem to be faced (the contamination issue). In order to take decisions, one further needs:

- indicators which will be referred to as decisional variables: these indicators will be used as reference values for both the risk assessment and the socio-economic analyses; they have thus to be defined in a way suited for both purposes;
- a good description of the physical system under investigation and modelling tools for quantifying ongoing physical processes and for calculating the indicators used for decision making;
- a socio-economic framework to be used for evaluating and ranking alternative responses proposed to solve the contamination problem.

The way these three aspects will be covered in the FRAC-WECO project, is described in the subsequent chapters from the perspective of risk assessment and socio-economic analysis. The objective is not to give all the details of the anticipated developments but to describe the general framework in which these developments are going to be accomplished.

3.1. Risk assessment framework

As mentioned in the proposal, the FRAC-WECO risk assessment methodology will be based on the determination of contaminant fluxes between the identified Source and Receptors (WP4, Task 4.1).

One could consider comparing the contaminant concentration at the different receptors as compared to the concentration of the contaminant released at the source as a risk assessment indicator. However, as discussed by several authors (e.g. Rao et al. 2002; Basu et al. 2006), concentration-based performance metrics are poor indicators for risk assessment and risk reduction as a significant source reduction is not always accompanied by a significant change in the concentration of released contaminants, and this is particularly the case for DNAPLs. A better alternative is to use contaminant flux or mass-discharge indicators and to compare the quantity of contaminant that reaches each receptor to the quantity of contaminant that is released at the source.

In mathematical terms, this requires estimation of the relative quantity of contaminant that reaches each Receptor R_i for a given quantity of contaminant released at the source.

The simplest way is to express this in the form of a recovery factor R_{Fi} (no unit) which is the mass ratio between the quantity of contaminant reaching any Receptor R_i, M_{Ri} (M) and the quantity of contaminant released at the source, M_s (M):

$$R_{Fi} = M_{Ri} / M_S$$

Because the pollution is historical, one may assume that a “steady state” regime is reached, in which case one can better express all these concepts in terms of contaminant mass fluxes rather than masses:

$$R_{Fi} = fM_{Ri} / fM_S = M'_{Ri} / M'_S$$

where,

- fM_s and fM_{Ri} are the contaminant mass fluxes released at the source S and reaching the different receptors R_i (M L^3 T^{-1});
- M'_S and M'_{Ri} are the contaminant masses released at the source and reaching the different receptors per unit time (M T^{-1}).

Since most risk assessment norms are generally concentration-based (EPA 1996, ECB 2003, ITRC 2005), one can derive concentration-based indicators from the contaminant mass flux indicators as follows:

$$C_S = fM_S / Q_S$$

$$C_{Ri} = fM_{Ri} / Q_{Ri}$$

where Q_S and Q_{Ri} are the quantities of water that flows across the source S and the different receptors R_i, respectively (L^3 T^{-1}).

Starting from these basic considerations, one can define representative variables for each component of the SPR system (Figure 3). For the Source and for each of the identified Receptors, one can define a group of indicators.

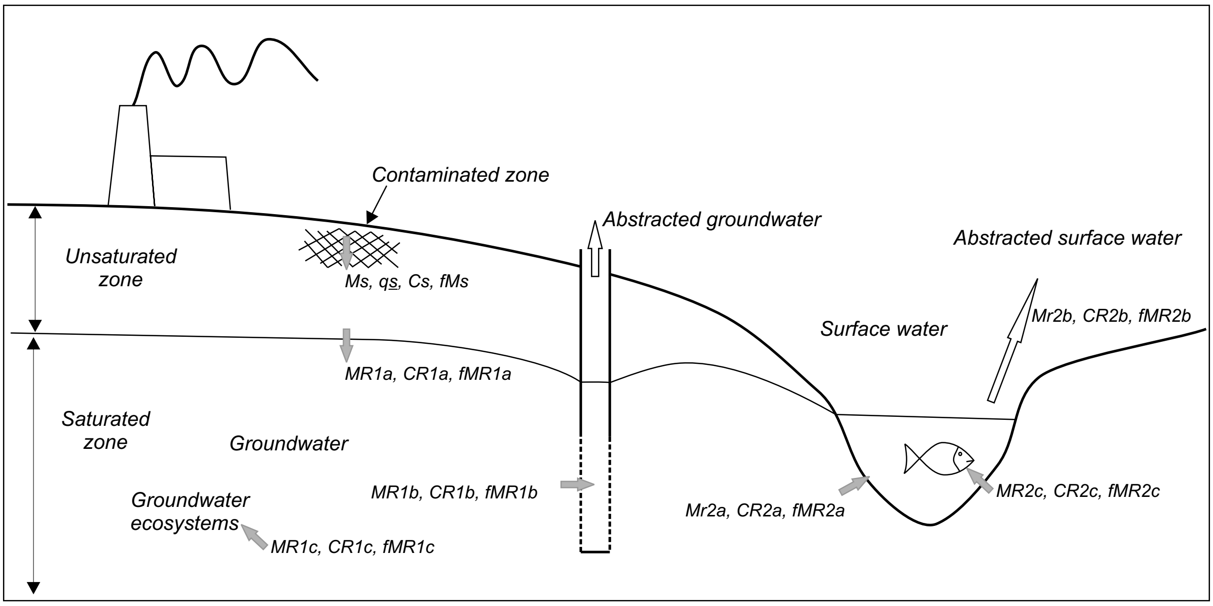

Figure 3. Risk assessment indicators defined for the source of contaminant and for the various receptors.

These considerations will be developed in the scope of FRAC-WECO in order to propose risk assessment methodologies and tools. As stated in the project proposal, such tools and concepts should be developed for the various steps of a tiered approach applicable to any contaminated site.

The risk assessment methodology itself will be developed based on a detailed overview of existing approaches (Deliverable D4.1: Comparison and validation of risk assessment tools, due at Month 18). Existing risk assessment tools will also be compiled and evaluated. The evaluation could be at two levels: 1) to use existing field data and measurements (e.g. concentrations in soils and groundwater) to test existing tools in order to identify those that are the most appropriate, 2) comparison on selected case studies of “basic” risk assessment tools and more advanced modelling tools.

In the next section, the different DPSIR indicators considered for the socio-economic analysis are defined, based on the same physical variables as those proposed for the risk assessment indicators.

