Geographical Information Systems
Dam and Watershed analysis
Mini Project Report

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Abstract

Geographical information systems (GIS) are proving to be very valuable tools in many natural resources applications such as hydrological modeling of terrain for water harvesting, visualization of different aspects of watershed etc. The basic entity in such applications is the watershed which is either manually delineated on topographic map sheets or derived from digital elevation model (DEM) data using computational methods. The construction of dam is a major part in watershed analysis. In rural India this is a major procedure for removing the scarcity of water during different seasons. A visual tool for constructing dam, checking water storage and catchments is implemented during the course of this project, and this tool is made compatible with the raster analysis module of the Windows based GRAM++ GIS, developed at Centre of Studies in Resources Engineering, Indian Institute of Technology, Bombay, India. The module is tested for the area of Belachiwadi and Gudwan, the two small hamlets of Raigad district, Mumbai.

In this report a brief description of various procedures and implementation is discussed. Calculation of water flow, storage and visualization of catchments is done in the first part. Next we discuss the various calculations regarding the construction of dam, its parameters and compare it with the parameters of dam of the two sites.

Keywords DEM, Flow Direction, Pour Point, Stream Order, Water Storage, Catchment Area.
Contents

1 Introduction: .............................................. 1
   1.1 Overview of Project .................................. 1
   1.2 Brief description of GRAM++: .......................... 1
   1.3 Outline of this report ................................ 1

2 Getting Started ........................................ 2
   2.1 Various Definitions ................................... 2
      2.1.1 GIS analysis: ...................................... 2
      2.1.2 Watershed .......................................... 2
      2.1.3 Digital Elevation Model (DEM) ..................... 2
      2.1.4 Raster Model ...................................... 2
      2.1.5 Tin Model .......................................... 2
      2.1.6 Scale Factor ...................................... 3
      2.1.7 Digitizing the Map ................................ 3

3 Water Delineation and Calculation of Drainage ............ 4
   3.1 Various Steps in Watershed Delineation ................. 4
      3.1.1 Removing sinks .................................... 4
      3.1.2 Removing flat areas ............................... 5
   3.2 Assigning flow directions ............................... 5
   3.3 Finding flow accumulation .............................. 6
   3.4 Apply Threshold ...................................... 6
   3.5 Pour Point Calculation ................................. 6
   3.6 Watershed Delineation ................................ 6

4 Constructing a Dam ...................................... 7

5 Storage Calculation ..................................... 7
   5.1 Algorithm for storage .................................. 7
   5.2 Validation of correctness and test ..................... 7

6 Catchment Calculation .................................. 10
   6.1 Algorithm for Catchment Calculation ................... 10
   6.2 Validation ............................................ 10

7 Visualization of map after dam construction ............... 10

8 Various Calculation regarding the dam ..................... 14
   8.1 Volume of dam ........................................ 14
   8.2 Surface Area calculation ................................ 15

9 Field Work during Project and Implementation .......... 16

10 Conclusion ............................................ 17

11 Acknowledgments ...................................... 17

12 References: ........................................... 18
## List of Figures

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Generating Tin Model from Spot Heights</td>
<td>4</td>
</tr>
<tr>
<td>2</td>
<td>Flow Directions</td>
<td>5</td>
</tr>
<tr>
<td>3</td>
<td>Inflow of Water to a Particular Cell</td>
<td>10</td>
</tr>
<tr>
<td>4</td>
<td>The raster image of an area</td>
<td>11</td>
</tr>
<tr>
<td>5</td>
<td>Drainage and Water Flow</td>
<td>12</td>
</tr>
<tr>
<td>6</td>
<td>Constructed dam and water storage</td>
<td>12</td>
</tr>
<tr>
<td>7</td>
<td>3D Visualization of relief after dam construction</td>
<td>13</td>
</tr>
<tr>
<td>8</td>
<td>The Cross Section of a Dam</td>
<td>14</td>
</tr>
<tr>
<td>9</td>
<td>Storage of dam in Belachiwadi Area</td>
<td>16</td>
</tr>
</tbody>
</table>
1 Introduction:

1.1 Overview of Project

During the course of this project we had to develop a visual tool that makes it feasible to draw and visualize different aspects of watershed and construction of dam. Our main focus were the two dam sites of Belachiwadi and Gudwan where dam are going to be constructed soon. This tool enables it to make the dam over different parts and visualize the storage, catchments etc. It also calculates the approximate volume and surface area of dam.

