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XGeoTiles: Tiling watersheds with hexagons for serious games^{*}

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ABSTRACT

Serious games on water governance at bring people on a particular question together such that they may overcome traditional positions and to trigger positive changes in both representation and behavior. To play with simplified but realistic watershed characteristics, we propose the **XGeoTiles** framework for the description of watershed elevation. It comes in the form of a 3D game board that is divided into hexagonal tiles (2D) and prisms (3D). Additional information such as land cover or stream network is also accounted.

Provided with a digital elevation model, land cover data and an outlet, the software returns a hexagonal model and a 3D OpenSCAD model that can be printed on appropriate devices. As an illustration, the hexagonal tiling is applied to a slightly undulating watershed. Results confirm a good representation of the hydrological and landscape properties when a relevant tile size is used.

1. Introduction

Serious games on water governance bring people on a particular question together such that they may overcome traditional positions and may trigger positive changes in both representation and behavior. Boards and role-playing, possibly enforced by computer simulations, have become key tools [8] to study water management in the presence of stakeholders. The virtual river game [3] is a good illustration of such a combination. Therein, a hexagonal tiling models rivers, channels and dikes. More generally, hexagonal boards, role play and simulation are also found in productivity and strategy game applications.

In the gaming framework, a hex tiling is a partition of a planar surface into hexagonal tiles. Present in nature-based solutions like honeycombs or crystals, hex tiles and hex prisms have a number of useful properties. Given a tile, the availability of 6 adjacent tiles and the equal distance between their centroids have retained the attention in a large number of strategy games. These tessellations offer more realistic movements on the board and a nicer representation of the landscape. Studied since a long time, the hexagonal tiling is receiving a renewed attention in the GIS modeling community. For instance, Wang et al. [11] model terrains from lidar data using a hexagonal lattice for the elevations to approximate the stream network along the edges.

Several methods are available to set up a 2D hex board. Hexagonal grid gaming papers sold for games

such as Dungeons and Dragons may be used in a basic manner. More generally, software and apps (e.g. HeXMapMaker or Hextml) exist to create boards with landscape hexagonal tiles that describe cities, agriculture, forests, and water bodies. Some user-defined stream network may be added. To date, such boards remain user-defined 2D landscapes, with a reduced physical meaning. However, unsurprisingly, these key features are also present in the so-called Corine Land Cover (CLC) data sets [4].

The **XGeoTiles** framework is designed go one step beyond. Its goals are to account for watershed elevation and land cover in a simplified but realistic manner. A hexagonal tiling is implemented simultaneously for the digital elevation model (DEM) and the land cover data. Each of the hexagons is assimilated as a flat horizontal homogeneous land parcel, the height and cover of which are the minimum height and the dominant cover over the parcel, respectively.


This implementation yields a hex digital elevation model (XDEM) of the watershed made of hexagonal prisms. Classical methods for watershed delineation, flow direction, flow accumulation, drainage basin and stream computation are to be adapted to restore the hydrological functioning of the watershed. Furthermore, the tiling of land cover into hexagons (XLC) may provide information on some biophysical processes, fauna and flora habitats, and practices such as agriculture, urbanization and land management.


The simplified bio-geophysical information stored in both XDEM and XLC may be, firstly, processed to print 2D or 3D boards and, secondly, accounted into rainfall-runoff simulations to play serious games with a realistic watershed board.

The layout of the paper is as follows. Some generalities about hexagon and square grids are recalled in section 2. The case study is introduced early in the

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paper for a better understanding. The workflow and implementation details, including tile descriptors and data storage, are provided in section 3. Numerical results from different points of view are presented and discussed in Section 4. Finally, the main findings of this study are summarized in the conclusion, section 5.

2. From terrain to landscape descriptors

A number of Digital Elevation Model (DEM) and land cover data (CLC, for instance) are nowadays freely available as rasters (tif images or ascii files) or shapefiles, respectively. These may come with a different coordinate reference system (CRS) and/or a different resolution. A particular attention should be thus brought to their alignment, as discussed in subsection 2.1.

Some generalities about regular tilings are recalled in subsection 2.2 and some essential biogeophysical descriptors [5] are introduced in subsection 2.3 prior to the design of boards from actual landscape datasets.

2.1. Case study and data preprocessing

The slightly undulating watershed of the Moderbach stream (Grand Est region, France) is chosen as an illustrative example [6, 10]. This stream has a length of 15 km and drains a rural catchment of 89 km² to the Albe stream, a left tributary of the Saar river. Elevations range from 210 to 305 m.a.s.l., see Fig. 1. The digital elevation model (DEM) raster is from BD Alti @75m - V2. By definition, such a raster data model makes use of a uniform regular grid of square pixels. Raster are usually provided as `tif` images or `ascii` files.