3.2. DPSIR Indicators

The DPSIR indicators will mostly be built taking advantage of the integration of the SPR concept in the DPSIR framework, taking into consideration the correspondence between the Source and Pressure and between the Receptors and the State components. The Impact indicators will be developed based on the socio-economic concepts.

Indicators of Pressures = Source indicators (S)

The quantity of contaminant Ms (M) present at the source is a priori, a relevant indicator for quantifying the source strength and for "monitoring" its expected depletion (risk reduction phase). However it remains often a challenge to determine with accuracy the volume of contaminant at the source, particularly for historical pollutions which are usually poorly documented. Another source indicator, as explained in § 3.1 is the contaminant flux or mass release from the source. This flux can be calculated as follows:

$$fM_S = Q_S \times C_S$$

As a first approximate for C_s, one can consider that the solubility limit (C_{solub}) is a good first approximate. The water flow rate (Q_S) that drives the mobility of contaminant has to be quantified in the field. If the source is located in the unsaturated zone, it is strongly related to the effective infiltration rate (I_{eff}, L T^{-1}). If the source is already in the groundwater, control planes have to be defined and groundwater fluxes across these planes have to be quantified.

Indicators of State = Receptor indicators

As mentioned in § 2.1, two categories of receptors have been identified: those associated to the groundwater system (R_{1x}) and those associated with the surface water system (R_{2x}). For all of these receptors, one needs to calculate contaminant fluxes that will serve as relevant indicators. If concentrations are required, they can straightforwardly be obtained from the corresponding mass-flux indicators.

Generally speaking, the indicators will take the form:

$$fM_{Ri} = C_{Ri} \times Q_{Ri}$$

Groundwater resource indicators (R1a)

These indicators refer to the quantity of contaminant that reaches the groundwater table (Receptor $R1$). In this case, the water flow rate reaching the groundwater table can still be considered as equal to the infiltration rate I_{eff}. The concentration of contaminant at the groundwater table (C_{R1a}) will have to be estimated using transport and reaction models (WP2.2), adapted to the degree of knowledge available at each step of the tiered approach, and estimated underground and contaminant properties.

Groundwater discharge indicators (R1b, R2a)

These indicators refer to the contaminant mass flux reaching any groundwater discharge point, i.e. pumping well, spring, drainage galleries…

For groundwater discharge in surface water (base flow), on should consider the fact that the contribution of groundwater to surface water flow varies during the hydrologic year. During the cold winter season, the base flow constitutes just a fraction of surface water flow, which is predominantly composed of runoff at the land surface. During the summer period, surface waters are at the recession stage and except during some stormy events, most of the surface water flow is sustained by the groundwater base flow. The discussion and developments envisaged at this level should take into consideration and probably start from the work performed in the BRIDGE FP6 project (Müller et al. 2006) which has proposed and developed concepts and methodologies for defining threshold values for contaminants in groundwater, considering the impact on surface water bodies.

Aquatic ecosystems indicators (R1c, R2c)

These indicators should be based on ecotoxicological considerations and will be developed in the scope of WP4, Task 4.2. However, once again, the variations with time of the contribution of groundwater base flow to surface water flow should be considered, at least examined. Usually, tests established by OECD are performed for an ecotoxicological evaluation and for hazard assessment.

If toxicity test results are available for very few species, the lowest toxicity value is divided by an application factor or safety factor that varies from 10 to 1000, depending on the number of species tested and whether the endpoint is based on acute mortality or effects (LC50 or EC50), or chronic non-observed-effect concentrations (NOEC). Applying safety factors in the range of 10-1000 for extrapolation from the laboratory to field is therefore appropriate.

So, hazard can be estimated as PEC/PNEC ratios. The Predicted Exposure Concentration (PEC) is the estimated concentration of a chemical in an environmental compartment calculated from available information on its physico-chemicals properties, its use and release patterns, and the produced/imported quantities involved. The Predicted No Observed Effect Concentration (PNEC) is the concentration below which exposure to a substance is not expected to cause adverse effects.

If $PEC/PNEC < 1$ → No hazard for the environment

If PEC/PNEC > 1 → Hazard for the environment

This risk assessment concept using the ratio between PEC and PNEC, as outlined in Figure 4, is widely accepted (Technical Guidance Document – published by European Chemicals Bureau, 2003).

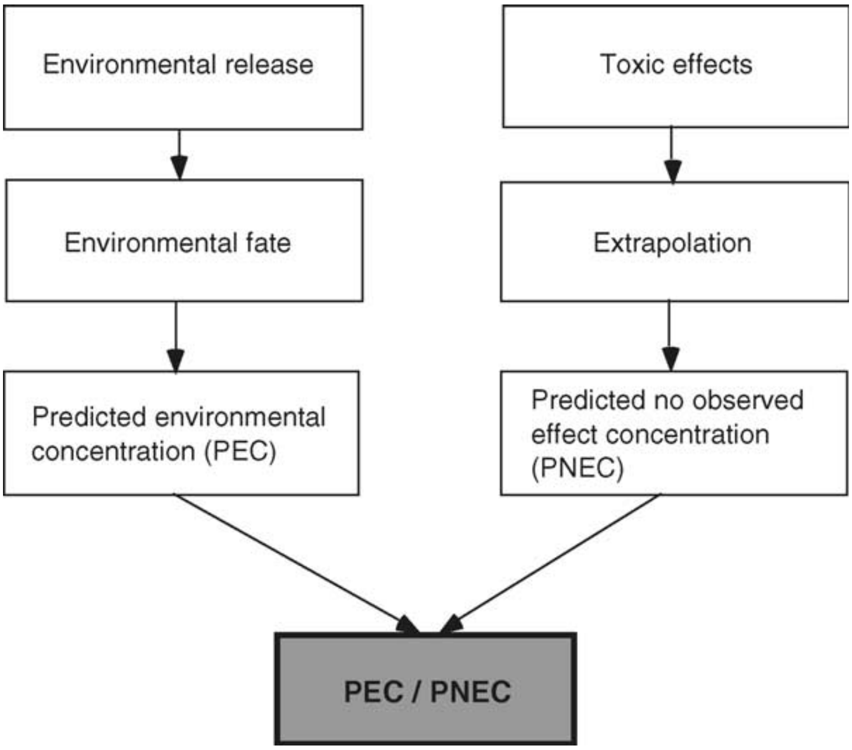

Figure 4. Environmental risk assessment (Technical Guidance Document – published by European Chemicals Bureau, 2003)

In concrete terms, from LC50 results, we will apply a safety factor of 1000 imposed by Technical Guidelines. It will give us the PNEC value and so we will be able to calculate the PEC/PNEC ratio for a mixture of pollutants.

