Transactions on Ecology and the Environment vol 50, © 2001 WIT Press, www.witpress.com, ISSN 1743-3541

Integrated hydrologic and landslide risk management in the Romagna River Basins using cartographic predictive modeling

A.Pistocchi , O.Zani
Autorità dei Bacini Regionali Romagnoli, Regione Emilia Romagna, Forlì, Italy

Abstract

The paper illustrates the general decision support system architecture set up by the Basin Authority, which includes descriptive cartography and databases concerning flooded areas and basic thematic maps, together with model-based cartography about terrain analysis, regionalized hydrological and soil properties data, simple distributed kinematic runoff modeling, stream hydraulic data and links to GIS-coupled simulation models.
The decision support system was set up by integrating existing technologies in the Arc-View GIS environment, and exploiting to full extent the modelling capabilities of the software. Most analytical operations are performed directly using GIS analytical tools, while for more specialized enquiries dynamic models are implemented.
At present, the decision support system scope concerns flood hydrology and hydraulic risk mitigation, while future development will regard water resource management and water quality.
As a special component of the system, an original methodology for the evaluation of requirements to keep land use change hydrologically invariant is implemented and is currently under field testing.
The system is directed to support communicative rationality in basin-level land use planning and management, and is strictly coupled with the steps of the planning and conflict management processes.

1 Introduction

In the last decade, Italy has implemented a great effort in the reorganization of basin management all over the country, through the institution of the river basin authorities. The main task of the Authorities is the implementation of basin masterplans concerning hydro-geological risk mitigation, rehabilitation of basin hydrology, ecological river quality, and water resource availability.
The new paradigm in planning concerns a *super partes* subject which must give the "game rules" for the sustainable exploitation of natural resources at the river basin scale, as the physiographic unit at which planning is effective.

Transactions on Ecology and the Environment vol 50, © 2001 WIT Press, www.witpress.com, ISSN 1743-3541

This paradigm involves description/prediction tools about the environmental processes and patterns, to build up a knowledge on which to found decisions that should be absolute from strategic choices, and should produce the sustainability criteria which must be applied at all levels of planning.
While studying the phenomena concerned with hydro-geologic hazards, a major issue is about how highly specialistic technical tools as mathematical models can be imported into more communicative frameworks as geographical information systems (GIS) for direct use in decision support.
In "traditional" planning, all knowledge that can be used for decisions about the use of natural resources is the one which has been socially constructed at the political level (Mazza, 1987; see also Innes, 1995), which implies that analyses can only be used as an *a posteriori* justification of choices, or a control procedure to check their impacts.
The planning level at which Basin Authorities work, instead, requires a strong scientific basis from which to move in making decisions, since it is about understanding and supporting correct development of natural processes and equilibria.
In other words, one can see the scientific analysis which underlies the basin plan as a "cause" whose "effects" are decisions and rules, while in the case of traditional planning this cause-effect relationship is rarely possible (Pistocchi, 2001a).Thus predictive models become nothing more than a tool to make the land use rules and constraints consistent, rational and transparent.
This sight on models overshoots the faith in some "scientific truth" and can prevent from their technocratic use: all the stakeholders, on one side, need to understand clearly the reasons why a constraint is set (and therefore models need to be understandable and communicable at a non-technical level), but on the other side they are also required to express their objections to the plan addresses based on some reasoning which shares the same consistency, transparency and rationality of the predictive models in use, rather than arbitrary subjective judgement. In such a way, models may become a vehicle for the spreading of a communicative rationality (Friedmann, 1987) in the discussions about the "game rules" in land exploitation given by the basin plan.
Basin management requires a relevant effort in putting together different scientific disciplines, investigation paradigms and predictive models in order to give integrated answers to complex problems. Analyses never represent a final stage of enquiry, but rather an ever improving observation of dynamic systems, which requires to make its limits explicit in order to support policies.

2 Main issues about the use of predictive modeling in land planning

The Romagna River Basin Authority decision support system (DSS) has been set up in order to handle the issue of hydrogeological risk mitigation, which includes concerns about landslides and floods over an area of about 4000 sq.km in northern-central Italy (figure 1). The DSS is based on a spatial database architecture designed over 10 years ago by the Regione Emilia Romagna-

Ufficio Cartografico e Geologico, and makes available for processing: a land instability inventory; soil maps; hydrography; roads and railways network maps; land use maps; surface geology themes. However, the themes already available are not oriented to modeling and prediction, but rather to descriptive mapping and are often poor for the purposes of extracting predictive model parameters. This has brought to developing a knowledge cycle that moves from existing data and exploits more and more complex models as data availability increases, but keeps a comprehensive sight on basin planning as a whole.

