# Hex-utils: A Tool Set Supporting HexASCII Hexagonal *rasters*

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Abstract: The advantages of hexagonal meshes over squared grids in discretising spatial variables have been known for long. Notwithstanding, the *raster* data formats used in geo-spatial disciplines to this purpose are still today almost exclusively reliant on squared grids. The HexASCII file format is a core element in an attempt to introduce hexagonal *rasters* to mainstream GIS, defining a simple vehicle to store and share such data structures. This article describes the `hex-utils` tool-kit, an Application Programming Interface (API) and a set of command line tools enabling the use of HexASCII *rasters*. Basic operations are supported: creation of new hexagonal *rasters* from different inputs and transformation into file formats readable by desktop GIS programmes. The API sets a framework for the development of further functionality.

## 1 INTRODUCTION

In Geographic Information Systems (GIS), the *raster* data structure provides a straightforward mean to capture real world phenomena, by discretising spatial variables into tessellations of samples. *Rasters* divide the cartographic plane regularly into small areas of the same shape, inside which the spatial variable in question is assumed to be constant. This is possible only with three regular geometric shapes (i.e., having all sides of equal length): the equilateral triangle, the square and the hexagon. *Raster* grids used in GIS have been predominantly organised in squared patterns in which the space between each row and each column of samples is constant; to a good extent this is a consequence of spatial data acquisition methods.

However, hexagonal *rasters* yield two essential advantages over square grids that are relevant in GIS. In first place is the higher spatial resolution provided by hexagonal meshes of equal area (Mersereau, 1979); or conversely, the lower number of cells required by a hexagonal *raster* to match the resolution of a squared counterpart. In second place is the isotropy of the hexagonal neighbourhood; in a square grid each cell has four neighbours to which it shares an edge and four with which it shares only a vertex. In a hexagonal *raster* each cell shares an edge with each of its six neighbours, and all their cell centroids are at the same distance.

On the downside, hexagons yield the distinctive characteristic of not being dividable into smaller hexagons, and neither forming a larger hexagon when agglomerated. This issue has been addressed in different ways, such as that proposed with the Generalised Balanced Ternary cell index system (Gibson and Lucas, 1982). Moreover, *raster* cell aggregation is not a frequent operation in spatial analysis processes.

The shortcomings of square grids became evident early in the history of Computer Science, motivating suggestions for a shift to hexagonal meshes already in 1960s (Golay, 1969). But in spite of further theoretical developments and other advantages identified, this shift never fully materialised. Likewise in the GIS field, neither hexagonal *raster* file formats, nor supporting tools were ever fully developed. Scant work with hexagonal sampling schemes or hexagonal meshes is conducted on vector topologies.

These were the motivations leading to the specification of the HexASCII file format (HASC for short), an open formalism to store and port hexagonal *rasters* as text files (de Sousa and Leitão, In review). This specification sets the minimum information required to capture cell geometry, mesh dimensions and location, plus the cell data themselves.

A prototype application is presented in this article, a set of tools developed to provide basic functionality for HexASCII *rasters*. It comprises an Application Programming Interface (API) and a set of command line tools demonstrating the creation of HexASCII *rasters* and their integration with existing GIS software. These assets intend to be a step towards the

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adoption of hexagonal *rasters* in GIS and spatial analysis practice.

These tools are gathered in a project called `hex-utils` released under an open source licence and made available at GitHub [1]. They can also be installed from a PyPi repository [2].

This article starts with a brief overview of the HexASCII file format in Section 2; Section 3 describes the API underlying the tool-kit and Section 4 goes through the various command line tools developed to date; Section 5 summarises the article and points to future work.

## 2 OVERVIEW OF THE HexASCII FILE FORMAT

An HexASCII *raster* is a text file composed by two parts: an opening metadata section and a string of cell values. The metadata section describes cell and mesh geometry and positions the *raster* in the cartographic domain. The metadata is described with a set of seven key and value pairs, of which five are mandatory and two are optional:

- `ncols`: number of columns;
- `nrows`: number of rows;
- `xll`: *x* coordinate of the lower left cell centroid;
- `yll`: *y* coordinate of the lower left cell centroid;
- `side`: cell side length;
- `angle`: mesh rotation angle (optional);
- `no_data`: string representing null or missing values (optional).

Listing 1 presents the HexASCII file for the hexagonal *raster* depicted in Figure 1. The full specification of this file format, as well as the reasoning leading to its structure, is available in (de Sousa and Leitão, In review).