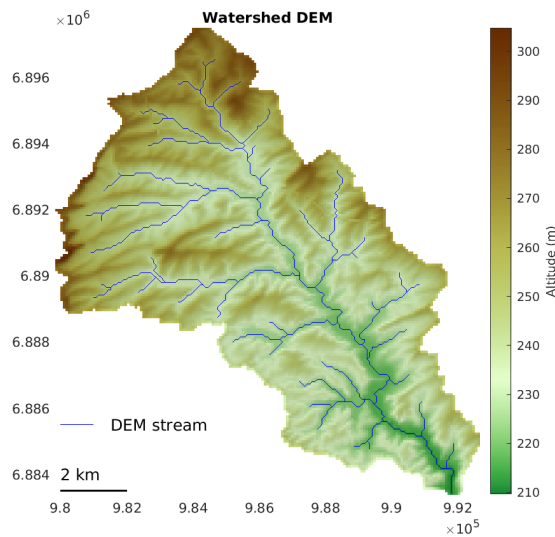


Figure 1: DEM of the Moderbach's catchment delineated using TopoToolbox [9] (extracted from BD Alti @75m - V2).

Land cover data provide tessellations/partitions into polygons that are either stored as shapefiles or rasters. The land cover shapefile used for Fig. 2 is from Corine Land Cover 12 with minimum mapping units of 0.25

km². This rural landscape comprises a number of small villages (red shades, $\simeq 10\%$), agricultural surfaces (yellow shades, $\simeq 66\%$), forests (green shades, $\simeq 22\%$), wetlands and 6 ponds (blue shades, $\simeq 2\%$) represented using polygons. Note that the rasterization of the polygons proposed in QGIS allows to create land cover grids.

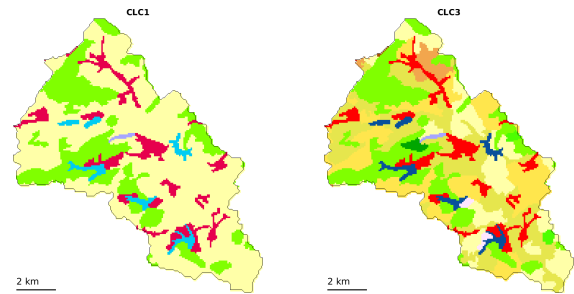


Figure 2: Land cover of the Moderbach's catchment. Red shades: artificial surfaces, yellow shades: agriculture, green shades: forests, blue shades: wetlands and waterbodies (extracted from Corine Land Cover 12.)

In the 1930s, the watershed was converted into a defense waterline based on 11 dams delineating 6 reservoirs (blue polygons of Fig. 2) on the Moderbach's tributaries and 5 forebays to be flooded along the main stream.

For consistency, DEM and land cover data has to be preprocessed to ensure the alignment of their CRS. Some reprojections and/or interpolations can be carried out on-the-fly using tools such as ArcGIS or QGIS. Prospecting further watershed simulations, actual or spurious low areas of the DEM, the so-called sinks, that disturb the surface water flow should be preferably filled to ensure of a decrease of the heights from the most upstream cells to the outlet. Appendix A describes the data collection and the preprocessing steps for this case study. This may serve as a basis for other data sets and watersheds.

2.2. Regular tiling patterns

In the two-dimensional Euclidean plane, a *tiling* or *tessellation* of a surface consists of a partition into geometrical shapes, called *tiles*. Landscape datasets are good examples. On the one hand, see Fig. 1, the pixels of a raster image may be viewed as a regular tiling of the plane into small identical squares. On the other hand, the CLC polygons form an irregular tiling as in Fig. 2.

A regular tiling may be built by translating a reference square or a reference hexagon. Figure 3 presents square and hexagonal neighboring patterns, the tiles of which are of the same area. Both generation processes may be driven by the edge length and can be set up easily. The paper focuses on hexagonal tilings.

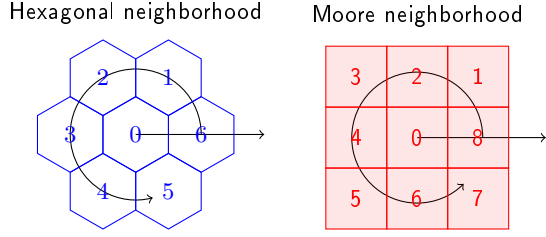


Figure 3: Tiling patterns and local numbering for the hexagonal and the Moore neighborhoods.

