A plot drainage network as a conceptual tool for the spatial representation of surface flow pathways in agricultural catchments

Pierre Aurousseau, Chantal Gascuel, Hervé Squividant, Ronan Trépos, Florent Tortrat, Marie-Odile Cordier

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Abstract: The drainage network must take the farming systems and the landscape structure into consideration to describe flow pathways in the agricultural catchment. A new approach is proposed to build the drainage network which is based on the identification of the inlets and outlets for surface water flow on each farmers' field (or plot), estimating the relative areas contributing to the surface yield. The delineation of these areas and their links in terms of surface flow pathways provides us with a pattern of relationships between individual plots, i.e. going from each plot to the other plots over the entire catchment. In this approach, flow directions are firstly calculated in the usual way by taking account of slope direction. Plot outlets are defined from the DEM then linked together using a tree structure. If present, linear networks such as hedges modify both the flow directions and the location of plot outlets, hence modify this tree structure. In a final step, the plots are themselves linked together using a graph structure illustrated by an arrow diagram. This drainage network based on plot outlets is applied to a 15-km² catchment area represented by 38,300 pixels and 2,000 plots. This new drainage network takes into consideration 5,300 plot outlets, which greatly reduces the number of objects in comparison with a drainage network made up of pixels or DEM cells. This method leads to a simple and functional representation of surface flow pathways in an agricultural catchment. It allows us to identify the key plots controlling stream water pollution where converging flow

pathways are coming from numerous or large-sized plots. Finally it produces a functional representation for decision support.

General comment

If a new review is required by the editor, we would like that the opinion of a third reviewer would be required, due to the completely opposite opinion of the two present reviewers. We can also suggest to get the opinion of a specialist in spatial analysis (such as A. Mc Bratney, Heuvelink,…) better than an hydrologist. Coupling this new spatial method with a hydrological model is not the focus of this paper despite it has been realized otherwise. The focus of the paper is to present a method for representing the spatial structure of rural catchments regarding to the surface flow pathways. This method is interesting by itself, with or without including it in a hydrological modelling.

Response to the first reviewer
 (1) I am nor sure that word 'spatialisation' is widely used by hydrologists. I think it might be better to replace it by 'representation' or 'representation of the spatial distribution'
(2) Abstract line 3 'these' not 'them'
(3) Abstract line 10 'modify' not 'modified'
(4) Page 2 line 27 'small-sized'
(5) Page 3 line 4 replace 'are' by 'being a'
(6) Page 3 line 7 'based on'
(7) Page 4 line 5 'a plot' not 'as plot'
(8) Page 4 lines 15 and 16. replace 'allow to get a' by 'permits the establishment of a'
(9) Page 4 line 19 'strips'
(10) Page 5 line 19 'In'
(11) Page 6 line 6 'by Tortrat (2005)'
(12) Line 9 Please define 'bocage' for non-French readers
(13) Page 10 line 18 'research in an operational mode'
(14) Page 10 lines 19 and 20 'thus affecting material transport'
(15) Page 11 line 7 'poorly suited'
(16) Page 11 line 13 insert 'and' after 'processed'
(17) Page 13 line 15 replace 'hydric erosion of soils' by 'water erosion' or 'erosion of soils by water'

Response : All these minor errors have been corrected.

Reviewer #2:

1.Is this a new and original contribution?
A comparison with classical methods needs to be conducted in order to show the originality of the method.

Response:

The first two lines of the abstract and the key words have been modified: the hydrological modelling is no more the objective of the paper. The words model or modelling have been removed and replaced by "spatial representation"or discretization of the catchment (p. 1, l7, l16, l27; p.2, l6, l25; p.3 l6, l20)

Coupling a transfer model in the discussion (§4.2 added)

Thus the paper is focused on a functional spatial representation of surface flow over the catchment. And, thus the contribution on the spatial representation of a rural catchment is completely original. And, thus, the comparison with the classical modelling approaches can not be addressed. The different way for the spatial representation of a catchment is more developed in introduction (p.2 l10 to l19; p.3 l7 to l8) Additional figures (Fig. 9 and 10) have been added to illustrate the interest in getting a

functional description of the catchment by this original method, and described in the text (p. 10, l19 to l28).The discussion on the interest of this original method has been extended in the discussion (§4.1 extended).

New arguments have been added on the interest of this method for future (p. 13, l20 to p. 14 l6)

2. Is the paper of interest to geoscientists, mathematicians, computer scientists, statisticians, or general?
Not, in its present form. The paper should include a comparison of the novel method to classical ones, and a demonstration of hydro-chemical modeling benefit through an application case.

Response : Coupling a transport model have been realized otherwise and submitted in an other paper. Nevertheless, the discussion treats this point in a new specific paragraph and discuss about the interest and limitations for coupling transport processes.

3. Are the conclusions and interpretations valid?
The paper lacks of a convincing application case illustrating the domain of application of the method and how it can be used in modeling water and pollutant transfer.

Response: see above.

5. Are the illustrations pertinent? Yes but not sufficient

Response: two illustrations have been added to convince of the interest of getting such a spatial representation of the catchment.

7. Can the text or illustrations be condensed? Yes

The paper is very short presenting and illustrating the method in14 pages with a double space interline.

9. Is the abstract informative?
Yes. However, the two first lines deal with pollution transfer while the paper doesn't present any application case.

Response: these first two lines have been removed.

10. Are the references adequate?
The references need to be completed by adding well-known references on channel network extraction (see for example O'Callaghan and Marks, 1984; Band, 1986 Water Resour. Res.; Montgomery and Dietrich, 1989, Water Resour. Res.; etc.).

Response: they have been added. Moreover it is detailed where these classical methods have be used (p. 5, l21 to l25), and where original methods have been developed (p. 6, l8 to l12; p.7, l24)

General comments :

The paper aims to present a methodology to spatialize surface flow pathways taking into account the plot plan structure. A GIS-procedure is developed using Digital Elevation Models, channel network location and plot limits. An application case is given on a 15 km² watershed. As stated by the authors, this approach can be used for "distributed models to understand and predict non-point source pollution in agricultural catchments". This topic is of international interest. However, the paper lacks of soundness, a justification in comparison to the state of the art, and a clear application case of the modeling approach. The paper should include a comparison of the novel method to classical ones, and

a demonstration of hydro-chemical modeling benefit through an application case. My major comments concern:

First : The paper presents an application case to extract and to identify a connectivity matrix of the treelike drainage network using a grid based Digital Elevation Models crossed with the plot limits. However, the paper doesn't present any application case to show how this spatial discretization can be used neither in distributed hydrological modeling, neither for non-point source pollution transfer as announced in the objectives. Generally, the watershed spatial discretization is conducted function of the structure of the hydrological model, the hydrological and hydro-chemical processes modeled, and the connectivity between surface, subsurface and aquifer flows. The paper doesn't state clearly, how the modeler can use the results of the study, and for what range of models and applications this discretization can be useful. Is this procedure adapted for existing grid-based models (i.e. the SHE model)? If not, what will be the constraints to develop a hydrological model
that takes into account this surface discretization (Does the model exist or needs to be developed? How to proceed?). What applications can this procedure be used for? An application case for hydro-chemical modeling should be conducted to demonstrate the domain of application of the procedure.

Response
We deliberately chose in this article to present only the spatial representation of the surface flow pathways for several reasons: (1) this representation requires sufficient space and it would have been difficult in space assigned to present this spatial representation simultaneously and satisfactorily with its use in a hydrological model, (2) the authors chose to present the hydrological transfer model dedicated for pesticide transport and coupled to this spatial representation (presented in an international conference and cited in reference: Cordier et al., 2005), (3) the spatial representation can be used for itself while it makes possible to highlight the portions of the catchment which do not contribute to feed the stream network by surface runoff (page 10, l. 4-6), those which contribute to it and the nodal points of the catchment where an obstacle to the surface transfer is particularly relevant to stop feeding the stream network (page 10, l. 8-12).
Thus, following the remark of this reviewer we decided to develop the use of the spatial representation for itself in this article, and to indicate that the insertion of this spatial model is possible in any hydrological model and already realized in one pesticide transfer model.
The reviewer requests also if this spatial representation can be adapted to existing models based on regular grids such as the SHE model. The answer to this question is positive but all the answers require a necessary adaptation since in a model with a grid system such as the SHE model, water is routed from cell to cell whereas in the model we developed, surface flow routing from cell to cell is replaced by contributive area to contributive area surface flow routing. Infiltration flow can be represented similarly per plot or part of plot, or stay per pixel as presently in the SHE model.

Second : The paper doesn't present clearly the originality of the approach in comparison to well known method used in GIS to extract the drainage network from DEMs (see for example O'Callaghan and Marks, 1984; Band, 1986 Water Resour. Res.; Montgomery and Dietrich, 1989, Water Resour. Res.; etc.). What will be the difference between the method presented herein, and a classical method which i) identifies sub-watersheds from DEM, and than ii) subdivide each watershed using the plot limits. A comparison between classical methods and the new one should be undertaken.