Listing 1: Example of an HexASCII file.

```
ncols    4
nrows    3
xll      3.1
yll      2.2
side     2
angle    15
no_data  9999
11  21  31  41
12  22  32  42
13  23  33  43
```

[1] https://github.com/ldesousa/hex-utils

[2] https://pypi.python.org/pypi/hex-utils

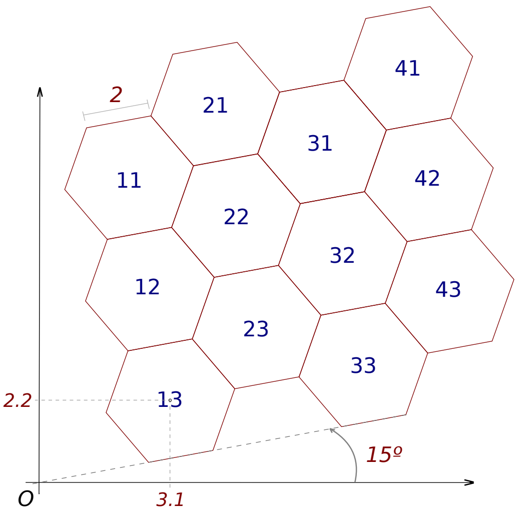


Figure 1: The hexagonal *raster* described by the HASC file in Listing 1.

## 3 THE HexASCII APPLICATION PROGRAMMING INTERFACE (API)

The tools enabling the HexASCII file format were developed in the Python programming language (Sanner et al., 1999). This language was chosen in first place for its versatility, as useful to *ad hoc* scripting as to high level object-oriented programming. Python also facilitates the manipulation of spatial data through a number of libraries such as GDAL/OGR (Warmerdam, 2008) OWSLib [3], Shapely [4] or GeoPandas [5], granting it growing popularity among geo-spatial programmers.

The prototype command line tools rely on the domain model depicted in Figure 2, describing *rasters* in general and then specific file formats. This domain model is the blueprint for the API implemented in the Python programming language. Both the HexASCII format and the ASCII squared *raster* format specified by ESRI [6] are included in this model. The latter is one of the data sources for the creation of new hexagonal *rasters*.

The model starts with the abstract class `Grid` that encloses various aspects of a *raster*. This class can be seen as a template for the minimum metadata, data and functionality required for a *raster* grid format.

[3] https://geopython.github.io/OWSLib/

[4] https://pypi.python.org/pypi/Shapely

[5] http://geopandas.org/

[6] http://resources.esri.com/help/9.3/arcgisdesktop/com/gp_toolref/spatial_analyst_tools/esri_ascii_raster_format.htm

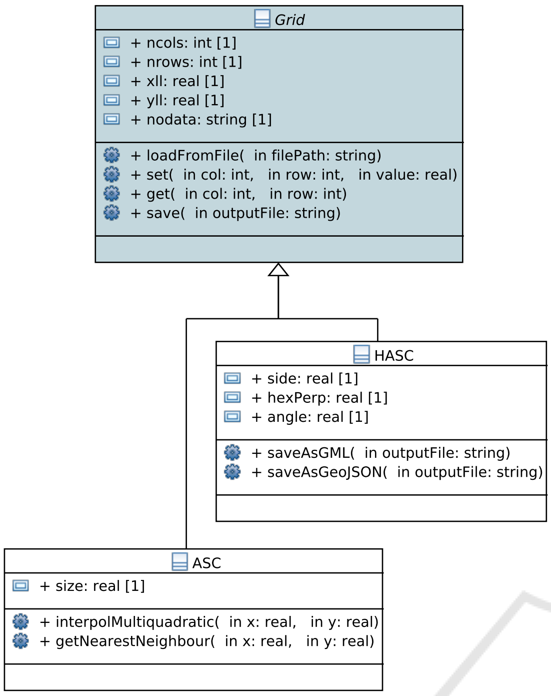

Grid
+ ncols: int [1]
+ nrows: int [1]
+ xll: real [1]
+ yll: real [1]
+ nodata: string [1]
+ loadFromFile( in filePath: string)
+ set( in col: int, in row: int, in value: real)
+ get( in col: int, in row: int)
+ save( in outputFile: string)
HASC
+ side: real [1]
+ hexPerp: real [1]
+ angle: real [1]
+ saveAsGML( in outputFile: string)
+ saveAsGeoJSON( in outputFile: string)
ASC
+ size: real [1]
+ interpolMultiquadratic( in x: real, in y: real)
+ getNearestNeighbour( in x: real, in y: real)

Figure 2: The domain model underlying the tools supporting the HASC file format.