1.2 Brief description of GRAM++:

GRAM++ is a Geographic Information System software package developed indigenously at the Centre of Studies in Resources Engineering, IIT Bombay. The software is organized as a number of modules including Import/Export of different format data, Map Editing, Raster Analysis, Vector Analysis, Network Analysis, Terrain modeling and watershed delineation, Digital Image Processing, and Map Layout. Support for Survey of India.s Digital Vector Data (DVD) format is added to the package to enhance the functionality in the Indian environment.

1.3 Outline of this report

In this report we first discuss the algorithm for delineating drainage and watersheds from Digital Elevation Model. This algorithm finds the flow of water from a point and thus calculates the drainage for a given map. If we are given a map of an area and we are required to make a dam over some channel of drainage, then the water storage due to that dam is calculated and a visual image in 2D or 3D is generated. Later we have discussed the visualization of catchment area. These algorithm for calculating the coverage and catchment makes it feasible to select an optimal dam site for that area. In the later part various calculations regarding the dam and practical usage of tool is discussed. The outcome of this tool is tested over the map of areas of two dam site of Belachiwadi and Gudwan.
2 Getting Started

2.1 Various Definitions

2.1.1 GIS analysis:

GIS analysis is a procedure for looking at geographical patterns in our data and the relationships between its features. A GIS is a system of hardware, software and procedures to facilitate the management, manipulation, analysis, modelling, representation and display of georeferenced data to solve complex problems regarding planning and management of resources.

All GIS software has been designed to handle spatial data, characterized by information about position, connections with different features and details of non-spatial characteristics.

2.1.2 Watershed

A watershed is normally described as the total area of water flowing to a given outlet point or more often known as pour point. The boundary between two adjacent watersheds is the drainage line. Pour point is the point at which the water flows out of the area. This is the lowest point in elevation along the boundary or the drainage lines. Delineation of watersheds depends on the catchment drainage pattern of the watershed. This in turn depends on the relief of the area considered.

2.1.3 Digital Elevation Model (DEM)

Digital elevation model is a matrix in which the elevations are given as different points equally spaced in horizontal and vertical directions. For most of the parts of the earth's surface, elevation data exist in analogue form as contour maps. These contour maps are converted into digital contour files and spatial interpolation procedures are applied to interpolate elevation values from irregularly spaced points to regular grid points

2.1.4 Raster Model

With the raster model, features are represented as a matrix of cells in continuous space. Each cell contains the height of that point on earth. For our implementation we have taken this as input file. The cell size we use for a raster layer affects the result of analysis and how the map looks.

2.1.5 Tin Model

For representation of terrain, an efficient model is the Triangulated Irregular Network (TIN), which represents a surface as a set of non-overlapping contiguous triangular faces, of irregular size and shape. In TIN model the surface is modelled in such a way that the vertices of each triangle are on the surface of area.
2.1.6 Scale Factor

The scale factor is defined as the ratio of one standard unit of digitized map to the standard unit of earth. For example if the toposheet have the scale of 1 : 1000 i.e. 1 cm of toposheet is equal to the 1000 cm of earth. So with this scale if the toposheet is mapped to the n cell of raster image in x-direction then the scale factor for the image is:

\[1 \text{ cell} = \frac{1000}{n} \text{ cm}\]
on earth in x-direction. Similarly the scale factor is defined in y-direction.

2.1.7 Digitizing the Map

The first step for any GIS application is to get the toposheet or the map of that area digitized. Conversion of map into intelligent maps is most accuracy deprives and time consuming job of any GIS project to implement. The digitized format of map may be in many formats as for example Vector model, Tin model, Raster model etc. For our implementation the digitized map taken as input is in the raster format. This raster format of map can be generated by any one of the following methods:

1. **Digitizing through spot heights** In reference to maps, spot height is defined as the height of various places of the region. So for the digitization we require the map of area with heights (above sea level) of different places. The quality of digitized image depends upon the number of spot heights and their distribution over the area. These spot heights are given as input as a different layer of map to GRAM++ package, from there the TIN model is generated [3]. The fundamental idea behind the generation of TIN from the spot heights is, there may be only one circle passing through three different points. The triangles are made in such a way that none of the points lie inside the other triangle. This is shown in figure 1. After generating the Tin model contour map is generated from this model and from this contour map the raster file is generated.
2. **Digitizing through contour map/toposheet** Through the scanned image of toposheet the contour map is made as a different layer in GRAM++. The contour layer is to be mapped according to the toposheet. The scale is also given as input that gives the variation between contours in map. This contour map is then converted to input raster file for our tool.