Response
The spatial representation presented in this article does not aim to replace traditional techniques of DEM treatment. The reviewer quotes two examples of classical DEM treatment:
   (1) Locating the stream network. This technique is not implemented since the true stream network, including the network of ditches, is initially introduced in a vector data base then imported in the raster data base by a procedure of rasterisation (page 5, l. 4).
   (2) Extraction of subcatchments. We did not carry out this extraction in our procedure. And the contours of studied catchments were extracted by the traditional procedure from DEM treatment before the use of our spatial method.
   (3) The originality of our method is in the addition of the classical procedure which aggregates the pixels according to a functional schema which consist in building a plot outlet tree and plot tree structure.
Thus, following this remark of this reviewer it is now clearly indicated that the originality does not consist in the basic treatment of the DEM but in a following and new further step which consists in the aggregation of the pixels according to functional units which are here the plot or a part of plot feeding a plot outlet, then the plot outlet tree and the plot tree.

Third : I'm not convinced that the use of a regular grid (herein 20 x 20 m) is well adapted to represent linear plot limits and ditches : for example plots limits or ditches have 0.1 to 2 m width (for example) while the spatial representation of the procedure presented herein is a set of square pixels of 400 m²! The authors must clarify for what kind of hydrological processes the discretization can be used, and how to represent surface flows on the identified units. What will be the uncertainty on the model results due to this approximation ?

Response:
The reviewer is right when he recalls that the plot limits and ditches have a width from 0,1 to 2 m whereas the spatial representation proposed here is based on pixels of 20 X 20 m, that is to say 400 m². But this question is largely beyond the purpose of this article and it is quite clear that distributed hydrological models have to evolve towards the use of multi-resolution data bases or variable resolution data bases. Some of the authors of our article who practise the techniques and software of the field of virtual reality know the technical solutions of spatial description by use of multi-resolution or variable resolution data bases : for example the techniques of the Levels Of Details (LOD) and of Active Surface Description (ASD). But their use in distributed hydrological models stay complex while the easy use of regular grid models imposes its law up to now including in topographic data bases. Hydrologists are expecting the production, marketing and diffusion of topographic data bases with variable resolution where the resolution evolves/moves according to topography - what is the base of the technique of the Levels of Details. It would constitute a first stage to evolve the distributed hydrological models towards a spatial description based on variable resolution.
To reconsider in a more detailed and explicit way the use of a regular grid structure to the upstream of our spatial representation, one can reconsider two types of objects where this question of resolution deserves discussion.
- *Concerning the stream and ditches network, the role of these networks are important: taking them into account seems essential even with the detriment of their real width.*
- *Concerning plot limits and hedges, the solution we proposed to circumvent - in a way that seems to us skilful - the question of their width since what we call the « wall » function which is at the base of the redirection of the flow drainage directions is ensured by an object without width, since this « wall » function is provided by the edge of the hedge pixels which are at the edge of the plot.*
Consequently, the choices we made as well concerning the stream network cells as the hedge cells do not deny the constraints imposed by the use of regular grid based models. The original solution for « hedges » pixels can be implemented in any spatial schema.

Fourth : The paper deals with linear networks such as ditches and hedges. How about other spatial elements? How these linear elements can be represented in a hydrological model? How to represent hydro-chemical processes on these elements? The identification of these linear elements, and the connectivity must be done function of the hydro-chemical processes to be modeled, and function of the space and time steps of input variables (rainfall, watertable, soil and landuse maps, etc.) : For example for hourly or daily time step input data, do we really need such a spatial discretization. The paper doesn't also present clearly the domain of application of the procedure : i.e. How to deal with flat areas? What are the limitation function of the grid size?

Response:
The linear objects such the hedges have two types of function: (1) a function on the directions of surface flow and (2) a hydro-chemical function on infiltration and bio-transformation (retention,…). In this paper, the role of these linear objects carries out on the directions of surface flow pathways. The hydro-chemical functions are generally integrated in the hydro-chemical model coupled to the spatial schema. It has be done by colleagues of our group (Beaujouan et al., 2002; Viaud et al., 2005). Thus, this it is implemented in the modelling more easily than in the spatial schema.
Regarding the management of the flat areas, we have implemented since years in our software of DEM treatment the algorithm of the gradient presented by P. Soille and developed first in his PhD and latter published in Morphological Image Analysis, Principles and applications. Springer-Verlag. 1999. This reference is added.

Specific comments :

Abstract : The first two lines deals with pollution transfer while the paper doesn't present any application case.

Response: they have been removed

Page 4, line 11 : Explain what kind of agricultural processes, and what will be the incidence on pathflows.
The sowing rows and roughness are directly determined by agricultural operations, and have an incidence on surface sealing flow pathways as well infiltration rate (see p. 3, l.3)

Page 4, Lines 12-13 : Why to choose field boundaries, hedges and ditches ?
Response: These elements are important in the study case, and more generally in gentle slope landscape, wet conditions, land use dedicated to animal breeding, as is it the case in the north western part of Europe (See p. 14, 20: segmented landscape mosaic).

Page 8, Line 25 : Justify the choice of a grid approach (20 x 20 m) for applications taking into account linear structures such as ditches, field limits and hedges.
Response: The 20 x 20 grid approach is available in any catchment, and thus useful for water management operation.

Page 9, Line 2 : The method used enables to reduce the number of pixels seven times. However, does the time of calculation still a problem? Why we cann't apply a model using all pixels (i.e. the SHE model).
Response: Improving the time of calculation is an argument in real time modelling approach. This point can be considered as a major point in some applications.

A plot drainage network as a conceptual tool for the spatial representation of surface flow pathways in agricultural catchments

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1. Introduction

A key challenge in dynamic modelling research is to find simple and accurate ways of describing and integrating physical processes [Burrough, 1998]. In recent years, geographical information systems (GIS) have emerged as a powerful tool for representing spatial heterogeneity in landscapes and analysing spatial patterns, as well as visualizing and managing spatial data [Burrough and McDonnell, 1998]. It remains difficult to represent spatial patterns and data of agricultural landscapes, since their complexity makes it necessary to apply simplifications [Wang and Pullar, 2005]. These landscapes are structured by the mosaic of farmers' fields, called plots in this paper, which show variable outlines and land use that change over time, and by different linear structures at the edge of the plots, such as hedgerows, hedges, ditches and roads, that are more or less connected to each other to form networks. Such man-made features are observed in all the agricultural landscape, but their density really varies from part to part. They are now well known to have an effect on catchment hydrology, erosion and water quality. This is because surface mass transport is related to the flow pathways and reactivity near these features, which may act as buffer zones [Viaud et al., 2004]. A key point of these complex agricultural landscapes is to represent adequately the flow pathways by a functional spatial discretization of the catchment.

Different methods have been used in the literature [Clark, 1998; Jones, 2001] which vary according to the scale of the data, and hence their availability, as well as the conceptualization of hydrological and hydrochemical processes. For large-sized catchments, covering a few hundreds of square kilometres, the spatialization of the catchment area is generally based on the delimitation of Hydrological Response Units (HRUs), which are defined as units of homogeneous response [León et al., 2001 and 2004]. With increasing size of catchment, these units can only take broader and broader account of the structure of the cultivated landscape [FitzHugh et al., 2000; Lacroix et al., 2002]. On the contrary, for small-sized catchments of around a few square km, the spatial discretization of the catchment area can be detailed to take explicitly into account the landscape

structures. Generally it is built up from square elementary grid cells. They can act as sources and sinks, and thus allow explicit exchanges of matter. The structure and functioning of man-made-man networks may be increasingly introduced. Generally, the structures are simplified; in many cases, only one kind of linear structure is considered, which may correspond to agricultural ditches [Carluer and De Marsily, 2004], or the hedgerows and hedges [Viaud et al., 2005]. The spatial discretization requires a small grid size (5 to 20 m) because of the narrowness of such structures. This fine-scale discretisation implies operations on a very large number of cells. As they function on square regular grids certain difficulties and geometrical approximations give rise related to the fact that the grids do not coincide with the boundaries of the plots or man-made networks [Shortridge and Clark, 1999]. To avoid these problems, other ways of spatial discretization have been explored among which we can cite: (1) raster structures with irregular grids, for example, using small-sized grids at the scale of small features such as ditches, hedges or banks, and larger-sized grids within the plots; (2) triangular Irregular Networks (TINs) [Palacios-Velez et al., 1998; Gandoy-Bernasconi and Palacios-Velez, 2003]; (3) TINs of regular size but of regular form of isosceles-rectangle type, which can be applied in other fields such as virtual reality describing the surface topography of very extensive territories; (4) stream tubes, as described by Moore [1988; 1991], and used in TOPOG [Vertessy et al., 1993] as well as in ANTHROPOG [Carluer and De Marsily, 2004]. These spatial discretizations function either constrained by topography or the outlines of plots or the adjacent linear elements of plots [van Kreveld, 1997; Tucker et al., 2001; Carluer and De Marsily, 2004]. However, these networks lead to more enough cumbersome models. All of these solutions are thus most commonly based on topography, described by quadrangle or triangular, regular or irregular networks, on which are superimposed constraints in terms of flow direction or functionality at the level of the plots or linear structures of the agricultural landscape. They are awkward to implement and time consuming to run, being oriented towards research and dedicated to small-sized areas. Moreover they present no interest by themselves: they do not provide a functional representation of the catchment. They are unsuitable for operational purposes that often concern intermediate scales of a few tens of km². Paradoxically, no solutions dedicated to

agricultural catchments are based on the plot plan, which is the basic structure for describing

farming practices and field boundaries, despite the surface flow pathways being directly a function

of the plot plan. For example the soil surface sealing and the sowing rows are function of the plot

plan. So it would be possible, in contrast with previous approaches, to develop solutions based on

the plot plan, on which are superimposed constraints in terms of topography as a supplement to this

basic information. This proposal subscribes in a general trend in GIS to represent the space as

closely as possible to the functional objects regarding to the processes they are dedicated to and

thus to escape to a cell discretization [Bithell and Macmillan, 2007].

