



Institut International d'Ingénierie de l'Eau et de l'Environnement  
International Institute for Water and Environmental Engineering

*Mapping groundwater intrinsic vulnerability using a new  
physically based modeling in Kou basin  
Bobo-Dioulasso/Burkina Faso*

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**FINAL PROJECT OF MASTER DEGREE IN  
HYDRAULIC-ENVIRONMENT AND INFRASTRUCTURES**

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*Presented publicly on June 2008 by*

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**Promotion 2007/2008**

*A Dieu soit la gloire pour ses merveilles dans ma vie*

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## DEDICATION

- ✚ **To the holy God, who created me and permit me to learn and to understand,**  
*Thank you for Jesus in my life. You are all that i need,*  
*And I know that with you I will go further than now.*
- ✚ **To my dear late Father,**  
*Who knew and asserted that school is the unique way to access to development,*  
*If you were here, you should have seen your dream become true.*  
*Some other fathers are seeing your dream. You didn't mistake.*
- ✚ **To my brave and sweet mother,**  
*You played both my father and my mother. It's time of your yield.*  
*Be in Joy. I love you so much,*
- ✚ **To my sister G. G. Madeleine,**  
*Be your days full of peace and joy. I could never forget you for all your help.*
- ✚ **To my dear uncle G. Pascal,**  
*You will receive all you spent because of me.*  
*Thank You uncle,*
- ✚ **To my dear uncle DIOMANDE Louti,**  
*Thank you for presence as our adoptive father. You did all for my brothers and sisters.*  
*May God bless you and all your family!*
- ✚ **To my dear uncle SAO Paul and family,**  
*Without you, I couldn't reach this level.*  
*Thank you so much.*
- ✚ **To my friend NGUESSAN Yapi Jean Edès,**  
*Thank you for you friendship.*
- ✚ **To my brothers and sisters in Christ of Cellule de Prière Évangélique du 2iE,**  
*Thank you for you prayers for me.*  
*Be blessed over your hope*
- ✚ **To my princess**  
*Thank you for your prayers and your love.*

## **ABBREVIATIONS AND ACRONYMS**

<b>2iE</b>	: International Institute of water engineering
<b>Bobo</b>	: Bobo-Dioulasso
<b>GIS/SIG</b>	: Geographic Information System/Système d'Information Géographique
<b>ESO Bobo</b>	: Projet "Appui à la gestion et à la protection des ressources en eaux souterraines exploitées dans la région de Bobo-dioulasso"
<b>GE-Eau</b>	: Projet "Renforcement structurel de la capacité de gestion des ressources en eau pour l'agriculture dans le bassin du Kou"
<b>APEFE</b>	: Association pour la <b>P</b> romotion de l' <b>E</b> ducation et de la <b>F</b> ormation à l' <b>E</b> tranger
<b>CONAGESE</b>	: Conseil <b>N</b> ational pour la <b>G</b> estion de l' <b>E</b> nvironnement
<b>DRAHRH</b>	: <b>D</b> irection Régionale de l' <b>A</b> griculture de l' <b>H</b> ydraulique et des <b>R</b> essources <b>H</b> alieutiques
<b>DRA</b>	: <b>D</b> irection Régionale de l' <b>A</b> griculture
<b>DIMA</b>	: <b>D</b> irection des <b>I</b> ntrants et de la <b>M</b> écanisation <b>A</b> gricole
<b>DT50</b>	: Duré de demi vie ou temps de dégradation de 50% de la molécule
<b>NPK</b>	: <b>N</b> itrates, <b>P</b> hosphates, <b>P</b> otassium
<b>NPKSB</b>	: <b>N</b> itrate <b>P</b> hosphate <b>P</b> otassium <b>S</b> oufre <b>B</b> ore
<b>ONEA</b>	: <b>O</b> ffice National de l' <b>E</b> au et de l' <b>A</b> ssainissement
<b>SAPHYTO</b>	: société africaine des produits phytosanitaires et d'insecticides
<b>SOFITEX</b>	: société des fibres textiles du Burkina Faso
<b>Ulg</b>	: University of liege (Belgium)

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## CHAPTER I: GENERAL INTRODUCTION

### I.1 Background

Groundwater recharge mechanisms and the natural contaminant attenuation capacity of subsoil profiles vary widely with near-surface geological conditions. Thus, instead of applying universal controls over potentially-polluting land uses and effluent discharges, it is more cost effective (and less prejudicial to economic development) to vary the type and level of control according to this attenuation capacity. This is the basic premise underlying the concept of aquifer pollution vulnerability and the need for vulnerability mapping. (*BI: Mapping Aquifer pollution Vulnerability, Technical Guide*)

#### **But where is the concept of vulnerability from?**

In hydrogeology the term vulnerability began to be used intuitively from the 1970s in France (Albinet & Margat, 1970) and more widely in the 1980s (Haertle, 1983; Aller *et al.*, 1987; Foster & Hirata, 1988). While the implication was of relative susceptibility of aquifers to anthropogenic pollution, initially the term was used without any attempt at formal definition.

The expression began to mean different things to different people. A useful and consistent definition would be to regard aquifer pollution vulnerability as those intrinsic characteristics of the strata separating the saturated aquifer from the land surface, which determine its sensitivity to being adversely affected by a surface-applied contaminant load (Foster, 1987). It would then be a function of:

- ↳ The accessibility of the saturated aquifer, in a hydraulic sense, to the penetration of pollutants;
- ↳ The attenuation capacity of strata overlying the saturated zone resulting from the physicochemical retention or reaction of pollutants.

In the same way, groundwater pollution hazard would then be defined as the probability that groundwater in the uppermost part of an aquifer will become contaminated to an unacceptable level by activities on the immediately-overlying land surface (Foster & Hirata, 1988; Adams & Foster, 1992).

The mapping the vulnerability of aquifer pollution will normally be the first step in ground water pollution hazard assessment and quality protection, when the interest is at municipal or regional scale like Bobo-dioulasso.



The concept of vulnerability is as valid for its appraisal at more local level within groundwater supply catchments areas as it is for all human activities water use.

## **I.2 Scope and objectives**

The object of this study is to apply a new approach validated in Belgium for mapping the vulnerability of bobo's groundwater using a physically based modeling.

It must lead to :

- To construction of visible and directly exploitable maps describing the sensitivity of bobo's aquifers to pollution.
- To the establishment of a comparison of two different approaches in mapping the vulnerability notably experimental and methodological method (the Belgian approach) and an empiric approach (Drastic Method)

## **I.3 Justification of study**

Anthropological activities are being intensified and permanent in Bobo-dioulasso. Industries and agricultural activities are rejecting more and more chemicals and pollutants. Even if this situation is under control at the present time nobody can predict it in five or ten years. Detect vulnerable zone requiring special attention is necessary to Burkina authorities. So this study has the goal to provide information in these domains and maps representing important tools for land-use planning.

This study has an ultimate aim of finding these vulnerable zones.

## **I.4 Methodology**

Data were totally collected by **The Belgian projects Eaux Souterraines de Bobo and GE-Eau** on one hand and on the other by ONEA and water management structures of Burkina.

These data were classified in a geodatabase built by the head of the project in Bobo-dioulasso, Mr GARDIN.

Therefore, apart specific visits to measure water level, this study was essentially consisted of:

- Data treatment,
- Preparation of information layers for Belgian vulnerability calculation program,
- Finalization of maps on ArcGIS and report redaction.

## I.5 Presentation of study zone



Figure1 : Study zone

## I.6 Presentation of the Belgian cooperation

The cooperation project APEFE/DRI/CGRI « Appui la gestion et à la protection des ressources en eaux souterraines exploitées dans la région de Bobo-Dioulasso » is a bilateral cooperation project relating the french speaking belgium and the government of Burkina Faso.

Three principal objectives were assigned to the project. They are:

- ✚ Improvement of knowledge about Bobo's groundwater functioning,
- ✚ Assessment of menaces overlying on this resources.
- ✚ Quantification of water resources

The DRAHRH-HB, ONEA and many other partners are implied in order to guarantee a total success of the project.

The Kou basin is located in western south Burkina and measures 1800 km<sup>2</sup>. It represents therefore 0,66 % of national area. Three administrative departments (Bama, Bobo-Dioulasso and Péni) are covered with a population of 600 ,000 inhabitants shared in differents activities with predominance in agriculture and artisanal work .

(Rapport de stage Ahmed KAM: 2007).

Other information about the basin are presented in APPENDICES C.

## **I.7 The report organization**

This report has five chapters. Chapter 1 is the general introduction which consists of background statements, scope and objectives, justification of the study, methodology and organization of the report. Literature review is presented in chapter 2. The third chapter deals with the description of the Belgian approach for mapping aquifers vulnerability. Results and discussion are presented in chapter 4. The last part of the report body is conclusion and recommendations. Details and additional information are presented in appendices.

## CHAPTER II: CONCEPT OF VULNERABILITY: LITERATURE REVIEW

### *II.1 Concept of vulnerability*

The vulnerability to pollution of an aquifer is its facility to be reached by a pollution which can be caused by:

- a punctual source such as  
(Rubbish dump, cemetery, domestic or industrial waste water reject)
- A lineal source such as  
Pipeline, used water network, agricultural drainage network etc).
- A diffuse source such as  
(Chemical fertilizer, pesticide, dispersal of used water etc...)

This pollution can occur by an accidental event (reversal of a car transporting dangerous products). It can also be caused by a permanent source like a rubbish dump (low and long-term percolation of effluent). Mohamed SINAN et Rachid MASLOUHI, décembre 2005. Subsequently two major professional working groups reviewed and pronounced upon the applicability of the vulnerability concept and come out strongly in favour of its usefulness (NRC, 1993; IAH/Vrba & Zaporozec, 1994). It would have been desirable for them to have made a clearer statement on the use of the term, for example associating it specifically with the intrinsic characteristics of the strata (unsaturated zone or confining beds) separating the saturated aquifer from the land surface (Foster & Skinner, 1995). This would (most importantly) have related it directly with the potential impact of land-use decisions at the location concerned on the immediately-underlying groundwater. Some, however, considered that a factor representing the natural mobility and persistence of pollutants in the saturated zone should be included in vulnerability. This, however, does not appear to view vulnerability mapping from the most useful perspective, namely that of providing a framework for planning and controlling activities at the land surface.

### *II.2 Vulnerability index*

Two main questions that arise in relation to aquifer pollution vulnerability are whether it is possible to:

- ✚ Present a single integrated vulnerability index, or be obliged to work with specific vulnerability to individual contaminants and to pollution scenarios,

- ✚ Provide an absolute indicator of integrated pollution vulnerability, or be restricted to much less useful relative vulnerability indices.

### ***II.3 Different approaches for unconfined water vulnerability characterization***

A number of other schemes of aquifer pollution vulnerability assessment have been presented in the literature, and these can be classified into three main groups according to the approach adopted (Vrba & Zaporozec, 1995):

- ✚ Hydrogeological Settings: these base vulnerability assessment in qualitative terms on the general characteristics of the setting using thematic maps (eg. Albinet & Margat, 1970)
- ✚ Analogue Models: these utilize mathematical expressions for key parameters (such as average vadose zone transit time) as an indicator of vulnerability index (EC/Fried approach in Monkhouse, 1983)
- ✚ Parametric Systems: these use selected parameters as indicative of vulnerability and assign their range of values and interactions to generate some form of relative or absolute vulnerability index (examples of this approach include Haertle (1983) and DRASTIC of Aller et al. (1987), in addition to the GOD methodology described in II.3.1 ). A further method of note in this category is EPIK, which is specifically designed for karst limestone aquifers only and usefully discussed by Gogu & Dassargues (2000).

#### **II.3.1 The god method**

The GOD method of aquifer pollution vulnerability assessment has had wide trials in Latin America and the Caribbean during the 1990s, and because of its simplicity of concept and application is the preferred.

Two basic factors are considered to determine aquifer pollution vulnerability:

- ✚ The level of hydraulic inaccessibility of the saturated zone of the aquifer
- ✚ The contaminant attenuation capacity of the strata overlying the saturated aquifer but they are not directly measurable and depend in turn on combinations of other parameters (Table 1.3).

Since data relating to many of these parameters are not generally available, simplification

of the list is unavoidable if a practical scheme of aquifer pollution vulnerability mapping is to be developed.

Based on such considerations, the GOD vulnerability index (Foster, 1987; Foster & Hirata, 1988) characterizes aquifer pollution vulnerability on the basis of the following (generally available or readily determined) parameters:

- (a) Groundwater hydraulic confinement, in the aquifer under consideration.
- (b) Overlying strata (vadose zone or confining beds), in terms of lithological character and degree of consolidation which determine their contaminant attenuation capacity
- (c) Depth to groundwater table or to groundwater strike in confined aquifers.

**Limits of this method**

Many parameters characterize groundwater and they should be considered in any approach to assessing their vulnerability. The original GOD vulnerability scheme did not include explicit consideration of soils in an agricultural sense. However, most of the processes causing pollutant attenuation and/or elimination in the subsurface occur at much higher rates in the biologically-active soil zone, as a result of its higher organic matter, larger clay mineral content and very much larger bacterial populations. (*Technical Guide Page 12 of 18*)

Besides these two parameters the approach focus on are not always measurable and then empirical value are chosen sometimes. In this way, with some luck, the result can represent at a rough reality but in general cases; it doesn't explain the real phenomenon.

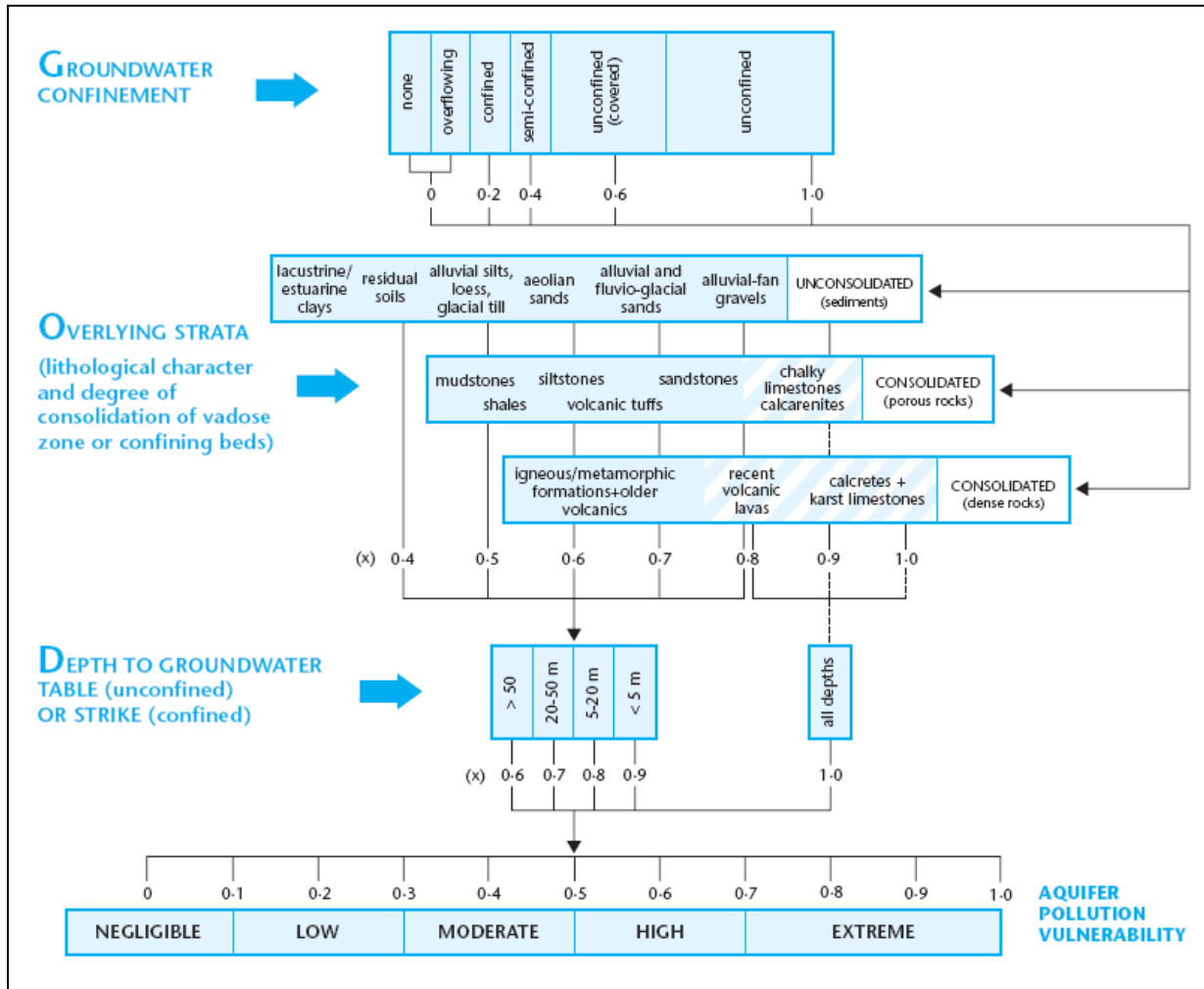


Figure2 : GOD system for evaluation of aquifer pollution vulnerability

(Groundwater Quality Protection: a guide for water utilities, municipal authorities and environment agencies)

### II.3.2 The drastic method

Amongst the vulnerability assessment approaches, the best known is the DRASTIC methodology. It attempts to quantify relative vulnerability by the summation of weighted indices for seven hydrogeological variables (Table 1.4). The weighting for each variable is given in parentheses, but changes (especially for parameters S and T) if vulnerability to diffuse agricultural pollution alone is under consideration.