3. **Water Delineation and Calculation of Drainage**

The input data was available in the form of a raster grid, with each cell value being the elevation above Mean Sea Level. In many cases, the area for which the data was available was not rectangular in shape. Hence, cells for which no data is available were given a special "no data" value. A high negative value was used as the "no data" value. If input raster is of size \((m, n)\), the raster actually used will be of size \(((m + 2), (n + 2))\). Rows 0 and \(m+1\), along with columns 0 and \(n+1\), will consist entirely of no-data cells. The actual data cells will be within the rows and columns \(1\ldots(m)\) and \(\ldots(n)\).

3.1 **Various Steps in Watershed Delineation**

3.1.1 **Removing sinks**

**Sink:** A sink (or depression) is a cell or a group of cells which is at a lower elevation than all its neighboring cells. If the cell has at least one cell adjacent to it, at a higher elevation, and no cells adjacent to it at a lower elevation then it is said to be **inflow sink**. Sinks occur due to error in measurement and are actually may not present. Hence sinks have to be removed.
So they are converted to flat areas.

3.1.2 Removing flat areas

This step takes the drainage map and delineates the watershed around this drainage. What this means is demarcating the area around a stream which flows into that particular stream. The outlet point is selected which is to be delineated. The pour points that eventually flow into this outlet are also delineated.

3.2 Assigning flow directions

After all sinks and flat areas are removed, flow directions are determined for the D.E.M., resulting in a grid (called FD), containing the flow direction for each cell. The basic principal for assigning flow directions is given as: From a cell, water flows to the neighboring cell that has the highest positive distance-weighted drop. Flow directions are encoded according to the figure 2

![Figure 2: Flow Directions](image)

For each cell C (at [i,j]) in the D.E.M., the following steps are performed:

1. Calculating the distance weighted drop to neighbouring cells:
   The distance-weighted drop to a neighbouring cell is defined as:
   
   \[
   \text{Drop} = (\text{Value of cell } C - \text{Value of the neighbouring cell}) / \text{Distance to the neighbouring cell}
   \]
   For cells which are horizontally or vertically adjacent to C, \(d = 1\)
   For cells which are diagonally adjacent to C, \(d = \sqrt{2}\)

2. The cell FD [i,j] is given the direction code of the neighbouring cell with the largest positive weighted drop.
   A special case is when the largest positive weighted drop occurs in more than one direction. In this case, the cell FD[i,j] is given the sum of the direction codes of all the directions in which the largest positive weighted drop occurs. The resulting code is called a combined direction code.

3. If the cell is a nodata cell the the Flow direction value is set as \(-1 \times 10^{4}\).
After the above steps, some cells in FD have a combined direction code. These are the cells for which the largest positive weighted drop occurs in more than one direction. These cells are assigned a single direction code using a lookup table.

3.3 Finding flow accumulation

After flow directions are assigned, the flow accumulation for each cell is calculated. The flow accumulation value of a cell is the sum of the flow accumulation values of the neighbouring cells which flow into it.

\[
\begin{array}{cccc}
32 & 64 & 64 & 128 \\
16 & 8 & 16 & 1 \\
16 & 1 & 1 & 1 \\
8 & 4 & 4 & 2 \\
\end{array}
\]

Table 1: An example for flow direction

\[
\begin{array}{cccc}
0 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 \\
2 & 0 & 1 & 2 \\
0 & 0 & 0 & 0 \\
\end{array}
\]

Table 2: The resultant flow accumulation

3.4 Apply Threshold

This step takes as input the output of the Flow Accumulation step. This is done to find out all pixels having a Flow Accumulation value above a certain value. This value is supplied by the user. This step is performed by comparing all the values with the specified value and all values which are greater than the input value are given a pre decided output value and stored in another file.