In this article, we present an original method that, in the first place, takes account of the plot plan

structure to spatialize surface flows pathways in catchments of a few tens of km². The method

developed here is based on the analysis of transfer relations between "plots" as type objects of the

catchment area (Tortrat, 2005). After describing the method, we then illustrate our approach with an

application that identifies and visualizes the relations between the plots of a catchment area. This

leads on to a discussion of the advantages and the limits of the approach.

2. Method

2.1 Principles

The main objective of this method developed for the spatial representation of surface flow pathways

in agricultural catchments is to formalize the relationships between all the plots of an agricultural

catchment in terms of surface flow pathways. These transfer relations can be multiple (Fig. 1).

Thus, an upstream plot can feed one (A -> E) or several plots located downstream (E - >H; E - >F),

and two plots can feed each other mutually ((D - > E; E - > D). A plot feeding several plots

downstream can be subdivided into hydrological sub-units according to the surface-area feeding

each plot located downstream. For this purpose, we define the outlets of plots, corresponding to the

points or lines where the water leaves a plot, as well as the contributing areas for each of these

quantified and associated outlets. At the end of the processing, the progressive establishment of relations between plots yields a formal expression of the transfer relations between plots in terms of a tree connecting the outlets of the plots between themselves, which is called plot outlet tree. Finally, we also obtain a diagram of plots that connects together all the plots of the catchment which is called a plot graph. The data processing used in the whole of this approach is schematised in Figure 2 and detailed below.

2.2 Data and pre-treatment

The following data are required: a Digital Elevation Model (DEM); a precise location of the stream network; the outlines of all the plots and a characterization of agricultural practices on these plots; the location and characteristics of the permanent or temporary field boundaries, such as hedges or ditches.

In the GIS, the drainage network, represented by a link array which contains a pointer from each pixel to some neighboring pixel as defined by Fairfield and Leymarie [1991], permits the establishment of a topographic drainage tree represented by a set of polylines corresponding to joined-up segments of lines, while the plot plan is represented by polygons, which are made up of joined-up and closed segments of lines. The network of ditches and their outlets are represented by polylines and points, respectively. A linear ditch is defined as having one outlet. The hedges and grassed filter strips or any other buffer zone at the edges of the plots, which are represented by polylines, are necessarily internal to the plots. The first step of this approach therefore consists of compiling a vector data base from information available on the catchment area.

2.3 Construction of a drainage network modified by the landscape structure

The second step is converting this data base into raster mode (Fig. 2). As a result of the rasterization, each pixel is associated with one of the four following types: river, ditch, standard plot

and plot margin (Table 1). Because of the exclusive membership of a given type, hierarchical laws are applied in the attribution of a type to each pixel. Thus, "river" pixels, created by rasterization of the drainage network described in vector mode, have priority over the "ditch" type, which itself has priority over the "plot" type. Attributes can be added to these various types: the "river" pixels do not have any attribute, while the "ditch" pixels are attributed an outlet number that identifies the exit points of the ditch network. Pixels are attributed to the "plot margin" if they refer to the edges of a plot, otherwise they are associated with "standard plots". The "standard plot" pixels have attributes that include a plot identifier, land use and various descriptors of the operational sequence/crop management sequence of the plot, such as, for example, the orientation of soil tillage and seeding and the dates of these operations; "plot margin" pixels are limited here to pixels occupied by a hedge, their attribute being the identifier of the plot to which they are assigned. With raster images representing the rivers, the ditches can then be skeletonized.

A monodirectional drainage network having the same precision as the DEM, is built automatically with the MNTsurf software [Aurousseau and Squividant, 1997], as already used and described by [Beaujouan et al., 2000; 2002]. Inconsistencies related to the inaccuracy of the data impose a certain number of corrections. Three principal corrections are carried out on the DEM: the first ensures that the flow directions of the "river" pixels are identical to those of the drainage network [Aurousseau and Squividant, 1997; Kenny and Matthews, 2005]; the second ensures that the directions of drainage of pixels adjacent to the drainage network are made consistent with the flow direction in the river system; a third procedure automatically corrects the drainage anomalies. These corrections are now a well known and used in GIS to extract the drainage network from DEMs [O'Callaghan and Marks, 1984; Band, 1986; Montgomery and Dietrich, 1989]. The location of the hydrographic network, including the network of ditches, is not inferred from the DEM, because directly included in the vector data base, and then imported in the raster data base. The ditches connected to the river system are regarded as an extension of the drainage network. The ditches unconnected to the drainage network, which thus flow into a plot, are corrected by a procedure analogous to that

performed on the stream network by ascending the drainage network. The network of monodirectional drainage created in this way is called a topographic drainage network. The drainage direction of the hedge pixels and adjacent pixels is determined by a method derived from Merot et al. (1999). The hedge is regarded as a wall that isolates the fields upstream and downstream from the hedge. Upstream of the hedge, the drainage follows the direction of the hedge, while, downstream from the hedge, it remains in conformity with the slope. The drainage anomalies related to the intersection of hedges are treated on a case-by-case basis by an interactive procedure on screen. This treatment of the hedges is based on the original study by Tortrat [2005]. This solution circumvents in a skilful way the question of the width of the hedge since what we call the wall function which is at the base of the redirection of the flow pathways ensured by an object which is without width or thickness, since this wall function is provided by the edge of the hedge pixels which are connected to the neighbour plot. It can lead to the isolation of a portion of the catchment, in particular at the crossing of two hedges, i.e. disconnecting this portion from the hydrological system functioning farther downstream in the catchment. ,

These treatments of the DEM lead to a drainage network modified by the landscape structure, which we here call a modified drainage network to distinguish it from the topographic drainage network described above.

2.4 Construction of a drainage network based on the definition of plot outlets

The drainage network based on the definition of plot outlet is based on an identification of the points or lines from which flow pathways emanate from the plots. These points or lines are called "outlet pixels". Although they belong to the plot, they are necessarily located on field boundaries. The flow direction on these pixels drives the flow pathways out of the plot. A plot outlet is defined as one or a group of outlet pixels that drains a given contributing area towards the same plot.

Two types of plot outlets are distinguished according to the characteristics of their contributing area (Fig. 3a, Table 1): i) plot outlets with their contributing area strictly included within a given plot, called "simple-plot outlets"; ii) plot outlets with their contributing area partly included within the plot and partly connected to an upslope plot, called a "multiple-plot outlet". For these two types of plot outlets, we further distinguish two types of contributing area according to whether or not it is included within a given plot. Finally, five types of pixels are distinguished, two for the pixel outlets (simple and multiple), and three for the contributing area pixels (Table 2).

The drainage network based on the definition of plot outlet is firstly defined by routing flow pathways throughout the catchment going from upslope to downslope in order to identify all the outlet pixels (Fig. 3a). In a second step, the drainage network is routed again, this time from downslope to upslope and from plot to plot, to characterise all the other pixels and define which contributing area type they belong to (Fig. 3b, c and d). This routing process is as follows: going upslope, we encounter pixels that are connected to simple outlet pixels and that are included within the studied plot (Fig. 3b). Then, going upslope, we identify upslope-connected pixels that correspond to pixels receiving water from upslope plots (Fig. 3c). Thirdly, we identify upslope-unconnected plot pixels that are connected to the pixels defined in the previous step (Fig. 3d). The outlet pixels of a given contributing area are then grouped to define a plot outlet. Different plot outlets are then listed and linked from upslope to downslope (fig. 3e). A given plot may possess more than one plot outlet. Only one plot outlet per plot may be linked to a downslope plot outlet (Fig. 3f). The relations between the plot outlets are then represented in the form of a tree (Fig. 3g, Table 1), with pointers representing the outlets. Each of the outlets is associated with an attribute corresponding to the inflow contributing area. This structure is called plot outlet tree. Lastly, a plot graph structure, here illustrated by an arrow diagram of the plots displays the whole set of transfer relations between plots (Fig. 3h). This part is completely original regarding the GIS literature.

The whole of the procedure is coded in language C under UNIX operating system. Initially, the program automatically builds the outlet tree in the computer memory. In a second step, it carries out

a pass through this tree to calculate the various variables for each outlet. Finally, it generates vector type outputs in Shape/ArcGis format. This involves the plot outlets, the drainage network based of the plot outlet, the plot outlet tree, the centres of the plots and finally the plot graph illustrated by a arrow diagram. The program also exports the result of calculations for each plot outlet and each plot into a DBF format file associated with the output vectors.