The central reference hexagon, number 0, is defined by its centroid (x_0, y_0) and the common apothem or inradius is hereafter denoted by a . The hexagon area is equal to $A = 2\sqrt{3}a^2$. Its 6 vertices $(x_0^i, y_0^i)_{i=1,\dots,6}$ are equally distributed at a distance of $e = 2\sqrt{3}a/3$ corresponding to the edge length, and an angle of 60° . Their coordinates satisfy:

$$\begin{aligned} x^i &= x_0 + a \cos((2i - 1)\pi/6), \quad \text{for } i = 1, \dots, 6, \\ y^i &= y_0 + a \sin((2i - 1)\pi/6). \end{aligned} \quad (1)$$

The six neighboring tiles of the tile 0 are equally distributed using $\alpha = 60^\circ$ and define a neighborhood with an area of $7A$. In the local coordinate system centered on (x_0, y_0) , neighbors centroids are located at points:

$$\begin{aligned} x_j &= x_0 + 2a \cos(j\pi/3), \quad \text{for } j = 1, \dots, 6, \\ y_j &= y_0 + 2a \sin(j\pi/3). \end{aligned} \quad (2)$$

These are also the translation vectors of length $2a$ used to generate the tiling. In other words, the centroid coordinates of an infinite hexagonal tiling satisfy:

$$C = \{(x_0, y_0) + k(a, \sqrt{3}a) + l(2a, 0), \forall k, l \in \mathbb{Z}\}. \quad (3)$$

As a comparison, the reference square has 8 neighbors that are distributed with an angle of 45° in the square tiling. The edge of square tiles is chosen equal to \sqrt{A} . With an area of $9A$, the Moore neighborhood has more surface than the hexagonal neighborhood. The main difference is in the distance between neighboring centroids: it varies by a factor $\sqrt{2}$ from even to odd local numbers. This signifies that moves in one direction or another may have a different weight.

The performance of the hexagonal tiling in the representation of simplified watersheds is evaluated in Section 4.

2.3. Tiling and biogeophysical descriptors

Biogeophysical descriptors [5] are used in a number of environmental applications. When a hexagonal tiling is applied to partition the DEM and CLC rasters, these scalar descriptors can be assigned to the tiles by averaging and/or by homogenizing the information encoded at the pixel level in the rasters.

Given a DEM and a user-defined outlet, GIS tools such as ArcGIS, QGIS, or TopoToolbox allow to carry out a watershed delineation. The slope and flow direction information are then computed as derivatives by applying some 2D first order finite difference operator to the DEM. At the pixel level, such a computation may be implemented by means of the Moore pattern for instance. Then, the resulting flow direction raster is used to deduce the flow accumulation raster and the stream network as a polyline. This process has to be adapted to be suited for a hexagonal tiling.

Two height approximations could be considered for each watershed tile. At a first glance, the average height seems suitable, however, this choice may create sinks in the tiled watershed model. Thus the minimum height is preferred to conserve the monotonic decrease in elevation from upstream tiles to the outlet tile. The virtual outlet of the tile is fixed in the middle of the nearest edge. This becomes the flow face.

A particular attention has to be brought to most upstream tiles and the downstream tile (related to the outlet) because they may partly lie outside the watershed.

For hydrological conceptual models [2, 7], useful properties at tile level are the areas of the tiles that overlap the watershed, the flow face and the downstream cell, and a set of soil parameters that are partly determined by the land cover.

In this simplified landscape representation, a dominant land cover may be assigned to each tile. In the CLC case, this can be defined using either the CLC nomenclature 1 for a coarse description, or the CLC nomenclature 3 for more features.

Implementation details about biogeophysical descriptors are provided in subsection 3.2.

3. Tiling and descriptor implementation

An overview of XGeoTiles framework for the tiling of watersheds with hexagons is presented in Fig. 4.

As a preprocessing, elevation and land cover files are loaded into a QGIS project so as to align the DEM and CLC rasters with each other, see Appendix A for details.

The tiling process comprises both the delineation of the watershed from a user defined outlet by means of Topotoolbox, subsection 3.1, and the generation of a hexagonal grid, subsection 3.2. Tiles of the hexagonal grid that overlap or partly overlap with the resulting drainage basin are gathered into the watershed tiling structure denoted by XMap. This process is implemented in the Matlab programming language.