All through the decision support process, virtually every stakeholder can take place in the debate about the reasons why to assign certain constraints at the state of the knowledge, and the consensus is easier to be obtained.

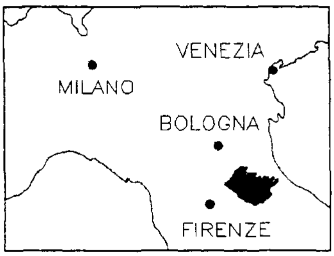

Figure 1 – location of the area

Moreover, every stakeholder knows that confutation of a rule, e.g. a constraint on housing in a given area, can be done through analyses only, which must have the same or a higher degree of reliability than the ones performed by the planner, and not through generic protest. The virtuous circle that such model-based planning process implements brings to an ever increasing degree of awareness about the mechanics of hydro-geologic phenomena and related risks, and is expected to act as an educational environment towards a more rational and appropriate land management and use in the future.

Such optimistic view may look unrealistic, since many plans in the past have been unattended despite models have been used for long time. It is widely observed, however, that state-of–the-art computing technologies and GIS, when appropriately used, can reduce the gap between scientific understanding of the basin functioning, the specification of rules for appropriate land management, and public acceptance of the rules and voluntary implementation of good practices. In the development of the basin masterplan, issues requiring predictive models include the evaluation of reliable design peak discharge and hydrograph with specified return period, potentially flooded areas and land elements at risk, risk mitigation strategies in terms of technical feasibility, and hydrological evaluation of land use change.

The fundamental maps on which basin planning is based are (1) a landslide risk zonation, and (2) a flood hazard zonation. Here a brief description follows of the procedures to obtain each of them.

3 Cartography and models implemented

The first map allows to detect the hydro-morphologic elementary units (Unità Idromorfologiche Elementari – UIE, i.e. the sub-watersheds corresponding to all hydrographic network elements recognizable at the scale 1:10,000) which require particular constraints in land use and slope stabilization works; this map is obtained by assigning each UIE the percentage of its area in which there are elements at risk due to landslides (figure 2).

For the sake of simplicity, the values were grouped through Boolean slicing into four risk classes. This map is obtained from simple overlaying of a vulnerable elements map (which represents houses, urban areas, historical monuments, infrastructures, etc., each having its "vulnerability weight") to the land instability inventory, and computation of the cross-statistics a the UIE level.

This map reflects the choice made by the analyst about the value of each element, although the vulnerability scale founds on principles that do not originate particular conflicts. Once the UIEs at highest risk have been detected, geomorphologic interpretation allows to map the unstable within them. This step is based on expert's judgement which undergoes technical discussion.

What so far implemented represents an early stage of analysis, but already allows to select "high priority" zones within the basin in a realistic way. A further step will consist in substituting the land instability inventory with a landslide hazard map (see e.g. Guzzetti *and others*, 2000). This step requires the modeling of landslide favourability based on "causal factors" (such as slope, aspect, lithology, snowmelt…) and can be performed through the favourability functions approach proposed by Chung and Fabbri (1993, 1999). It must be said that an early attempt to model favourability using this approach has been done using the available data (Pistocchi and others, 2000) but it has led to the understanding that further data acquisition is required, particularly about topography and terrain modeling, in order to achieve acceptable prediction capabilities.

