# HYDROLOGICAL MODELS FOR THE ASSESSMENT OF IMPACTS OF INFRASTRUCTURE ON WATER-DRIVEN GEOMORPHOLOGICAL PROCESSES

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## ABSTRACT

The construction of roads and motorways implies a variety of environmental impacts on landscape features. Some of those features are essentially static and impacts on them can be assessed using straight-forward methods. However, impacts on dynamic landscape features will have to be evaluated in other ways, since the impact itself will also be of a dynamic nature.
Fundamental to the geomorphological impact of any construction is the way in which hydrology is affected. Changes imposed upon the landscape by road construction and use will affect mechanisms such as infiltration, runoff and erosion. These impacts cannot be assessed directly, due to the complexity of hydrological processes and the way in which the processes are interrelated, both spatially and temporally.

Insights into the hydrological response to construction ask for the understanding of underlying hydrological mechanisms. A way to achieve a better understanding of these processes is by modelling them. If spatial and temporal variability are accounted for in such a model, the behaviour of hydrological mechanisms and their interactions could be predicted. Incorporating the presence of infrastructure in such model can lead to a better prediction and assessment of the effects of road construction.

The development of a procedure for linking this type of models with a spatial database can generate useful information regarding the assessment of the hydrological response of the environment to alterations imposed by road construction. Such a procedure should be valid for situations where data availability is sub-optimal (which will often be the case within the framework of EIA).

## 1 INTRODUCTION

The construction of any transportation system will have a number of environmental impacts (physical, biological, aesthetic, socio-economic). Early consideration of the full implications of an environmental impact should lead to better design of the structure (Beinat *et al*., 1999). Since many decisions can not be made by means of public debate, methods have been sought that provide a rational basis for decision making. Environmental impact assessment (EIA) is one of those methods for evaluation of the sum of impacts. EIA is defined as the process of identifying the likely consequences of the implementation of a particular activity for the biophysical environment and people's health and welfare and conveying this information in a stage when it can materially affect the decision to those responsible for taking such decisions (Wathern, 1988). Environmental Impact Assessment provides a basis for resource management to achieve the goal of sustainability (Sebastiani *et al*., 1998). As a tool EIA provides preventive environmental protection and early integration of environmental considerations in decision making (Feldman, 1998).

A number of such impacts are directly or indirectly related to geomorphological characteristics. For the purpose of an EIA within a geomorphological framework, a division can be made in three main groups of geomorphological components (Rivas *et al.,* 1997): (1) geomorphological resources (consumable); (2) geomorphological assets (non-consumable); and (3) geomorphological processes. In the third group indirect, secondary, cumulative, etc. effects of impacts can be considerable. When assessing impacts on processes, a problem arises due to the fact that predictions have to be made with respect to dynamic rather than static qualities of the landscape. Impacts on static landscape features can be assessed with relatively straight-forward methods. For example, consumable resources present in the area that will be affected by the activity can be expressed as a volume and a corresponding market value. The volume change associated with the construction of the transportation system can be calculated and the comparison of pre- and post-values allows for a quantification of the impact (Rivas *et al.,* 1997). Impacts on dynamic landscape features will have to be evaluated in a different manner, since the impact itself will be of a dynamic nature. Under certain conditions the use of models allows for deterministic or probabilistic predictions. They are a tool which can contribute to the wider process of decision making, e.g. exploration of strategies. Although they cannot replace direct data sources, they allow the most to be made of existing data, where data are scarce or unavailable such as data on future conditions (Bathurst & O'Connell, 1992).

## 2 CASE STUDY

he study concerns the construction of the new Vitoria-Eibar motorway in the Gipuzkoa territory (western part of the Basque Country, Spain; figure 1). This motorway will provide a shorter and faster link between the northern Castilian plateau and San Sebastián and the French border.