3. Results

3.1. Site

To test this approach, we chose the 15-km² Frémeur catchment in western France (Fig. 4). This catchment has a 28-km-long stream network with a drainage density of 1.65 km/km². The slopes are moderate, and the landscape is made up of a more or less dense bocage. Bocage names a typical landscape often dedicated to animal breeding where plots are hedged. Cultivated land accounts for 72% of the total area, the remainder being distributed between woods and wasteland on the one hand, and residential areas on the other hand. This catchment area comprises approximately 2000 plots. The plots have an average surface-area of 0.008 km², while exhibiting a very great variability. The DEM was extracted from the elevation data base for Brittany with a step of 20 m, produced by stereoplotting of panchromatic SPOT images to a resolution of 10 m. The plot plan was digitized from the land registry map of the commune on a scale of 1:5,000. The drainage network was extracted from the 1:25,000 IGN map and from the land register. Field surveys allowed us to supplement this network and locate the ditches and their outlets, as well as the hedges and grassed filter strips or any buffer zone adjacent to the plots. Compiling the vector data base from information available on the Frémeur catchment area allow to get its vectorial representation (Fig. 4).

3.2. Characteristics of the drainage network based on the definition of plot outlets

The geographical data base describing the Frémeur catchment comprises approximately 38,300 pixels of 20 x 20 m. On average, the plots include about twenty pixels. The proposed approach results in defining 5,300 plot outlets on this catchment, that is to say, approximately 2.5 outlets per plot. Each plot is thus divided up into 2.5 hydrological sub-units with an average area of 0.003 km², which represents the inflow area contributing to each plot outlet. This approach leads to a considerable reduction in the processing of objects, since there are approximately seven times less plot outlets than pixels, which therefore also applies to the contributing areas associated with these outlets. This approach, which is based on making a tree of plot outlets, thus allows a significant simplification of the representation of the water flow pathways.

The number of plot outlets (5,300) is still relatively large in comparison with the number of plots (2,000). Since the plot size is relatively heterogeneous, with a high proportion of small plots, we can assume that some of these outlets are fed by very small contributing areas. Therefore, there is some potential for further simplifying the modelling of flow paths by eliminating from the outlet tree those outlets supplied by very small contributing areas. This can be done while only marginally modifying the operation of the spatial discretization of the catchment. With this aim, we removed a number of very small contributing areas from the outlet tree (Table 3). By eliminating outlets supplied by a contributing area of only one pixel, we remove 1747 outlets for a total surface-area of only 0.7 km². By eliminating the outlets supplied by a contributing area of up to 3 pixels, we remove 3192 outlets and rule out of account an area of 2.08 km². The resulting simplification leads to a plot outlet tree with 2119 outlets, corresponding to a level of complexity very close to the plot graph, while giving a better representation of the hydrological structure of the agricultural catchment area. Thus, for a given number of objects, this approach allows a more adequate representation of the water flow pathways. The cartographic representation of the results (Fig. 5)

shows that most of the plots have a proportion of their area fed by an upstream plot. Although this proportional area is relatively small, it concerns a large number of plots.

The hedges contribute to isolating 22 small areas of very variable extent, ranging from 0.002 to 0.19 km ^{2}, amounting to a total surface-area of 0.6 km ^{2} (Fig. 6). This accounts for only 5% of the total surface-area of the catchment, but, in certain sectors, affects a large proportion of the land.

Figure 7 presents the plot outlet tree for a small sector. This tree is sometimes relatively dense, particularly when the plots are small and have multiple outlets. This is especially the case in built-up areas (at the bottom, on the left and on the right). The tree is sometimes very simple, visualising the points of convergence of water pathways within the catchment area. This tree also illustrates possible interruptions of the water flow pathways, in particular at the level of hedges. Figure 8 illustrates the transfer relations between plots on this same sector. This plot graph where arrows visualized transfer relations shows that the large plots exchange water with many other nearby plots. However, this more conceptual representation appears less operational than the plot outlet tree. Although the relations between plots are identified, they are not detailed either in terms of the space allotted or the quantification of the exchange.

The catchment presents 670 plot outlets adjacent to the stream, i.e. 670 points are feeding directly the stream by the way of 670 plot outlet trees [Trepos, 2008]. A large ratio of these trees presents a small number of plots (Fig. 9). Tress with only one plot are numerous but correspond for most of them to trees with non cultivated plots. The number of plot outlet trees is decreasing with the number of plot per tree. The distribution appears to be a log normal distribution. The surface areas of the plot outlet trees is maximal for the plot tree with around 6 plots The plot outlet trees comprising between 6 and 11 plots are larger than 80 ha. This approach which constitutes a representation of the catchment based on trees allows a functional representation of the surface flow pathways. We can see that the largest trees are located at the middle of the catchment and generally converge directly to one plot, sometimes directly to the stream (Fig. 10).

4. Discussion

4.1. A functional and operational spatial representation of the catchment

The spatial representation of surface transfer has several objectives, and is confronted with several difficulties, including: (1) the need to change over from small areas, where the research objectives are concerned with processes, to larger areas and catchments, to allow the application of the results from research into an operational mode; (2) to take into account small-sized structures such as ditches, hedges and banks that contribute greatly to surface water circulation, thus affecting the material transport. The approach developed here is intermediate between HRU or plot tree and a spatial discretisation based on a regular grid of the catchment, such as generally carried out from a DEM. Regular grids are poorly suited to large catchments (more than 50 km²), as much in terms of awkwardness of data-processing as well as calculation time. At the same time, regular grids are rather unsuitable for taking account of the development of rural areas and agricultural practices. On the other hand, HRU or plot tree approaches based solely on homogeneous units, one or many plots would not allow us to take account of the water pathways within the plot, particularly the directional distribution of different plots located downstream. Thus, the developed approach is a compromise between the number of objects to be processed and the capacity to consider the hydrological and agronomic aspects of the processed objects.

Moreover, compared to a drainage network with a grid, the construction of a plot outlet tree leads to a better identification and display of the inputs from the plots, as well as the exchanges inside the catchment area. It helps the water managers to identify the role of landscape structures, allowing the location of sites where it would be beneficial to add structures based on the analysis of flow convergence and the identification of plot outlets. The plot outlet tree is thus a decision support tool helping water managers to locate the better places to establish buffer areas such as grass strips or to close outlets [Trepos, 2008]. It can also contribute to understanding the functioning of the agro-

ecosystem through analysis of the plot plan connectivity. It constitutes an operational tool for water management and landscaping (Fig. 10). In certain action plans, the plot outlets are surveyed in the field. It is thus possible to use the same concepts on the field and on the GIS, or/and to validate the results obtained by computer.

4.2. Interest and limitation for coupling hydro-chemical modelling

This approach also opens up perspectives for coupling with transfer models. It allows us to model, in a simplified way, the surface transfers in cultivated catchments, in particular using models that would be based on the analysis of agricultural practices and crop sequences to consider the parameters controlling infiltration and runoff, as in the case of STREAM [Cerdan et al., 2001]. A first application of this model has been carried out [Tortrat et al., 2004; Tortrat, 2005]. In this way, calculated flows are easily quantified and visualised plot by plot. This type of spatialization could be usefull to model soil erosion or pesticide transfer in a simplified manner, where it is also important to identify areas connected to the drainage network that lead to transfer towards the river system, as well as unconnected areas that give rise to sedimentation or infiltration within the catchment. This spatial representation has been coupled with a pesticide transfer model otherwise [Cordier et al., 2005; Trepos, 2008].

This methodology presents a certain number of disadvantages, among which we can mention: (1) as in a classical regular raster model, the ditches and the streams have an exaggerated width because they are fixed by the grid-cell size of the original DEM used; (2) the same hydrological behaviour is assumed throughout a given contributing area, so we cannot take into account the variability of hydrological behaviour within the contributing areas, including, for example, differences of input to the local runoff or re-infiltration. These disadvantages can be overcome.

4.3. Future devlopments

The approach developed here, as such, is likely to find some applications in future developments. Notably, it can be used for building plot outlet trees and plot graphs where the links could be evaluated according to the contributing areas involved in the relations between upstream and downstream plots. Such trees or graphs could also serve as dynamic diagrams, in which the relations are activated according to the magnitude of the flows, or simply according to the establishment of crops or landscape feature that prevent the circulation of water in the plot tree during certain periods. We could also widen the scope of the method by considering flow directions within the plots, related to agricultural operations such as tillage operations, to establish the drainage directions. Solutions have been proposed by Souchère et al. [1998], based on the amplitude of roughness parallel and perpendicular to the direction of soil tillage, the angle between the slope and the soil tillage direction, which have been integrated into the STREAM model [Cerdan et al., 2001]. The plot margins oriented perpendicular to the direction of soil tillage could be treated in the same way, taking them as indicating for the direction of soil tillage. A dynamic plot graph would be particularly useful for taking into account these structures, which can evolve relatively quickly through human influence, as with the soil tillage, or under the influence of climatic factors. Finally, it would also be possible to extend the method for taking account of hedges to incorporate all the networks of linear structures, particularly the ditches and roads. As with the hedges, the water pathways must be treated differently upstream and downstream from each of these structures.

More generally, the future will probably come from the techniques and softwares of the field of virtual reality which use technical solutions based on multi-resolution or variable resolution data bases, such as the techniques of the levels of details (LOD) and of Active Surface Description (ASD) [Krus et al., 2004; SGI, 2002). The easy use of regular grid for the spatial representation of the catchment imposes its law up to now including in topographic data bases. Hydrologists are expecting the production, marketing and diffusion of topographic data bases with variable resolution where the resolution evolves according to the topography, which is the base of the technique of the Levels of Details and softwares able to manage such multi-resolution or variable

resolution data bases. It would constitute a important stage towards a spatial description of the catchment based on variable resolution according to the topography and any other physical properties. It allow us to build physically based plot outlet trees, taking into account the spatial variability within the plot and for a set of plots at a relevant level, delineating subplots and subplot trees regarding to their outlets as it it now the case, but also to the spatial variability of the plot and the efficiency of the outlines.