The method has been the subject of various evaluations (Holden et al., 1992; Bates et al., 1993; Kalinski et al., 1994; Rosen, 1994). All of these evaluations revealed both various benefits and numerous shortcomings, of this methodology. On balance, it is considered that the method tends to generate a vulnerability index whose significance is rather obscure. This is a consequence of the interaction of too many weighted parameters, some of which are not independent but quite strongly correlated. The fact that similar indices can be obtained by a very different combination of circumstances may lead to dangers in decision-making. (Technical guide).

<b>Factor and weightings in the Drastic pollution vulnerability index</b>		
<b>(i)</b>	<b>Depth to groundwater</b>	<b>(ii) Recharge rate (natural)</b>
<b>(iii)</b>	<b>Aquifer media</b>	<b>(iv) Soil media</b>
<b>(v)</b>	<b>Topographic aspect</b>	<b>(vi) Impact of vadose zone</b>
<b>(vii)</b>	<b>Conductivity (hydraulic)</b>	

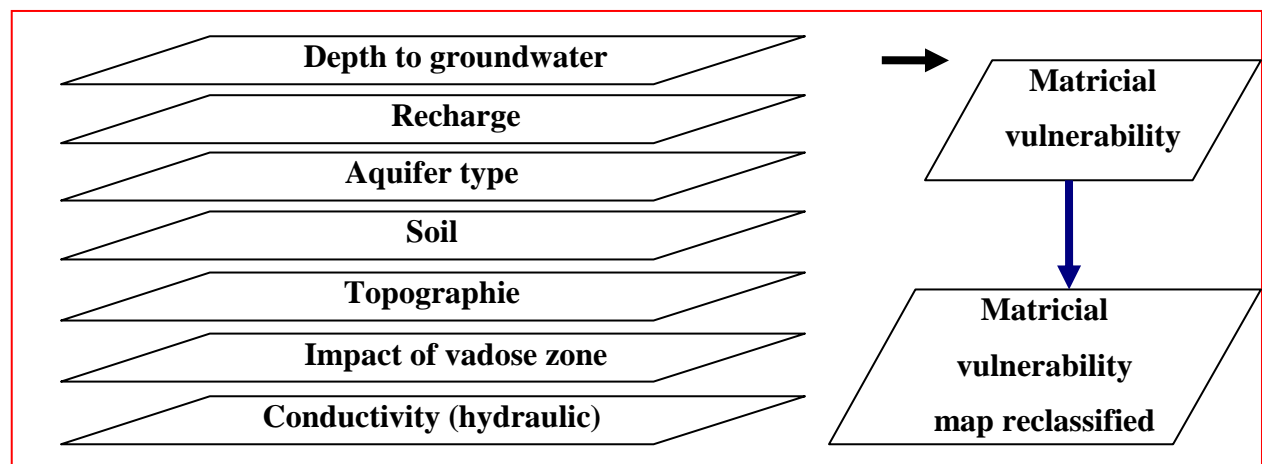


Figure3 : Drastic parameters



### II.3.3 The improved drastic method

This approach is closed to DRASTIC but the impact of unsaturated zone is not taken into account. Weigh of each parameter are different than in Drastic.

### II.3.4 The Belgian method (APSU)

This approach is a new one and very different from the first because it is relayed on many physical parameters of concerned aquifers such as topography, meteorology, geology, soil types and classes, water level in the ground... Besides, it goes deeper by treatments on these information leading then to quantifiable values.

This approach criticizes the lack of precision with the others, lack of objective and quantifiable criteria.

The new approach proposes selected criteria taking up three important questions.

**Question 1:** In the case of pollution, the time it will take to reach the receptor.

**Question 2:** Which level in term of concentration will this contamination reach?

**Question 3:** How long will the polluted water stayed contaminated?

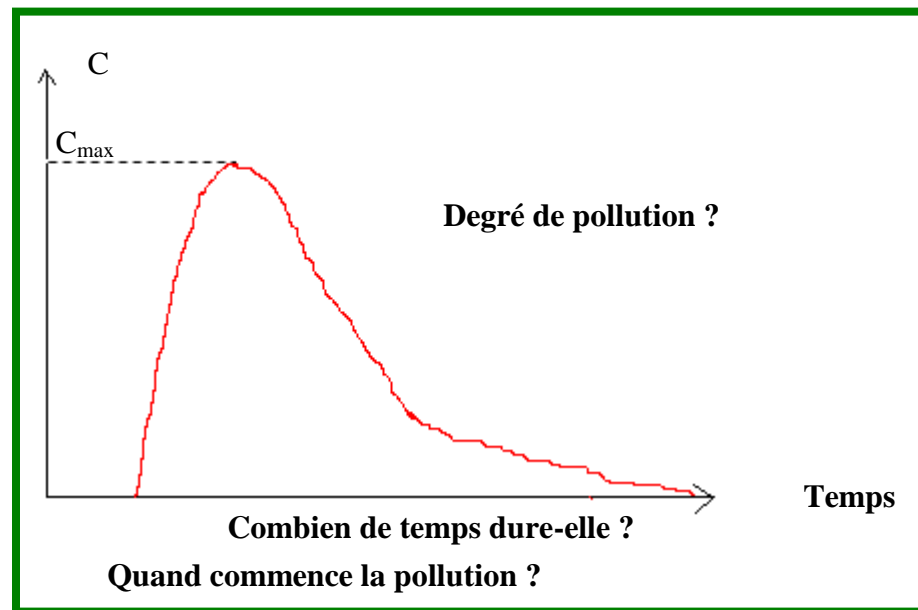


Figure4 : Physical, objective and quantifiable criteria underlying the vulnerability in the new approach (Brouyère et Al., 2001)

Next chapter is consecrated to this approach for the assessment of vulnerability of aquifers.

## II.4 Previous studies about Bobo-Dioulasso's aquifers

### II.4.1 General Studies

Many studies have been done in the region. Some are dated since years 1960. They concern meteorological data and geological mapping. Some other are recent and were ordered by the project.

#### II.4.1.1 Topography

Kou basin's topography dominated by a shelf reaching 500 m of altitude in the western south. By north and eastern north, it decreases regularly to 300 m.

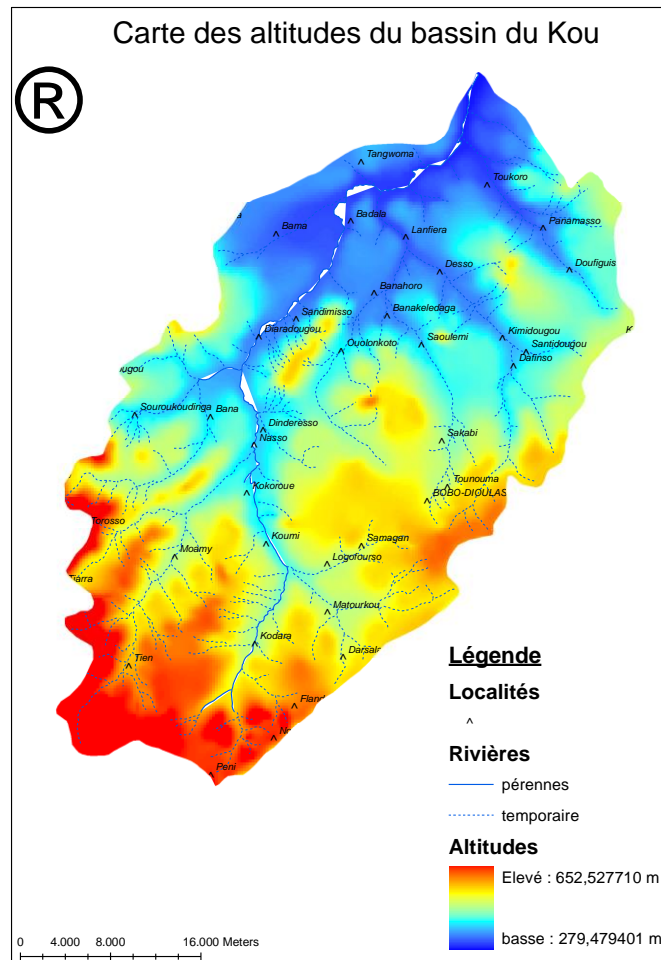


Figure5 : Topography map (MNT)

### II.4.1.2 hydrographic network

There are three international basins in Faso (Basins of Comoé, Niger and Volta) and thirteen national basins. The widest is Mouhoun basin which Kou basin. In our study zone, kou river is the most important. It is provided from upstream by the sources of Kodala, Nasso, Guinguette, Desso, Pessou. Its rejoin Mouhoun River northern.

(Source : synthèse géologique du bassin hydrographique du kou : Clément OUEDRAOGO géologue AEDE Janvier 2007).

### II.4.1.4 Soil occupation

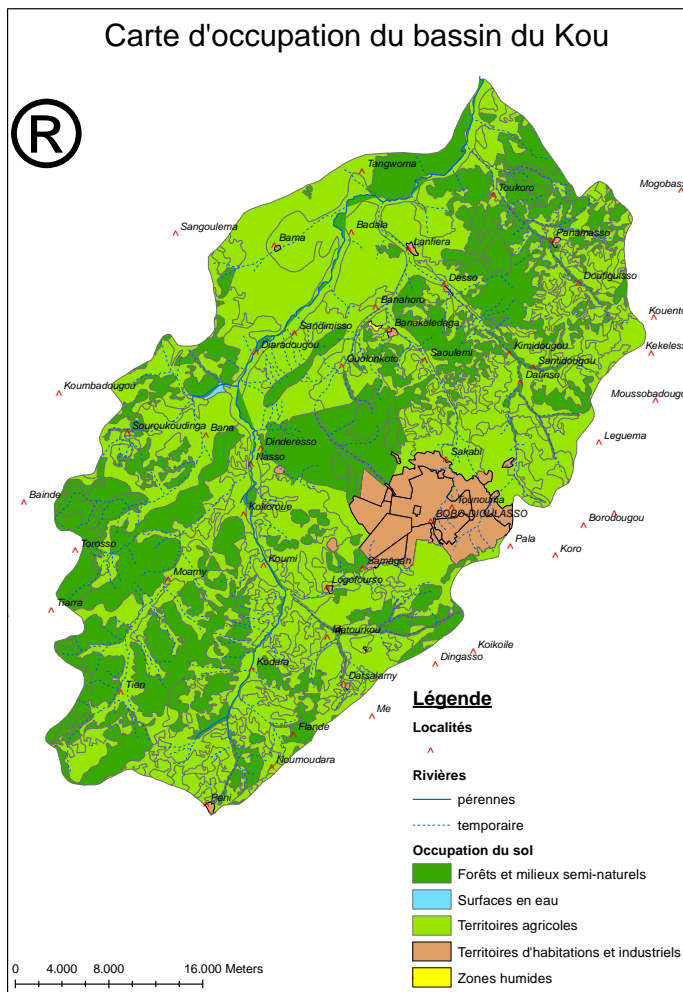


Figure6 : Soil occupation map

Kou basin is consisted of agricultural areas, industrial zones, forests, villages and urban zones. In these last five years, Bobo-dioulasso is in full extension due to the development of industrial and agricultural activities.

60% in term of surface is used by agriculture, 35% for forests and 5% occupied by urban zone.

*Lorenzini Gaëlle, 2006*

### II.4.1.5 Soil type map

The different types of soil met in Kou basin can be classified in six classes of the american textural diagram. Hydro dispersive parameters of these soils are needed for the assessment of infiltration.

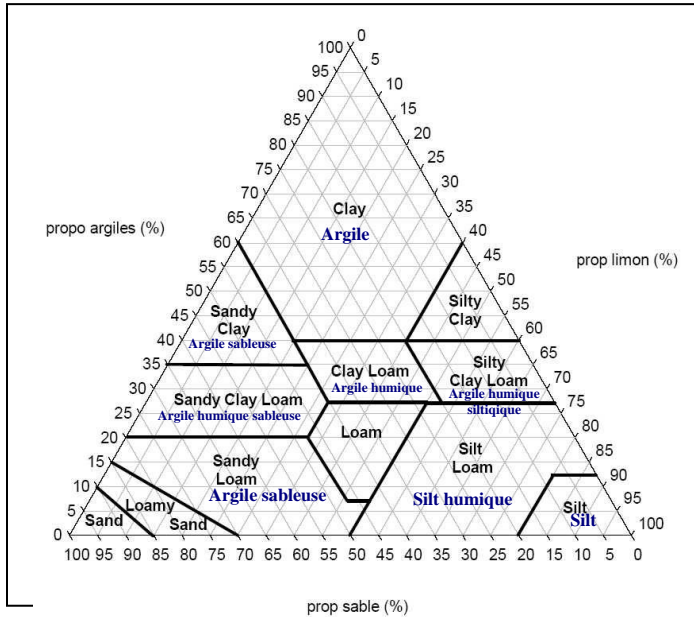


Figure7 : Soil occupation map

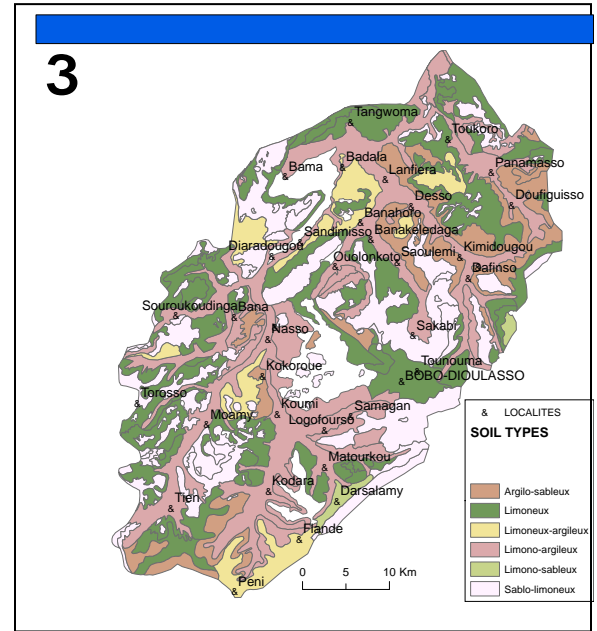


Figure8 : American textural diagram

Source : GE-Eau

### II.4.1.6 Geology

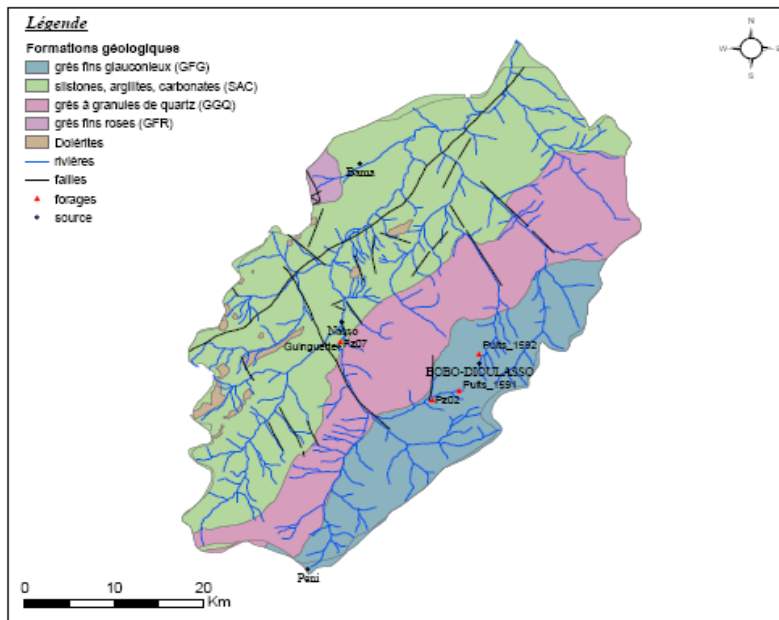


Figure9 : geologic map

Geology in Kou basin is dominated by sedimentary formations of sandstone.

There five main geologic In this study, geologic formation where classified in for different groups.

- Dolerite,
- GFG,
- GGQ,
- SAC
- GFR

They hydrodispersive parameters were taken into account in vulnerability assessment in APSU approach.