The length of the highway will be approximately 80 km and it will cross the Cantabrian Range from the Castilian Meseta to an area near the coast. A large part of the route will run through the watershed of the Deba River. The Deba River is situated in the most western part of the Gipuzkoa territory and is 62 km long. Its watershed covers 539 $km^2$. Annual average rainfall and discharge are 1384 mm and 14,08$m^3s^{-1}$ respectively.


Figure 1 Location of study area

The goals to be achieved through the construction of the new motorway are providing better conditions for economic development, reducing the congestion of National I road, reducing deaths, injuries and damages due to traffic accidents and improving the environmental quality of urban areas affected by the present road.

Main concerns with respect to the potential impact of the motorway which have been initially identified are traffic increase through and at either end of the new transportation axis, introduction of a barrier

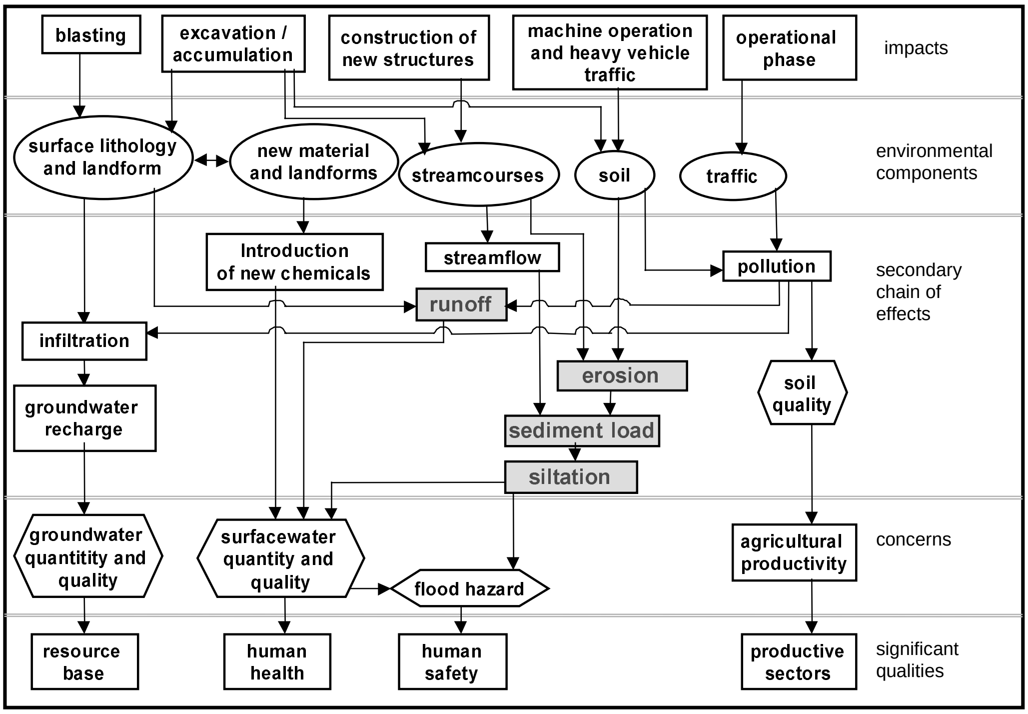


Figure 2 Expected effects on hydrology and related processes due to motorway construction

which may represent a difficulty for communication between the two sides of the motorway, visual impact of the new infrastructure, land occupation or degradation in an area where available land with a high potential for use is quite limited and interference with natural processes and hazards. These include terrain instability (landslides, collapse, subsidence) and infiltration and runoff related processes (groundwater recharge and pollution, soil erosion, channel erosion, water quality, siltation, waterlogging and flooding (figure 2).

## 3 HYDROLOGICAL IMPACTS

### 3.1 Nature of impacts

Fundamental to the geomorphological impact of transportation systems is the way in which hydrology is affected. Even if impacts on the processes considered are not relevant, their simulation allows for the assessment of their relevance. Changes imposed upon the landscape by construction and use of infrastructure will affect mechanisms such as infiltration, runoff, erosion and pollution.