These include: number of columns (`ncols`), number of rows (`nrows`), coordinates positioning the grid in the cartographic space (`xll` and `yll`) and an identifier for empty or null values (`nodata`). The data is stored internally as a two-dimensional array, that can not be directly assessed (it is a protected property).

The `init()` method initialises the properties described above in a child instance of the `Grid` class. To assign a new value to a grid cell there is the `set()` method, that takes as arguments a column number, a row number and a new value. Conversely, to retrieve the value of a cell, there is the `get()` method, taking as arguments a column and a row number. The `loadFromFile()` method provides the functionality to read the *raster* metadata and data from an existing file. Finally, the `save()` method is available to create a persistent file on disk with the current data and metadata of the instance, according to the format subscribed to by the child class.

The `ASC` class is a concrete implementation of the `Grid` type, representing the ESRI ASCII *raster* format. Beyond the properties inherited from `Grid`, this class adds the `size` property, another metadata element determining the width and height of each grid cell. The `init()` method is redefined to allow the set up of this additional property. Two new methods are introduced in this class, both concerning the interpolation of data values: (i) `getNearestNeighbour()`, that simply returns the value of the cell whose centroid is nearest to the given coordinates, and (ii) `interpolMultiquadratic()`, that for a given pair of coordinates applies the multi-quadratic interpolation technique (Chaplot et al., 2006) with the values of the nine nearest cells. These methods are used to interpolate grid values for a resulting HexASCII type grid.

Lastly there is the `HASC` class, the concrete implementation of the HexASCII file format. It adds three properties: (i) `side` - the length of an hexagonal cell side; (ii) `hexPerp` - the distance between two parallel sides of a cell; and (iii) `angle` - the angle of rotation of the grid. The `hexPerp` property is required in various calculations (e.g. cell area, cell centroids), thus it keeps the value at hand avoiding its constant computation. An important difference from the ESRI ASCII *raster* file format to HexASCII is grid positioning. While in the HexASCII format the positional coordinates (the `xll` and `yll` properties) refer to the centre of the lower left cell, in the ESRI format these coordinates refer to the lower left corner of the lower left cell.

The `HASC` class also introduces a few methods. The `init()` method is again redefined to set up the class specific properties. The `getCellCentroidCoords()` method returns the cartographic location of a cell, given its discrete coordinates (column and row). The `saveAsGML()` method persists the mesh instance as a vector file using the Geography Markup Language (GML) (Burggraf, 2006), a standard maintained by the Open Geospatial Consortium (OGC). This method creates an hexagonal polygon for each grid cell, to which is assigned an attribute named `value` with the respective cell value. A similar output is produced by the `saveAsGeoJSON()` method, but producing a vector file using the GeoJSON language (Butler et al., 2008).

## 4 COMMAND LINE TOOLS

Using the API described above, a number of command line tools are made available with `hex-utils` to perform basic operations with HexASCII grids; each one is detailed below.

### 4.1 `asc2hasc`

This tool provides a simple mean to create an hexagonal *raster* from an existing square *raster*. It calculates the geometry of the resulting hexagonal mesh and uses either the nearest neighbour or the multi-quadratic interpolation techniques to calculate its values (using the `getNearestNeighbour()` and `interpolMultiquadratic()` methods of the `ASC` class).

The `asc2hasc` tool functions in two distinctive modes: either preserving cell area (using the `-a` flag) or preserving spatial resolution (`-r` flag). In the first mode the resulting hexagonal cells are conceived to have the same area of the original squares; this means a larger number of cells in the resulting hexagonal mesh. In the `-r` mode the resulting hexagonal cells are 13.4% larger than the original squares. This last mode does not preserve entirely the same spatial resolution, since the interpolation itself induces a certain loss of signal detail. From this hexagonal cell area parameter is derived the hexagonal cell side ($S_h$), a key element in the ensuing calculations.