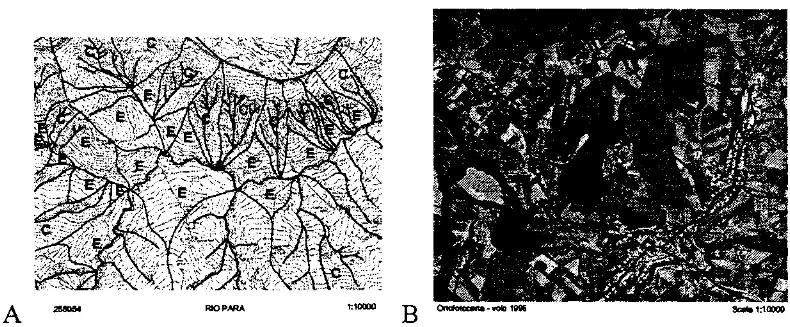

Figure 2 – (A) UIE delineation (C and E represent different morphologic types of UIE); (B) landslide risk map definition: observed landslides are overlaid to the UIE map in order to compute the hazard rate as a percentage of the UIE area covered by mass movement. Aerial photographs are used for ease of interpretation.

Transactions on Ecology and the Environment vol 50, © 2001 WIT Press, www.witpress.com, ISSN 1743-3541

The second map is obtained through floodplain encroachment delineation. Due to the presence of two different morphologies (semi-natural channels in valley bottoms, and reaches with artificial levees in plain land), different methodologies are used in order to evaluate flood propagation outside the main channel, in cases when the section limits are overtopped by the water level.

In the first case, simple extension of the hydraulic section to the morphological boundary to water flow allows to detect potentially flooded areas corresponding to the peak discharge according to a non-uniform, steady flow model. It must be stressed that flood propagation over areas beside the main channel require a characterization of surface roughness, presence of obstacles to flow, etc., which result in the modeling of ineffective flow areas and areas with limited flow capacity (e.g. USACE, 2001a). In the lack of such characterization, which will be performed in future steps, it has been chosen to compute the water level corresponding to the whole discharge contained within the width of the hydraulic section, assuming that water levels increase vertically once the upper limits of the section are reached. This precautionary solution brings to consider as potentially flooded all areas with lower elevation compared to the computed water level. In the second case, a maximum discharge that can be contained in the levee-bounded section is first defined using steady flow assumptions, and subsequently the volume of water potentially outgoing the channel is computed from the design discharge hydrograph with given return period (see figure 3). The volume potentially outgoing the channel is then distributed overland according to the presumed flow directions and available volumes in the plain.

Due to their strong physical basis, potentially flooded areas should be seen as "hard" planning indications to be strictly considered in siting human activities. However, many uncertainties affect the potentially flooded areas evaluation, and especially: (1) the decision about a design discharge hydrograph (in the plan, all hydrologic data concerning discharges and rainfall derive from a regionalization study using the index variable method and a TCEV probability density function distribution: Franchini and Galeati, 1994), (2) the possibility of dam break phenomena linked to levee top erosion and breaching; and (3) difficulties in correctly mapping overland flow directions because of lacking topographic information in flat areas, incomplete knowledge of preferential flow paths in culverts, underpasses etc. Although many algorithms –either based on overland flow modeling (e.g. Todini et al., 1996) or on simplified morphological analyses (e.g. Kress et al., 2000) - have been successfully used, in the Romagna Basins it has not been possible to use any of these at the state of available knowledge.

This has lead to evaluate potentially flooded areas simply through a water volume balance, by detecting "hydraulic cells", i.e. portions of land delimited by obstacles assumed to behave as tanks, filled in cascade from the closest to the river section to the farthest in case a flood volume would exit the main channel due to insufficient sections. Flow directions between cells are determined according to obstacles height and terrain slope. In cases where detecting a clear physical limit (and the consequent storage capacity) to the cell was not possible, it has been assumed conventionally that the area within the cell might host a 20 cm deep water flow. The choice copes with an empirical evaluation of the areas expected to be inundated. In principle, for reasons of safety a water depth not higher than 0.5 m (deemed as the limit over which a risk for human safety occurs) should be considered. The choice of a conventional value of the water depth directly affects the extension of potentially flooded areas, and must be regarded as a weak point of the procedure that can be overcame only using more detailed terrain analyses. In figure 3 the hydraulic cells considered in the study are represented. From what above reported, it is clear that potentially flooded area delineation in the case of levee-bounded channels is affected by a high degree of uncertainty. However, physically based reasoning allows to introduce a transparent and consistent methodology which is acceptably realistic in estimating flood volumes and brings to the definition of scenarios to be used as a basis for planning (see figure 3). Future developments will concern accurate ground elevation and obstacles mapping and a more precise definition of flow directions.