3.5 Pour Point Calculation

This step is performed to calculate the points on the streams that indicate that it is flowing into another stream.

3.6 Watershed Delineation

This step takes the drainage map and delineates the watershed around this drainage. What this means is demarcating the area around a stream which flows into that particular stream. The outlet point is selected which is to be delineated. The pour points that eventually flow into this outlet are also delineated.
4  Constructing a Dam

In previous section we have seen how to calculated the flow direction of an input raster image. The watershed is delineated and the flow of water in the form of drainage is shown. This is called as burning of DEM file. After the above procedure drainage flow of water is calculated for various points on the stream. This enables us to select the suitable point over the stream to construct the dam. These two points are selected by the user and various parameters are provided to construct the dam. The maximum height of dam is calculated according to the two points. The various parameters that are to be supplied are:

- Aspect Ratio.
- Width of top of dam.
- Height of dam (this height should be less than maximum height).
- The scale factor corresponding to the x-axis and y-axis.
- Foundation depth.

After giving the above parameters the dam is constructed over the map and the new modified area is stored, through which the storage and catchment can be calculated. In this new map the elevation of points is raised to the height of dam so that the new modified geographical image can be viewed. The volume, surface area, end points of dam for this height and spill height is also estimated for this construction.

5  Storage Calculation

The storage of dam is the amount of water that is stored in the dam. From the raster image the number of cell that is covered with water is found. This number of cells when multiplied with cell area gives the storage of water. For calculation of coverage area take the center point and go on visiting recursively all those neighbors whose height is less than the dam height and is connect to the center cell through other cells. The base case for this algorithm will be the boundary condition or finding the cell whose all non visited neighbor have height more than the dam height.

5.1 Algorithm for storage

The algorithm for calculating the storage is given in Algorithm 1.

5.2 Validation of correctness and test

All those points which are at height more than the dam height will not be covered with water. And hence will not be shown in visualization. All the points that are connected to the center point and height lesser than the height of dam will be found by above algorithm and will be shown in visualization. The cell area is calculated based on the scale factor given by the user and the volume of water stored is (cell area \times number of cell).

The result calculated for the dam site of Belachiwadi and Gudwan are:
Algorithm 1 Storage Calculation

1: I: float height; \{height is the height of dam\}
2: int xc, yc \{xc,yc is the center point to be selected by user\}
3: \([n, m] = \text{size(Raster Image)}\) \{n is the size of row, i.e. the maximum size of y and m is the size of column i.e. the maximum size of x in raster image\}
4: for \(i = 0\) to \(m + 1\) do
5:   for \(j = 0\) to \(n + 1\) do
6:     \(\text{coverage-colour}[i][j] = 0\)
7:     \(\text{cell-colour}[i][j] = 0\) \{initialize each to zero\}
8:   end for
9: end for
10: NOTE: \{coverage-colour = 0 if the cell is not in the storage of dam. For the boundary condition assign all the boundary point of Raster image to -1. For finding the storage search for all those cells that are connected to the center point and having height less than dam. These point will be in the coverage part of dam. Search for each neighbor if it is inside the coverage of dam.\}
11: The value of cell-colour is:
12: cell-colour = 1 if the cell is currently performing the search.
13: cell-colour = 2 if search is complete for this cell. \{The function set-colour performs the search for storage cell\}
14: set-colour(xc,yc)
15: 2: FUNCTION set-colour(int x, int y)
16:   \(\text{cell-colour}[x][y] \leftarrow 1;\)
17:   do for neighbor \((x - 1, y), (x + 1, y), (x, y - 1)\) and \((x, y + 1)\):
18:     if cell-colour[neighbor] \(\neq 0\) and height of neighbor \(\leq\) height of dam then
19:       set-colour[neighbor] \{go on calling recursively unless find a base case\}
20:   end if
21: end function
22: 3: for all cells
23: if coverage-colour[i][j] = 1 then
24:   The point is in the storage of dam. So for visualization set the colour of this pixel different
25: end if
1. Belachiwadi:

- The cell area is 0.16 sq. m. for Belachiwadi (This is regarding the cell of raster map used in Gram++)
- The maximum height of dam is 99.5 m above sea level.
- The bed of river is 93.3 m above the sea level.