### II.4.1.7 Piezometry

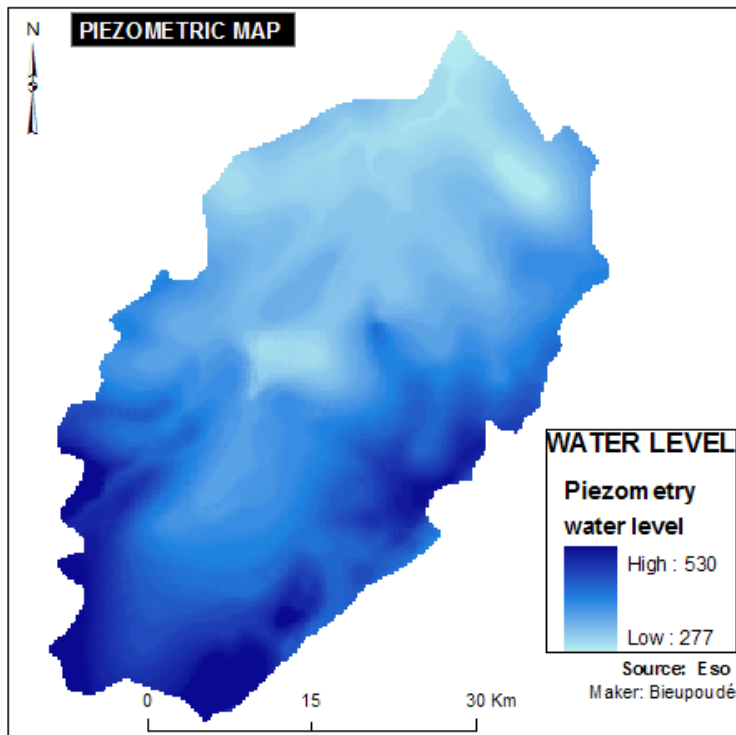


Figure10 : Water level map

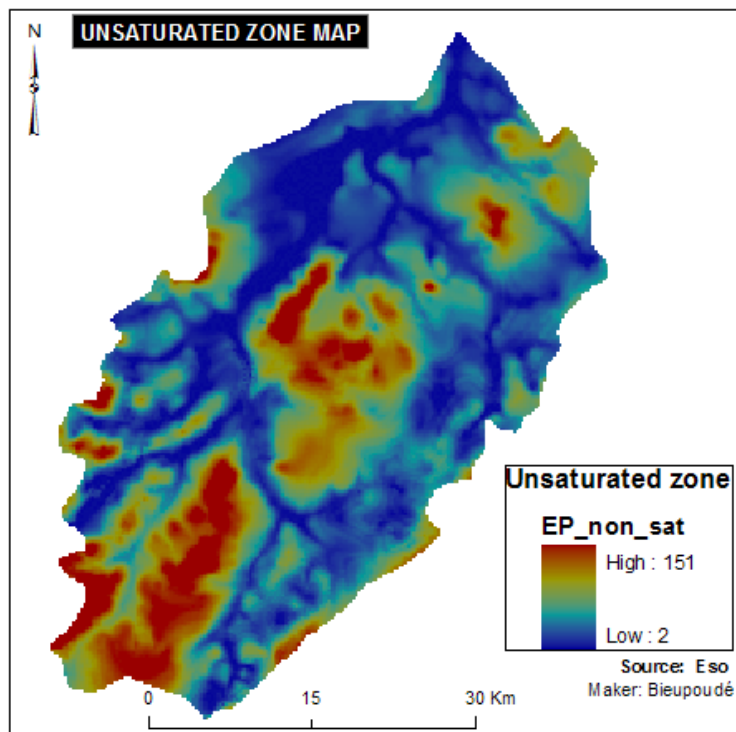


Figure11: Unsaturated zone map

Some piezometers implanted by ESO Bobo and some wells permitted to establish a piezometric map. All the basin have not been covered by this data. By location, interpolations were resorted in order to have a total covering of the basin. On the next map, we have the layer that shows the vadose zone. (Thickness of unsaturated zone).

This layer is the result of (MNT-Piezo Map).

Thicknesses of unsaturated zone vary from 2 to 151 meters. It is a fundamental parameter used in assessment of vulnerability of aquifers.

#### **II.4.2 Studies of Bobo's aquifers vulnerability**

Before this study, some approaches have been done on the basin to evaluate its vulnerability. Lorenzini Gaelle in her report *Etat des lieux des ressources en eaux du bassin versant du Kou* started to evoke vulnerability notion but not deeper. She limited her investigations to infiltration. In December 2007, KAM A. Massa in his report presented the first vulnerability map; applied DRASTIC method but he early suggested to the project to continue the vulnerability study with other scientific approach. In his study only the bed load lowland and downstream BOBO were very vulnerable. (figure 25).

## CHAPTER III: THE BELGIAN APPROACH FOR WATER RESOURCE VULNERABILITY MAPPING

### III.1 PRINCIPLES UNDERLYING THE METHOD

Starting from the observation that lacks and drawbacks of existing vulnerability methods are strongly related to the fuzzy and ambiguous definitions on which these concepts rely, a more physical point of view of the concept of vulnerability is proposed. An applied definition is derived from what actually underlines the concept of groundwater pollution. For intrinsic vulnerability, three factors describing pollution by a conservative contaminant are defined: **contaminant transfer time**, **contamination duration** and **level of concentration reached by the contaminant** (see figure4). These factors are schematically put into a three-dimensional diagram, called the vulnerability cube, which can be used to assess or validate the vulnerability of any point within a given catchment.

(Evaluation and validation of vulnerability concepts using a physically based approach).

### III.2 METHOD CONCEPTUALISATION

#### III.2.1 Comprehension of vulnerability concept

This concept is lying on consideration that unsaturated zone offers a certain protection against contaminants infiltration in aquifers (Vrba&Zporec, 1994).

Three notions are distinguished:

- ✚ **Intrinsic vulnerability:** it considers only geographic, geological, hydrological and hydrogeological characteristics and reflects the capacity of the environment to reduce the contamination independently from the type of contaminant.
- ✚ **Specific vulnerability:** it takes notice of intrinsic vulnerability, physical, chemical or bacterial interactions between the contaminant and subterranean areas.
- ✚ **Risk:** it integrates possible scenarios of contamination, the probability for a contamination to occur and the bulk of its consequences if it happens.

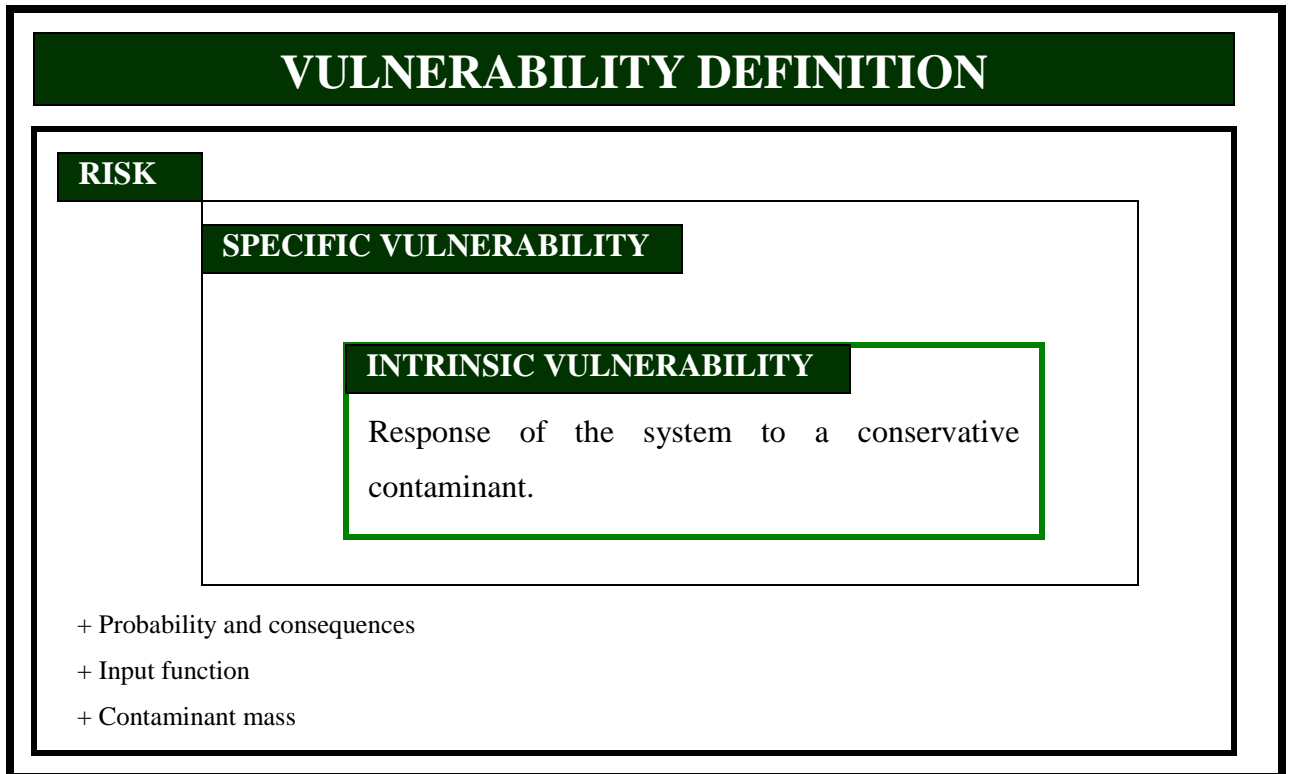


Figure12 : Definition vulnerability concept (Brouyère and Al, 2001)

### III.2.2 Pollutant flow from the surface to the ground

In this study, we focus only intrinsic vulnerability of aquifers. Thus, specific behaviors of neither contaminants nor pollution scenario will be considered. We established the impact of a conservative contaminant emitted from a point of the basin surface on whole aquifers 'scale.

Depending, on infiltration conditions, this contaminant can stream or infiltrated partly or totally. The approach evaluates its flow in unsaturated soils layers under the ground regarding at hydro dynamical and dispersive parameters which intervene in alteration of the contaminant's spatial and temporal distribution. *(Tests d'une méthode de cartographie de la vulnérabilité intrinsèque applicable aux nappes aquifères de la Région Wallonne. Application à l'aquifère du Néblon. A Dassargues, Serge Brouyère.)*



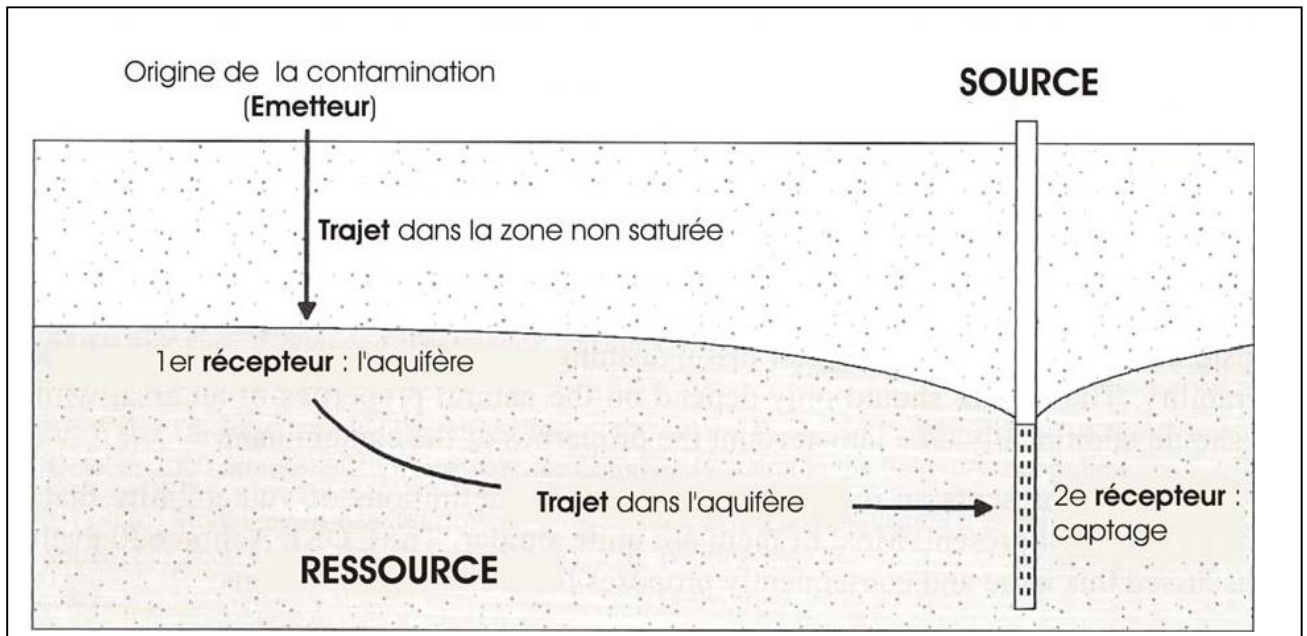


Figure13 : Chart describing « Emitter – Pathway – Receptor» model (Goldscheider, 2004)

The concept of vulnerability as shown and developed by ULg is based on « Emitter – Pathway – Receptor» model presented as above.

- ✚ **The emitter** is the point where a contamination happens (on soil surface).
- ✚ **The receptor** corresponds to the target (objective) to be protected. If it is the whole aquifer, the suitable term is vulnerability of the resource. If it is a specific capitation point, it is vulnerability of the source. In this study, we were interested by the first term.
- ✚ **The pathway** describes the progression of contaminant since it is emitted until it reaches the receptor. In this study, the resource vulnerability is the goal; therefore the pathway is vertical through unsaturated zone.

### III.2.3 Potential dangerousity, real dangerousity

Two approaches in two phases sustain APSU method. The first assess the potential danger of contamination of groundwater.

It is consisted of estimating how the contaminant distributes to the surface of the basin and what are the proportions that infiltrate or stream to the surface of every point where it passes in transit. The second aims to evaluate the vulnerability of the resource from the moment where a contaminant penetrates under the ground.

It is considered that there is a dangerosity when the contaminant is able to infiltrate.

(DP) Potential dangerosity is defined to be the maximal potential risk for the environment caused by pollution that happen on the surface of the basin. It doesn't depend on the attenuation capacity of aquifers. To summarize, it corresponds to the risk for the contaminant to permeate (Popescu and Al, 2004).

A contamination can cause a direct or lateral impact on an aquifer. **Direct impact** correspond to the risk of contamination by direct infiltration way. If some part of contaminant streams before permeating downstream, it is called **lateral impact**.

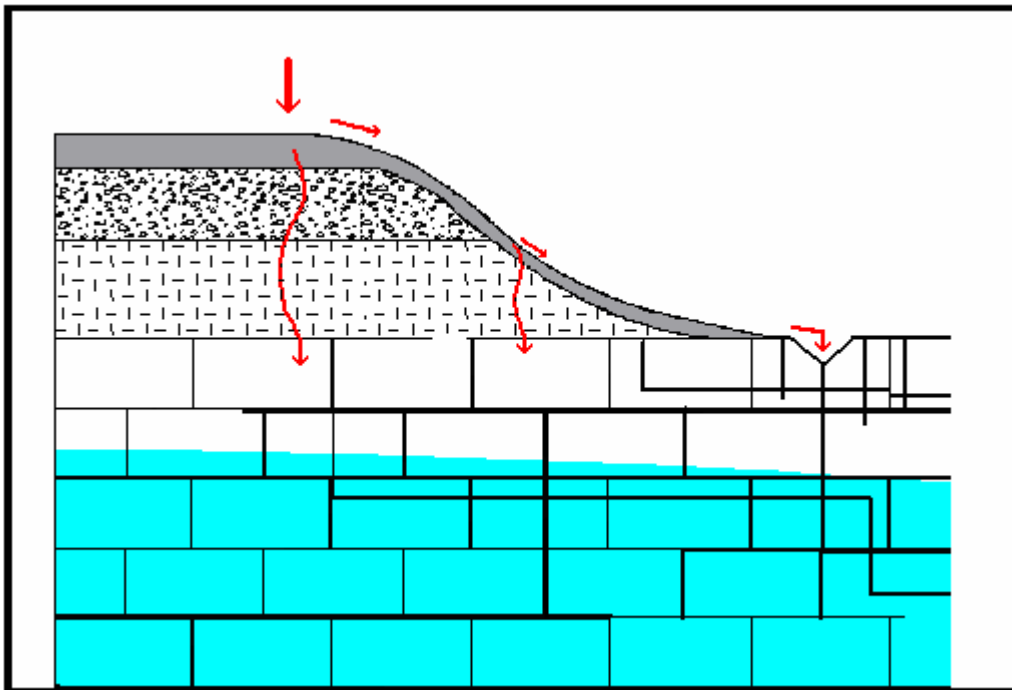


Figure14 : pollutant mobility on and under the ground (Popescu and Al., 2004)

Relating direct and lateral impact with potential dangerosity, it is possible to define on any point of surface of the basin:

- A **direct potential dangerosity** ( $DPDi$ ): it represents direct potential impact of the pollution where it happens.
- A **Lateral potential dangerosity** ( $DPLi$ ) : it corresponds to the lateral potential pollution. It depends on infiltration and streaming possibilities in different point situated downstream of a considered point.