5. Conclusion

The complexity of cultivated landscapes requires spatial representations if we wish to contribute to the planning and management of rural areas. The connectivity of water flow paths in the landscape plays an essential role in the control of water quality and the erosion of soils by water. The proposed method aims to highlight the connectivity of water flow paths plot by plot within the catchment area. This method couples agronomic and hydrological entities, by taking the plot as a basic element and dividing it up into hydrological sub-units according to the "outlet points' of the water from the plot. This description of each plot allows us to incorporate the plots into an outlet plot tree and a plot graph that express the transfer relations between plots. This new approach has potential applications in landscapes with moderate to steep slopes, in areas that are highly segmented by the landscape mosaic, and where the cultures, and hence the soil surface conditions, vary over the catchment.

14

making aid: how to link together knowledge and action in agriculture, agro-food industry and rural areas". We thank Mike Carpenter for revising the English.

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Figure captions

Figure 1. Conceptual sketch diagram of surface flow relationships between plots. This diagam is conceptual because the arrows representing flow relationships are not located on the real flow pathways.

Figure 2. Structure of spatial data treatment.

Figure 3. Building the plot outlet tree. The different outlet pixels (a) are built in steps a, b, c, d, and e, then progressively the three types of contributing areas of the plot (b, c and d); f) aggregation of the plot contributing areas into a plot outlet tree, where A, B and C represent the attributes of the plot, and A1, A2, A3, etc., the different contributing areas within these plots ; g) plot outlet tree ; h) arrow diagram on the directed graph showing relations between plots.

Figure 4. Vectorial representation of data from the Frémeur catchment.

Figure 5. Map of plot contributing areas in the Frémeur catchment. We distinguish areas included within a plot (within-plot contributing areas), from areas partly depending on an upslope plot (upslope-connected plot contributing areas).

Object	Type	Attribute
Drainage network	Linear	Identification number

Ditch	Linear	Ditch outlet number
Plot	Areal	Plot number
		Land use
Descriptors of operational sequence		
Plot margin	Linear	Hedge number
In this case, hedges-banks		Plot number

1 **Table 2**

2

3

Plot outlet type	Pixel type	Contributing area type and description
Simple plot outlet type	Simple plot outlet pixel (dark blue)	Outlet pixel whose entire contributing area is included within the studied plot, called a single plot outlet pixel
	Internal plot pixel (pale blue)	Pixel whose entire contributing area is included within the studied plot, called a internal plot contributing area.
Multiple plot outlet type	Multiple plot outlet pixel (dark green)	Outlet pixel whose contributing area is not entirely included within the studied plot, called a multiple plot outlet pixel
	Upslope connected pixel (green)	Pixel whose contributing area is partly included in the studied plot and partly fed by an upslope plot, called an upslope connected plot pixel
	Upslope-unconnected plot pixel (yellow)	Pixel belonging to a contributing area included within the studied plot, but feeding an upslope connected pixel or area (green), called an upslope unconnected plot contributing area

4 **Table 3**

5

Number of pixels belonging to the contributing area of an outlet	Cumulated upslope connected plot areas taken in account by the model (km²)	Cumulative upslope unconnected plot contributing areas taken into account by the model (km²)	Area ignored (in km²)	Number of remaining plot outlets
0	6.33	7.8	0	5311
1	5.99	7.44	0.7	3564
2	5.66	7.06	1.41	2683
3	5.34	6.71	2.08	2119
4	5.01	6.39	2.73	1717
5	4.79	6.12	3.22	1466
6	4.61	5.88	3.64	1291
7	4.41	5.6	4.12	1119
8	4.19	5.39	4.55	985
9	4.04	5.19	4.9	888
10	3.89	4.98	5.26	801