Therefore at different heights:

<table>
<thead>
<tr>
<th>Height</th>
<th>Volume of water</th>
</tr>
</thead>
<tbody>
<tr>
<td>94</td>
<td>16.8 cu. m</td>
</tr>
<tr>
<td>95</td>
<td>298 cu. m</td>
</tr>
<tr>
<td>96</td>
<td>1127 cu. m</td>
</tr>
<tr>
<td>97</td>
<td>3334 cu. m</td>
</tr>
<tr>
<td>97.5</td>
<td>5000 cu. m</td>
</tr>
<tr>
<td>98</td>
<td>7060 cu. m</td>
</tr>
<tr>
<td>98.5</td>
<td>9100 cu. m</td>
</tr>
<tr>
<td>99</td>
<td>11757 cu. m</td>
</tr>
</tbody>
</table>

Table 3: Volume of water in Belachiwadi

2. Gudwan:

- The cell area is 0.16 sq. meter (This is regarding the cell of raster map used in Gram++)
- The base level of river is 93.5 m above sea level.
- The maximum height of dam is 99.5 meter.

<table>
<thead>
<tr>
<th>Height</th>
<th>Volume of water</th>
</tr>
</thead>
<tbody>
<tr>
<td>95</td>
<td>61 cu. m</td>
</tr>
<tr>
<td>96</td>
<td>506.4 cu. m</td>
</tr>
<tr>
<td>97</td>
<td>1870.56 cu. m</td>
</tr>
<tr>
<td>97.5</td>
<td>2837.28 cu. m</td>
</tr>
<tr>
<td>98</td>
<td>4542 cu. m</td>
</tr>
<tr>
<td>98.5</td>
<td>6237 cu. m</td>
</tr>
<tr>
<td>99</td>
<td>7210 cu. m</td>
</tr>
<tr>
<td>100</td>
<td>11600 cu. m</td>
</tr>
<tr>
<td>101</td>
<td>13248 cu. m</td>
</tr>
</tbody>
</table>

Table 4: Volume of water in Gudwan

(The heights at 100 and 101 m are found after extending the end points of dam, as they were more than maximum height between the selected points.)
6 Catchment Calculation

The catchment of dam is defined as the area through which the inflow of water occurs into the dam. Therefore for any cell x the flow of water will be in this cell if the flow direction of neighboring cell are given in figure ??

![Inflow of Water to a Particular Cell](image)

Figure 3: Inflow of Water to a Particular Cell

Thus for all boundary cell of storage map check if the flow of not visited neighboring cell is into this cell then go that cell and find all those cell whose flow is into this cell. Similarly go on visiting the entire neighboring cell whose flow is towards the storage area. The base case for this will be finding boundary condition or finding a cell whose none of the neighbor flows into this cell. The corresponding algorithm is shown in algorithm 2. The inflow map is the map for a cell giving the value of its neighboring cell from which inflow to this cell can occur.

6.1 Algorithm for Catchment Calculation

The basic algorithm used to calculate the catchment of dam is given in Algorithm 2.

6.2 Validation

For the entire cell on the boundary of coverage area we are recursively finding those entire cells from which the water will flow into this cell and through this cell into the storage area of dam. Thus all these area will result into the catchment of dam.

7 Visualization of map after dam construction

The visualization of raster map and drainage is given in figure 4 and figure 5. Figure ?? shows a sample input raster image of an area for which the drainage is to be found and dam is to be constructed. The corresponding drainage area is shown in figure 5. These are the raster mage before the construction of dam. After construction of dam the map of area has been edited and the new map in raster form with dam constructed and water storage is shown in figure 6 and corresponding 3D visualization of the relief map is shown in figure 7.
Algorithm 2 Catchment Calculation

```c
int x,y;
2: fd[x][y] is the flow direction matrix for all cells. {catchment-colour contains the values as:}
   catchment-colour[x][y] = 0 if cell is not visited during search
4: catchment-colour[x][y] = -1 if cell at the boundary of raster amp
   catchment-colour[x][y] = 3 if cell is a storage point
6: catchment-colour[x][y] = 4 if cell is a dam point
   catchment-colour[x][y] = 1 if cell is currently searching its neighbor for inflow of water
8: catchment-colour[x][y] = 2 if for the cell the search for all neighbor cell is completed {for all storage boundary cell}
   catchment(x,y) {function catchment searches and marks all those cell through which the inflow of water occurs to this cell}
1: catchment(x,y)
2: FUNCTION catchment(x,y)
   catchment-colour(x,y) = 1
14: end if
   catchment-colour[neighbor] = 0 and inflow map is valid for neighbor then
   catchment[neighbor]
12: if catchment-colour[neighbor] = 0 and inflow map is valid for neighbor then
   catchment-colour(x,y) = 2
16: end if
   for all cells
   if catchment-colour[i][j] = 1 then
18: The point is in the storage of dam. So for visualization set the colour of this pixel different
   end if
```