### III.2.4 Attenuation capacity and vulnerability

The three identified parameters (II.3.4) expressed in these questions are determinant.

- (i) : Contaminant transfer time;
- (ii) : Contamination duration;
- (iii) : Level of concentration reached by the contamination.

The environment will be all the more vulnerable that the transfer time is short, that pollution level is high and the pollution duration is long. After infiltration, the transfer time and concentration level of the pollutant depend on the hydrodynamic and hydro dispersive parameters of aquifers.

Intrinsic vulnerability quantifies in each cell of the basin, the migration of a conservative pollutant in unsaturated zone. Only physical processes intervening in pollutant mobility are envisioned (Dilution, dispersion and immobile water effects).

The three characteristic parameters defining the vulnerability are calculated with advection – dispersion equation. This equation permits to describe physical processes inherent to one-dimensional vertical propagation.

Combined to potential dangerousity, these information permit to assess the vulnerability.

### III.2.6 Vulnerability map

The three criteria identified are pondered by direct and lateral dangerousity factors. The results of this weighting are:

- Equivalent transfer time:
- Equivalent duration of contaminants:
- Equivalent maximal concentration

They are illustrated by three vulnerability maps. Transfer time map, duration map and concentration level map.

The final map is calculated with data contained by these three maps.

$$\mathbf{V = \alpha V_t + \beta V_c + \gamma V_d}$$

$\alpha$ ,  $\beta$  and  $\gamma$  are under constraint of  $\alpha + \beta + \gamma = 1$

$\alpha$ ,  $\beta$  and  $\gamma$  are weights chosen in concert with resources managers. In this study we used:  $\alpha=\gamma=0.45$  and  $\beta= 0.10$ .

$V_t$ : transfer time vulnerability

$V_c$ : Level of concentration vulnerability

$V_d$ : pollution duration vulnerability.

### III.2.7 study data

This section describes data used in this study.

- a) Topography (a MNT was already available in the Project),
- b) Water level data (already available in the Project),
- c) Data of pedology (features and shape files) available in the project,
- d) Soil occupation data (already available in the Project),
- e) Hydro meteorological data (already available in the Project, got with general direction of meteorology).
- f) Data of geology.

All these data were submitted to GIS treatment and presented in **rasters** used by a **program** to determine the final and intermediary vulnerability maps.

Main lines of this program are shown in appendices C.

### III.3 ALGORITHM OF THE METHOD

#### III.3.1 Main equations of the algorithm

##### III.3.1.1 Equation for Dangerosity assessment

###### ✚ Hypothesis

- In the case of incapacity for the soil to attenuate pollution, potential dangerosity equals to real dangerosity.  $DR = DP$ ; Most often  $DR \leq DP$
- Pollution is considered unitary, so  $0 \leq DP$  Then  $0 \leq DP \leq DR$
- A null value of DP means that there is no danger and 1 signifies maximal the danger is:

###### ✚ Dangerosity weight

When direct potential and lateral potential dangerosity are taken into account, the final equation of potential dangerosity in a point can be established for each cell of the basin and is:

$$DP_i = DPD_i + \sum_{J \subset N_i} DPL_i^j$$

*EQ1*

$DP_i$  : Potential dangerosity  
 $DPD_i$  : Potential direct dangerosity  
 $DPL_i$  : Potential lateral dangerosity  
*i* : each cell considered

##### III.3.1.2 Equation for attenuation capacity assessment

The protection assured by an aquifer and its environment can be approached by studying the migration of a pollutant emitted on the surface of the basin.

The equation solved by apsu code is the vertical one-dimensional equation through porous zone.

$$\frac{\partial(n_e c)}{\partial t} = \frac{\partial}{\partial z} \left( D \frac{\partial c}{\partial z} \right) - v_e \frac{\partial c}{\partial z}$$

*AVECTION-DISPERSION EQUATION SOLVED BY THE  
CODE APSU*

$n_e$  : teneur en eau mobile [ $L^3 L^{-3}$ ]  
 $z$  : la distance parcourue [L]  
 $t$  : le temps [T]  
 $v_e$  : vitesse effective [ $LT^{-1}$ ]  
 $c$  : concentration [ $ML^{-3}$ ]  
 $D$  : Dispersion [ $L^2 T^{-1}$ ]

### III.3.1.3 Equation for vulnerability assessment

The equation (EQ2) in previous page calculates the evolution of concentration in each cell of unsaturated zone. Thus, three determinant criteria can be calculated to assess the vulnerability. They are:

- Transfert time  $t_i$
- Contamination duration  $d_i$
- Level of pollution  $C_i^{\max}$  or its consequence **Attenuation:**  $C_i^* = \frac{C_i^{\max}}{C_0}$ ;  $C_0$  is initial concentration of the pollutant when it reaches the surface of the basin.

Considering dangerousity weigh calculated above (III.3.11), news equivalent parameters are calculated with following equations:

<p>(i) <math>t_{i(eq)} = DPD_i \times t_i + \sum_{J \subset \eta_i} DPL_i^j \times t_j</math></p> <p>(ii) <math>d_{i(eq)} = DPD_i \times d_i + \sum_{J \subset \eta_i} DPL_i^j \times d_j</math></p> <p>(iii) <math>c_{i(eq)} = DPD_i \times c_i + \sum_{J \subset \eta_i} DPL_i^j \times c_j</math></p>
--

These news equivalent parameters lead directly respectively to:

- a : Transfer time map,
- b : map of pollution duration,
- c : map of concentration level.

Global or final vulnerability is then obtained by:

$$\mathbf{V} = \alpha \mathbf{V}_t + \beta \mathbf{V}_c + \gamma \mathbf{V}_d \quad (\text{See III.2.6})$$

### III.3.2 The Fortran program for calculation

This program is described in appendices. It can summarily be explained or commented to be the transcription of all these equations above in computer language. It automates data input, calculations and output in ASCII format directly usable by any GIS software. At the present time, it is developed to assess intrinsic vulnerability of aquifers. Its conceptors of liege University envisage integrating specific vulnerability in the coming years.

## III.4 DATA ACQUISITION AND TREATMENT

### III.4.1 required data

Vulnerability assessment needs series of information:

- a) Topography data presented by a MNT,

- b) Flow direction,
- c) Slope classes,
- d) Soil occupations,
- e) Type of soil,
- f) Temperature and rain values,
- g) Thickness of unsaturated zone,
- h) Type of material met in unsaturated zone.

All these data are collected from primary information collected by the project, its partners and former studies made on Kou basin. To be usable by the apsu code, they were treated by GIS and presented in grid celled by (250m x 250m). In this study, 85% of the time was dedicated to data treatment, 5 % to literature review, 2% to measures 8% to redaction of the report.

### III.4.2 Data collection

The project ESO Bobo which commanded this study had collected a lot of data early before this study starts. Some were bought with ASECNA, some with IGB or provided by partners like ONEA, GE-Eau and AEDE...

Some visits in field or specific studies were organized and realized fluently to confirm certain information.

### III.4.3 Data treatment

#### Needed programs (Software)

Programs	Needed	Usage frequency
Microsoft Excel, ACCESS+sql	To analyze and correct data	25%
Notepad, Bloc note, Ms Excel,	For manual correction in grids and the input file confection.	10%
ARCGIS 9	Data treatment and mapping	62%
Visual FORTRAN studio, APSU.exe	Running apsu code	3%

## CHAPTER IV: RESULTS, DISCUSSION AND ANALYSIS

### V.1 STUDY RESULTS

#### V.1.1 Results of input grids preparation

##### Final topography map

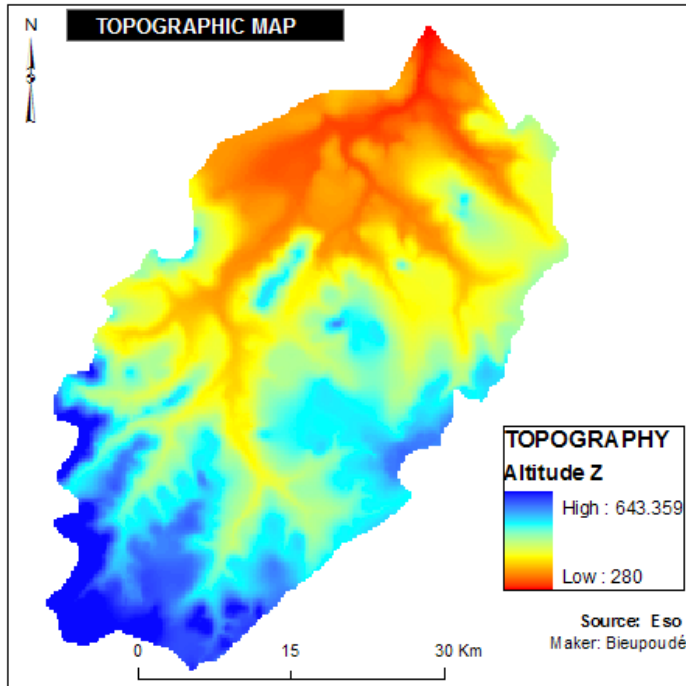


Figure15 : MNT after correction

##### Piezometry map

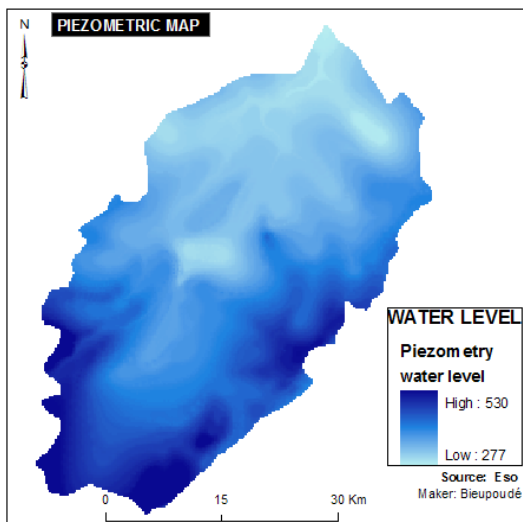


Figure16 : Piezometric map

MNT is the numeric model of the basin topography.

It is mapped from altitude of each point in the basin.

To be usable in our work, it has been treated and corrected by fill and sink function with ArcGIS. This handling permit to diminish irregularities caused by imprecise values or incorrect interpolation values.

Water level is regularly measured in wells and piezometers of the basin. These measures give for distant point some value that we interpolate. This interpolation comes after building isopieze lines.

In Kou basin, alluvial lowland is the lowest in term of absolute water level



In fact, more forages and piezometers are, best the result (water level map) in term of precision is. But in this study, one of our problems was the lack of information in many points due to insufficient number of piezometers.

**Unsaturated zone map:**

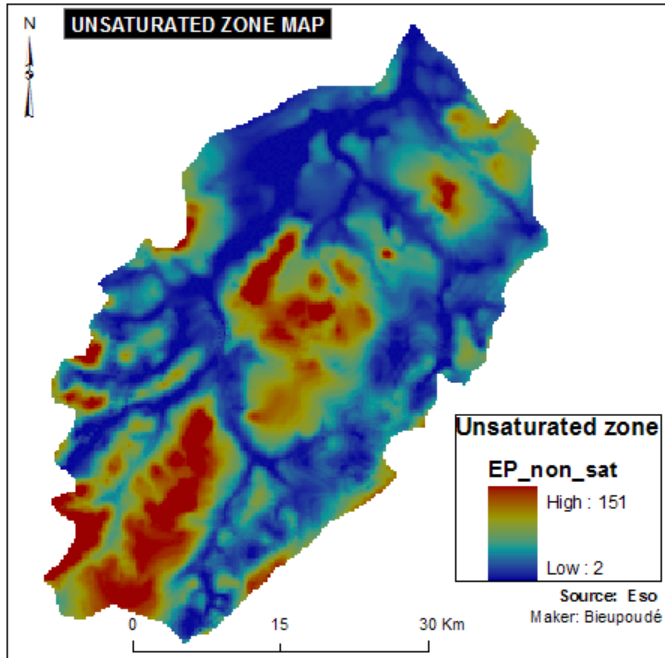


Figure 17: Unsaturated zone map

**Type of soils**

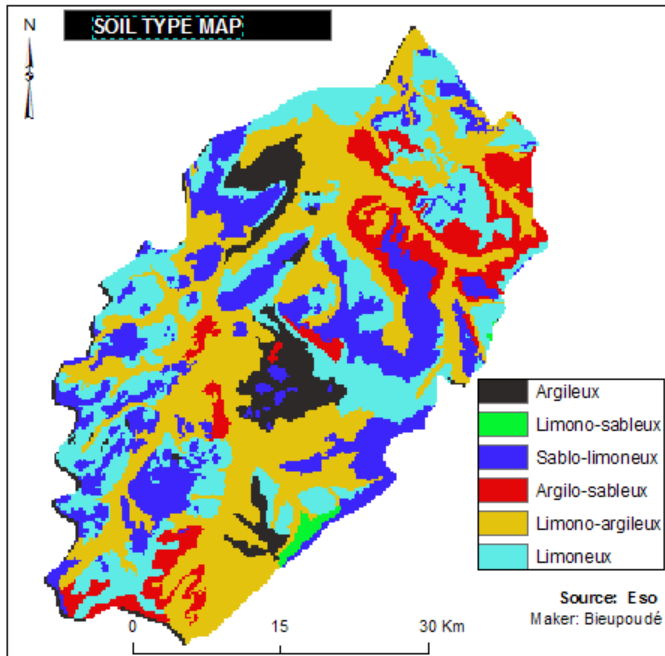


Figure18 : type of soil

Unsaturated zone map is very important in vulnerability assessment.

First, it permits to estimate the distance a pollutant has to cross before reaching water. This distance and hydro dynamic parameters lead to transfer time determination.

This study reveals that in the Kou basin some point where water level is higher than the MNT.

In those cases and in lowland situation, water level has been fixed to be two meter below the surface.

BURNASOL made a first study revealing that many types of soil exist in Kou basin regarding to their texture.

Classification in American diagram was done and finally, for this study kou basin soils were classified into six classes. Apsu code takes mention of them in its input file where weight of porosity and dispersivity are taken into account.

They are important in determination of hydrologic response unity by the code.

## Type of materials

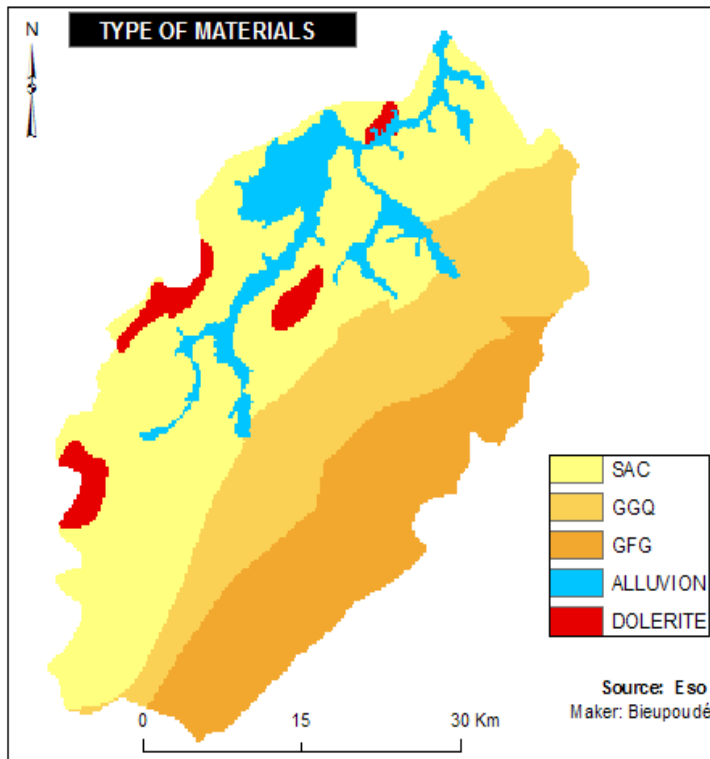


Figure 19: Type of materials

The APSU method uses the grid of each material which includes hydro dispersive parameters. Their importance is capital this study's approach.