On the one hand, LC50 values will be obtained for a mixture of pollutants, on the other hand, laboratory tests will be achieved on each toxic separately. However, first of all, a literature review will be performed on the ecotoxicity of each pollutant.

Indicators of Impacts

As mentioned above, impacts consist in environmental damage or benefits and are defined as the change in total economic value of the aquatic system as a result of the change of the state of this system. Impacts will be expressed (when possible) in monetary terms (€). Environmental damage related to groundwater degradation will be expressed as a function of the aquatic system state indicators:

In case of degradation of the groundwater system only:

$$Environmental\ damage = f(R1a, R1b, R1c)$$

In case of degradation of the surface water system too (due to groundwater discharge):

$$Environmental\ damage = f(R1a, R1b, R1c, R2a, R2b, R2c)$$

3.3. Process studies (Pressures-State relationships)

In FRAC-WECO, process studies should contribute at two levels: i) to a better understanding of physical and biogeochemical processes governing the fate of water and contaminants in the studied system, ii) to the development of modelling tools used to integrate these processes in order to calculate the relevant indicators for risk assessment and socio-economic analysis. Physical and biogeochemical processes can be classified as follows.

Processes governing water flow

- Water budgeting at the land surface
- Variably saturated groundwater flow across the unsaturated zone, in the saturated zone and discharge in pumping wells or in surface water

Surface water budgeting (Figure 5) and, more in particular, groundwater recharge modelling is the objective of WP2, Task 2.1 of the FRAC-WECO project, under the responsibility of VUB.

For determining the infiltrating flux of water towards a groundwater body, water recharge has to be quantified. An important factor determining the spatial and temporal variation in groundwater recharge is the distribution of different types of land cover. In urban and industrial areas, land cover is more complex than in rural environments and a lot of infrastructures make the surface less permeable or impervious. In order to produce detailed land-cover information for the FRAC-WECO test sites, high-resolution satellite imagery will be used (Ikonos data). Land-cover information obtained from these data will be used as input for surface water budgeting. The main objectives of the research on run-off routing and groundwater recharge simulation are the following:

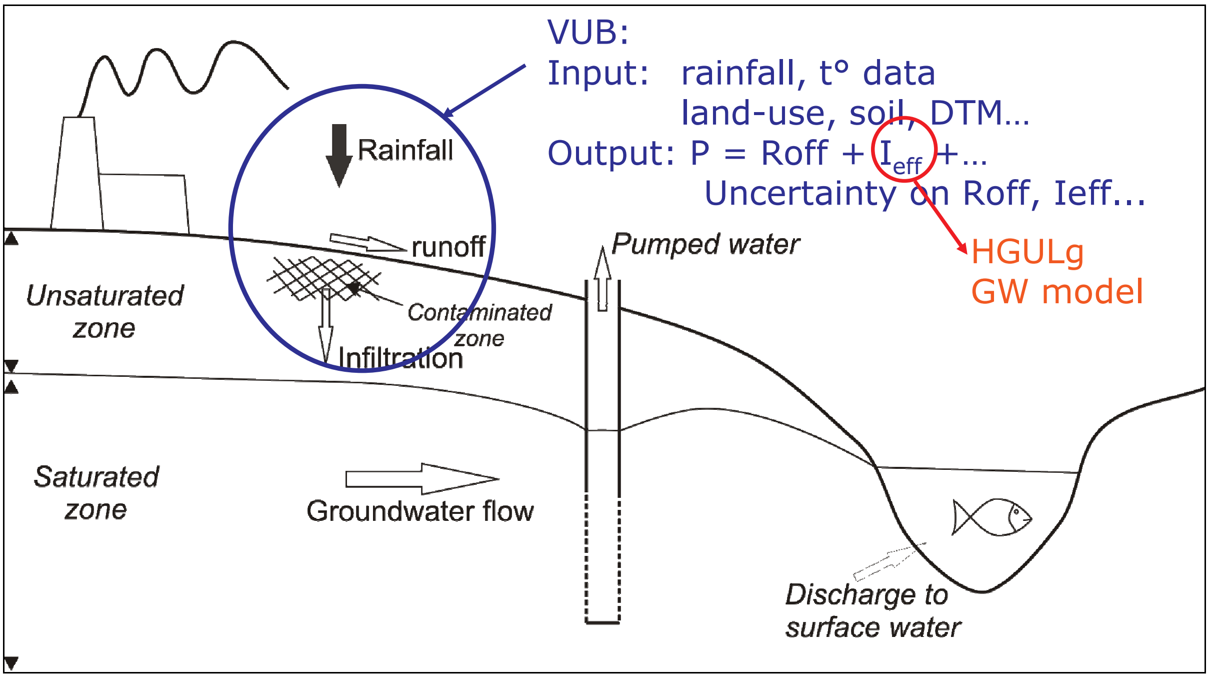

Figure 5. Water budgeting at the land surface: data requirements and expected outcomes

Object-oriented land-cover mapping

Because high-resolution sensors like Ikonos have a limited spectral resolution, they do not allow distinguishing well between some types of land cover that are important in the context of hydrological modelling, based on spectral information only. Therefore an object-oriented classification approach will be adopted (Baatz and Schäpe 2000). This method allows the use of geometric, textural and contextual information next to spectral data to improve the labelling of image objects representing different types of land cover. A knowledge-based approach will be adopted to select optimal sets of object features that properly describe the land-cover pattern of the test sites, taking into account the land cover types that are considered important for run-off and groundwater recharge modelling.

To improve discrimination between land-use types that are characterized by a different multi-temporal variation in land cover, images will be acquired for different periods of the same year (before, during, after the summer growing season). The derived land cover maps will be used in different surface water budgeting simulations, resulting in high-resolution estimates, varying in space and time, of water fluxes to and in the test site(s).

Spatially distributed surface water budgeting and uncertainty modelling

The surface water budgeting will be simulated with the WetSpass and Wetspa models, developed at the Department of Hydrology and Hydraulic Engineering of the Vrije

Universiteit Brussel (Batelaan and De Smedt 2007). WetsSpass estimates spatially distributed run-off, evapotranspiration and groundwater recharge in function of land cover, soil type and topography with low temporal dynamics while WetSpa simulates water balance components with high temporal dynamics.