The following step is the computation of the number of columns and rows in the resulting mesh. The number of columns is calculated as the minimum number that can entirely cover the horizontal span of the grid, as given in the following expression:

$$C_h = \left\lceil \frac{C_s S_s}{3S_h/2} \right\rceil \qquad (1)$$

Where $C_h$ is the number of columns in the hexagonal grid, $C_s$ the number of columns in the square grid, $S_s$ the side of the input square cells and $S_h$ the side of the resulting hexagonal cells. $3S_h/2$ is the distance between two opposite vertices of the hexagonal cell. The application of the ceiling operation guarantees that all square cells are covered in the horizontal sense.

This computation is not as straightforward for the number of rows, since there is a vertical displacement of $3S_h/2$ between two consecutive columns in a North-South hexagonal grid (where two sides of each hexagon are parallel to the $xx$ axis). To save space, the option in this case is to cover only partially the input square cells at the bottom row; the number of rows is thus calculated as follows:

$$R_h = \left\lceil \frac{R_s S_s}{\sqrt{3} S_h} \right\rceil \qquad (2)$$

Where $R_h$ is the number of rows in the hexagonal mesh and $R_s$ the number of rows in the square grid.

The resulting mesh is positioned in space with the number of rows in mind. Even columns are set in order to cover exactly the top square row; odd rows thus miss partially the bottom square row. This bottom sleave uncovered by odd rows is at most $\sqrt{3}S_h/4$ in height. The concrete coordinates of the lower left hexagonal centroid are thus computed as:

$$x0_h = x0_s + S_h/2 \qquad (3)$$

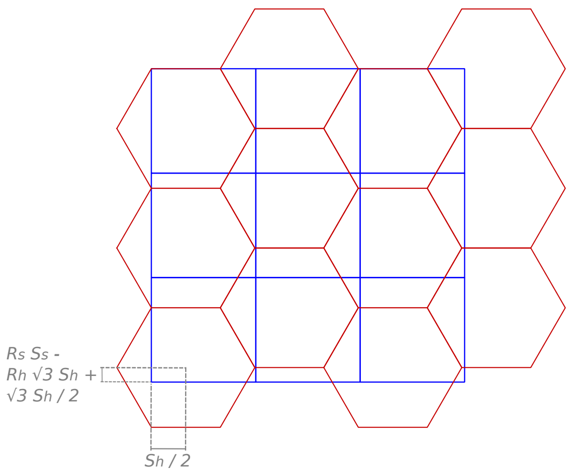


Figure 3: Positioning of an HASC grid relative to the square grid of origin.

$$y0_h = y0_s + R_s S_s - R_h \sqrt{3} S_h + \sqrt{3} S_h/2 \qquad (4)$$

Where the pair $(x0_s, y0_s)$ are the coordinates of the lower left corner of the square grid and $(x0_h, y0_h)$ the centroid coordinates of the lower left hexagonal cell. Figure 3 exemplifies these calculations.

The resulting hexagonal mesh covers as much as possible of the original square without exceedingly exaggeratedly the original extent. This option "by excess" means extra extents along the margins of the original grid. The top half of the top cells in odd columns and part of the bottom of cells in even columns lay beyond the extent of the original grid[7]. The leftmost column can exceed the original extent by as much as $3S_h/2$.

Beyond the arguments determining cell dimensions, the `asc2hasc` tool takes also the `-m` flag defining which interpolation technique to use. Two options are available: `mq` for multi-quadratic interpolation and `nn` for the nearest neighbour. Finally, the flags `-i` and `-o` provide the paths to the input ESRI ASCII square *raster* and the output HexASCII file. An example of use:

```
asc2hasc -r -m mq -i /path/to/input.asc
 -o /path/to/output.hasc
```

## 4.2 csv2hasc

This tool creates a new HexASCII *raster* from a set of point samples. This is a common operation in GIS, in which users extrapolate a regular mesh over a region of interest from a collection of sparsely located observations. Spatial variables subject to such treatment may be temperature, rainfall, altitude, soil quality, etc.

[7]Note that grid indexing starts with zero, e.g. the leftmost cell columns in Figure 3 are even.

The basic input to the tool is a comma separated values (CSV) file (Shafranovich, 2005), structured in three columns representing in succession: easting coordinate, northing coordinate and observed value. Each row corresponds to an individual observation. Listing 2 provides an example.

Listing 2: Example of a CSV file input to `csv2hasc`.

```
1002.5,845.2,57.3,
1005.1,850.7,66.2,
 998.6,841.9,42.7,
1007.2,852.4,38.9,
```

The user must also declare an area of interest to be covered by the resulting *raster*. This is particularly useful if the observations do not cover exactly the region under study. Additionally, the desired cell geometry must be specified too. These inputs are provided to the tool through a set of arguments:

`-x` : the bottom *x* coordinate of the area of interest.