In Kou basin, three different materials were found. The soil which thickness ranges from 1 to 1,4 meters. Alluviums/alteration materials layer is found just after the first layer. The third is the bed-rock (mainly sandstone). To adapt materials layers to the method, it has been considered that, after the surface soil, five type of material are representative (see opposite)

## Soil occupation

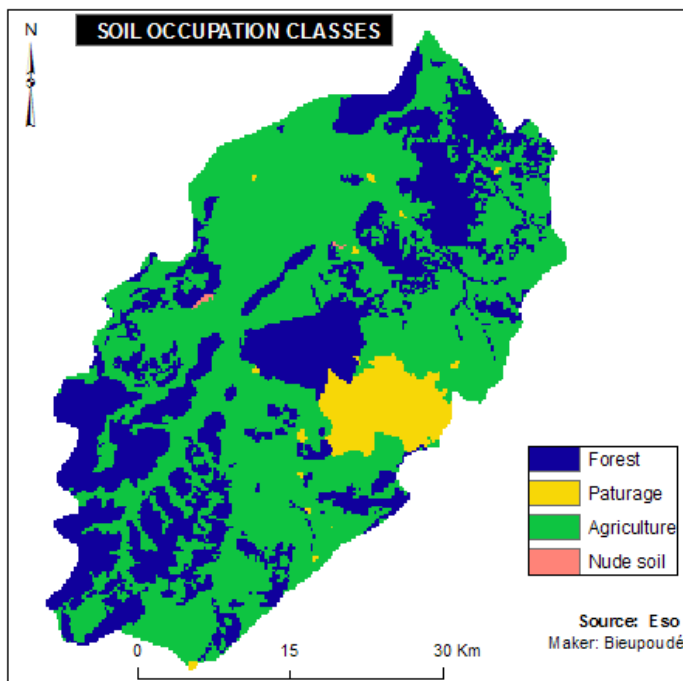


Figure 20: Type of materials

Soil occupation layer allow taking into account the runoff potential of the surface. Data collected by the project (ESO bobo) and treated in this study reveal that more than 70% of soil is in permanent reshuffle because of human activities.

Obviously, the infiltration of a pollutant is all the more important that its reshuffle's degree is high.

It is evident that urban zone like bobo can't be considered as nude soil because soils there are not impermeable. ■

Beside this six information layers, limit of basin, rainfall, temperature and a file called input\_file are needed to run Apsu code. Some of them are available in appendices.

### V.1.2 Results of vulnerability parameters calculations

A lot of parameters are calculated after the first stage of data treatment with ArcGIS.

Carte de dangerosité directe (écrite par SaveResults)
Carte de dangerosité latérale totale (écrite par SaveResults)
Carte de dangerosité latérale cumulée (")
Coefficients de dangerosité cellule par cellule
Classes de pente calculées en interne
Bilans en eau calculés sur base des données météo
Carte des temps de transfert minimaux
Carte des durées de pollution
Carte des coefficients d'atténuation
Carte des temps de transfert minimaux pondérés
Carte des durées de pollution pondérées
Carte des coefficients d'atténuation pondérés

Among this parameters, some are pre-prepared handly.

Water checkup is calculated from meteorological information collected by Eso Bobo. They reveal that temperature can be considered identically in all the part the basin but many hydrologic response units were found due to the soil types and topography.

Dangerosity map are presented in appendices. Information they include are used cell per cell with transfer time, pollution duration and pollution level layer in order to assess vulnerability related to these three aspects.

### V.1.3 Final vulnerability maps

Three principle maps are decided to be considered in this study.

#### Transfer time map: The principle map

This map makes itself essential because it shows the time a pollutant thrown on surface will spend before reaching groundwater. Thus in a case of accidental pollution such as dispersal of a toxic product, water managers can know exactly the time left before it reaches water causing contamination.

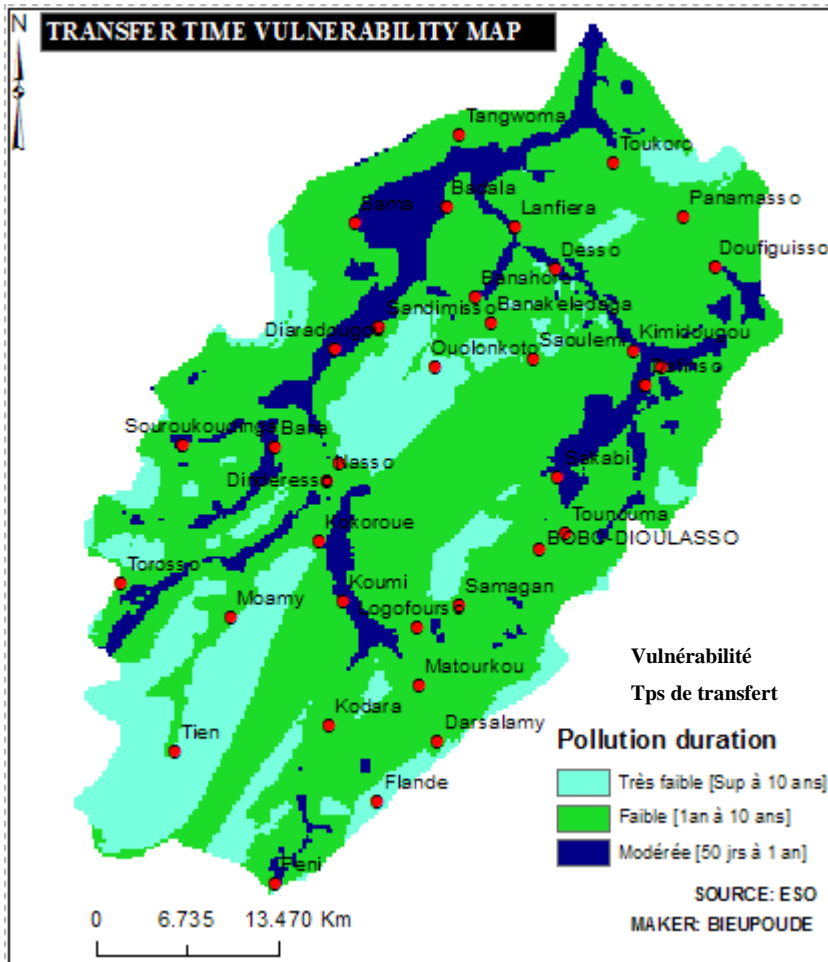


Figure 21: Transfer time vulnerability

This study revealed that alluvial lowland of Kou basin and the downstream of Bobo-dioulasso are dangerous zone in term of transfer time vulnerability. It means directly that in case of a reject of a dangerous product in these zones, the pollution will be imminent and dangerous because they are the most populated zone because of agricultural and industrial activities.

✚ Pollution duration map

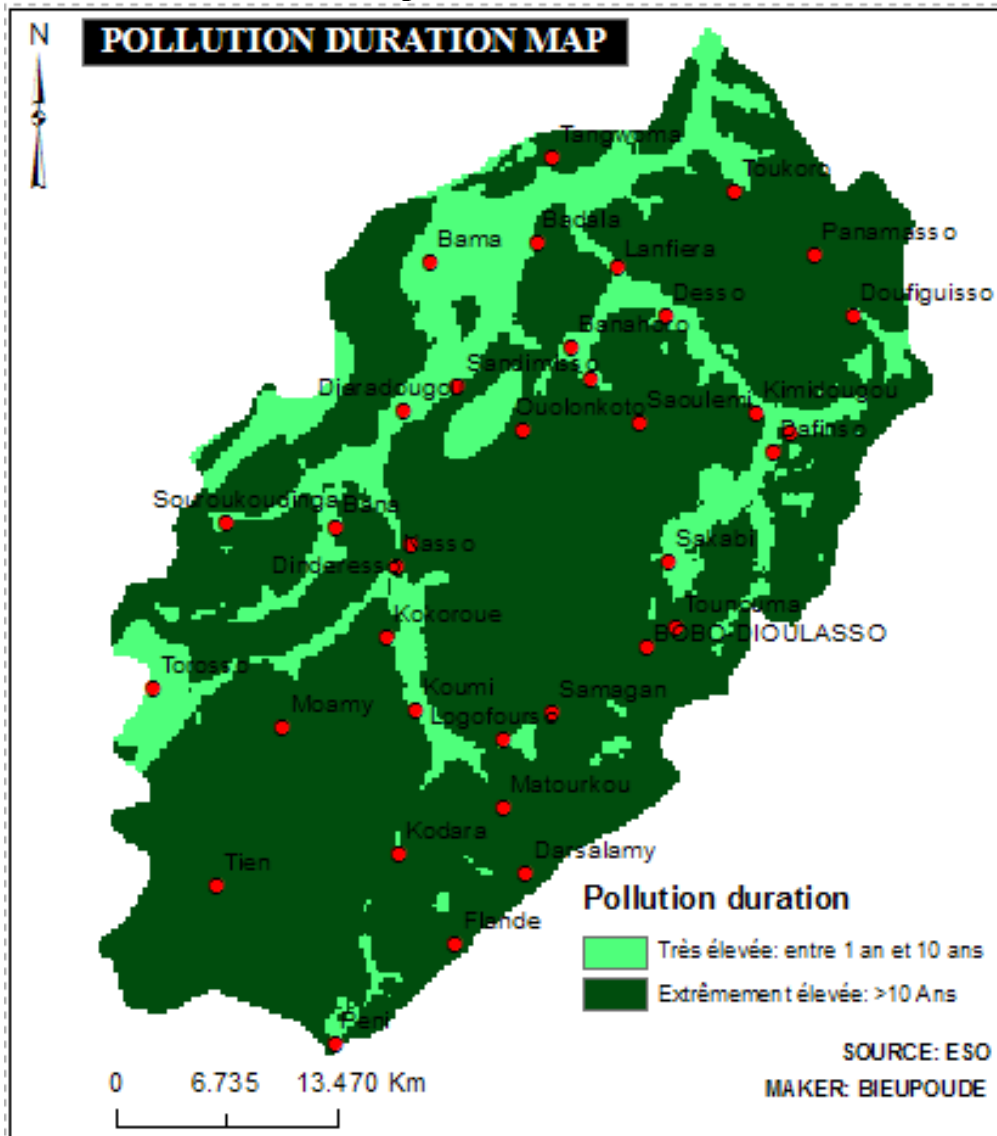


Figure 22: Pollution duration vulnerability map

This study exposed also that alluvium aquifer Kou basin and the downstream of Bobo-dioulasso are dangerous zone in term of pollution duration but they are less leveled than the rest of basin.

Globally, speaking, Kou basin is very vulnerable regarding at time of pollution. In a case of pollution at Nasso, more than ten years are needed before water quality becomes acceptable. Two senses of the explanation can be given to this level of vulnerability. The thickness of unsaturated zone and hydro dispersive parameters of each vertical line to water are the causes.

### Global vulnerability map

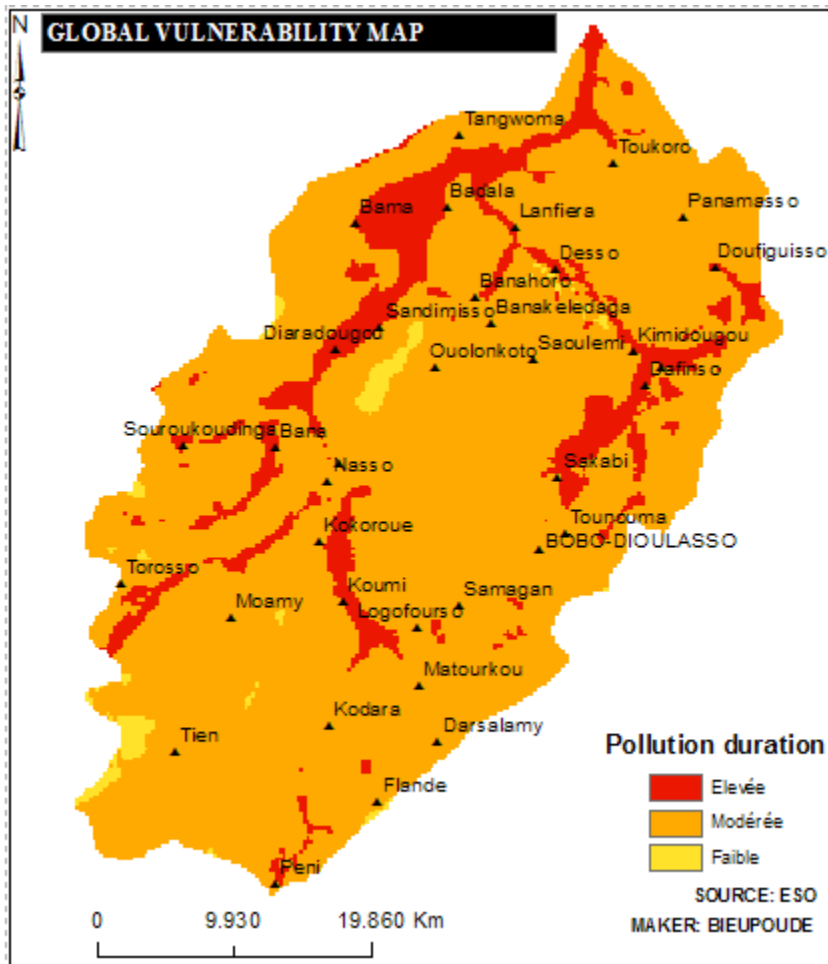


Figure 23: Transfer time vulnerability

In an approach of prevention, red colored zone are very sensible. They are vulnerable at a high level. Activities in these zones have to be under control any time. This map can guide urbanism authorities to choose the adequate places for new industrial activities and the square to eject pollutants. Even dolerite zones yellow colored and less vulnerable are sensible because this study didn't go deeper in assessing these zones' porosity with precision.

### V.1.4 Confrontation of results to human activities in Kou basin

An interesting approach is to estimate vulnerability of aquifers, but how can these information be usable in a situation of territory management?

If a zone not very populated reveals a very high vulnerability, it won't be eerie than in high population density areas. That's reason why confronting vulnerability map to human activity is important for deciders.