Because of confusion between different land-cover types, the land-cover maps obtained from satellite image interpretation will contain some level of uncertainty. This will have an impact on the outcome of the run-off and groundwater recharge modelling. To examine this impact, alternative land-cover uncertainty models will be defined. A Monte Carlo approach will be adopted to estimate the impact of uncertainty in land-cover definition on hydrological model output. This will allow evaluation of uncertainty with respect to the fluxes taking contaminants along their flow paths.

The infiltrating flux of water will be used as an input for variably saturated groundwater modelling in WP2 Task 2.2, under the responsibility of HGULg (Figure 6).

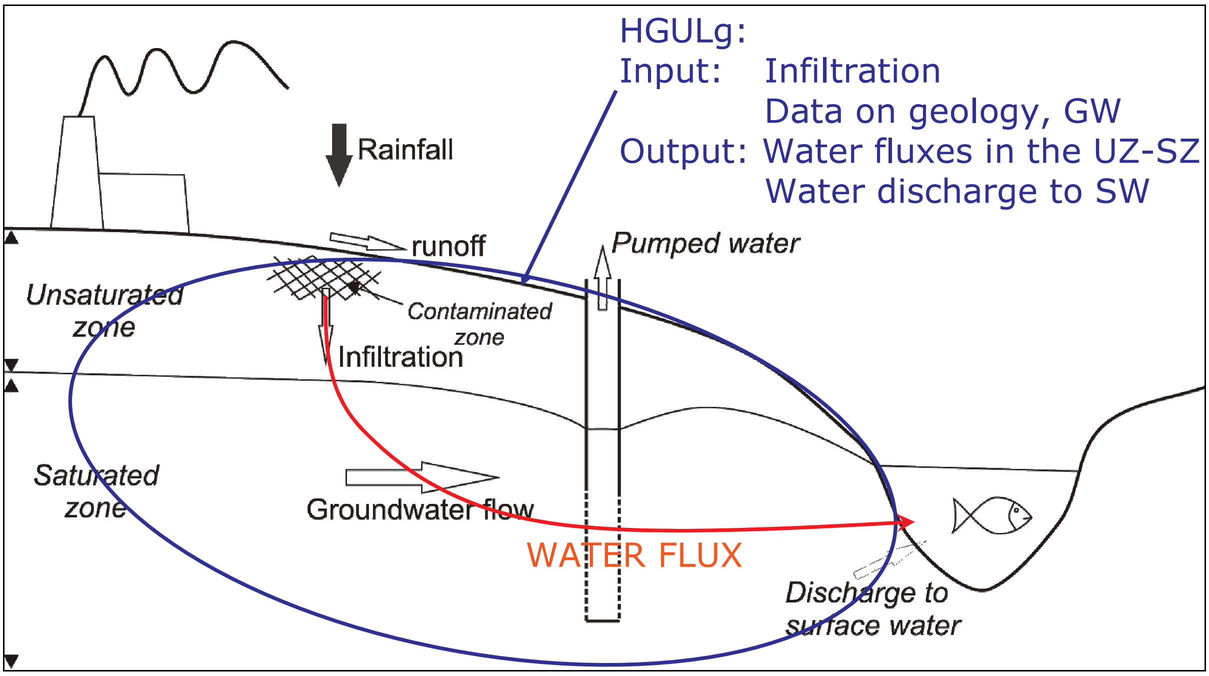

Figure 6. Variably saturated groundwater modelling: data requirements and expected outcomes

In this component of the project, HGULg has several objectives in terms of developments, as summarized hereafter.

Quantification of groundwater fluxes and their dynamics in the field

HGULg has recently developed a new tracer technique (Brouyère et al. 2007), called the Finite Volume Point Dilution Method (FVPDM) that allows estimating and monitoring groundwater fluxes in observation wells. This technique has been applied satisfactorily to quantify Darcy flux in two contrasted case studies in the scope of the FP6 AquaTerra project (), including a contaminated site close to the Meuse river in the region of Liège, Belgium. It is well recognized (RFES: Winter et al. 1998, Ford 2005) that the dynamics of exchanges between groundwater and surface water systems have a major effect on the fate of contaminants (specificity of biogeochemical processes in the transition zone, changes in the directions of fluxes…). In the scope of FRAC-WECO, HGULg is going to develop and test the use of the FVPDM technique for middle to long term monitoring of Darcy fluxes and groundwater-surface water exchanges in the underground transition zone. Combining that information with a detailed monitoring of groundwater and surface water dynamics will lead to a better assessment of groundwater and contaminant fluxes in the combined groundwater – surface water system.

Variably saturated groundwater flow modelling

In a first step, detailed groundwater flow models will be developed for the different test sites considered in the project (ongoing activity). Various numerical models will be considered: MODFLOW (USGS), SUFT3D (HGULg) and HydroGeoSphere (ULaval & UWaterloo). MODFLOW has the advantage of being freely available, well tested and commonly used. SUFT3D is the development code of HGULg and HydroGeoSphere has the advantage of solving coupled surface and subsurface flow equations.

The developed groundwater flow model will be used essentially for calculating groundwater flow and groundwater discharge to surface water (base flow), which is a prerequisite for evaluating contaminant fluxes. To develop that model, HGULg requires, among others, spatially distributed infiltration rates as calculated by VUB and information on the hydrodynamic properties of geological formations.

Processes governing contaminant fluxes

- Contaminant characteristics: retardation, transformation processes (sorption – desorption, biodegradation, biotransformation), ecotoxicity…
- Migration processes (advection, hydrodynamic dispersion, diffusion)

Prior to modelling the fate of contaminants from the source of contamination to the Receptors, one needs to define their specificities (Figure 7). This is the objective of WP3, Task 3.1 and

Task 3.3, under the responsibilities of VITO (biogeochemical properties of contaminants) and LEAE-ULg (ecotoxicity of contaminants).