Full understanding of physical processes should allow for quantitative predictions with respect to the response of dynamic processes. A way to achieve a better understanding of these processes and making predictions is by environmental modelling (in this case hydrological modelling). In general, a model is fed by knowledge of a certain discipline; the use of such a model (and its predictions) for impact assessment and decision support, aims at transferring such knowledge across disciplines.

If a model simulates the physical system in a satisfactory way, it is assumed the processes are represented in a manner that corresponds with their behaviour in the physical system. Incorporating the presence of the project (a transportation system) in the model can lead to a quantification of the impacts of the transportation system on hydrological processes. When spatial and temporal variability are accounted for in the model, the behaviour of hydrological mechanisms (in time and space) and the way in which they interact can be assessed with respect to the presence of a transport system. For example, large amounts of runoff from the highway surface will favour downslope erosion, which will decrease soil thickness, which will decrease storage capacity of the soil, which in turn will limit infiltration and thus favour runoff generation.

### 3.2 Problems for the assessment of hydrological impacts

It must be recognised that, although many environmental models have been developed, we will rarely have models at our disposal that can provide sound, quantitative estimates. This is partly due to the fact that these models have been developed for research areas that are usually of orders of magnitude smaller than management areas (Grayson *et al.*, 1993). Research areas are often selected on the basis of interest in a specific phenomenon or process or on the basis of data availability. This is not appropriate within an impact assessment framework, where the study area is provided not by an interest in a specific process but rather by the focus of the project (in this case the construction of infrastructure) or a particular hazard (flooding of a given river). Considerable database development is needed for analysis of urban watersheds (Maidment, 1996). Lumped models have traditionally been developed for application to large watersheds and require less data input, but they are clearly not capable of providing distributed information.

In general, environmental models usually require a large amount of data input. Very often in the case of EIA, not all data one would desire are available or can be collected. Therefore the study of geomorphological processes does not allow for precise predictions with respect to the impacts on these processes (Rivas *et al.,* 1997). Lack of data for future conditions also constrains possibilities for calibration and validation. A model which calculates predictions for future conditions, will have to be evaluated on a non-mathematical basis. This must be done with simple reasoning (Grayson *et al*., 1993) to provide some sort of validation, where no data is available for proper validation. This corresponds to the term “face validity” which describes the models credibility (Marcot *et al.*, 1983).

Reliance solely on these models should be replaced with a combination of quantitative understanding of hydrological response and simple reasoning to assist in the decision making process. These methods will be no more accurate than complex models, but are simpler and more modest. Such approaches may be undertaken within or outside a GIS environment and are consistent with data availability and our ability to mathematically represent hydrological systems (Grayson *et al*., 1993).

A second problem concerns the interpretation of predictions with respect to EIA. At present the possibility for individuals outside the EIA team (e.g. decision makers) to run simulations of the expected impacts and evaluate consequences from their own perspective is rather limited (Beinat *et al*., 1999). When decision makers are not familiar with the nature of the impact considered, they will encounter difficulties taking the predictions into account when making a decision (for example, someone with limited knowledge of soil erosion processes will have difficulties interpreting a value for increase in annual soil erosion). The need for expertise (amongst other factors, such as ideological blindness or malice) can limit a user's ability to retrieve the correct information from a map (Van Herwijnen, 1999). User-friendly graphics assist individuals with little experience in hydrological matters in running a hydrological model and producing good-looking graphics. Sophisticated visualisations and data handling tend to seduce the user into an unrealistic sense of model accuracy (Grayson *et al*., 1993). A potential danger is thus that digital data always appear to be of high quality and information on data quality and errors is either neglected or in some cases not available (Thieken et al, 1999). "Maps provide an excellent communications medium for presenting results in a form that most people think they can understand" (Openshaw, 1991).

Additionally, interpretation-related problems can arise when a number of fundamentally different impact predictions have to be compared to each other (e.g. balancing a change in project costs with a predicted change in annual soil erosion is not that obvious).