1

Figure 1
Click here to download high resolution image
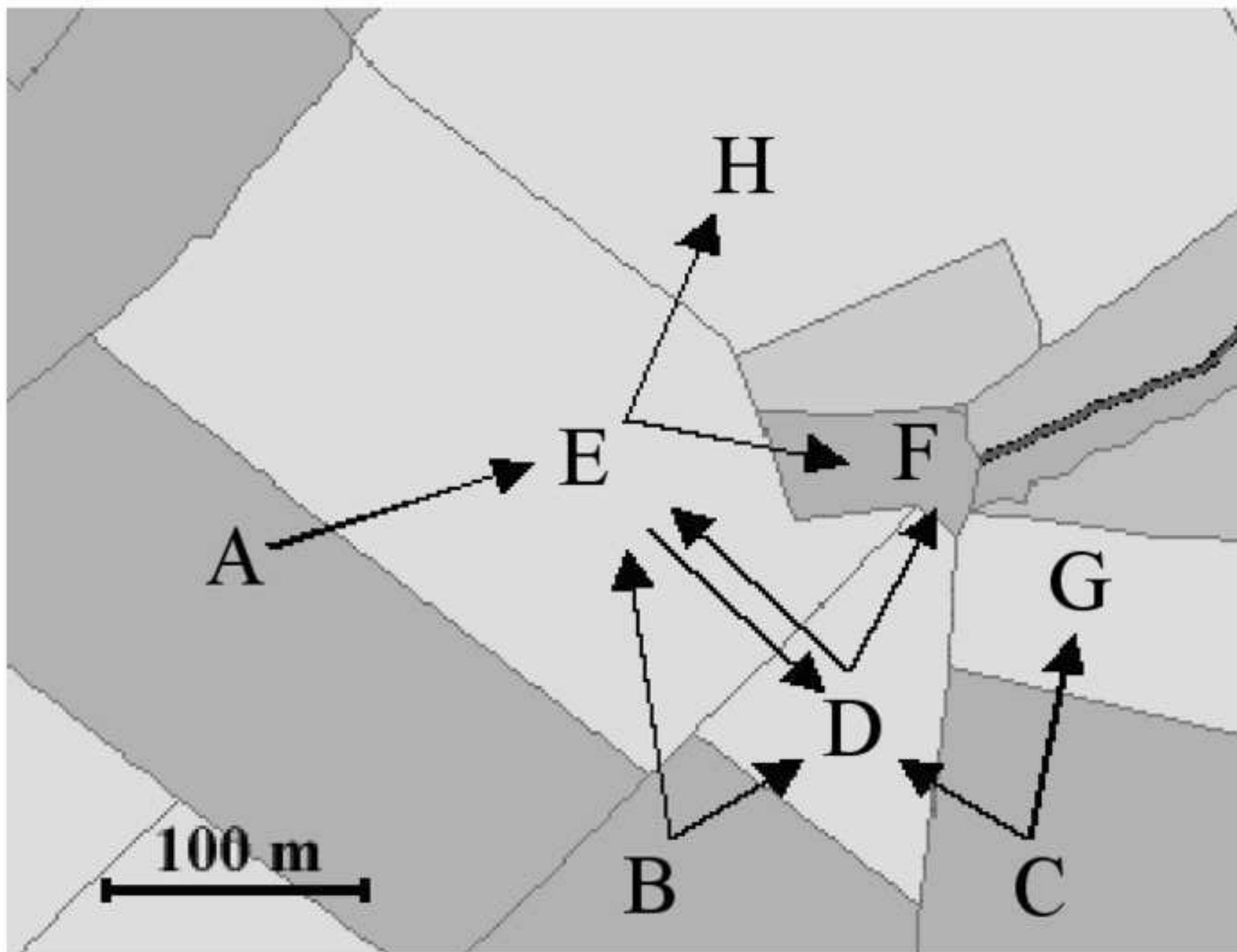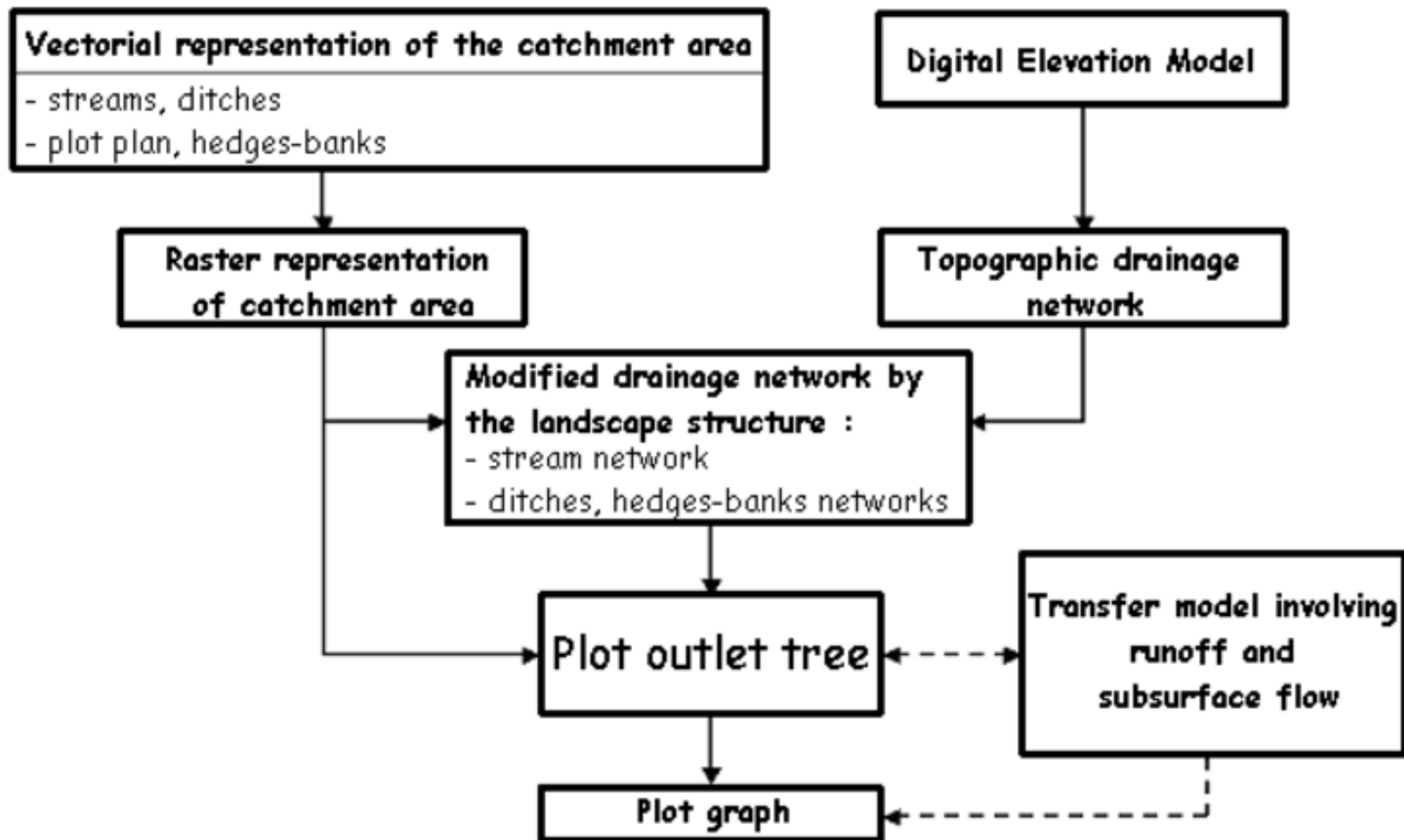
Figure 3
Click here to download high resolution image
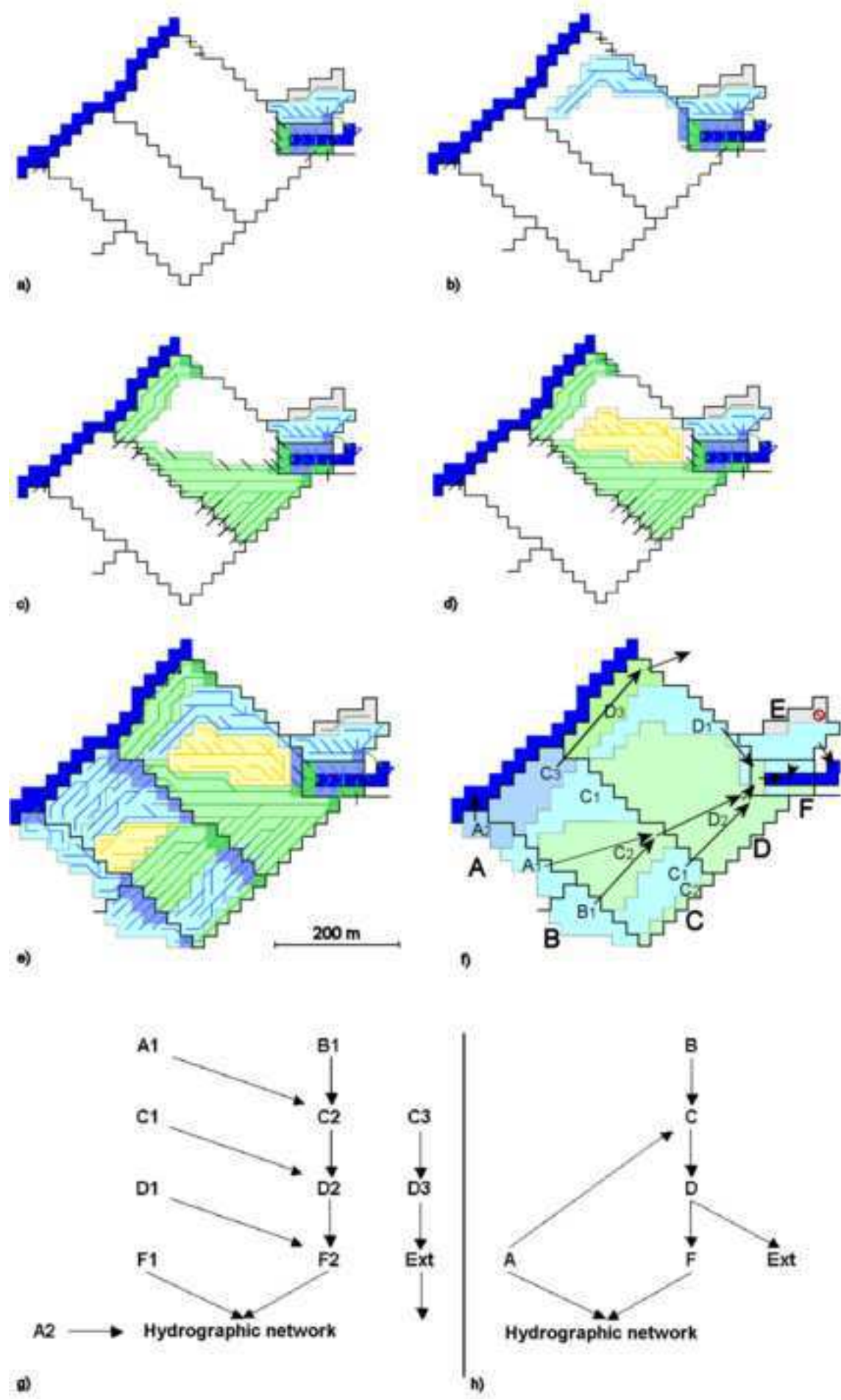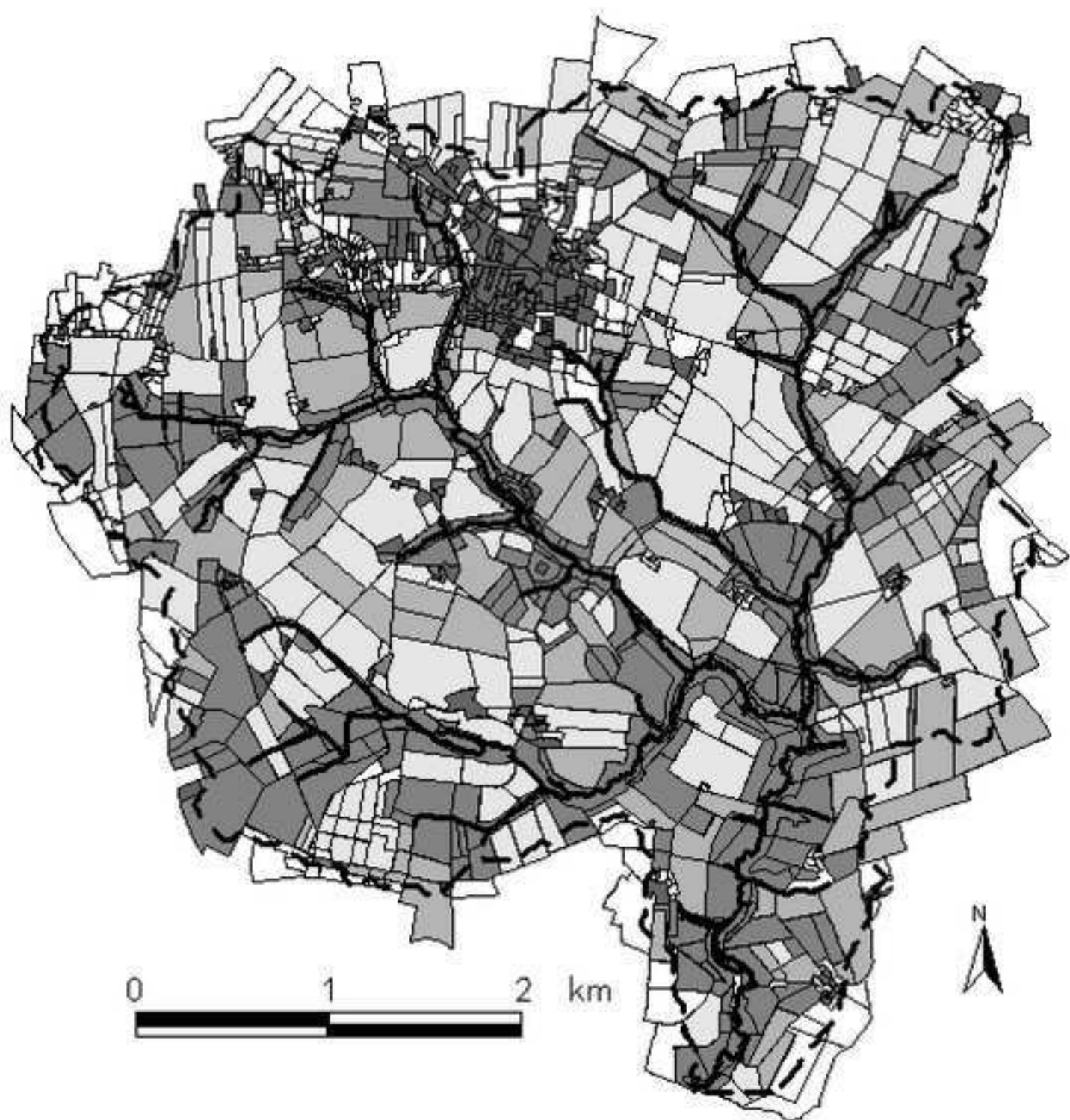
Figure 4 - caption
Click here to download high resolution image