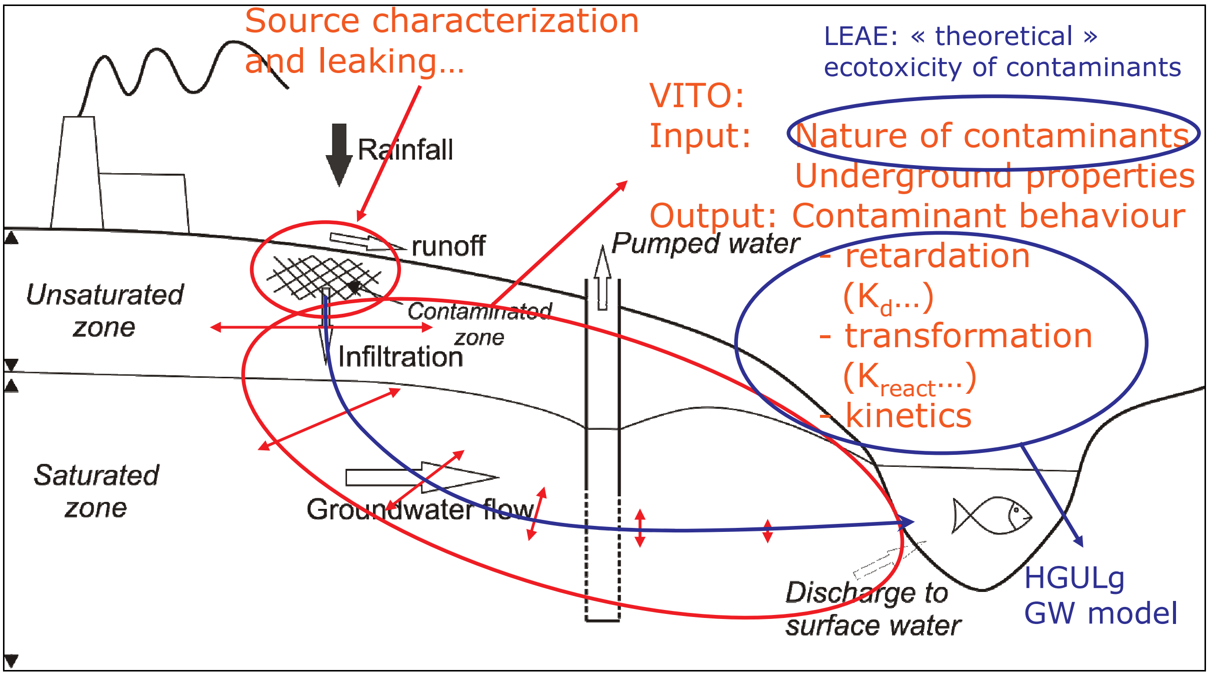

Figure 7. Characterization of contaminants: source, specific behaviour in the underground and ecotoxicity

Identification and quantification of (stimulated) natural attenuation potential in aquifers and sediments

In the EU-project SEDBARCAH VITO has determined the role of the microbial community present in sediments in the biodegradation and transformation of groundwater pollutants infiltrating a riverbed. The boundary conditions and the possibility to increase and sustain removal activities in the sediment zone were explored, while tools for *in situ* monitoring were developed (SEDBARCAH 2005, 2006). Thorough laboratory and field study was performed on the physico-chemical and microbial processes occurring in the sediments of different river systems, including a CAH-contaminated site close to the Zenne river in the region of Vilvoorde, Belgium. In the project the studied sediment biobarrier was identified as highly effective as a groundwater remediation technology and a risk prevention measure. The remediation potential was quantified and modelled. In the scope of FRAC-WECO, VITO is going to experience further the SEDBARCAH methodology on how to measure, quantify, stimulate and model degradation, in the sediment interface as well as in the upstream aquifers, in order to describe, quantify and model the biogeochemical behaviour of the present contaminants. In the FRAC-WECO-project the SEDBARCAH remediation technology for CAH pollution will be deepened, as well as expanded to other contaminants. The microbial transformation processes will be monitored by quantitative PCR and DGGE techniques and microbial activity in the aquifer will be stimulated accordingly in order to validate different remediation concepts.

Biogeochemical properties of contaminants

In WP 3.1 the biochemical processes influencing the fate of common pollutants as well as more specific and less known pollutants will be identified and quantified in function of changing environmental conditions (pH, ORP, organic matter, electron acceptors,…).

The site that was studied thoroughly in the SEDBARCAH project will be used further as a FRAC-WECO test site. The main pollutants are CAH, with BTEX to a lesser extent and some minor concentrations of metals. As the sediment interface was already explored in SEDBARCAH, the technology will be applied on the upstream aquifer that discharges into the river (sediment). Sorption and degradation (microbial and chemical) processes in the aquifer will be studied by means of batch experiments, in which the stimulating effect of the addition of different substrates (carbon sources, inoculum…) will be evaluated. The present microbial communities will be studied by PCR and DGGE techniques and the identification of catabolic genes. The degradation data will be used to study degradation kinetics and to derive degradation constants (K-values) that will be used as an input parameter in the reactive transport model that is being developed for the site.

In a second stage the methodology will be expanded to a variety of contaminants and to other test sites.

Ecotoxicity of contaminants

Contamination sites are important sources of pollution and may result in ecotoxicological effects on terrestrial, groundwater and aquatic ecosystems. The main problem lies in long-term chronic effects. Ecotoxicological effects occur at all levels of biological organization, from the molecular to the ecosystem level. Not only some organisms may be affected, but the ecosystems as a whole, both terrestrial and aquatic, in its function and structure. Contaminants at large contaminated sites often share critical properties such as high acute and/or chronic toxicity, high environmental persistence, often high mobility leading to contamination of groundwater, and high lipophilicity leading to bioaccumulation in food webs.

The bioavailability of chemicals, which is dependent on biogeochemical processes, is an important factor in ecotoxicological evaluation and hazard assessment. The bioavailable fraction is the critical parameter for uptake and ultimately for the concentration at the target sites in organisms, which is the critical parameter for toxicity (Figure 8).