## 4 METHODOLOGY

### 4.1 Introduction

The development of a workable methodology for the adaptation of environmental models to their use in EIA and converting the model into an interactive tool that generates useful information regarding the implications of the proposed construction could be a very useful aid to environmental management (useful in the sense that the results can be: (1) interpreted by decision makers; and (2) compared to other impacts). "Information technology, and in particular the integration of database management systems, GIS, remote sensing and image processing, simulation and multi-criteria optimisation models, expert systems and computer graphics provide some of the tools for effective decision support in natural resources management." (Fedra, 1995). The combination of a distributed hydrological model and the mapping capabilities of a GIS greatly reduce processing time for data preparation and presentation. This combination is sometimes referred to as a decision support system (Grayson *et al.*, 1993). The main rationale for the development and use of decision support systems is its power to reduce redundancy by summarising, categorising and projecting relevant data (Barr & Sharda, 1997). This should ideally decrease the amount of cognitive effort required for processing large amounts of information.

Bathurst & O'Connell (1992) give a two-stage procedure for the application of a hydrological model within the context of a decision support system. In the first stage a model is set up for the required watershed and conditions. In this stage hydrological expertise is fundamental. In the second stage the model is applied to the evaluation of impacts of proposed changes. Less technical expertise will be required, since the model has been validated and implementation should be backed up by user-friendly support. The policy maker should then be able to examine the effect of the proposed change on the output attribute of interest. The representation of attributes should allow for trade-offs between environmental and socio-economic qualities.

### 4.1 Model Development

An approach is presented for the development of hydrological models for specific use within an EIA framework. The approach is divided into three main steps: (A) the development of a dynamic, spatially distributed hydrological model for a specific part of the hydrological regime (related to concerns) in a given area; (B) implementation a proposed project in the model; and (C) implementation of the model in the EIA framework for aid in decision support. These three phases are interrelated. That is, the models structure will depend on both nature of the infrastructure considered and desired output (if flood hazard is a major concern, relevant output indicators would be area potentially affected, flood frequency/level etc.).
Changes in the hydrological regime can then be used to assess the expected effects on geomorphological processes such as channel flow, soil and channel erosion, waterlogging, or sediment production and transport.

In figure 2 the methodological sequence is presented, accompanied by its application to a concrete case study. Impacts have been considered for two distinct phases: construction and operation of the highway, but only the first phase is represented in the figure. During the construction phase land cover destruction, soil perturbation and excavation and accumulation elsewhere will alter infiltration and runoff. This will have consequences for discharge, which in turn may affect flood hazard.