`-y` : the left *y* coordinate of the area of interest.

`-X` : the top *x* coordinate of the area of interest.

`-Y` : the right *y* coordinate of the area of interest.

`-s` : the length of the cell side in the resulting grid.

`-i` : path to the input CSV file.

`-o` : path to the output HASC *raster* file.

The output hexagonal mesh is dimensioned and positioned in the Cartographic space using the same process described in Section 4.1 and exemplified in Figure 3. The values of the new HexASCII *raster* are interpolated using the multi-quadratic method, applied to the five samples closest to each cell centroid. An example of usage:

```
csv2hasc -x 0 -y 0 -X 2000 -Y 2000
 -s 0.62 -i input.csv -o output.hasc
```

## 4.3 `surface2hasc` and `surface2asc`

In order to assess the comparative performance of hexagonal and square *rasters* of similar spatial resolution two tools where developed that sample directly a given continuous surface. With these tools a same method or process can be applied on equivalent *rasters* to investigate different results between hexagons and squares. Sampling directly a continuous surface avoids the signal losses that would occur interpolating from an existing *raster* or from a set of sparse observations.

As their name imply, `surface2hasc` produces an HexASCII *raster* and `surface2asc` an ESRI ASCII grid. They require a series of inputs that declare the spatial extent to sample, the geometry of the resulting mesh and identify the location of the surface function. Each of these inputs is provided with a specific argument:

`-x` : the bottom *x* coordinate of the extent to sample.

`-y` : the left *y* coordinate of the extent to sample.

`-X` : the top *x* coordinate of the extent to sample.

`-Y` : the right *y* coordinate of the extent to sample.

`-s` : the length of the cell side in the resulting grid.

`-m` : the Python module containing the surface function.

`-f` : the name of the surface function.

`-o` : path to the output *raster* file.

The tool starts by calculating cell geometry and then positions a mesh overlapping the extent declared. In the hexagonal case the same "by excess" approach employed in the `asc2hasc` tool is applied. The surface function is then imported; it is assumed it resides in a reachable Python module, declared with the `-m` argument. The function is assumed to take in two arguments, the easting and northing coordinates, and to return a numerical value [8]. Figure 4 presents an example surface and the resulting HexASCII grid produced with the following command:

```
surface2hasc -x 0 -y 0 -X 2000 -Y 2000
 -s 19.6 -m surfaces.surfaceGaussian
 -f fun -o output.hasc
```

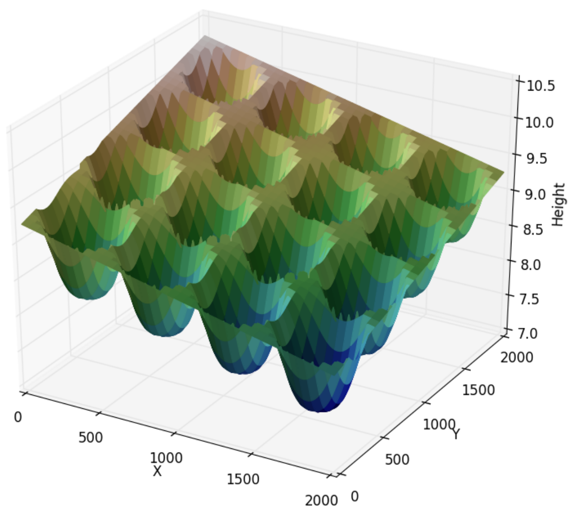
## 4.4 `hasc2gml` and `hasc2geojson`

The `hasc2gml` tool creates a GML file representing the input HexASCII *raster*. For each cell of the *raster* a polygon feature is created in the GML file with its exact geometry. To each feature is assigned an attribute named *value* containing the value of the corresponding HexASCII cell. The resulting GML file is usually thirty times larger than the original HexASCII, stressing the usefulness of the latter as a portable file format.