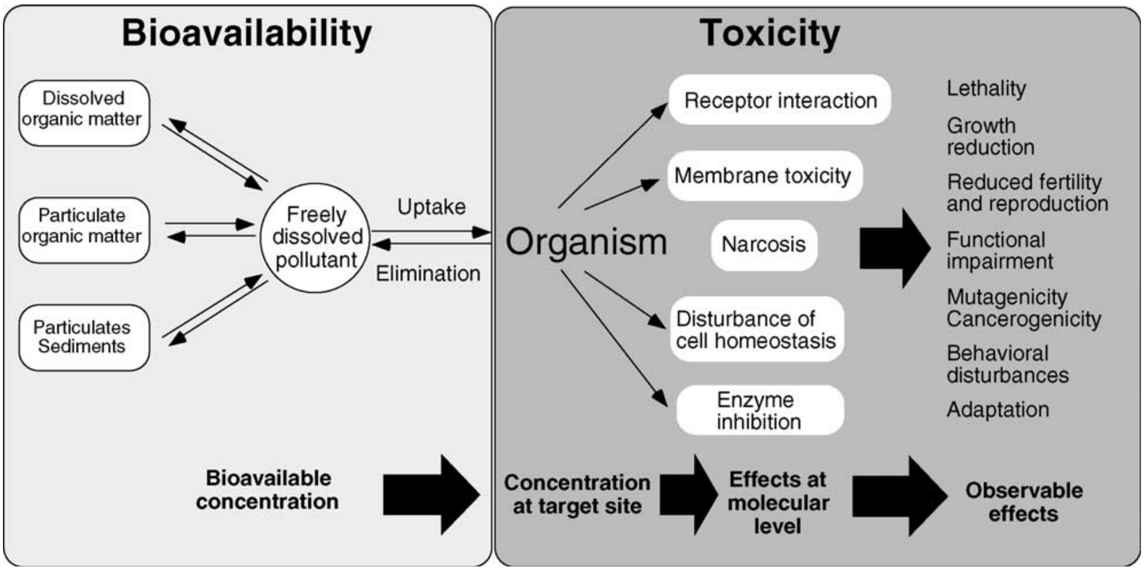

Figure 8. Ecotoxicological effects are dependent on the bioavailable fraction of pollutants. Concentrations at the target sites induce molecular effects that propagate to a variety of toxic manifestations in organisms (source: Fent, 2004)

According to the type of xenobiotic, ecotoxicological impacts will be different. So, we will search in literature LC50 values of the various pollutants studied in the project.

As illustrated in Figure 9, the combination between information on water fluxes, source of contamination and contaminant behaviour and information on hydrodispersive properties of the underground medium will allow one to compute contaminant mass fluxes from the Source to the various Receptors (WP2, Task 2.2). This will further allow one to perform a risk assessment analysis based on the calculated indicators and associated threshold values, and to perform the socio-economic analysis as described in the next chapter.

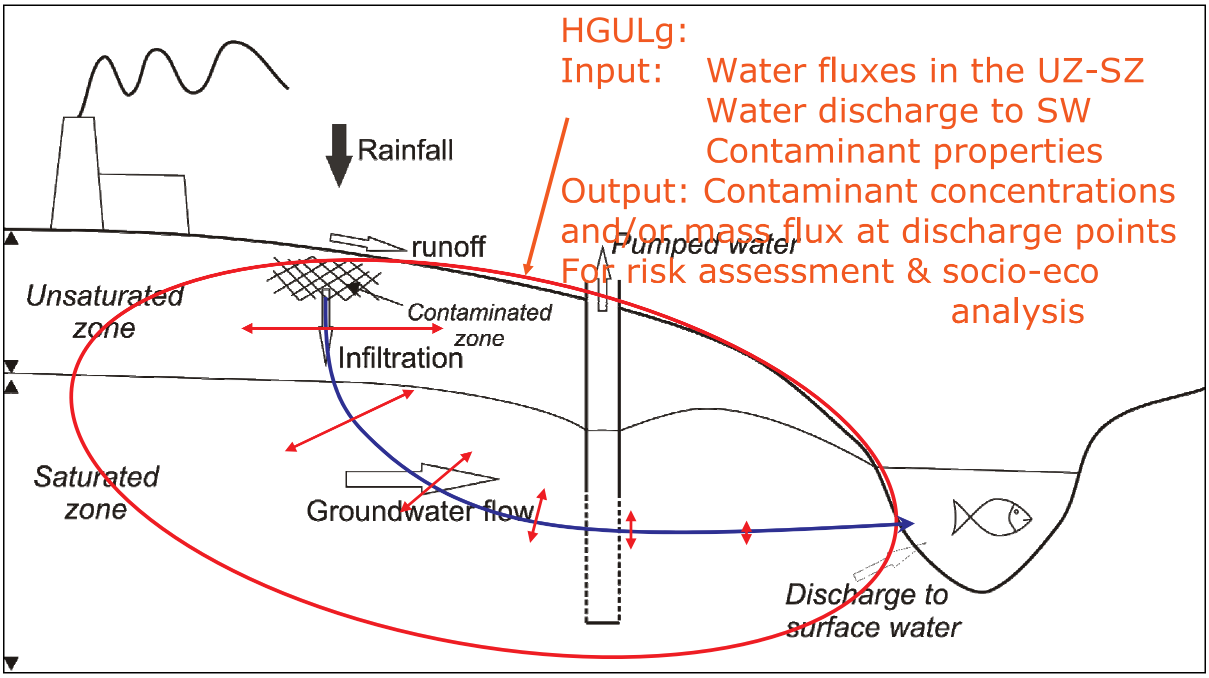

Figure 9. Modelling contaminant mass fluxes from the Source to the Receptors and Indicators

In this component of the project, HGULg has several objectives in terms of developments. These objectives are summarized hereafter.

Quantification of hydrodispersive properties and contaminant mass fluxes in the field

The objective will be here to contribute to a better assessment of hydrodispersive properties in the field. This includes the development of natural gradient tracer experiments monitored by geophysical equipment. As opposed to sampling, geophysical exploration techniques allow non-invasive imaging of the subsurface. The planned experiments include the monitoring of the spontaneous potential to access flow information and redox conditions (e.g. Naudet et al., 2003), electrical resistivity and induced polarization imaging to map the evolution in two or three dimensions of plume contaminants (e.g. Nguyen et al., 2007), thereby allowing the quantification of convection-dispersion parameters and eventually the degradation of e.g. DNAPL. In addition, higher resolution images of the subsurface will be obtained by ground penetrating radar to relate structural heterogeneities, flow patterns and contaminants (e.g. Lopez et al., 2003). These investigations will be combined to classical tracer sampling and monitoring, in particular with the use of the FVPDM single well technique. It is expected that the confrontation of the results will allow for a better quantification of groundwater flow in the field

Modelling contaminant transport in the field

Contaminant transport models will be developed for the different test sites. Different options will be evaluated: MT3D, RT3D, HydroGeoSphere. These models will integrate the various research components (groundwater flow modelling, contaminant properties etc) and will serve several objectives:

- calculating the contaminant mass fluxes between the pollution sources and the different receptors, for both risk assessment and socio-economic analyses;
- comparative testing and validation of tools adopted and/or developed at the various steps of the risk assessment tiered approach;
- testing in a second step various remediation alternatives.