4 Management tools, non-structural strategies and the plan

Many troubles about hydrogelogic equilibria result from the specific modalities of land use, especially in agriculture and urban expansion. Strategies adopted by the Basin Authority to improve land management include soil conservation practices, no-hydrologic-effect urban transformation, distributed cartographic modeling in order to detect and understand fine-scale hydrogeologic patterns and equilibria, and the standardisation of procedures to compute design flow rates for culverts, bridges, and all hydraulic works in general.

As far as soil conservation is concerned, the Romagna Basin masterplan prescribes the adoption of good agricultural practices (which have been historically very difficult to implement in Italy also because on their being pursued through a command-and-control policy which has been just recently been replaced by volunteer planning tools in the interest of farmers). These practices are well established and do not require further comments, while the matter is about making them effective.

For what concerns "no-hydrological-effect" urban transformation and expansion, the basin masterplan requires a minimum storage volume per unit area to be built when a pervious surface is substituted by a partially impervious one, in order to keep the peak urban flood discharge constant after the land use transformation. The volume is computed through equating peak runoff expected before and after transformation with a simple linear reservoir model, as the ones widely used in Italy in dimensioning storm sewers (e.g. Paoletti, 1996). The formula to compute the minimum required volume is:

$$w = w^\circ \left(\frac{\phi}{\phi^\circ} \right)^{\frac{1}{1-n}} \qquad (1)$$

where w is the volume (m^3/ha) to build in the transformed area in order to keep the peak discharge constant, ϕ and ϕ° are the infiltration coefficients after and before transformation, and w° is the volume available to rainfall before transformation. The exponent n depends on storm rainfall features, and can be shown to be n=0.48 for small areas (time of concentration < 1 hour). Further details on the topic are reported in Pistocchi, 2001b. Volumes resulting from the above formula are of the order of magnitude of 500 m^3/ha assuming a w°= 50 m^3/ha (which is a representative value taken from the literature). A definition of appropriate values of w° will come from experiments currently under implementation, while ϕ and $\phi°$ are assumed from the literature (Paoletti, 1996). The advantage of the approach is that it gives local administrators a "self tuning" criterion for urban expansion under the constraint of hydrologic sustainability (e.g. by adopting higher percentages of impervious urban surface (i.e. increasing the $\phi/\phi°$ ratio), w increases and implies higher urbanization costs, but a denser housing, while keeping the $\phi/\phi°$ ratio low results in lower values of w but requires wider pervious spaces and less dense housing).

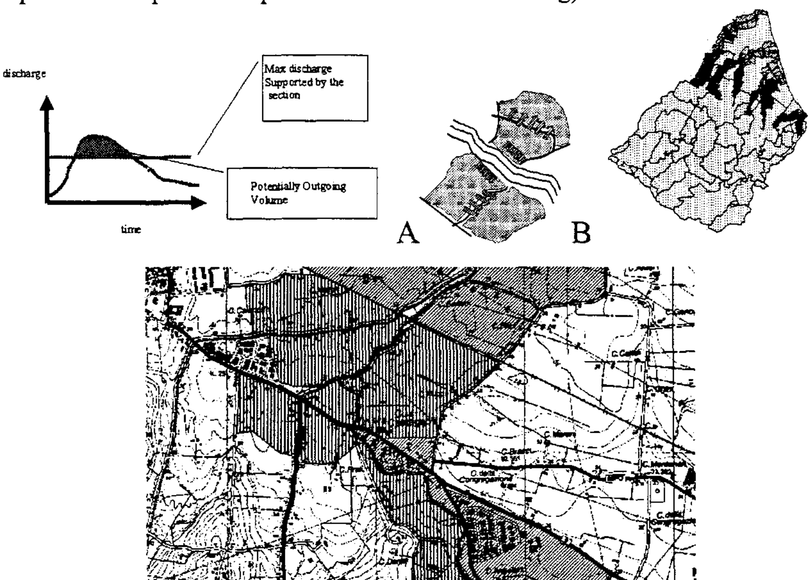

Figure 3 – scheme for the definition of outgoing volume in a levee-bounded section (A,B) and hydraulic cells considered in the study (C: in light grey are represented the cells for which a clear physical boundary exists); (D) shows a map describing a potentially flooded area from a levee-bounded river channel (vertical stripes represent areas with flooding return period 30 years, grey areas return period 200 years)

Cartographic modeling is to be introduced in order to manage hydrologic processes at a distributed level. Patterns of different water availability, groundwater recharge, and sediment erosion/deposition rates within a catchment resulting from the analyses can be used as a guidance to good management practices and water resource management policies. The models implemented include water budget, and erosion/deposition models such as the extension to the catchment scale of the well known USLE suggested by Mitasova et al., 1996, or other topographic indexes.