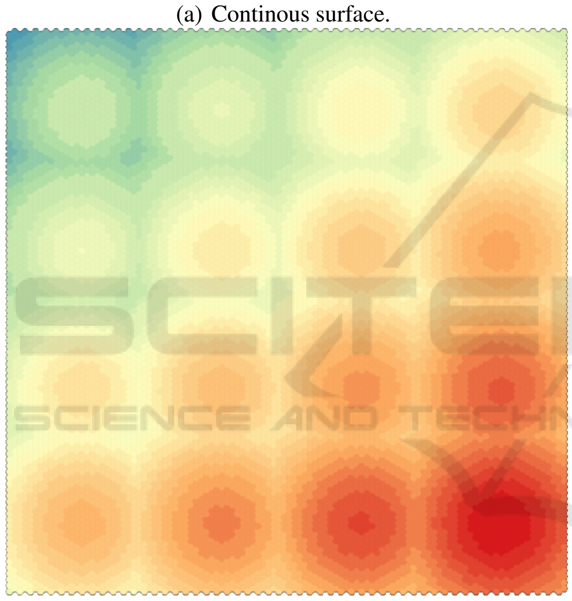
`hasc2gml` uses directly the `loadFromFile()` and `saveAsGML()` methods of the `HASC` class. It takes no additional arguments, beyond the paths to the input and output files. The following exemplifies its use:

```
hasc2gml /path/to/input.hasc
 /path/to/output.gml
```

[8] A few surface examples are available at the GitHub repository, in the `surfaces` package.



(a) Continous surface.



(b) HASC displayed as a GML layer in QGIS.

Figure 4: A sample surface and the resulting HASC grid displayed in QGIS.

The `hasc2geojson` tool is in all similar, with the difference being the output data format, GeoJSON (Butler et al., 2008) in this case. This data format requires in general one third less disk space than GML; still it requires some twenty times the space used by the original HexASCII.

```
hasc2geojson /path/to/input.hasc
 /path/to/output.json
```

The purpose of these tools is to facilitate the visualisation of HexASCII grids in traditional GIS desktop software. The resulting GML or GeoJSON files can be seamlessly loaded into one of such programmes and there be subject to styling with choro-

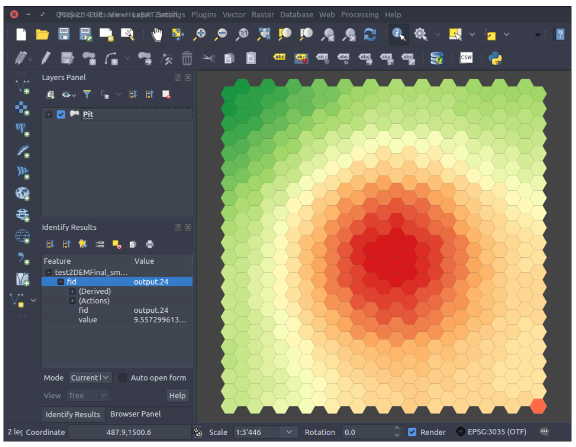


Figure 5: An HASC *raster* displayed through a GML layer in QGIS.

pleths, feature selection, feature inquiring, geometrical assessment and so forth. Figure 5 portraits a GML file created from an HexASCII *raster* displayed in QGIS (Team et al., 2013).

## 5 SUMMARY AND FUTURE WORK

In spite of their well known advantages over traditional square grids, hexagonal *rasters* are yet to be adopted as a common data structure in GIS. Such evolution is unlikely to happen without tools facilitating the use of this space partitioning pattern. The `hex-utils` tool-kit is a first step in this direction, towards the ultimate goal of making hexagonal meshes as easy to use as their squared counterparts in GIS.

The `hex-utils` tool-kit comprises a basic API and a set of command line tools providing essential functionality to manipulate HexASCII *rasters*. They make possible the creation of hexagonal *rasters* and their visualisation in desktop GIS software. The API can be the basis for the development of further software supporting hexagonal *rasters*.

The next steps towards a simplified use of hexagonal *rasters* will have to address data acquisition, with mechanisms to translate other common spatial data sources into hexagonal *rasters*. Tools to transform LiDAR point clouds or to discretise vectors into HexASCII *rasters* are therefore natural extensions to the `hex-utils` tool-kit. Another step concerns the development of hexagonal map algebra tools; a prototype previously developed in the C# language (de Sousa, 2006) is a candidate to be integrated into the tool-kit.

Modern GIS software has become increasingly easy to evolve and extend. The development of advanced tools and data structures, such as `hex-utils` and the HexASCII file format, is today not only simpler, but also easier to reach by a wide range of potential users. All elements seem to be in place for hexagonal *rasters* to finally start entering the mainstream GIS.

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