Once again, one of the critical aspects of these robustness and accuracy of these modelling applications will strongly depend on the availability of reliable estimates of groundwater fluxes and contaminant mass fluxes in the different test sites.

3.4. Socio-economic analysis (State-Impacts relationships and analysis of Response)

Policy context

DPSIR framework combined with economic analysis can help to support decision making, in particular:

(i) By assessing the impact of groundwater degradation (environmental damage). This can then be used for justifying the need for action;

(ii) By providing relevant information for understanding economic assessment of possible technical measures for instance cost-effectiveness analysis (CEA) and cost-benefit analysis (CBA).

Economic analysis of environmental damage and management plans is in line with the requirements of the Water Framework Directive (EC, 2000) and the objective for water bodies to reach a good ecological and chemical status by 2015. Concerning groundwater bodies, the Daughter Directive (EC, 2006) mentions that quality threshold values have to be established by Member States by the end of 2008 in all groundwater bodies that were characterised in the recent first WFD reporting obligations as being at risk. As (i) this process will be under way during the first part of FRAC-WECO project, and (ii) the methodology for groundwater risk assessment and management of contaminated sites is still under development, economic analysis will thus be carried out in close collaboration with the end-users of the project that are involved in water resources and contaminated sites management (OVAM, SPAQuE, DGRNE).

Assessing environmental damage (State-Impact relationships)

The objectives are to identify and assess environmental damage due to the contamination of water resources (groundwater and/ or surface water due to groundwater contamination). Damage due to a contaminated water resource may occur at various time periods (short-term, long-term) and spatial scales (in-site, off-site).

The identification of damage will address not only the direct use value of water (e.g. avoidance costs for water users who may have to undertake costly corrective actions), but also non-use value (existence value) and indirect use value (e.g. increased fear and anxiety, loss of recreational value, loss of property value).

The method(s) to be used for the assessment of damage will depend on the typology of environmental damage that is identified in the previous step. Various economic valuation methods exist and may be used:

- Revealed preference valuation methods (hedonic pricing, travel cost method, averting behaviour and defensive expenditure, cost of illness and lost output calculation);
- Stated preference valuation (contingent valuation).

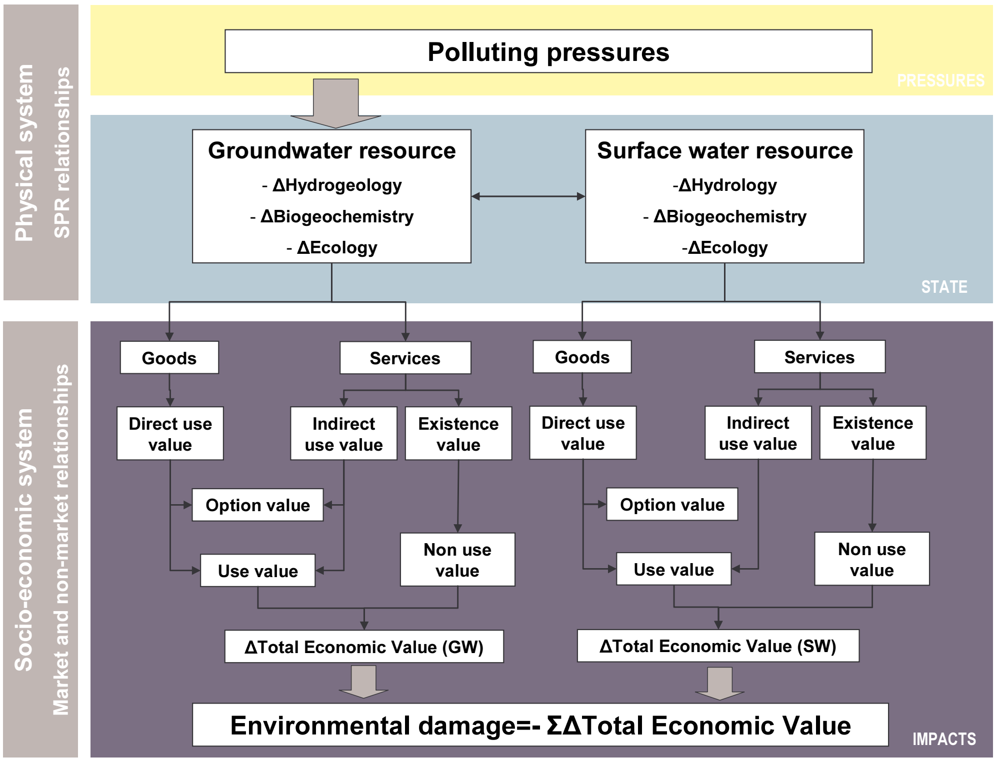

Figure 10. Characterisation of environmental damage related to groundwater degradation (scheme adapted from Brouwer, 2005)

When possible, damage will be expressed as a function of physical indicators (Figure 11).

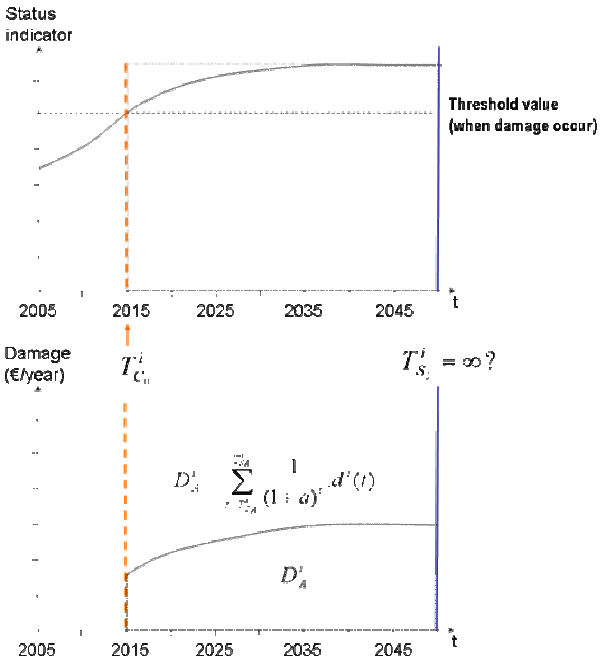

Figure 11. Relations between State indicator and Environmental damage (from Hérivaux *et al.*, 2006)

Cost Benefit Analysis (Analysis of Responses)

Benefits of environmental projects are usually assessed as the avoided damage. CBA can help to compare and select a programme of measures. This method already has an important role to play in current policy development, such as the economic analysis required for the implementation of the WFD and CBA recommended by the French approach of contaminated sites management. In CBA, benefits are defined as increases in human wellbeing and costs are defined as reduction in human wellbeing (OECD, 2006). A project or policy is recommended according to CBA if the benefits it brings to the society exceed the costs of its implementation (society = sum of individuals).