Figure 4: The raster image of an area
Figure 5: Drainage and Water Flow

Figure 6: Constructed dam and water storage
Figure 7: 3D Visualization of relief after dam construction
8 Various Calculation regarding the dam

8.1 Volume of dam

Consider the cross section of dam to be constructed as shown in figure 8. Therefore the cross section area of dam can be taken as:

\[ \text{crosssection} = W(H + f) + B(H + 2 \times f) \]

where

1. cross section is the cross section area of dam at some point.
2. W is the width of the top of dam.
3. H is the height of dam above the ground.
4. f is the foundation depth.
5. B is the width at ground.

If the aspect ratio is given as AS then

\[ \text{crosssection} = W(H + f) + \left( \frac{H}{AS} \right)(H + 2 \times f) \]

From the input height we calculate the end points and thus the length of dam using the scale factor in x-direction and y-direction. From the end points we know the starting cell and the ending cell, also the number of cell that will be covered by the dam. Therefore if the above cross section is considered for any cell then the length of dam in a particular cell is:

\[ \text{Length} / (\text{number of cells}) \]

As for a particular cell the height is constant and varies with the variation of cells, therefore the overall volume of dam is:

\[ \text{Volume} = (\Sigma W(H_i + f) + (H_i/AS)(H_i + 2 \times f)) \times \text{Length} / (\text{number of cells in dam}) \]
Therefore if we are given the input parameter as:

- Height of Dam above mean sea level.
- Aspect Ratio
- Width of top of dam
- Foundation depth

Then the volume of dam can be calculated. Here we are assuming that the portion of length dam is equal in each cell (cell actually corresponds to the pixel value of screen). As for a visual tool the further division of pixel is not possible so this approximation can result to some errors in calculation, which can be neglected as it may not be significant.

8.2 Surface Area calculation

For the parameters as above, the perimeter of cross section is

\[ PM = W + 2 \times \sqrt{(H^2 + B^2)} \]
\[ PM = W + 2 \times \sqrt{H^2 + (H/AS)^2} \]

Therefore the surface area of dam will be given as

\[ SA = \Sigma((W + 2 \times \sqrt{(H_1)^2 + ((H_1)/AS)^2)} \times \text{Length/number of cells in dam}) \]

Thus the surface area and volume of dam can be calculated once the input parameter is given along with the scale factor of x-axis and y-axis.

9 Field Work during Project and Implementation

The two dam site where the construction of dam is to be started soon are Belachiwadi and Gudwan dam site. CTARA and the Academy of Development Science, Kashele (henceforth ADS) plan to construct small dams in these hamlets. The main objective of these dams is to hold enough water so that drinking water needs for the villagers and their livestock are met for the whole year. These two dam sites were the major area of consideration for my project. We have developed a visualization tool that will prove to be useful for the various aspects of making dam. Figure 9 shows the storage of dam in Belachiwadi area.
Figure 9: Storage of dam in Belachiwadi Area
10 Conclusion

In this report I have tried to give a brief overview of the algorithms used during the implementation of water catchment, coverage and construction of dam to the software GRAM++. We have also given some results for the test case of Belachiwadi and Gudwan dam site.

11 Acknowledgments

I would like to thank my guide, Prof. Milind Sohoni for his invaluable motivation and direction fed in my work. His guidance and suggestions given during the course of this seminar have been extremely helpful. I would also like to thank Mr. Mayur Pandya and Prof. P.Venkatachalam of CSRE for their assest during the course of project.

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