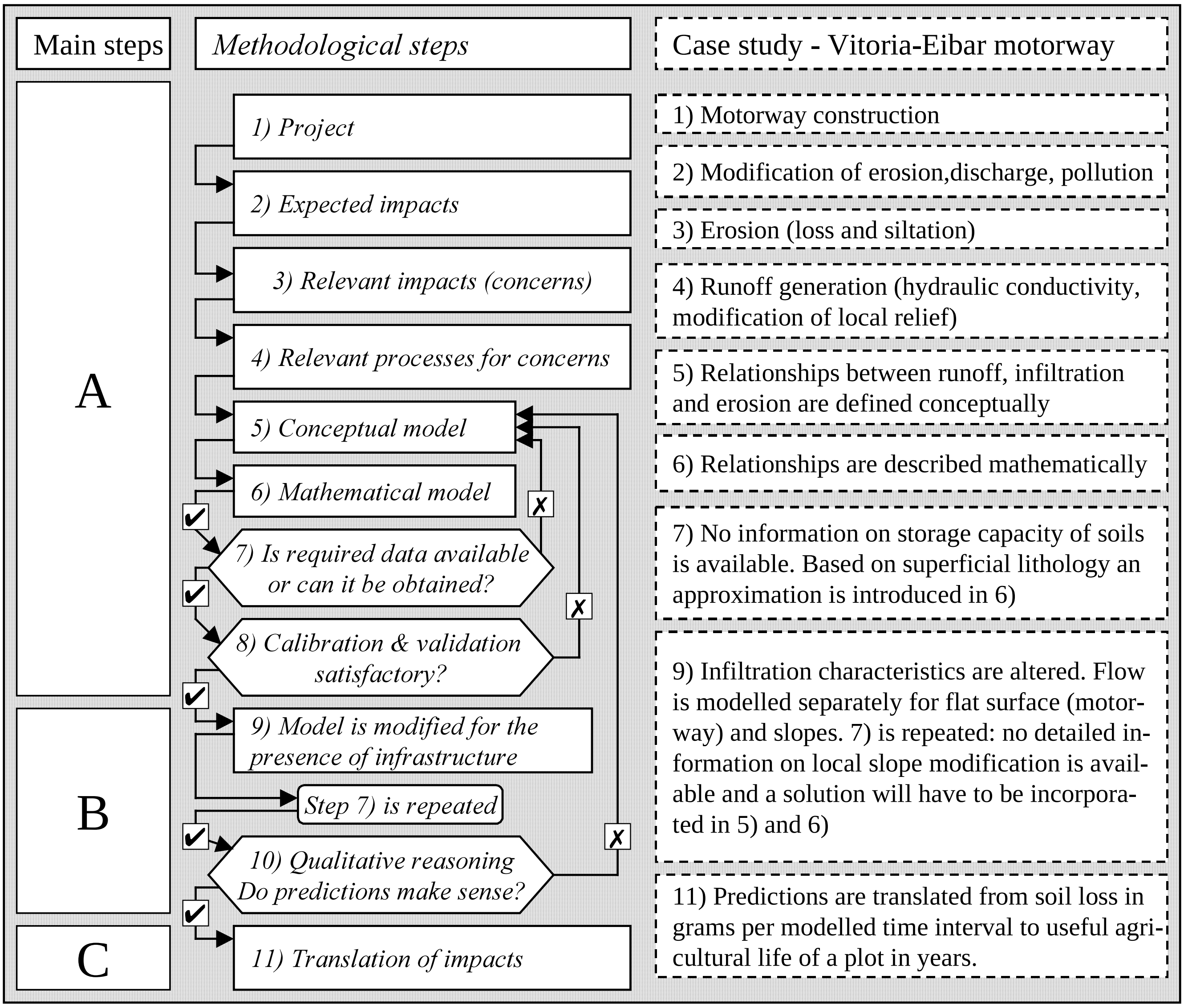


Figure 3. Methodological sequence for the development of an EIA specific hydrological model(the numbers between parenthesis in the text correspond to the boxes in the figure)

Land disturbance and runoff will affect soil erosion and the consequent change in channel sediment load. This effect is likely to be enhanced by channel erosion, which could increase directly as a result of modifications by roadworks and indirectly by the increase in streamflow. The net result will be alteration of suspended load in channel, with the consequent decrease in water quality for aquatic life. Changes in sediment load will affect channel and reservoir siltation. Chemical pollution of surface waters is also likely to occur, due to operation of machinery and use of a variety of chemical substances during the construction period. Most of the effects described are likely to disappear when the construction phase is over.

During the operational phase, the main impact will probably be increase and diversion of runoff (a significant area will be covered with asphalt). Overland flow will be diverted, either by the construction of ditches and gutters, or indirectly due to landform changes which introduce barriers, depressions, small valleys, etc. The pattern of runoff and channel discharge will be altered. Although overall discharge of main water courses is unlikely to be significantly affected, changes could be important in some small streams and local increases in flood hazard may occur. Increased water-logging problems in some areas may also appear as a consequence of landform changes. These changes may affect erosion and related effects, although probably not as much as during the construction phase. On the other hand, pollution of surface and groundwater is likely to be more important at this stage. Combustion pollutants and leaks from vehicles will affect soil and groundwater in the vicinity of the motorway and surface waters downstream from it. In figure 3 the impacts resulting from construction are considered.