Figure 12 presents how DPSIR components may be used for cost – benefit analysis. It should be stressed that at least two scenarios (in the future) should be identified:

- Scenario A representing the business as usual scenario with current management measures (which in turn might lead to deterioration of water resources with negative impacts on water uses/ natural ecosystem) and
- Scenario B representing the possible management measures (Responses) that will influence different components of the system into consideration.

The main steps to be carried out for CBA implementation are the following:

- Identity the Reference scenario (business as usual): this scenario should assess the main pressures (P^A) exerted on the system, assess how groundwater (and surface water) quality (S^A) may be affected by polluting pressures and assess related environmental damage (I^A). To be performed, this step should integrate physical modelling results and environmental damage assessment.
- Identify the management scenario and describe potential measures (Responses) that aim to limit/prevent the degradation of water resources and mitigate the impacts. The same analysis as in the reference scenario should then be done to assess Pressures (P^B), State (S^B) and Impacts (I^B).
- Cost-benefit analysis: Comparison of the status of water resources between the reference and management scenario helps to assess the effect of the proposed measures. The comparison of the environmental damage between the scenarios will support the assessment of the benefits of the proposed measures.

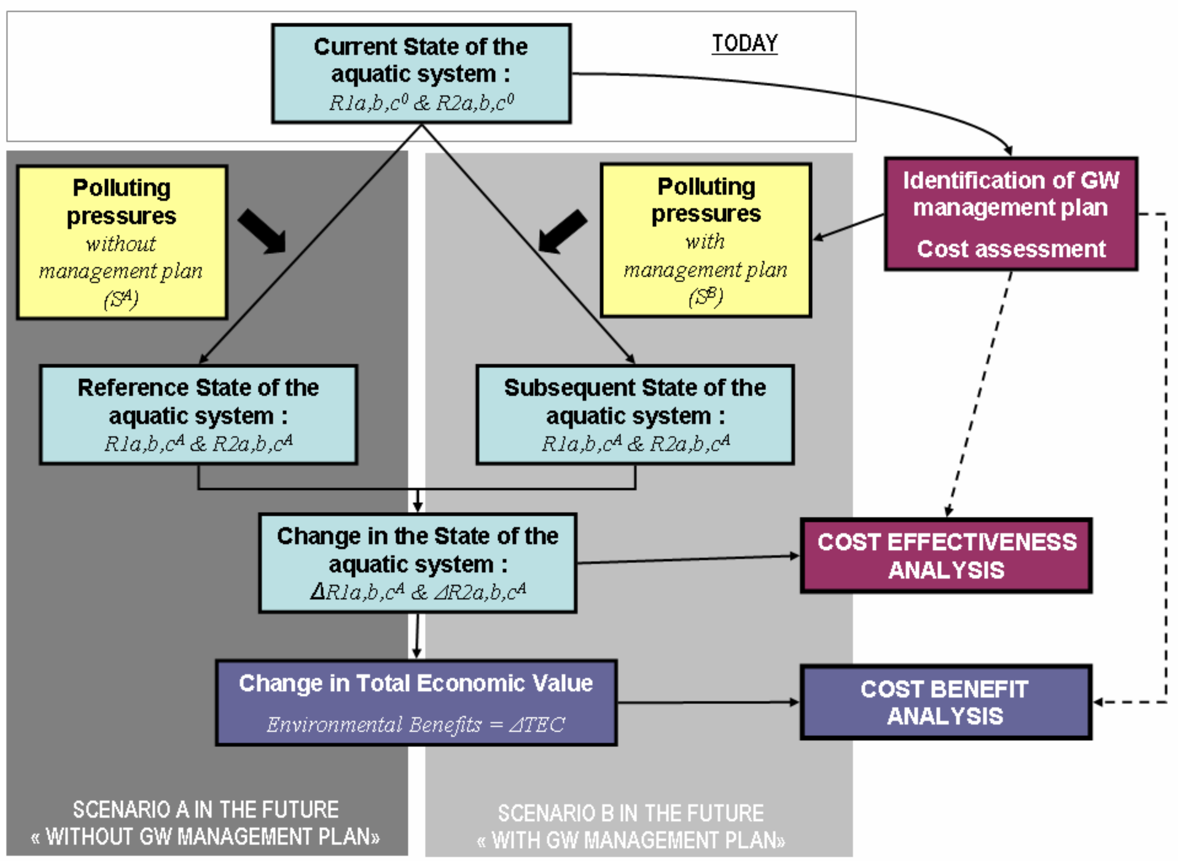

Figure 12. Use of the DPSIR components in cost effectiveness and cost benefit analysis (adapted from Hérivaux *et al.*, 2006)

As costs and benefits are rarely known with certainty, risk (probabilistic outcomes) and uncertainty (when no probabilities are known) also have to be taken into account (OECD, 2006). A sensitivity analysis can be undertaken to assess how results of CBA would change if the values of some key indicators for the different components (P, S, I) would be modified.

4. Conclusions

This deliverable has allowed one to clarify the objectives of the different partners involved in the FRAC-WECO project and how they are going to interact, to exchange data, research results and knowledge in order to meet the ambitious objectives of the project.

Particularly, the complex interactions between researches dealing with physical processes and with socio-economic aspects have been described in details. The modelling applications will constitute the key interacting tools as they are going to integrate all the information on water and contaminant mass fluxes and on biogeochemical processes affecting the fate of contaminant in the field and they are also going to be used to produce all data required for risk assessment and for the socio-economic analysis which are two of the most important expected outcomes of the project.

The deliverable has also clarified the use of flux-based concepts through the definition of risk assessment indicators in the form of contaminant mass fluxes and discharge at the various considered receptors.

Finally, this document has also allowed one to clarify the scope and the limits of the researches foreseen in the FRAC-WECO project that will focus on the risk of contaminant leaching to groundwater, of contaminant dispersion through groundwater and on the impact of contaminant on groundwater and surface water as affected by groundwater discharge and on the impact on aquatic ecosystems.

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