The tiling structure allows for a number of additional prints, subsection 3.3. The 2D boards may be printed as Matlab figures. The hexagonal tiling data information is implemented as an OpenSCAD script to generate a set of joined hexagonal prisms, the height of

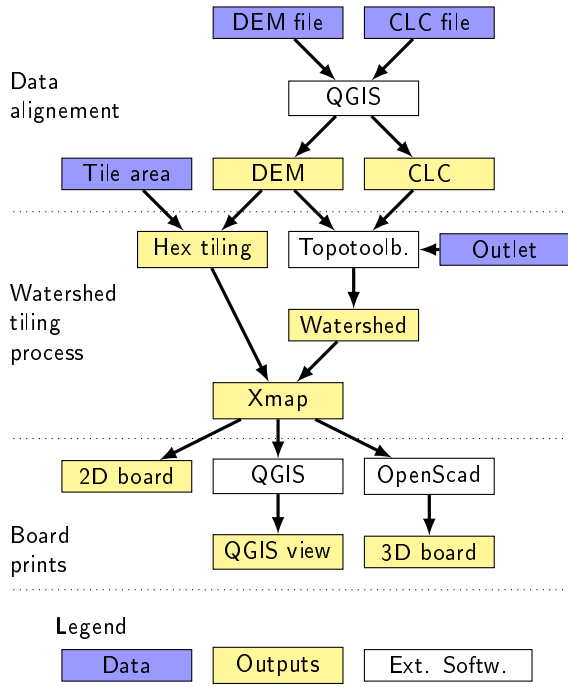


Figure 4: 2D and 3D board design process.)

which accounts for the tile elevation.

3.1. DEM analysis in Matlab

The Matlab Mapping toolbox provides very few GIS features when compared to dedicated software. In the Matlab framework, the `TopoToolbox` library is an object-oriented open source toolbox dedicated to the analysis of DEMs. It provides hydrologists with a much better experience of watershed handling than the Mapping toolbox.

In `TopoToolbox`, the DEM raster is loaded as an object of the `@GRIDobj` class, hereafter denoted by `DEM`. The main properties of the `DEM` object are for the elevation data stored as a matrix `DEM.Z` and a 3-by-2 affine transformation as in the Mapping toolbox. This small reference matrix comprises the geographical coordinates of the upper left (reference) pixel of the DEM raster, and the two translation vectors needed to recover the geographical coordinates of the other pixels.

An object of the `@FLOWobj` class is then built by carving the filled DEM. It imposes a monotonically decreasing sequence of heights along the flow directions and removes sinks. This flow representation allows to deduce the stream network as an object of the `@STREAMobj` class. A user-defined outlet chosen on the stream allows for the delineation and the storage of the corresponding drainage basin as a `GRIDobj` object. Such a process underlies the generation of Fig. 1.

As discussed in subsection 2.1, the `XGeoTiles` framework assumes that the land cover information is provided as a raster aligned with the DEM raster. This

raster is also provided as a `@GRIDobj` object. Note that `TopoToolbox` provides methods for the rasterization of shapefiles, the reprojection and the resampling of `GRIDobj` variables. However, to facilitate the uptake by geographers, we recommend to align the two rasters as described in Appendix A.

As shown in Figs. 1 and 2, the bounding box of the drainage basin can be used to crop the two rasters for a better rendering and for to manage smaller grid objects in the tiling process.

3.2. Tiling structure

The hexagonal partition into tiles of area A is carried out from the reference pixel in the directions indicated in the reference matrix following equation (3). In this formula, bounds for indices k and l may be deduced from the pixel size and the bounding box of the DEM. The watershed tiling is limited to the set of tiles that overlap or partly overlap the drainage basin. A threshold, for instance an overlap larger than $0.5A$, may be imposed.

As an illustration, see Fig. 5. The Moderbach's watershed DEM is partitioned into 89 tiles of 1 km^2 , the color of which corresponds to their minimum height. This tiling into hexagon is named `XDEM`. The stream network computed with the DEM is still plotted to ease the understanding. The construction of a simplified stream network (called `XStream`) and adapted to the tiling is discussed in subsection 3.2.1.

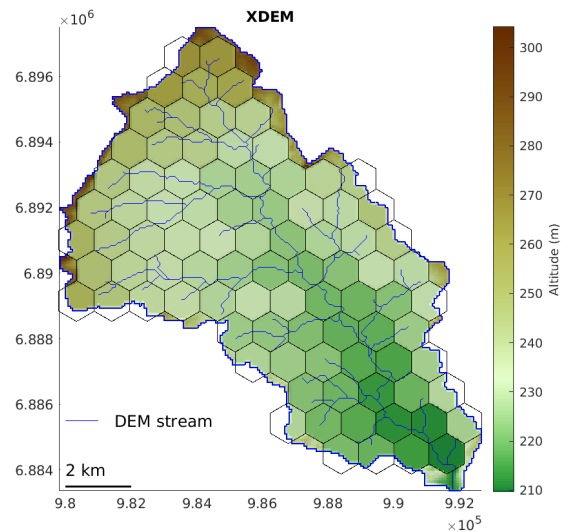


Figure 5: Watershed tiling into 89 tiles of 1 km^2 , threshold of 0.5.