Land use :

■	Buildings
■	Woods, plantations & meadow
■	Maize
▫	Cereal, colza & vegetables
□	Unknown

/\/ Catchment boundary

/\/ River

——— Plot boundaries

Figure 5
Click here to download high resolution image
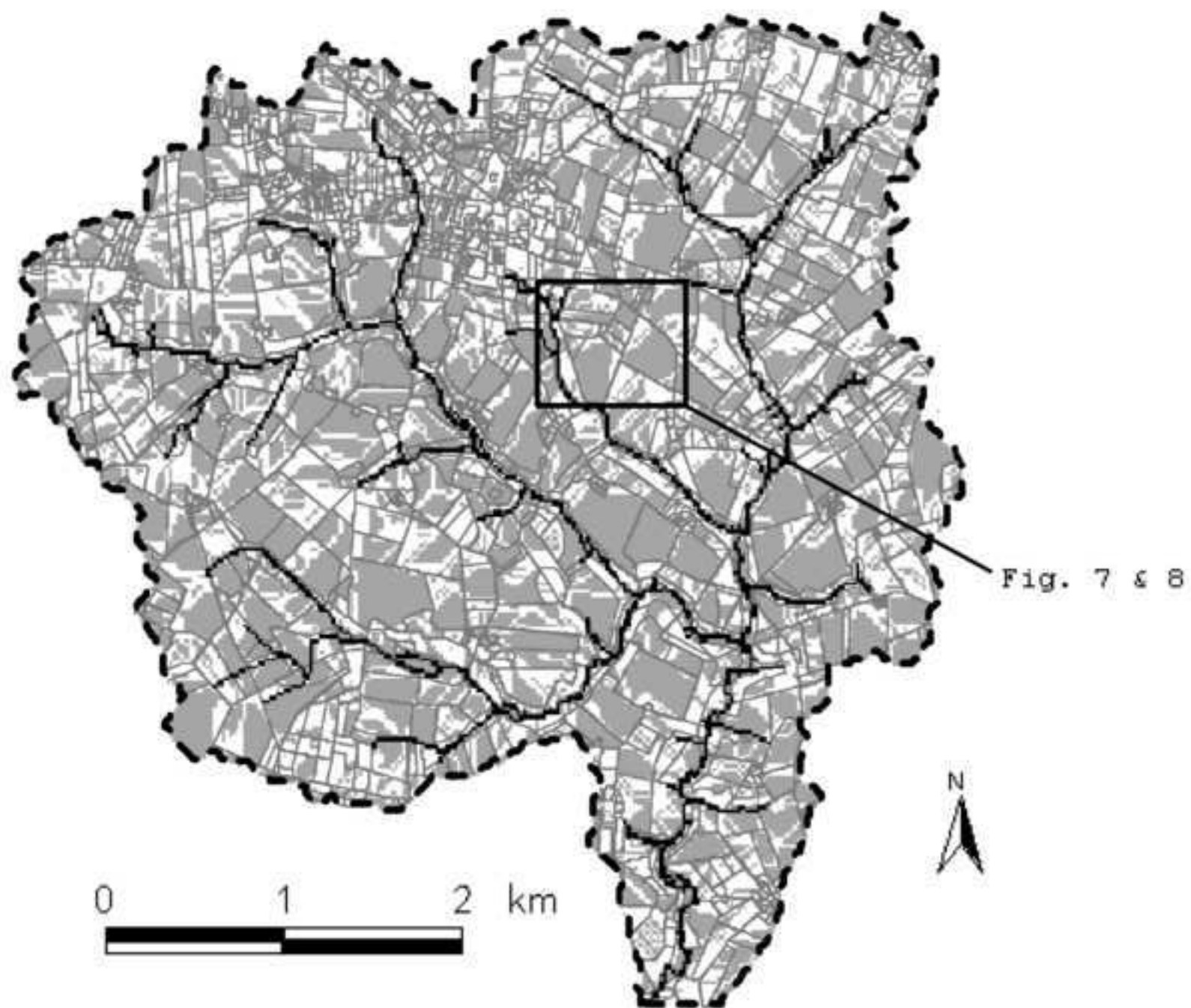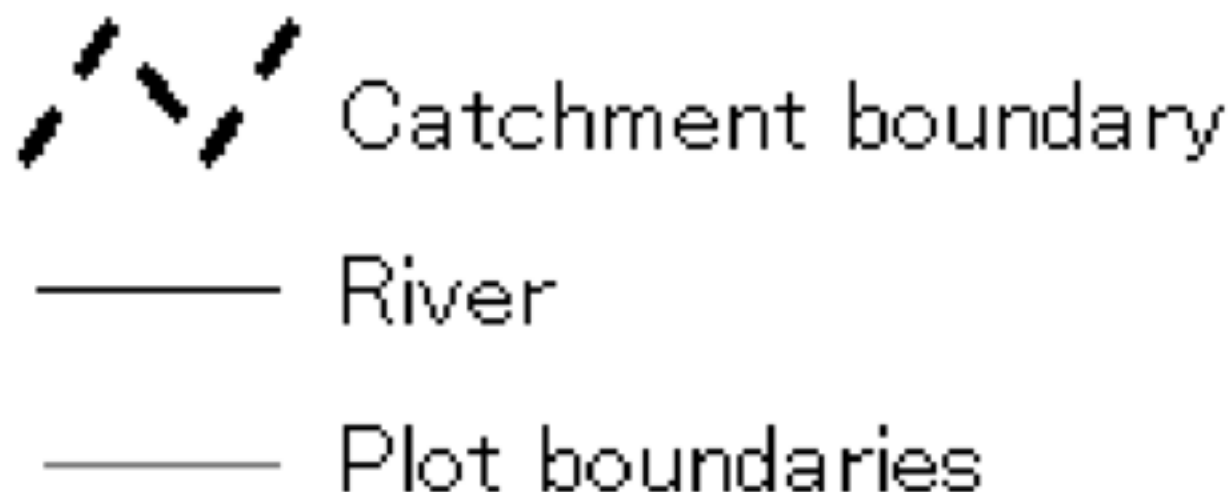
Fig. 7 & 8