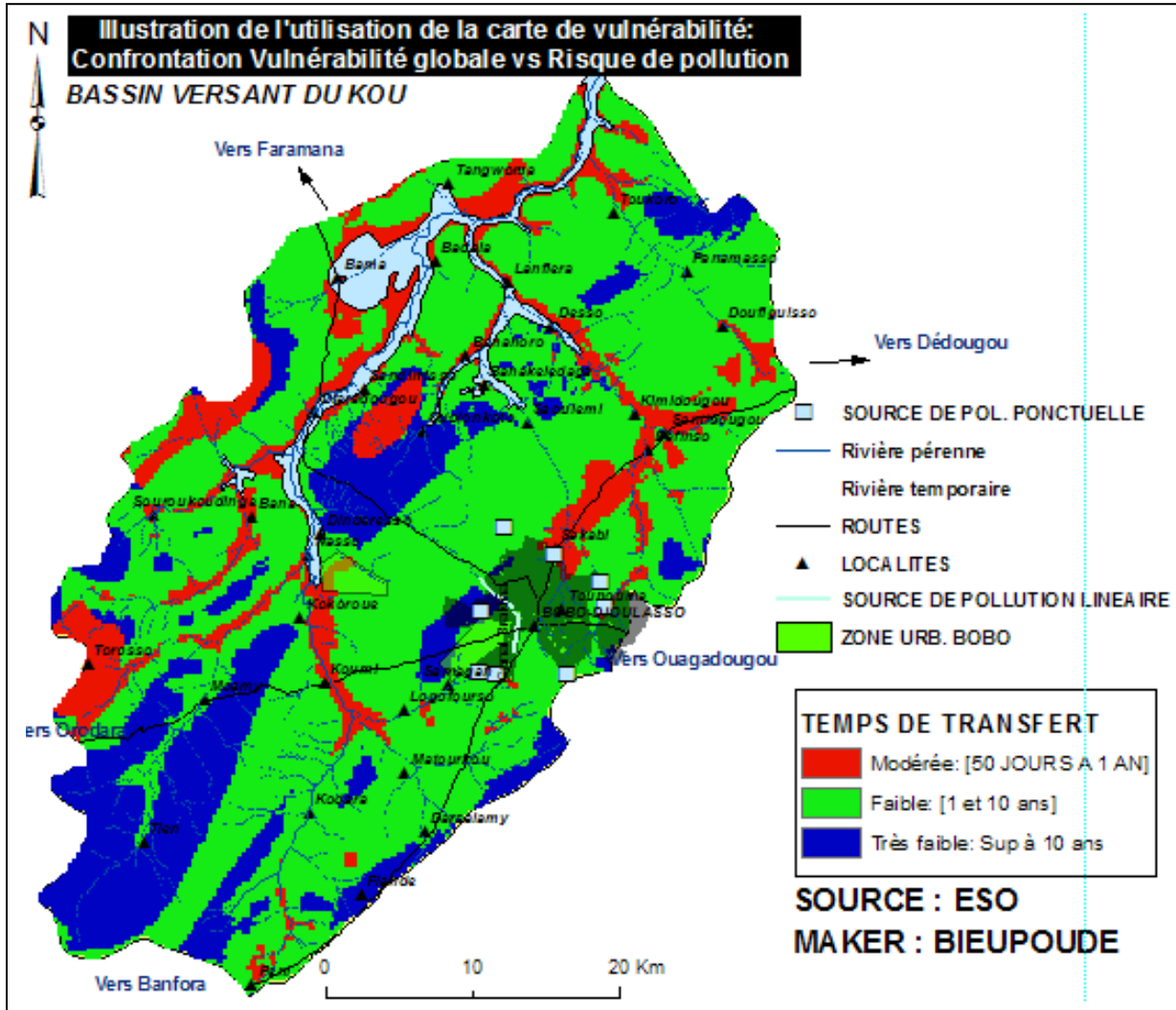


Figure 24: Transfer time vulnerability map

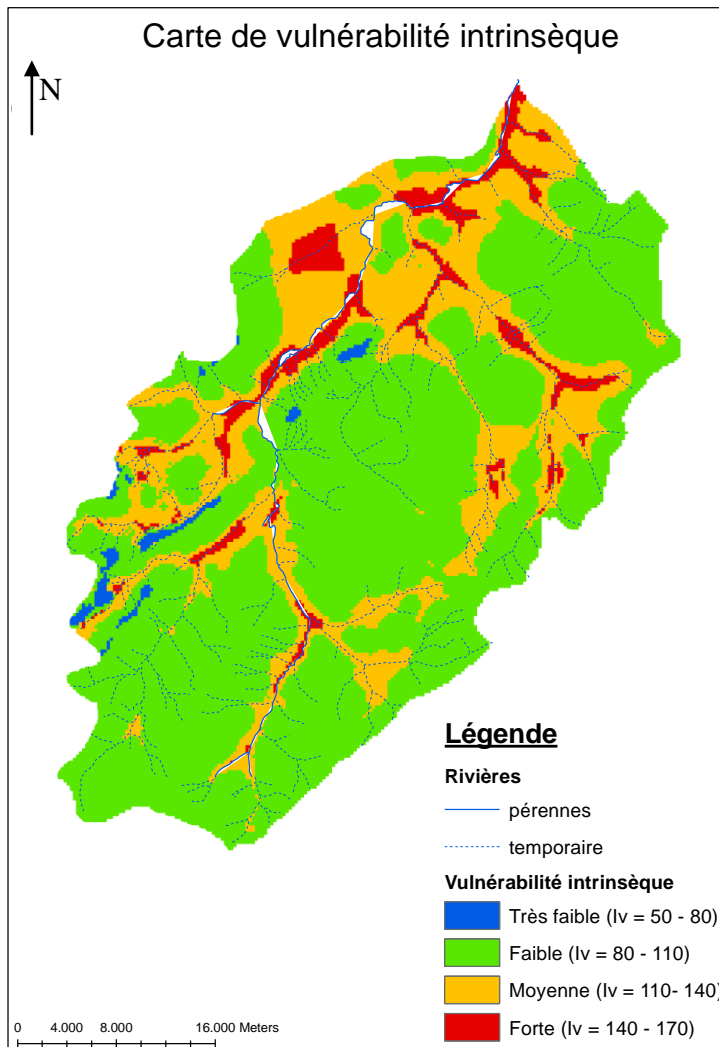
This study reveals unfortunately that intense activities zones of Kou basin are vulnerable. Even if intrinsic vulnerability is object in this study it doesn't abide less right that future result of specific vulnerability can confirm this result. ONEA should control strictly upstream Nasso. Municipal authorities of Bobo would better stay up on industrials.

## V.2 DISCUSSION AND ANALYSIS

### V.2.1 Comparison with former studies on kou basin

Besides mapping Kou basin's aquifers vulnerability, this study had to apply a new method and analyze by comparing its results with other methods'. But it hasn't been possible to establish real links to be used for comparisons because a scientific comparison must be based on identical study data and we were unable to provide these data in this study.

Yet, DRASTIC method apply Ahmed Kam, Dec 2007 is in parfait adequation with our results.



### Important remarks

This study reveals that unsaturated zone grid is as important in apsu approach as in DRASTIC method.

In fact, independently to other information, where the thickness of vadose zone is weak, vulnerability is high.

In summary, agricultural zone and downstream Bobo are revealed by these two studies to be very sensible. They should be really under surveillance.

Figure 25: DRASTIC vulnerability map  
Ahmed KAM, Dec. 2007



### **V.2.2 Critical analysis of APSU approach**

This approach raises doubt on the conclusion of the empiric character of former vulnerability assessment methods such as DRASTIC or God.

Apsu proves to be pertinent by producing physical measurable parameters which represents the main aspects of the aquifers vulnerability

In this study, Apsu approach didn't show limit. Contrary, it provides numeric results such as transfer time and pollution duration not available in former empiric methods.

Its principle characteristic to be opened is fundamental and adapted to many regions..

Yet, Apsu uses thornwaite approach (which is known to have limits in contrasted climate countries) in the assessment of the infiltration.

## CONCLUSION AND RECOMMENDATION

### Conclusion

Two objectives were given to this work. They are summarized in testing in a different context of hydrogeology Apsu method, developed by Ulg to assess the intrinsic vulnerability of Kou basin.

The study zone is limited to Kou basin characterized by sandstone aquifers ranging from sandy to sandy loamy to clay loamy. Vulnerability studied here concerns the first water table met from surface.

The approach principle is to assess first surface dangerousity regarding streaming and infiltration first. Secondly, the attenuation capacity of the ground is assessed. From these two information, the vulnerability is assessed. An important work in data preparation has been done with GIS to have needed grid for Apsu code. All these information grids were discretized on mesh of 250x250m.

The method defines three criteria to estimate groundwater vulnerability:

- minimal transfer time of a pollutant;
- contamination duration in unsaturated zone;
- concentration level in water table.

Transfer time and the identification of water resources to be protected are compatible with prevention zone definition.

This study reveals that the alluvial lowland, upstream Nasso source and downstream Bobo are the most vulnerable zones.

## Recommandations and perspectives

- ✚ This study focuses on intrinsic vulnerability mapping. Thus no idea was given about specific pollutant actions on water tables. We recommend a study to determine specific vulnerability which explains vulnerability regarding besides intrinsic parameters, characteristics of the pollutant.
  
- ✚ A new map can be done with new data if some news forages are built updating then information about water level and unsaturated zone. It is told that this study lacked many precise data such as:
  - porosity of dolerite zone;
  - topography in a grid celled by 50mx50m;
  - hydro dispersive parameters of geologic materials with precision.
  
- ✚ Ultimately we recommend that the result in this study should be taken into account for land-use planning in or near Kou basin territory. ONEA is invited to exploit these results to assure surveillance activity.

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#### **Internet links.**

- Groundwater quality protection guide – Part B1 ([http://www-wds.worldbank.org/external/default/WDSContentServer/IW3P/IB/2002/12/14/000094946\\_02112704014826/additional/280868028\\_200501470700135.pdf](http://www-wds.worldbank.org/external/default/WDSContentServer/IW3P/IB/2002/12/14/000094946_02112704014826/additional/280868028_200501470700135.pdf)) le 15 Mai 2008.
- <http://www.apefe.org>      <http://www.2ie-edu.org>

## APPENDICES

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APPENDICE A- Hydro dynamic parameters and values used in this study

<b>Matériau</b>	<b>Conductivité hydraulique à saturation</b>	<b>Porosité effective</b>	<b>Rapport dispersivité/Epaisseur</b>
Limons	$5.10^{-6}$	0.45	20
Limons lourds	$2.10^{-6}$	0.46	20
Limons argileux	$1.10^{-6}$	0.43	20
Sable limoneux	$5.10^{-7}$	0.39	20
Argile limoneuse	$1.10^{-7}$	0.43	20
Argile	$5.10^{-8}$	0.41	20
Imperméable	$1.10^{-10}$	$1.10^{-3}$	20
Sables tertiaires	$1.10^{-4}$	0.1	10
Grès	$1.10^{-4}$	0.05	5
Schiste	$1.10^{-7}$	0.05	20
Calcaire fracturé	$1.10^{-3}$	0.05	5
Calcaire très fracturé	$1.10^{+1}$	0.5	1

APPENDICE B- Description générale des principaux fichiers nécessaires à l'exécution du programme

Contenu du fichier	Unité Fortran	Extension
Fichier d'entrée général	15	*.inp
Fichier de sortie général	16	*.out
Fichier messages d'erreur	10	*.err
Modèle numérique de terrain	17	*.grd
Délimitation du bassin	18	*.bas
Unités de réponse hydrologique	21	*.hru
Pentes	22	*.slo
Directions d'écoulement	23	*.fld
Carte d'occupation du sol	24	*.lco
Carte des sols	25	*.sot
Zones d'influence des stations météorologiques	26	*.mst
Données météorologiques	27	*.msd
Géologie : épaisseur des formations, couche par couche	28	*xx.thk, xx = n° de la couche
Géologie : numéro de matériau (lithologie), couche par couche	29	*xx.lit, xx = n° de la couche
Eau utile (infiltration + runoff)	31	*.efw
Carte de dangerosité directe (écrite par SaveResults)	32	*.did
Carte de dangerosité latérale totale (écrite par SaveResults)	33	*.tld
Carte de dangerosité latérale cumulée ("")	34	*.cld
Coefficients de dangerosité cellule par cellule	35	*.ccd
Classes de pente calculées en interne	36	*.slc
Bilans en eau calculés sur base des données météo	37	*.wbg
Carte des temps de transfert minimaux	41	*.tmi
Carte des durées de pollution	42	*.dur
Carte des coefficients d'atténuation	43	*.att
Carte des temps de transfert minimaux pondérés	44	*.wtm
Carte des durées de pollution pondérées	45	*.wdu
Carte des coefficients d'atténuation pondérés	46	*.wat
Carte de vulnérabilité temps de transfert	47	*.vtm
Carte de vulnérabilité durées de pollution	48	*.vdu
Carte de vulnérabilité atténuation	49	*.vat
Carte de vulnérabilité temps de transfert pondérés	50	*.wvt
Carte de vulnérabilité durées de pollution pondérées	51	*.wvd
Carte de vulnérabilité atténuations pondérées	52	*.wva
Carte de vulnérabilité finale	53	*.vul



## APPENDICE C- Description du Fichier d'entrée général (1/3)

**Ligne 1** : Titre de la simulation

SimulationTitle (chaîne de 70 caractères)

Format : CHARACTER(LEN=70)

**Ligne 2** : Nombre de colonnes et de lignes dans le maillage

NCol, NRow

Format (libre) : 2 INTEGER(KIND=4)

**Ligne 3** : Dimensions de base des pixels composant la grille 2D

XllCorner, Xleng, YllCorner, Yleng

Format (libre) : 4 REAL(KIND=4)

**Ligne 4** : Valeur par défaut pour les cellules où l'on ne définit rien (NODATA dans ArcView)

4

NoDataVal

Format (libre) : integer

**Ligne 5** : Utilisation ou non des header files de ArcView (entrées et sorties)

IUseAVHeader

Format (libre) : logical

Si IUseAVHeader = .true., les headers sont lus et écrits dans les fichiers préparés avec ArcView ou

sauvés pour lecture avec ArcView, si IUseAVHeader = .false., ils ne le sont pas.

**Ligne 6** : Calcul interne ou externe des pentes à partir du MNT

IComputeSlope

Format (libre) : logical

Si IComputeSlope = .true. , les pentes sont calculées au sein du programme à partir des altitudes du

MNT ; si IComputeSlope = .false. , les pentes sont lues dans un fichier externe (\*.slo).

Actuellement : les pentes doivent être lues dans un fichier externe, la sous routine de calcul interne

n'étant pas encore programmée

**Ligne 7** : Calcul interne ou externe des directions d'écoulement

IComputeFlowDir

Format (libre) : logical

Si IComputeFlowDir = .TRUE. , les directions d'écoulement sont calculées au sein du programme

; si IComputeFlowDir = .false. , les directions d'écoulement sont lues dans un fichier externe

(\*.fld).

Actuellement : les directions d'écoulement doivent être lues dans un fichier externe, la sous routine

de calcul interne n'étant pas encore programmée

**Ligne 8** : Nombre de minima locaux au sein du bassin (pertes, ...)

NumLocMin

Si NumLocMin >0 : Coordonnées de cellules (colonnes, lignes) de ces NumLocMin minima

locaux : iCol, iRow (NumLocMin lignes nécessaires)

## APPENDICE C- Description du Fichier d'entrée général (2/3)

**Ligne 9** : Détermination des unités de réponse hydrologique

IComputeHRU

5

Format (libre) : logical

Si IComputeHRU = .TRUE., les HRUs sont déterminées au sein du programme ; si

IComputeHRU

= .false. , les HRUs sont lues dans un fichier externe (\*.hru).

**Ligne 10** : Estimation de l'eau utile (infiltration + runoff) associée à chaque HRU

IComputeEffWater

Format (libre) : logical

Si IComputeEffWater = .TRUE. , les eaux utiles sont calculées au sein du programme ; si

IComputeEffWater = .false. , les eaux utiles sont lues dans un fichier externe (\*.efw).

**Ligne 11** : Définition du nombre de stations (nMeteoData) et du nombre de données météo qui

leurs sont associées (nTime)

REM : La ligne 11 n'existe que si le bilan en eau est calculé en interne

(IComputeEffWater =

.TRUE.)

nMeteoData, nTime

Format (libre) : 2 INTEGER(KIND=4)

**Ligne 12** : Sauvetage des dangersités directes (si valeur .true.) dans le fichier \*.did (Unit 32)

ISaveDirectDangerosity

Format : logical

**Ligne 13** : Sauvetage des dangersités latérales (si valeur .TRUE.) dans le fichier \*.tld

(Unit 33)

ISaveLateralDangerosity

Format : logical

**Ligne 14** : Sauvetage des dangersités latérales cumulées (si valeur .TRUE.) dans le fichier \*.cld

(Unit 34)

ISaveCumLatDangerosity

Format : logical

**Ligne 15** : Sauvetage des dangersités associées à une liste de cellules (si valeur .TRUE.) dans le

fichier \*.ccd, unit 35

ISaveCellbyCellDangerosity

Format : logical

6

Si ISaveCellbyCellDangerosity = .TRUE.

**Ligne 16** : Nombre de cellules pour lesquelles on souhaite sauver l'ensemble des coefficients de

dangersité

nCbyCSave

Format : integer(kind=4)

**Ligne 17** : Liste des cellules (n° de colonne et de ligne) pour lesquelles on souhaite sauver

l'ensemble des coefficients de dangersité (ligne répétée nCbyCSave fois)

iCbyCCol, iCbyCrow

Format : 2 integer(kind=4)

## APPENDICE C- Description du Fichier d'entrée général (3/3)

**Ligne 17bis** : Conditionne l'exécution de la suite du programme

Si .TRUE., on calcule les coefficients de vulnérabilité ; si .FALSE. on génère les coefficients de dangerosité sans calcul de la vulnérabilité

**Ligne 18** : Nombre de couches et des matériaux (nLayer, nMat)

Format : 2 integer(kind=4)

**Ligne 19** : Lecture des matériaux (nMAT lignes nécessaires)

MatName (10 ch), Ksat(real\*4), Neff(real\*4), Pec(real\*4), IPref(0 ou 1), HPond(real\*4)

MatName : nom donné au matériau

KSat: Conductivité hydraulique à saturation (LT-1)

Neff : Porosité effective (-)

Pec : Nombre de Péclet physique ( $Pec = L / aL$ ), L = distance verticale à travers la couche, aL =

coefficient de dispersivité

IPref : 0 : pas d'écoulement préférentiel, 1 : écoulement préférentiel possible

HPond : Hauteur de charge de la lame d'eau gouvernant la mobilité des polluants à travers la couche (L)

**Ligne 19bis** : Utilisation des classes pour les critères physiques

Si .TRUE., on utilise des classes ; si .FALSE. on utilise des relations f(Pec)

**Ligne 20** : Valeurs des coefficients de pondération des critères physiques de vulnérabilité : !

7

**Ligne 21** : Sauvetage des facteurs de vulnérabilité de subsurface (si valeur .true.) dans les fichiers

\*.tmi (Unit 41), \*.dur (Unit 42) et \*.att (Unit 43)

LSaveSubsurfVulnFactors

Format : logical

**Ligne 22** : Sauvetage des facteurs pondérés de vulnérabilité de subsurface (si valeur .true.) dans les

fichiers \*.wtm (Unit 44), \*.wdu (Unit 45) et \*.wat (Unit 46)

ISaveSubsurfWeightedVulnFactors

Format : logical

**Ligne 23** : Sauvetage des classes de vulnérabilité (si valeur .true.) dans les fichiers \*.vtm (Unit 47),

\*.vdu (Unit 48) et \*.vat (Unit 49)

ISaveSubsurfVulnClasses

Format : logical

**Ligne 24** : Sauvetage des classes pondérées de vulnérabilité (si valeur .true.) dans les fichiers

\*.wvt (Unit 50), \*.wvd (Unit 51) et \*.wva (Unit 52)

ISaveSubsurfWeightedVulnClasses

Format : logical

**Ligne 24** : Sauvetage de carte de vulnérabilité (si valeur .true.) dans le fichier \*.vul (Unit 53)

ISaveVulnerabilityMap

Format : logical

## APPENDICE D- Le traitement de données sur ARGIS

### 1) Shapefiles et grilles de base

Certains shapefiles et grilles de base sont nécessaires pour préparer les couches d'informations :

- a. délimitation du bassin (shapefile-polygone). Ce polygone servira notamment à découper (clip) d'autres shapefiles ;
- b. un cadre circonscrivant la zone d'étude ;
- c. conversion du shapefile « bassin » en grille au moyen de la fonction FEATURE TO RASTER du menu CONVERSION TOOLS de l'ARCTOOLBOX: la grille est formée de cellules de valeur 1 à l'intérieur du bassin et de No Data à l'extérieur de celui-ci ; un shapefile pour chaque lithologie considérée. Par souci de simplification, certains regroupements de lithologies sont nécessaires.
- d. conversion des shapefiles « lithologie » en grilles : ID identifiant la lithologie là où elle est présente, No Data ailleurs

Les différentes couches d'informations sont passées en revue ci-après.