A Matlab structure denoted `XMap` is chosen to store tile and descriptor information into fields. The naming convention is displayed in Tab. 1 together with their siting (tile centroid, tile or neighborhood (NBH)) and their unit. The tile inradius and circumradius can be deduced from the vertices coordinates. Fields for the

mean height or the soil properties may be added to this minimal XMap structure. The XMap structure may be saved as a .csv file using the writetable function of Matlab.

Table 1

Fields of a watershed tiling structure XMap.

Fields	Siting	Units	Comment
ID	Centroid	-	Unique identifier (-)
X0	Centroid	m	Abscissa (m)
Y0	Centroid	m	Ordinate (m)
X	Tile	m	Vertex abscissas
Y	Tile	m	Vertex ordinates
Area	Tile	m ²	Of the overlap with the watershed (m ²)
Z0	Tile	m	Outlet elevation
OutFace	Tile	-	Outlet face (local numbering)
DownTile	NBH	-	Downstream tile ID
MainCLC1	Tile	-	Main code, nomen. 1
MainCLC3	Tile	-	Main code, nomen. 3

3.2.1. Simplified streamflow

For most watersheds, the stream network exhibits a tree-like pattern and sub-basins have a unique outlet. This may not be the case when a tiling is implemented.

The choice is made to assign a unique outlet to the tile, located at the point of the minimum elevation of the DEM pixels inside the tile and the watershed. Thereby, the carving preprocess ensures that this pixel lies near to the tile boundary and determines the outlet face and the downstream tile.

As implemented, this coarse but functional stream network XStream suffices to reestablish a monotonic height decreasing sequence of tiles running from the upstream tiles to the outlet tile. The simplified XStream network is plotted by linking one tile after another the centroid to the centroid of its downstream tile.

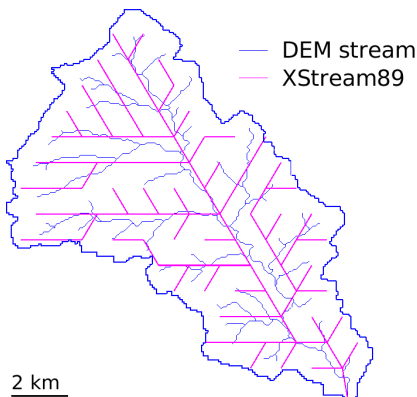


Figure 6: Comparison of the stream networks for a watershed tiling into 89 hexagons of 1 km².

Figure 6 compares XStream to the DEM stream net-

work. Clearly there are a number of deviations, the geographic extent depends on the tile area and the distance between the hills in the landscape. A refined tiling improves the accuracy of the representation as shown in section 4.

3.2.2. Land cover indicators

In a nutshell, the CLC information is encoded using a three-level hierarchical nomenclature that distinguishes 5 main categories at level 1 (nomenclature 1), 15 categories at level 2, and 44 categories at level 3 (nomenclature 3). The CLC codes are strings of 3 digits. The first digit encodes the main category, see Fig. 2. This allows to simplify the representation and/or to initialize a game board.

For now, the dominant land cover is assigned to the tile. Figure 7 draws the resulting hexagonal tilings XCLC1 and XCLC3, computed with the nomenclature 1 (left picture) and the nomenclature 3 (right picture), respectively.

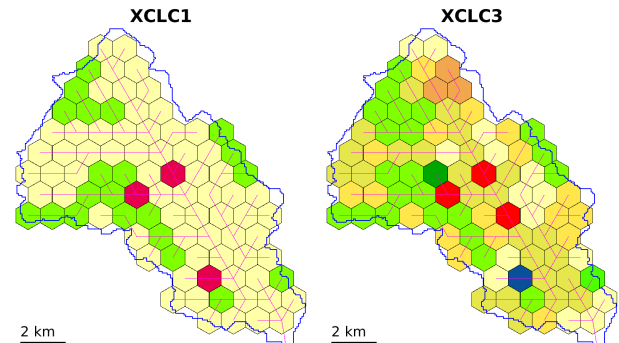


Figure 7: Land cover, 89 tiles of 1 km², nomenclatures 1 and 3.

The differences are mainly due to the mosaic of distinct agricultural practices taking place on a tile. Although a tile may be mostly dedicated to agriculture, the dominant cover may be the urban fabrics as for the central red tile of XCLX3. A similar explanation arises for the blue tile of XCLC3. As can be seen in Fig. 2, the lower urban fabrics represented in XCLC1 divides in two categories in the nomenclature 3, the areas of which are smaller than the area of the waterbody. Again, some refinement improves the representation as demonstrated in section 4.