0   1   2   km

N

Figure 5 - caption
Click here to download high resolution image

Catchment boundary

River

Plot boundaries

Pixel for which

All the contributing area is included within the studied plot.
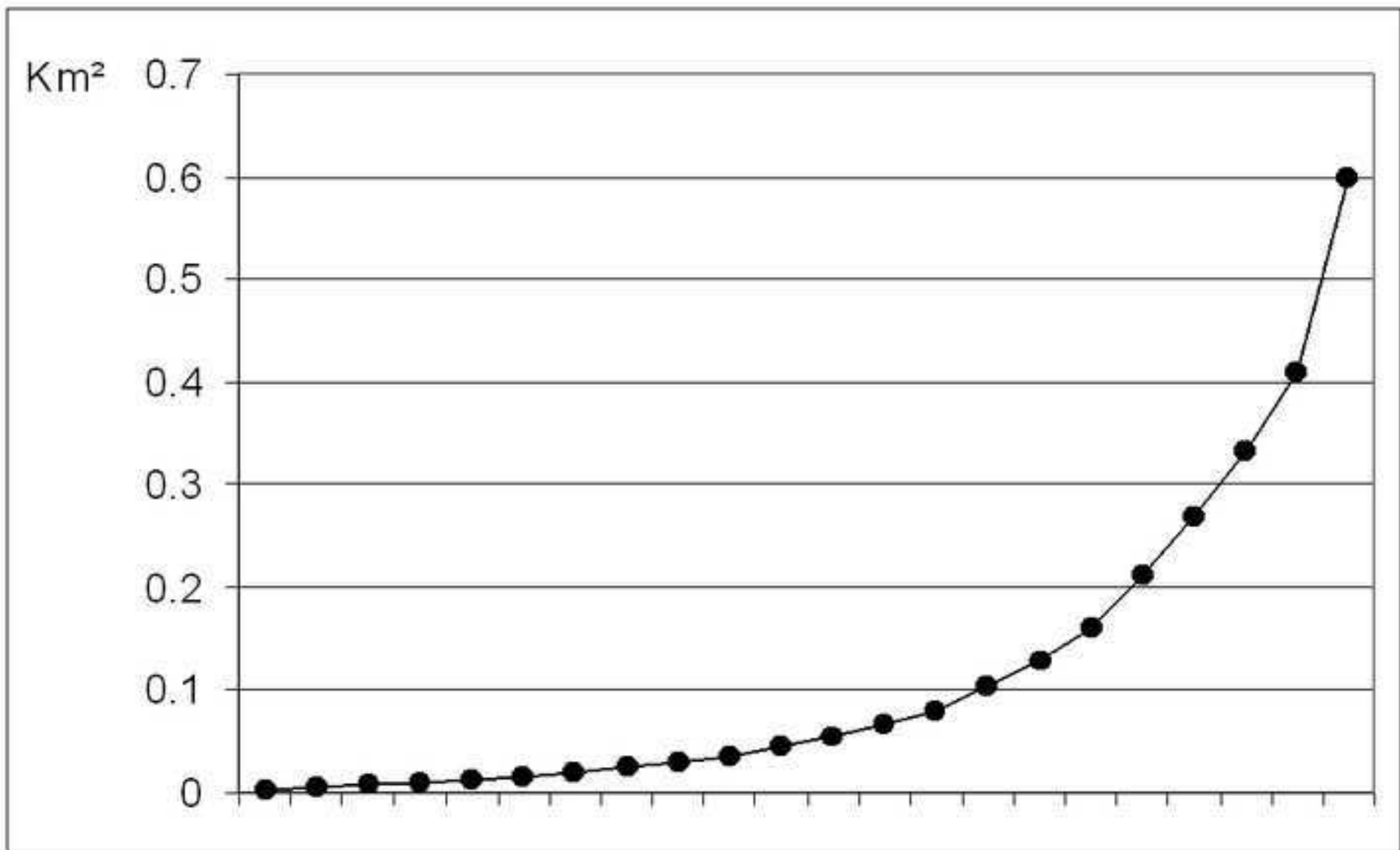
The contributing area is not entirely included within the studied plot.
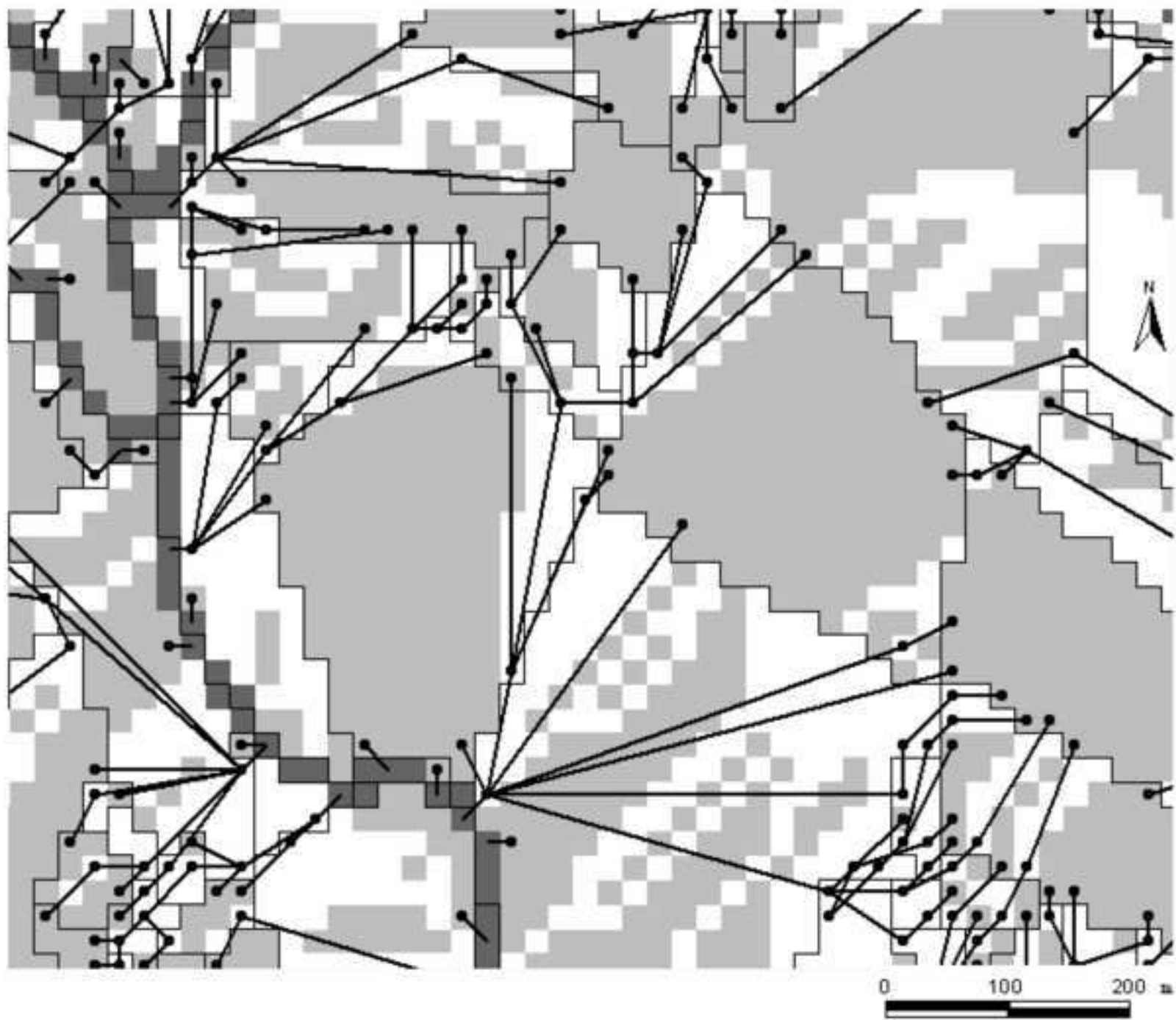
/ Plot Outlet Tree

● Plot Outlets

/ Plot Boundaries

▬ River Pixel

Pixel for which

▭ All the contributing area is included within the studied plot.

▭ The contributing area is not entirely included within the studied plot.

Figure 8
[Click here to download high resolution image](#)

Figure 8 - caption
Click here to download high resolution image

✈ Plot Arrow Diagram

╱ Plot Boundaries

▮ River Pixel

Pixel for which

▭ All the contributing area is included within the studied plot.

▭ The contributing area is not entirely included within the studied plot.

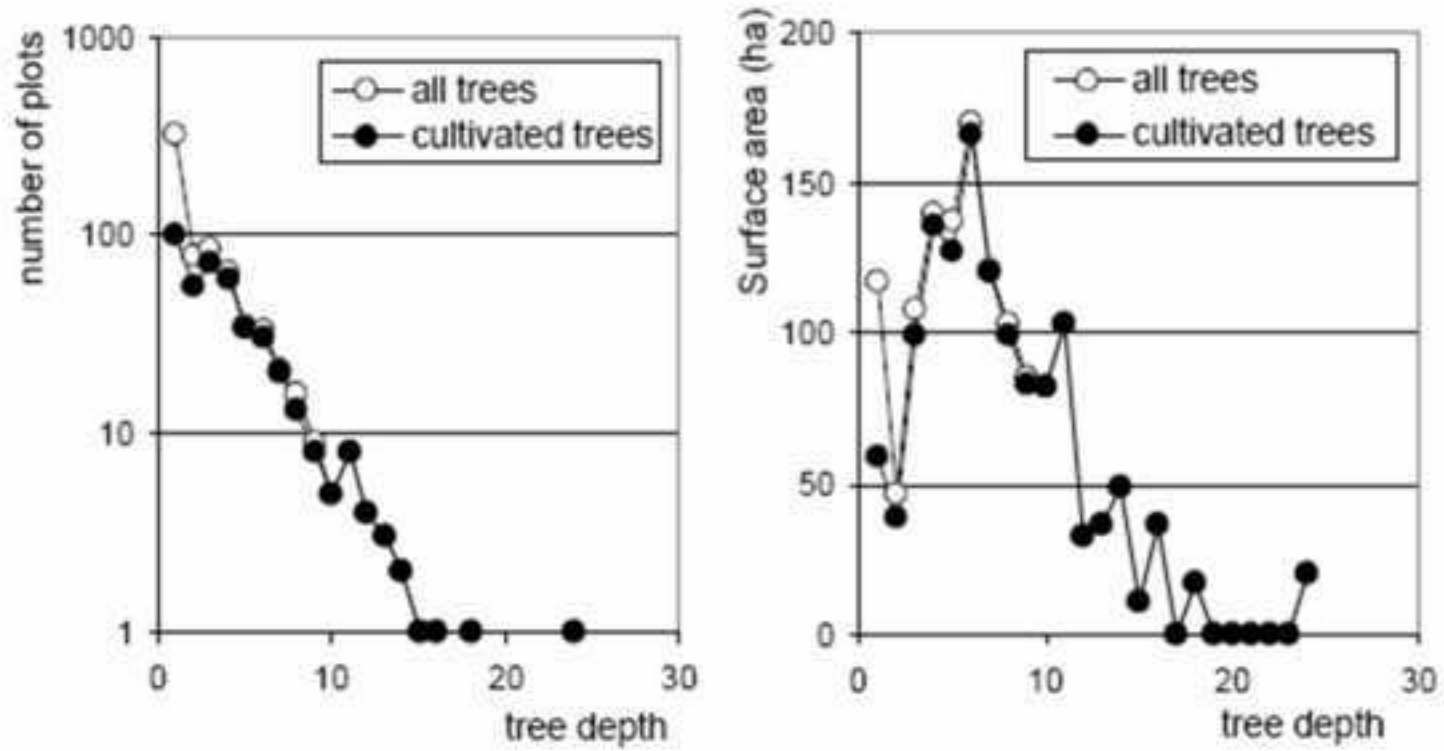**Figure 9**
Click here to download high resolution image

Figure 10
[Click here to download high resolution image](#)