As shown in figure 2, soil erosion has been identified as a potentially significant impact *(3)*. The Deba river is highly polluted and additional pollution is not a major concern. Relevant processes *(4)* are all processes related to erosion; runoff, infiltration, surface roughness etcetera.

Fundamental relations between these processes are conceptually established *(5)* and transformed into a mathematical model *(6)*, where relations are represented by equations and parameters represent field characteristics. If all model input can be obtained the model is calibrated and validated *(8)*. Thus, relevant processes are formulated in a way that complies to the limits of data availability (Maidment, 1996).

If not, conceptual and/or mathematical changes (simplification of interrelations) will have to be introduced *(7→5,6)* or reasonable estimates can be used. In this case study e.g. no data on storage capacity of soils is available. Thus, storage capacity can be estimated as a function of soil type. In *(9)* surface characteristics for the location of the planned project are altered for post-project conditions. Since no detailed information on slope modification can be obtained at pre-project stage (and will probably occur at sub-grid scale), adjustments in the model will have to be made. Since no means of calibrating and validating the output of the model with respect to the effects of infrastructure exist, alternative validation methods must be used *(10)*. A possible way of calibrating the model, especially during the construction phase, is the determination of suspended load in streams. As a last step the model's predictions are translated from soil loss values (gram per unit area per time interval) to relevant terms which allow for interpretation and comparison (e.g. "equivalent" agricultural land loss, useful life of a reservoir due to siltation).

### 5.3 Model application

The application of the model requires a minimum of input data: a digital elevation model (as detailed as possible), rainfall data (time series at hourly timescale), soil characteristics and land cover. The final model output will be, as mentioned above, stream discharge and suspended sediment load (expressed in terms that are significant for EIA).
Discharge records with sufficient detail are available two small watersheds within the Deba watershed (Urkulu; 7.5km$^2$ and Aixola; 4.7km$^2$). These have been selected as particularly suitable for the initial application, calibration and validation of the model (figure 4).

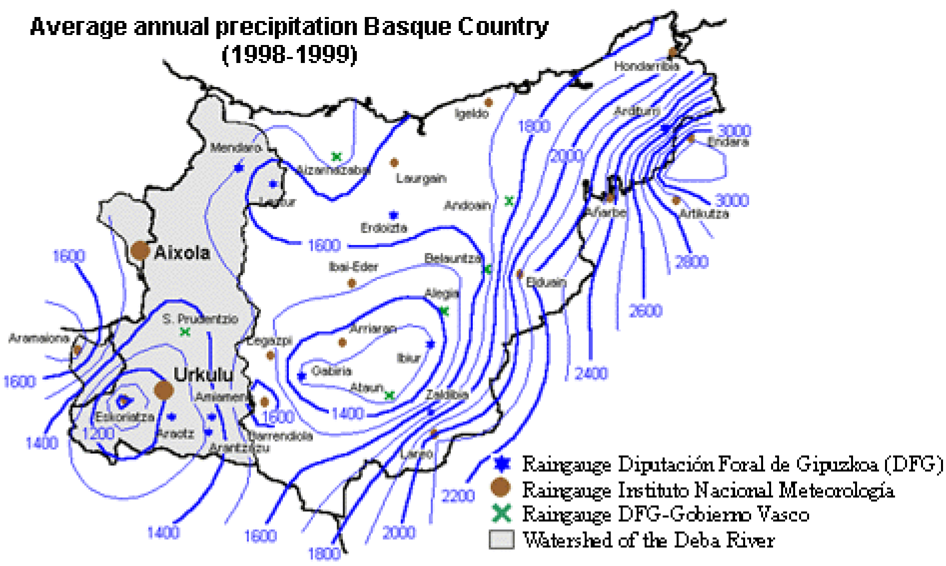


Figure 4. Annual precipitation (mm/year) and raingauge stations for the Basque Country, Spain,

A digital elevation model is available for the entire study area with a coarse resolution (25 meter contour intervals). Since this is not considered to be sufficiently accurate, a more detailed digital elevation model is being prepared for the mentioned test sites (with contour intervals of 5 meter). Soil and land cover maps, originally made at the 1:25.000 scale, are available in digital form. As more detail is needed for the analysis, these maps are being revised. Detailed precipitation records are available for both watersheds (figure 4).