3.3. Board rendering and printing

Apart from the image file format proposed in Matlab, the XMap data contain the information needed for the implementation of a number of less conventional plots and prints. Among them, shapefiles for QGIS and STL files for 3D printers are the most promising in the context of serious games.

On the one hand, the XMap fields required to generate a land cover shapefile are the ID, the vertex co-

ordinate arrays X and Y , the CLC codes `MainCLC1` and `MainCLC3` for nomenclatures 1 and 3 respectively, and an additional `Geometry` field set to `Polygon` for all the tiles. These are gathered in a new Matlab structure to be saved with the `shapewrite` method. The resulting shapefile may be viewed using QGIS and a `.qml` file adapted to the CLC data. This geographical hexagonal tiling may be used within QGIS to clip any other raster data by extent so as to project the resulting image on a board.

On the other hand, the centroid coordinates X_0 , Y_0 and minimum height Z_0 stored in the `XMap` structure may be used to pave the watershed with vertical hexagonal prisms. Assuming scales of 1:100000 in the horizontal plane and 1:5000 for the heights, the resulting prismatic model may be printed on a small 3D printer. In practice, the list of tiles of `XMap`, here defined by (X_0, Y_0, Z_0) , are turned into a list of calls of the `Xprism` module reported Appendix B. This is interpreted by OpenSCAD, Fig. 8, to produce a stl file. This small scale prototype of a watershed board involving 89 tiles has been successfully printed on an Original Prusa MINI+.

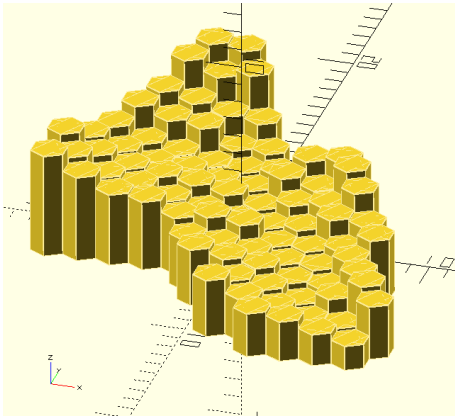


Figure 8: OpenSCAD model for the watershed tiling.

The TikZ package, used for Fig. 3, may also be used to create such graphic hexagonal or prismatic elements in L^AT_EX.

4. Experiments and discussion

The reliability of the hexagonal tiling is evaluated with respect to hydrology and land cover representation on refined grids to exhibit strengths, weaknesses and opportunities.

4.1. Watershed tiling and hydrology

Conceptual hydrological models such as [2, 7] rely on a very few soil and vegetation parameters to link the rainfall over a watershed to the discharge at its outlet. Therein, the area acts as a scaling factor applied to calculations operated on a unit of field.

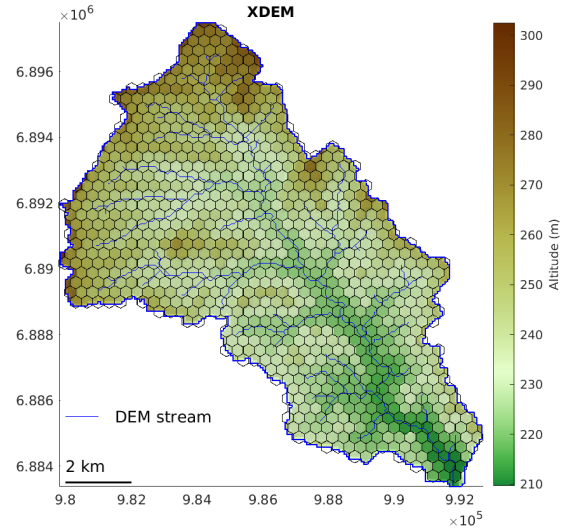


Figure 9: Watershed XDEM, 897 tiles of 0.1 km².

This subsection analyses how the hexagonal tiling complies with a conceptual model by evaluating discrepancies on the total area and by comparing the visual agreement between the DEM and XDEM stream networks. Computations are carried out by using tiles of 0.1 km² and a threshold of 0.5 to determine whether a hexagon is or not accounted in the watershed tiling.

Table 2

Watershed tilings at different resolutions.

Tiling	Tile area (km ²)			Watershed
	1.0	.25	.10	
Threshold	.5	.50	.50	
#Tiles	89	362	897	1
Area (km ²)	89.0	90.5	89.7	89.4
max. height (m)	265.1	278.5	283.3	304.8
min. height (m)	210.4	209.7	209.8	209.7
Time (s)	10.3	22.2	45.8	2.5

Table 2 shows some topographical characteristics of tiled watersheds computed for a range of areas. On the one hand, tiles of 1 km² may be useful to play a serious game with a relatively small number of tiles. On the other hand, smaller tiles yields more accurate representations for the height. The relative error on area is of the order of 1% in all the three experiments.