### 2) Directions d'écoulement

Les directions d'écoulement sont obtenues en dérivant le MNT à l'aide de la fonction FLOW

DIRECTION du menu HYDROLOGY (extension SPATIAL ANALYST). L'output de la fonction FLOW

DIRECTION est une grille affichant pour chaque cellule un nombre entier variant de 1 à 255. Les valeurs de chacune des directions à partir d'une cellule centrale sont les suivantes :

32	64	128
16		1
8	4	2

Le MNT doit faire au préalable l'objet d'un travail de correction au moyen des fonctions SINK et FILL du menu HYDROLOGY (extension SPATIAL ANALYST).

### 3 Pentés et classes de pente

Les pentes sont obtenues en dérivant le MNT à l'aide de la fonction SLOPE du menu SURFACE (extension SPATIAL ANALYST). Ces pentes doivent ensuite être regroupées en 4 classes

Le regroupement des pentes s'effectue à l'aide de la fonction RECLASSIFY (extension SPATIAL ANALYST).

Pente	Classe de pennte
0 – 0.5	1
0.5 - 5	2
5 - 10	3
>10	4
NoData	NoData

#### 4 Occupation du sol

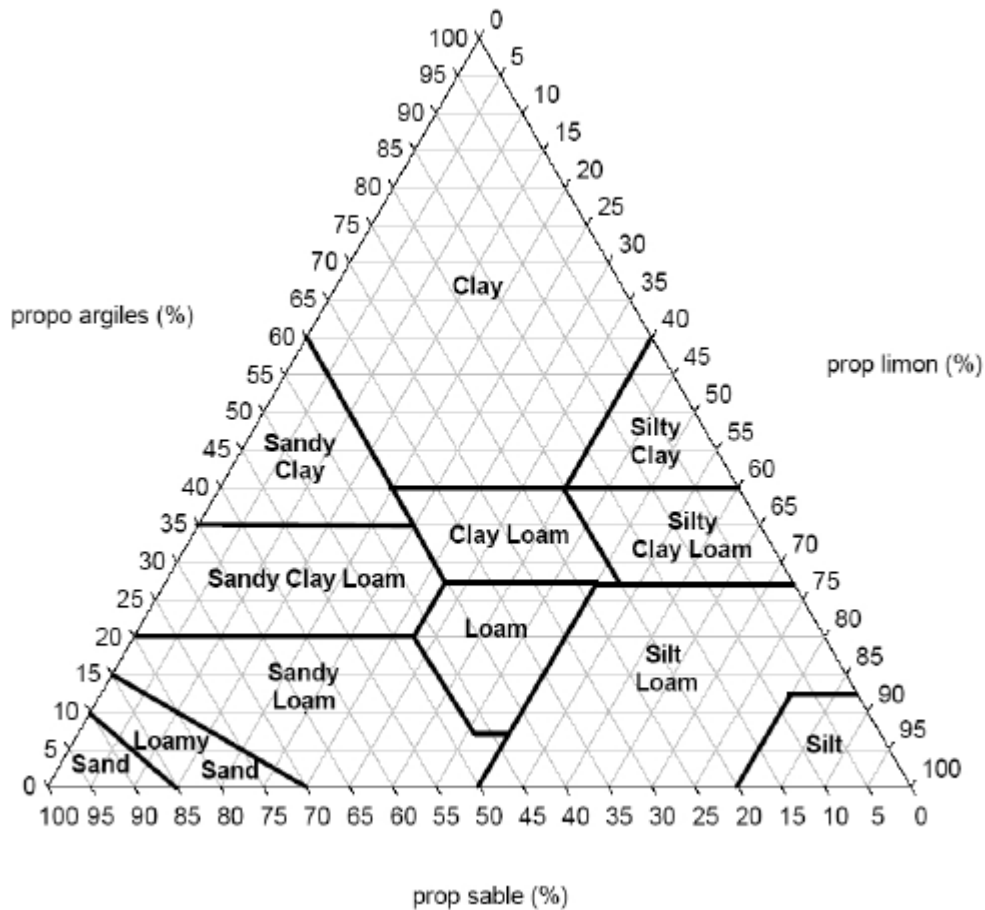
L'outil de calcul de la vulnérabilité tient compte de 4 classes d'occupation du sol. Le Tableau ci dessus présente les différentes occupations du sol définies dans le cadre de cette étude. Le regroupement des classes s'effectue à l'aide de la fonction RECLASSIFY (extension SPATIAL ANALYST).

OCCUPATION DU SOL – PROJET CORINE	DESCRIPTION (CORINE)	CLASSE D'OCCUPATION DU SOL – CALCUL DE LA VULNÉRABILITÉ	DESCRIPTION (VULNÉRABILITÉ)
1	Bois et forêt de feuillus	1	Forêt
2	Bois et forêt de résineux	1	Forêt
3	Bois et forêt mixtes	1	Forêt
4	Friches et terrains incultes	2	Pâturages
5	Prairie permanente	2	Pâturages
6	Culture saisonnière et autres	3	Cultures
7	Espace vert urbain	2	Pâturages
8	Habitat dense	4	Sol nu
9	Habitat discontinu	4	Sol nu
10	Habitat et services	4	Sol nu
11	Industrie et services	4	Sol nu
12	Carrière, sablière et terril	4	Sol nu
13	Terrain et aérodrome militaires	4	Sol nu
14	Réseau hydrographique	4	Sol nu
15	Réseau routier	4	Sol nu
16	Réseau ferroviaire	4	Sol nu

#### 5 Types et épaisseurs de sol

Le shapefile initial décrivant les types et l'épaisseur des différents sols doit être coupé aux limites du bassin à l'aide de la fonction CLIP (ANALYSIS TOOLS). Il doit ensuite être converti en grille au moyen de la fonction FEATURE TO RASTER. Deux grilles doivent être créées : une identifiant pour chaque cellule l'épaisseur du sol et une identifiant le type de

sol. Les différents types de sol couvrant la zone d'étude doivent être regroupés en 13 classes correspondant aux 12 classes de sol définies dans le diagramme textural américain et à une classe supplémentaire correspondant à l'absence de sol. Chaque classe doit être identifiée par un ID<sub>1</sub>. Un travail de correspondance entre la classification texturale nationale et la classification américaine doit être réalisé sur base des profils pédologiques connus et des notices explicatives de cartes couvrant la zone d'étude.



**Diagramme textural américain**

Une méthode consiste à calculer les moyennes pondérées des teneurs en argile, limon et sable pour chaque profil connu sur base de l'épaisseur des différents horizons. Ces teneurs moyennes sont ensuite reportées sur le diagramme textural américain.

La conversion des classes de sol dans la grille s'effectue à l'aide de la fonction RECLASSIFY.

## **6 Carte hydrométéorologique**

Les polygones de Thiessen sont calculés à l'aide de l'outil ET GeoWizards à partir du shapefile décrivant la position des différentes stations météorologiques, chaque station étant identifiée par un ID. Le shapefile résultant doit être coupé aux limites du bassin et converti en grille (voir ci-dessus). La grille résultante est formée de cellules de valeurs correspondantes aux ID des différentes stations à l'intérieur du bassin et de No Data à l'extérieur de celui-ci.

## **7 Grilles définissant les matériaux**

Si l'approche retenue correspond à l'évaluation de la vulnérabilité du premier aquifère rencontré depuis la surface, il faut considérer une nappe par matériau géologique pris en compte.

La grille déterminant l'étendue des matériaux considérés doit être calée sur le MNT. Elle affiche

un ID déterminé (à choisir) là où le matériau est rencontré et No Data ailleurs.

Chacune de ces couches correspond à une grille provenant de la fusion des grilles correspondant à l'étendue des différents matériaux la constituant, chacun identifié par un ID. Dans le cas du bed-rock, la grille a été ainsi construite à partir de la fusion des grilles correspondant à l'extension des grès fammenniens, des calcaires carbonifères et schistes et grès houillers. Chacune de ces grilles est obtenue par conversion des shapefiles initiaux en rasters.

## **8 Grilles définissant les cotes piézométriques**

Si l'on considère le premier aquifère rencontré depuis la surface, là où il y a une succession verticale de plusieurs matériaux, seul l'aquifère du premier matériau rencontré depuis la surface sera pris en compte. Deux cas peuvent être envisagés selon l'existence ou l'absence de données piézométriques suffisantes.

Les isopièzes de la nappe doivent être convertis en points à l'aide, par exemple, de la fonction Polyline to Point de l'outil ET GeoWizards. Un shapefile point est généré. Celui-ci devra comporter un champ « cote piézo ». Les cotes piézométriques doivent ensuite être interpolées vers une grille d'extension similaire à celle du matériau. Ceci est

réalisé via la fonction INTERPOLATION (SPATIAL ANALYST). Plusieurs méthodes d'interpolation sont proposées, dans le cas de la Berwinne, le choix s'est porté sur la méthode SPLINE. Le Z value field précisé est celui de la cote piézométrique. L'output cell size doit correspondre à la taille des cellules du MNT. Les autres paramètres sont pris par défaut. Il convient également de compléter deux champs dans les « *general settings* » (option « *environment settings*»), ceux de « l'extent » et du « *snap raster* » avec comme choix le MNT. Une fois la grille générée, elle doit être " clipée " aux dimensions de la grille d'extension du matériau via la fonction

EXTRACT BY MASK (SPATIAL ANALYST).

Les résultats devront ensuite être vérifiés : est-ce que les résultats se trouvent dans l'intervalle des valeurs escomptées ? Y a-t-il des valeurs extrêmes (négatives ou positives) ? Est-ce que les cotes piézométriques sont supérieures aux cotes du toit de la formation ou aux cotes topographiques ?

Les valeurs aberrantes peuvent être corrigées de deux manières :

- Imposer des cotes piézométriques aux endroits problématiques par ajout d'isopièzes dans le shapefile polyline ou de points dans le shapefile points;
- Corriger directement les valeurs dans la grille de résultats à l'aide du MANUAL GRID EDITOR disponible dans la version ArcView 3.2.

En cas d'absence de données piézométriques suffisantes, une profondeur moyenne du niveau de la nappe devra être imposée. Cette épaisseur est retranchée du MNT à l'aide de la fonction MINUS (menu MATH du SPATIAL ANALYST). Cette approche a été retenue pour le Houiller dans les études du Néblon et de la Berwinne.

## **9 Détermination de l'épaisseur non saturée du sol**

Les données nécessaires sont :

- Une grille piézométrique globale issue de la fusion des différentes grilles calculées à l'étape précédente (fonction MERGE via le MAP ALGEBRA du SPATIAL ANALYST) ;
- Une grille correspondant à l'épaisseur du sol sur toute la zone d'étude. Cette grille doit afficher NoData là où le sol est absent (fosses d'extraction ou réseau routier par exemple) ;
- Le modèle numérique de terrain (MNT)

Deux cas peuvent être envisagés dans l'évaluation de l'épaisseur non saturée du sol :

- Le premier cas correspond à un niveau piézométrique passant dans le matériau sous-



jacent au sol (l'ensemble de la tranche de sol est non saturée) ;

- Le second cas correspond à un niveau piézométrique passant dans la tranche de sol (seule une partie du sol est non saturée)

### **Cellules où l'ensemble de la tranche de sol doit être considérée**

Les étapes du traitement sont les suivantes :

- Calculer à l'aide de la fonction MINUS (menu MATH du SPATIAL ANALYST) la grille obtenue par soustraction de la grille « épaisseur du sol » au MNT ;

- Chercher à l'aide de la fonction GREATER THAN (SPATIAL ANALYST) les cellules où « MNT

- épaisseur du sol > cote piézométrique » : le résultat est la grille 1 (à conserver) ;

A l'aide de la fonction RECLASSIFY (SPATIAL ANALYST) transformer les 0 de la grille 1 en NoData, les valeurs 1 et NoData d'origine étant conservées : le résultat est la grille 2 (à conserver) ;

• A l'aide de la fonction EXTRACT BY MASK (SPATIAL ANALYST), extraire de la grille d'épaisseur du sol la zone couverte par la grille 2 : le résultat, la grille 3 (à conserver), correspond à l'épaisseur du sol au droit des cellules où le niveau piézométrique passe dans le matériau sous-jacent au sol.

### **Cellules où seule une partie du sol doit être considérée**

Les étapes du traitement sont les suivantes :

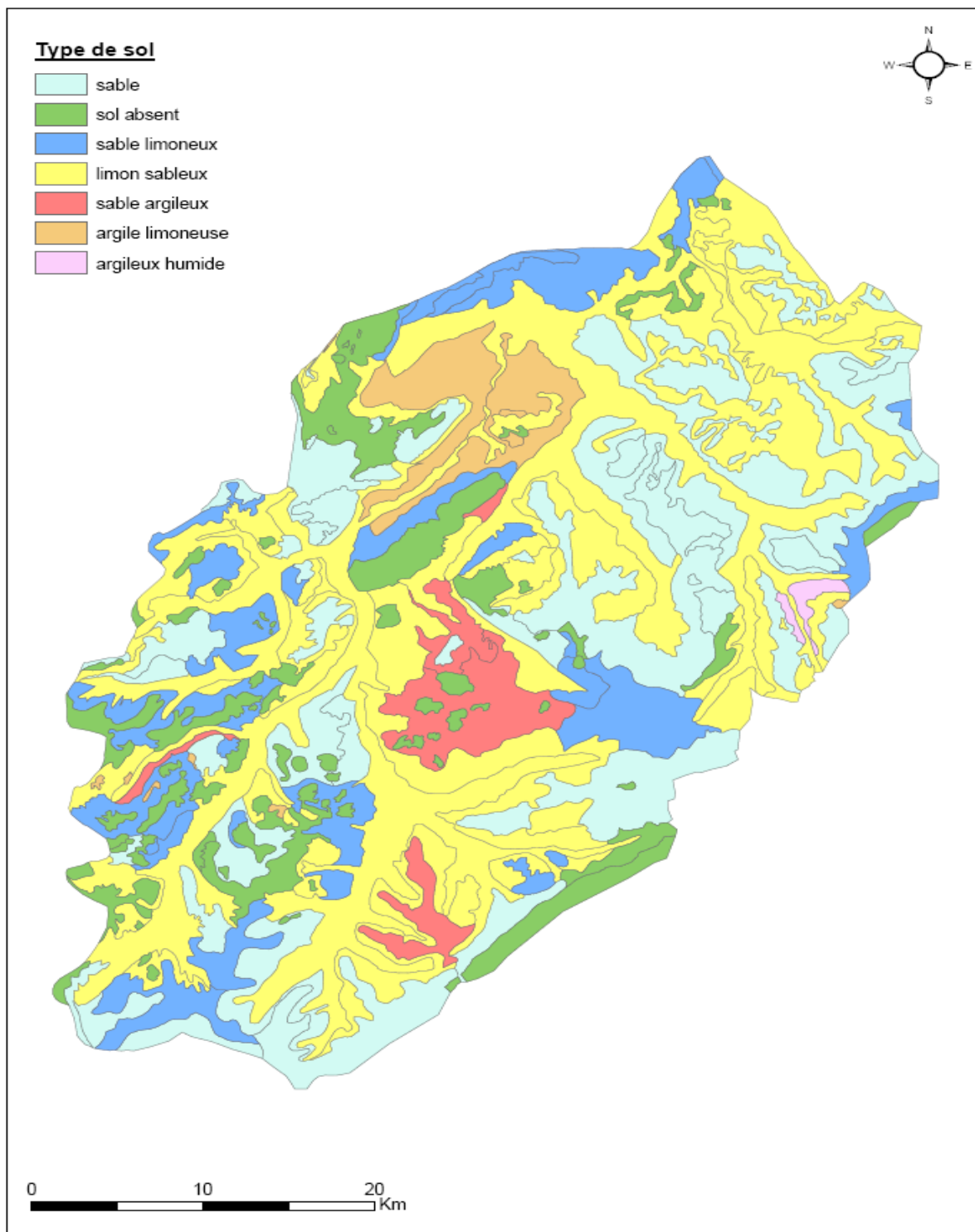
• Transformer à l'aide de la fonction RECLASSIFY les 1 de la grille 1 en NoData et les 0 en 1, les NoData d'origine étant conservés : le résultat est la grille 4 à conserver.