The relationships between the input described above are expressed as mathematical expressions. Input from precipitation will reach the surface. Water can the infiltrate or remain on the surface. Infiltration is calulated according to the Green & Ampt model (*equation 1*, Amaru' Michele, 1995).

$$\Delta F = -\frac{(2 \cdot F - K \cdot \Delta t)}{2} + \frac{\sqrt{\left[(2 \cdot F - K \cdot \Delta t)^2 + 8 \cdot K \cdot \Delta t \cdot (\psi \cdot \Delta\theta + F)\right]}}{2} \qquad \textit{(equation 1)}$$

Potential infiltration is calculated for each timestep as a function of hydraulic conductivity *(K)*, cumulative infiltration in previous timesteps *(F)*, the suction head at the wetting front *(ψ)* and change in moisture content *(Δθ)*.Potential infiltration is used as value for infiltration if the storage capacity of the soil allows infiltration. Water that can not infiltrate (either due to limited potential infiltration or limited storage capacity), will remain on the surface, after which it will move through the watershed according to either channel flow or overland flow.

Channel flow is modelled as a kinematic wave (without accelerations due to the characteristics of flow itself). Flow velocity can the be calculated with the Darcy-Weisbach equation (*equation 2*)

$$v = \sqrt{\frac{8g}{f} \cdot R \cdot S} \quad \left(in \quad which \quad \sqrt{\frac{8g}{f}} = Chezy's \quad C\right) \qquad \textit{(equation 2)}$$

where $g$ is gravity acceleration, $f$ is the Darcy-Weisbach friction factor, $R$ is the hydraulic radius and $S$ is the slope. When Chezy's C is regarded equal to $R^{1/6}/n$, Manning's equation for the calculation of open channel flow velocity is obtained (*equation 3*),

$$v = \frac{R^{2/3} S^{1/2}}{n} \qquad \textit{(equation 3)}$$

where is the Manning's roughness coefficient, which depends on land cover.

Overland flow will occur on a sloping surface. Three possible situations can be identified. First, a surface with a hydraulic conductivity smaller than the precipitation intensity, (infiltration excess), secondly saturation from above (saturation), and thirdly saturation from under (exfiltration). Equation 4 is the kinematic wave equation for overland flow,

$$w_{eff} - (m+1) U_{uo}(s,t) \frac{\partial Y_o(s,t)}{\partial s} = \frac{\partial Y_o(s,t)}{\partial t} \qquad \textit{(equation 4)}$$

Where $W_{eff}$ is effective precipitation (here precipitation minus infiltration), $m$ is a factor (set at 0.5), $U$ is discharge form a pixel and $Y_o(s,t)$ is the depth of flow. Solutions for equation 4 can be found using the method of characteristics.

Values for these parameters are updated after each time interval. Output for each time interval they are used as inputs for the aaplication of the soil erosion model, the output of which consist of estimates of sediment production. This output, in turn, is used for the calculation of suspended sediment load. The latter parameter can be measured during and after construction for model calibration and validation.

## 6 CONCLUSIONS

The approach presented provides a means to make certain predictions concerning the likely modeifications of hydrology related processes as a consequence of changes due to infrastructure construction and operation.
The method described, based on the sequential application of a series of dynamic, distributed models, will produce a final output in terms of measurable parameters, significant for EIA (channel discharge, soil loss, sediment load). These parameters can be determined to test and calibrate the model both prior to and during construction.
Minimum inputs required for the model are precipitation records, digital elevation, a soil and land cover map. These inputs are often available or can be obtained relatively easily. The only insurmountable difficulty is, obviously, lack of precipitation data.

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