Finally, the safety of constructions and hydraulic works is evaluated using design discharges often obtained from rainfall data through simple conceptual rainfall-runoff models (rational method, USDA-SCS "Curve Number" Method), especially where direct discharge measurements are not available. For this reason, the Basin Authority has launched an experimental campaign aimed at producing infiltration coefficient maps and guidelines for the evaluation of design peak discharges consistent with the ones derived by statistical regionalisation of discharge data available (Franchini and Galeati, 1994), in order to set a homogeneous methodology for hydraulic design in the whole basin which will be also automated through a dedicated script running under the ArcView GIS, currently under development.

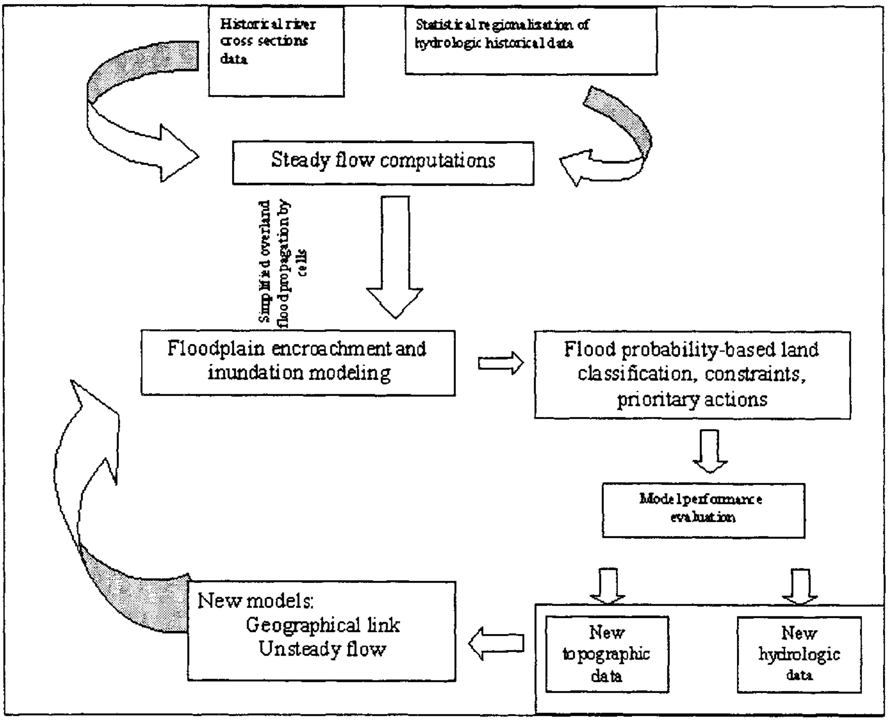

Figure 4 – "knowledge spiral2 for hydraulic risk management

5 Conclusions

The decision support system architecture that was designed at the Romagna River Basin Auhority seeks a full integration between the planning process and the analytical tools which are often used in a deeply specialistic way so to determine a gap between the level of planning and the one of scientific enquiry aimed at producing the planning addresses.
The use of spatial hydrology and geographical information systems allows to put in a communicative fashion all scientific analyses and to produce model-based cartography, which supports the definition of "game rules" which are expected to be accepted by all social actors in the planning process thanks to the rationality, replicability and transparency of their use.
The analyses performed so far represent an initial stage of the "knowledge spiral" (see figure 4) which aims at integrating the DSS with hydrologic and hydraulic models coupled with GIS (USACE, 2001b) and supporting unsteady flow simulations (USACE, 1996), a management-oriented water quality scenario model (ECETOC, 1999) among others (USEPA, 2001), and an analysis of dam break risk from levee collapses based on an extensive field and lab geotechnical campaign and dynamic models.
The aim is to develop a unique system capable of supporting all stages of basin management, from planning to the design of engineering works, so to bridge the gap between the level of design, where site-specific data of great detail are often acquired but seldom transferred to a consistent database for general knowledge augmentation. The availability of tools for coupled cartography and predictive modeling is now allowing to keep a tight link between all phases of decision in land management, and to make rational procedures for the setting of "game rules" in land exploitation easily communicable and therefore presumably easier to be shared with all social actors involved in basin planning.