• A l'aide de la fonction EXTRACT BY MASK, extraire de la grille d'épaisseur du sol la zone couverte par la grille 4 : le résultat, la grille 5 (à conserver), correspond à l'épaisseur du sol au droit des cellules où le niveau piézométrique se trouve dans la tranche de sol.

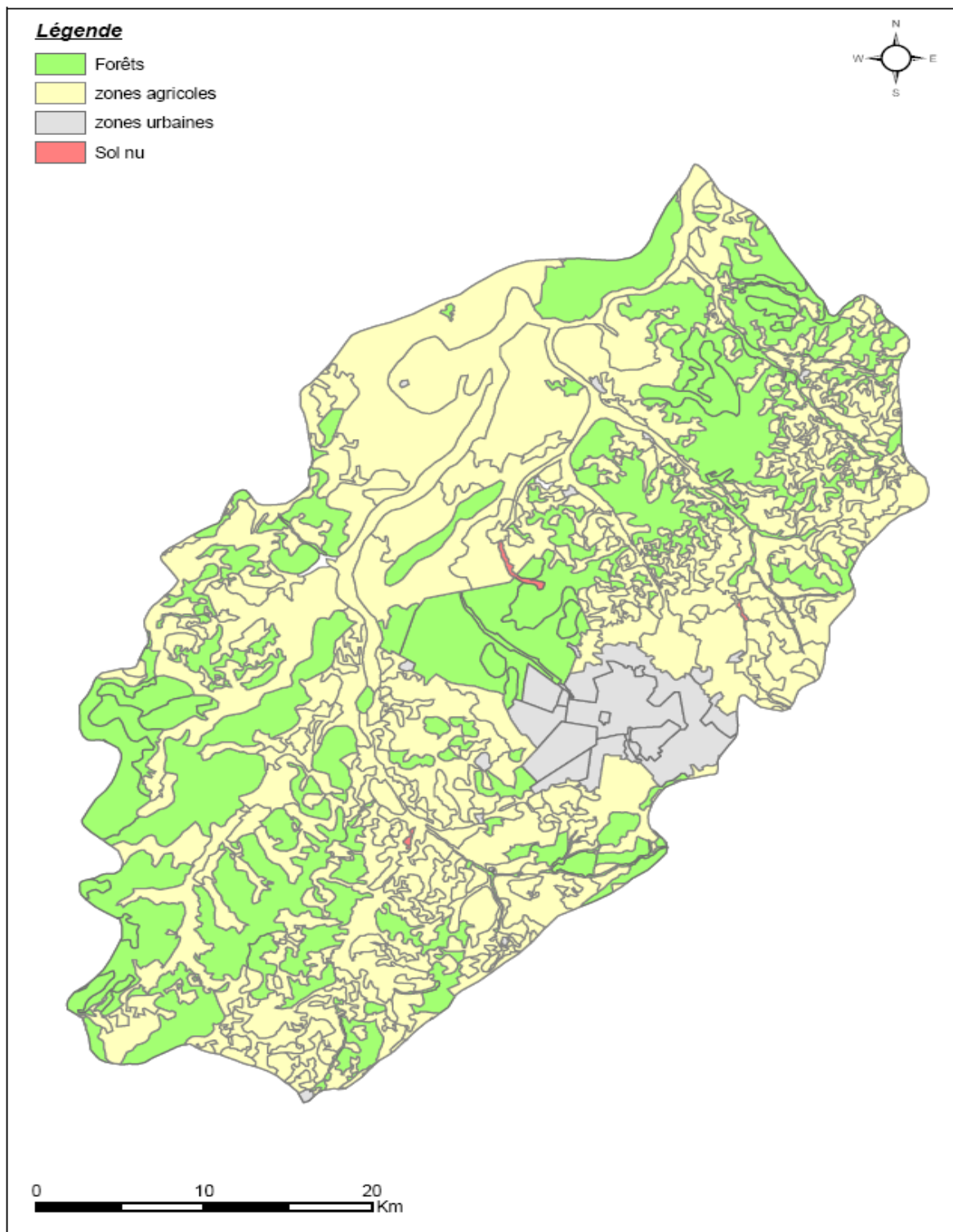
### **Regroupement des données d'épaisseur non saturée du sol**

La grille globale d'épaisseur non saturée du sol est réalisée par fusion des grilles 3 et 5 calculées à l'étape précédente (fonction MERGE via le MAP ALGEBRA du SPATIAL ANALYST).

## APPENDICE E- Final soil map (enlarged)

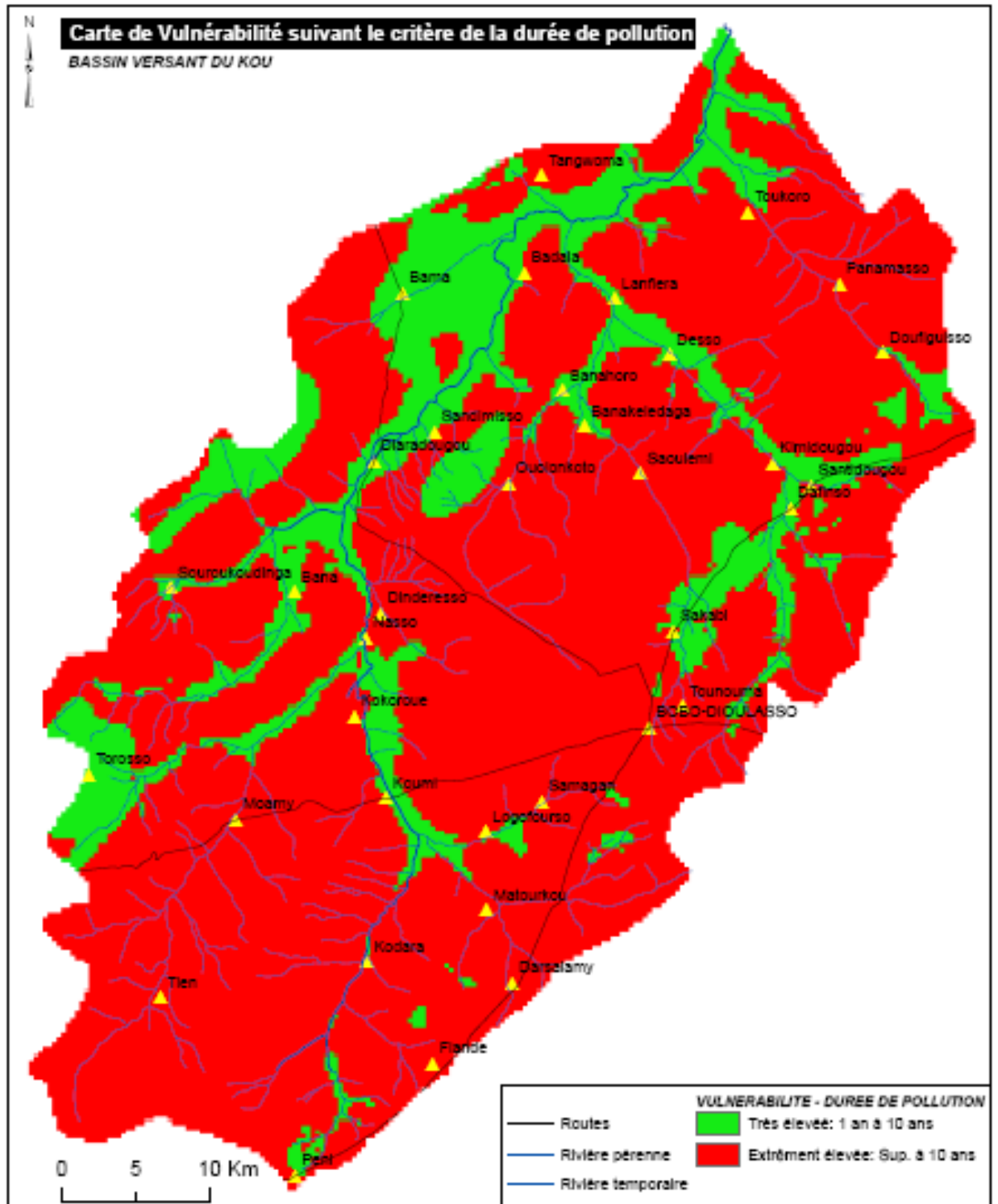


APPENDICE F- Final soil occupation map (enlarged)



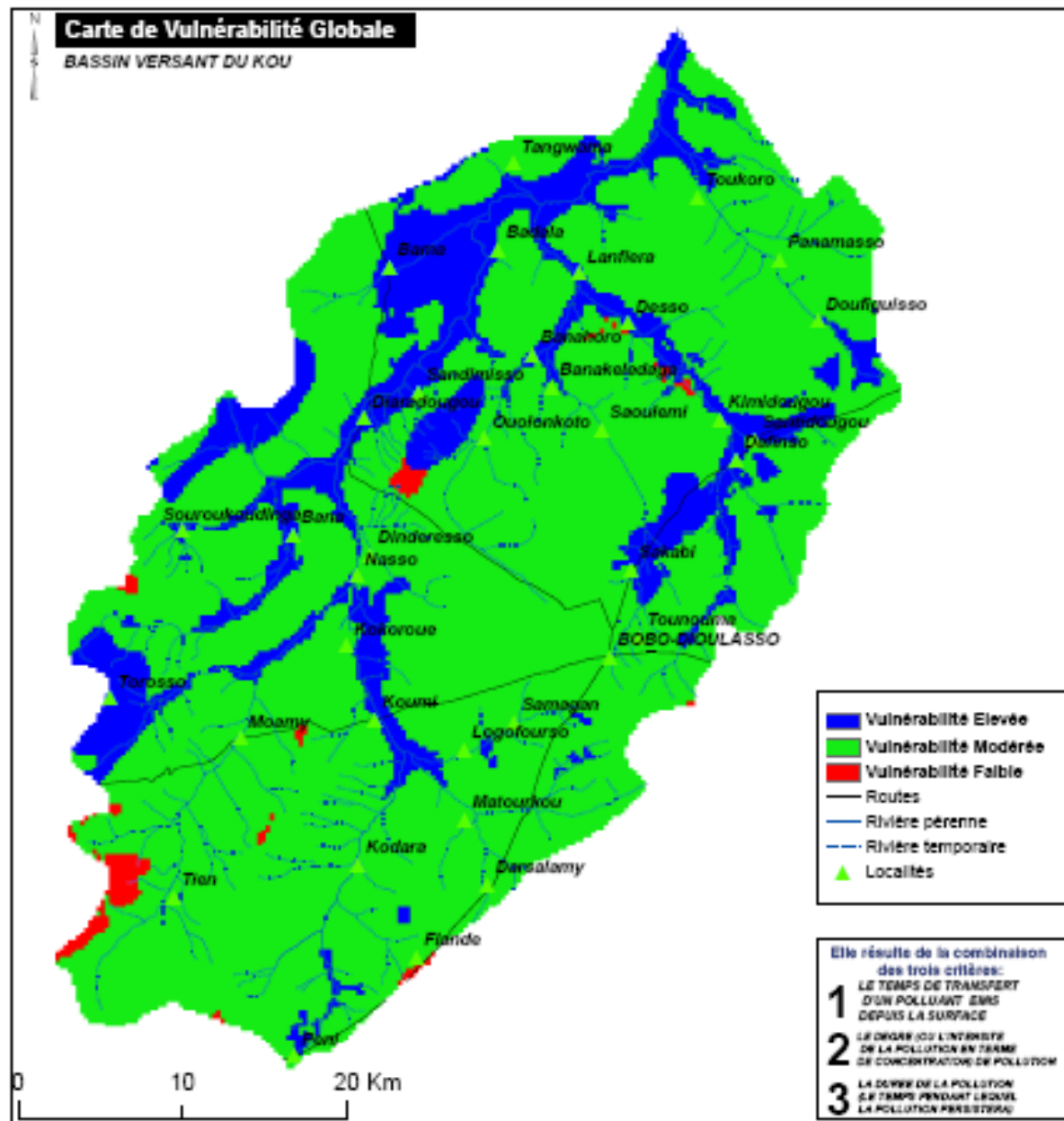


APPENDICE H- POLLUTION DURATION VULNERABILITY MAP (ENLARGED)



*Cette carte présente la durée de la dégradation de la qualité des eaux souterraines à la suite d'une pollution et s'il ne fallait tenir compte que du pouvoir autoépurateur du milieu pour restaurer la qualité de ces eaux.*

## APPENDICE I- GLOBAL VULNERABILITY MAP (ENLARGED)



### INTERPRETATION

*L'approche utilisée dans cette étude donne six classes de vulnérabilité pour un aquifère (Très faible, Faible, Modérée, Elevée, Très élevée, Extrêmement Elevée) Cette carte révèle que le Bassin versant du Kou se trouve en grande partie à un niveau non alarmant de vulnérabilité. Cependant toute la plaine alluviale du Kou, l'amont de la source de Nasso et l'aval de la zone urbaine de Bobo-Dioulasso représentent des zones très sensibles qui devraient attirer l'attention et la vigilance de tous.*

## Résumé

La méthode APSU est une méthode de cartographie de la vulnérabilité intrinsèque développée en 2004 par l'Université de Liège (Belgique). Contrairement aux nombreuses autres méthodes existantes dans le domaine, cette approche présente la particularité de fournir des résultats quantifiés (temps de transfert d'un polluant, durée de la contamination, importance de la contamination). C'est pourquoi elle est dite "physiquement basée" alors que les autres méthodes sont dites indexées (elles produisent des indices censés refléter la vulnérabilité des aquifères). Cette méthode, acceptée par la commission scientifique européenne, a donné des résultats convainquants pour les bassins où elle a été appliquée. Au cours de la présente, elle a été appliquée au bassin du Kou (Burkina Faso), c'est-à-dire dans un contexte climatique et hydrogéologique très différent des études antérieures.

Ce bassin situé en zone climatique soudano-sahélienne (caractérisé par une saison sèche et une saison des pluies) couvre une superficie d'environ 1860 km<sup>2</sup>. Il est principalement constitué d'aquifères alluviaux et gréseux.

Cette étude a fourni aux gestionnaires des ressources en eaux de ce bassin des moyens de décision en matière d'aménagement du territoire.

Même si le concept est bien établi et que les résultats apparaissent physiquement cohérents, des études précises sur la porosité, sur la recharge ainsi que sur les paramètres hydro dispersifs des matériaux doivent être menées pour l'alimentation de la méthode en données fiables. Une étape de validation des résultats générés par le code APSU utilisé, en terme de ruissellement et d'infiltration, pourrait également être réalisée. Une fois validée et les améliorations apportées, la méthode pourrait être étendue à l'évaluation de la vulnérabilité spécifique de la ressource notamment au regard des problématiques de contamination en intrants agricoles dans le bassin.

### Mots Clés :

**1 - Aquifères                    3 – Gestion des ressources en eaux   2 – Burkina Faso  
4 – Vulnérabilité   5 – Système d'information géographique (SIG)**

## Summary

APSU is a new approach in mapping the intrinsic vulnerability of aquifers developed in 2004 by University of Liege (Belgium).

Contrary to former methods in this domain, APSU is unique in providing quantifiable results such as transfer time of a pollutant, duration of contamination and level of contamination in terms of concentration. It is for this reason that APSU is called a "physically based approach" whereas others are called "index-link" in which they produce indices reflecting aquifers vulnerability.

The APSU method is approved by the European scientific commission and has already presented convincing results for basins where it has been applied. In this study of the Kou basin, it is applied in a different climate and hydro geological context from former studies.

Kou basin is located in *soudano-sahelian* climate characterized by a long dry season of eight months with four rainy months. It has a surface area of 1860 km<sup>2</sup> and consists mainly of sandstone and alluvial aquifers.

This study provides water resources managers a tool to use for their land-use planning.

Even though the APSU approach provides physically coherent results, precise studies on recharge, porosity and hydro dynamic parameters are needed to continue improve the approach method and data. One potential step towards validating results from APSU would be improving infiltration and streaming of results given by Apsu code. After these eventual improvements, APSU use could be extended to include the assessment of specific vulnerability notably in regards to problems caused by the abusive use of agricultural manures in Kou basin.

### Key words:

**1 – Aquifers   2 – Water resources management   3 – Burkina Faso  
4 – Vulnerability   5 – Geographic information system (GIS)**