Figure 10 plots the DEM stream network and the stream network built during a tiling design process into 10 times more hexagons than used in Fig. 6. As already suggested in subsection 3.2.1, the use of smaller tiles improves the agreement between these two networks.

4.2. Land cover tiling and serious game

The water-food-energy security nexus is central to sustainable development. Agriculture is a key actor in all three, consuming freshwater and energy to produce

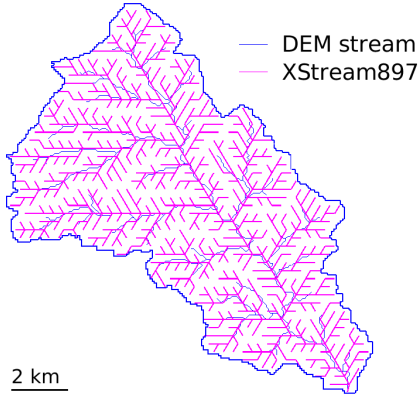


Figure 10: Comparison of the stream networks for the watershed tiling into 897 hexagons of 0.1 km^2 .

food. Consequently, Utilized Agricultural Land (UAL) may be a key criterion in serious games about water management. Within the proposed tiling, UAL corresponds to tiles with yellow shades.

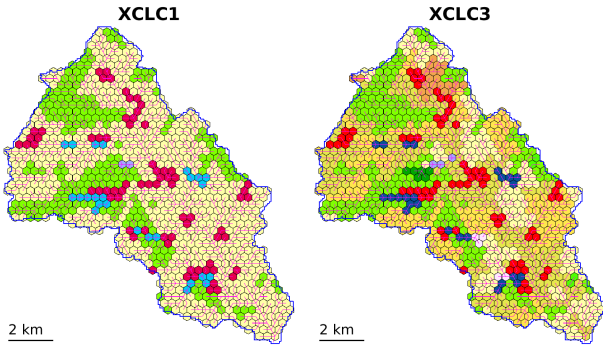


Figure 11: Land cover tiling into 897 tiles of $.1 \text{ km}^2$, nomenclatures 1 and 3.

Figure 11 presents the land cover tiling into 897 tiles of 0.1 km^2 using the nomenclatures 1 and 3. Such a refinement improves the visual agreement between the land cover tilings and the original land cover map considerably. As expected, smaller hexagonal tiles promote the land cover parcels with a aspect ratio near to 1. This is especially the case for agriculture and forest surfaces. Villages with a compact shape are better represented. The complex shape of the small waterbodies is captured at the raster pixel level only.

Errors between the CLC1 and XCLC1 pixel values are plotted in Fig. 12 with the CLC1 colormap to assess this statement for the coarse (89) and refined (897) tilings. The errors evaluated as:

$$\begin{aligned} \text{disc} &= \text{abs}(\text{CLC1.Z} - \text{XCLC1.Z}); \\ \text{DIF1} &= (\text{disc./disc}). * \text{CLC1.Z}; \end{aligned} \quad (4)$$

take place at the interfaces between land categories. Note that the non arithmetic values (NaN) that result

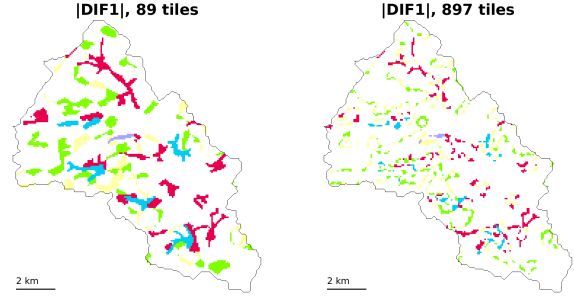


Figure 12: Differences on land cover representation for the partitions into 89 and 897 tiles, nomenclature 1.

from equation (4) are not considered by Matlab at plotting time.

As expected, the error calculation, Fig. 13, carried out for the nomenclature 3 reveals more differences in agricultural and forested areas because more land categories are considered.

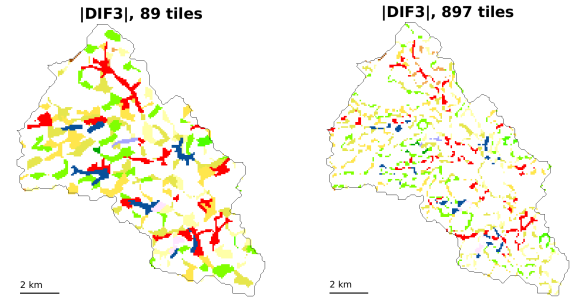


Figure 13: Errors on land cover representation for the partitions into 89 and 897 tiles, nomenclature 1.