6 Acknowledgements

The paper describes the analytical structure of the Romagna basin masterplan, which has been the product of a shared effort by Domenico Donati, Erminio Ferrucci, Gabriele Cassani, Carla Gugnoni and Susi Gaudenzi together with the authors, under the leadership of Stenio Naldi. The staff above is gratefully acknowledged.

7 References

[1] Chung, C.F., Fabbri, A.G. , Probabilistic prediction models for landslide hazard mapping, Photogrammetric Engineering and remote sensing, vol. 65, n. 12, pp. 1389-1399, 1999
[2] Chung,C.F., Fabbri,A.G., The representation of geoscience information for data integration, Non Renewable Resources, 1220-1232, 1993
[3] ECETOC, GREAT-ER User's manual, Special Report no. 16, Brussels, 1999

[4] Franchini, M., Galeati, G., La regionalizzazione delle piogge intense mediante il modello TCEV: Un'applicazione alla regione Romagna-Marche, Idrotecnica, n. 5, 223-242, 1994

[5] Friedmann, J., *Planning in the public domain*, tr.it. Pianificazione e dominio pubblico, Dedalo, Bari, 1987

[6] Guzzetti, F., Cardinali, M., Reichenbach, P., Carrara, A., Comparing landslide maps: a case study in the upper Tiber river basin, Central Italy, Environmental Management, vol. 25, n. 3, 135-147, 2000

[7] Innes, J., Information in communicative planning, University of California at Berkeley, Working Paper 679, 1995

[8] Kress, M.R., Ballard, J.R:, Goldman, R.C., Spatially explicit overland flood routing model, in Proceedings of the 4th International Conference on Integrating GIS and Environmental Modeling (GIS/EM4): Problems, Prospects and Research Needs. Banff, Alberta, Canada: http://www.colorado.edu/research/cires/banff/upload, 2000

[9] Mazza, L., Teoria dell'urbanistica, CELID, Torino, 1987

[10] Mitasova, H., Hofierka, J., Zlocha, M., Iverson, L.R., Modeling topographic potential for erosion and deposition using GIS, Int. J. GIS, vol. 10, n. 5, 629-641, 1996

[11] Paoletti, A., (ed) *Sistemi di fognatura e di drenaggio urbano*, CUSL, Milano, 1996

[12] Pistocchi, A. La valutazione idrologica dei piani urbanistici.Un metodo semplificato per l'invarianza idraulica dei piani regolatori generali 2001b

[13] Pistocchi, A., Il ruolo della modellistica delle georisorse nei processi di pianificazione territoriale, PhD thesis, University of Bologna, School of Engineering, Department of Chemical, Mining and Environmental Engineering (DICMA), 2001a

[14] Pistocchi, A., Luzi, L., Napolitano, P., The use of predictive modeling techniques *for optimal exploitation of spatial databases: a case study in landslide hazard mapping with expert system-like methods, submitted for publication to Environmental Geology, 2000*

[15] Todini, E., Di Giammarco, P., Lamberti, P., A conservative finite elements approach to overland flow: the control volume finite element formulation, Journal of Hydrology, n. 175, pp. 267-291, 1996

[16] US Army Corps of Engineers, UNET, One-Dimensional Unsteady Flow Through a Full

[17] USACE, HEC_RAS 3.0 hydraulic reference manual, http://www.hec.usace.army.mil/publications/pubs_distrib/hec-ras/hydref/hydref.html, 2001a

[18] USACE, HEC-GeoRAS + HEC-GeoHMS, http://www.hec.usace.army.mil/software/software_distrib/index.html, 2001b

[19] USACE, UNET, One-Dimensional Unsteady Flow Through a Full Network of Open Channels, User's Manual, publ. Code CPD-66 - Version 3.1, 1996

[20] USEPA, Better Assessment Science Integrating Point and Nonpoint Sources (BASINS) http://www.epa.gov/OST/BASINS/, 2001