Land cover ratios are measured in Tabs. 3 and 4, respectively. For most of the indicators, the smaller the tile area is, the smaller are the deviations to the watershed ratios. In particular, such a trend may be observed for the large indicators (UAL, forests and artificial urban area). The very small land cover indicators (water bodies) are more sensitive.

Table 3
Land cover ratios, nomenclature 1.

Nomen. 1	Tile area (km^2)			Watershed
	1.0	.25	.10	
Artif. surf.	.0337	.0608	.0792	.0958
Agri. area (UAL)	.7303	.6851	.6533	.6597
Forests	.2360	.2376	.2375	.2226
Wetlands	.0000	.0000	.0021	.0043
Wat. bodies	.0000	.0165	.0279	.0176

Note that, prior to their usage in a serious game, the land cover indicators may be modified in the XMap structure in a simple manner so as to propose a board

Table 4

Land cover ratios for nomenclature 3, summed with respect to nomenclature 1.

\sum Nomen. 3	Tile area (km ²)			Watershed
	1.0	.25	.10	
Artif. surf.	.0337	.0636	.0803	.0958
Agri. area (UAL)	.6854	.6657	.6533	.6597
Forests	.2697	.2486	.2353	.2226
Wetlands	.0000	.0028	.0032	.0043
Wat. bodies	.0112	.0193	.0279	.0176

that could better satisfy the landscape representation by the players. Furthermore, the game may be initialized with the XCLC1 tiling to propose a simplified representation. Then, the XCLC3 tiling may be used to evaluate if and how the players' actions on UAL tiles have changed their landscape management during the game.

5. Conclusion

The XGeoTile framework is proposed for the representation of actual watersheds as 2D and 3D boards as to preserve the hydrological and geographical meanings. Hexagonal tiles and prisms are favored as they offer more directions for the moves of water and other resources from one tile to the others.

Although serious games on water governance/management are the main intended application, the numerical experiments prove the reliability of the representation with respect to the area, which acts as a scaling factor in any hydrological simulation. Similarly, the land cover information is well represented as soon as a sufficient granularity of tiles is considered.

Combined with hydrological simulations, these boards will be tested during workshops involving farmers and stakeholders in a serious game [1] dedicated to the management of the water quality in rural watersheds.

A. Preprocessing data

For the sake of reproducibility, this appendix describes the data collection and preprocessing steps for the Moderbach watershed (Région Grand Est, France).

- Data & providers
 - BD ALTI (®), free 75 m raster file,
 - Regional Corine Land Cover, free vector file,
- QGIS project
 - Add Raster Layer:
 - BDALTI2_75M_FXX_0975_6900_MNT_LAMB93_IGN69,
 - Add Vector Layer: CLC12_RACAL_RGF and define the SCR of the project using this CLC file. Note the qml file is missing.

- Rasterize CLC12_RACAL_RGF as follows:
 - * Open Attribute Table,
 - * Run the field calculator to convert the CLC CODE_12 string values to integer values,
 - Create a new field icode12, with type "integer",
 - Use Expression: to_int("CODE_12"),
 - * Rasterize using:
 - icode12 as field,
 - Georeferenced units,
 - Width=Height=75,
 - Output extent of the DEM,
- Clip the two rasters by (the same) extent and save them in GeoTIFF format.

This CLC rasterization is described with more detail in websie.cefe.cnrs.fr/formations/qgis-2020.

B. OpenSCAD model

The OpenSCAD model is based on translations in the horizontal plane of hexagonal prisms, the circumradius of which is equal to 1. The height of the prisms is variable.

The 3D board is built as the union of prisms generated by the successive calls to the `hexa2scad` function that creates the `map2scad.txt` file. This contains calls to the `Xprism` module. The small code written in listing B allows to generate Fig. 8 and the corresponding `stl` file.

```

1 // XBoard
2 // map2scad calls the Xprism module
3 // using centroid coordinates as inputs
4 union()
5 { include <map2scad.txt>
6 }
7
8 module Xprism(x,y,z)
9 //adapted from thingiverse/thing:277727
10 //hexagonal prism; circumradius=1
11 translate([x,y,z/2])
12 {union()
13 {rotate([0,0,30])
14   cube([1, sqrt(3),z], center= true);
15   rotate([0,0,90])
16   cube([1, sqrt(3),z], center= true);
17   rotate([0,0,150])
18   cube([1, sqrt(3),z], center= true);
19 }
20 }
```

Listing 1: General OpenSCAD file for Xboard printing.

CRediT authorship contribution statement

I Charpentier: Conceptualization of this study, Methodology, Software, Writing.

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