Giuseppe Cosentino & Francesco Pennica

GEOLOGY TOOLS

Version 0.2

2026

Geology Tools (Version 1.0, 2026) describes a suite of QGIS plugins developed by *Giuseppe Cosentino*[1] and *Francesco Pennica*[2], designed to streamline geological, hydrological, and seismic microzonation analyses.

The following is a summary of the main modules and their functionalities:

Geology Mapping

The **Geology from points and lines** tool automates the creation of geological maps.

- **Workflow**: The user draws geological contact lines to form closed polygons and places points with geological attributes (formation codes, lithology, etc.) inside them.
- **Automation**: The algorithm cleans duplicate geometries, creates polygons from the line network, and transfers the attributes from the points to the resulting polygons.
- **Output**: Produces topologically clean geological polygons and contact lines ready for GIS analysis.

Hydrology

The **Hydrological Analysis Stream Network (HASN)** module utilizes an integrated approach, leveraging **GRASS GIS** and **SAGA GIS** algorithms for robust watershed analysis.

- **Terrain Correction**: It uses the Wang & Liu algorithm to fill sinks in Digital Terrain Models (DTM), ensuring a hydrologically correct surface.
- **Flow & Indices**: It calculates drainage directions and flow accumulation to derive the **Topographic Wetness Index (TWI)**, which identifies areas prone to saturation and runoff
- **Stream Delineation**: The tool generates a vector stream network from the DTM, offering both a raw version for analysis and a "smooth" version for better cartographic visualization.

Seismic Microzonation

This section includes tools for evaluating ground stability and seismic risk:

- **Lateral Spreading Analysis (LSA)**: Identifies horizontal soil movement risks during earthquakes by crossing the **Liquefaction Index (IL)**with terrain slope percentages. It classifies areas into **Respect Zones (RZ), Susceptibility Zones (SZ)**, or **Low Susceptibility Zones (Z0)**.
- **Seismic Zones with Morphological Gradient (SZMG)**: Identifies areas with slopes > 15° within seismic zones. This is critical because steep morphological gradients can amplify seismic waves and increase the risk of seismic-caused landslides.

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Software installation

Installation is performed directly from the QGIS plugins section (QGIS Plugins Section) by entering the keyword "Geology" in the search box (.Figure 2 Plugin Search and Installation). Once installed, the plugin will be available in the Processing Tools section (Figure 3 QGIS Processing Tools Section).

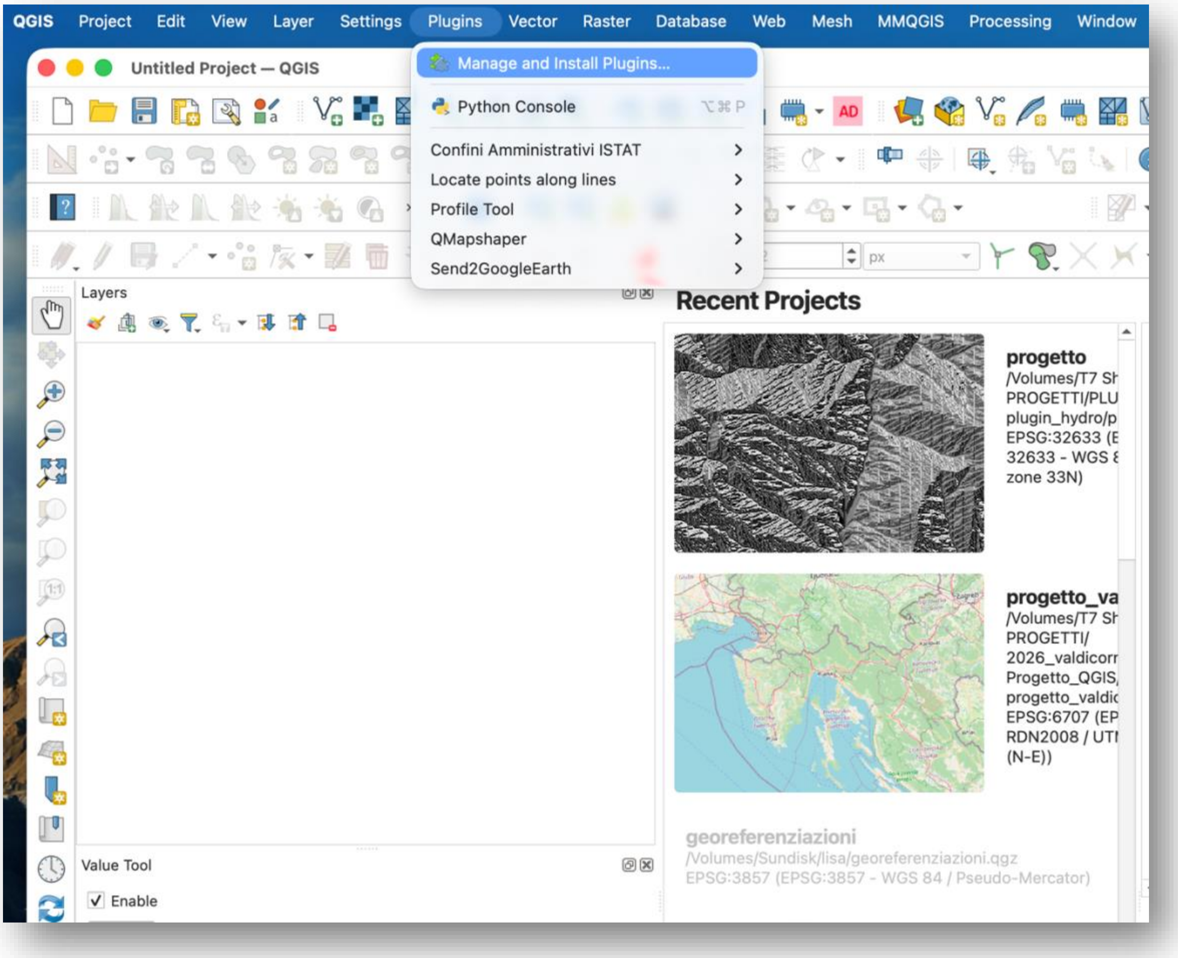

Figure 1. QGIS plugin section

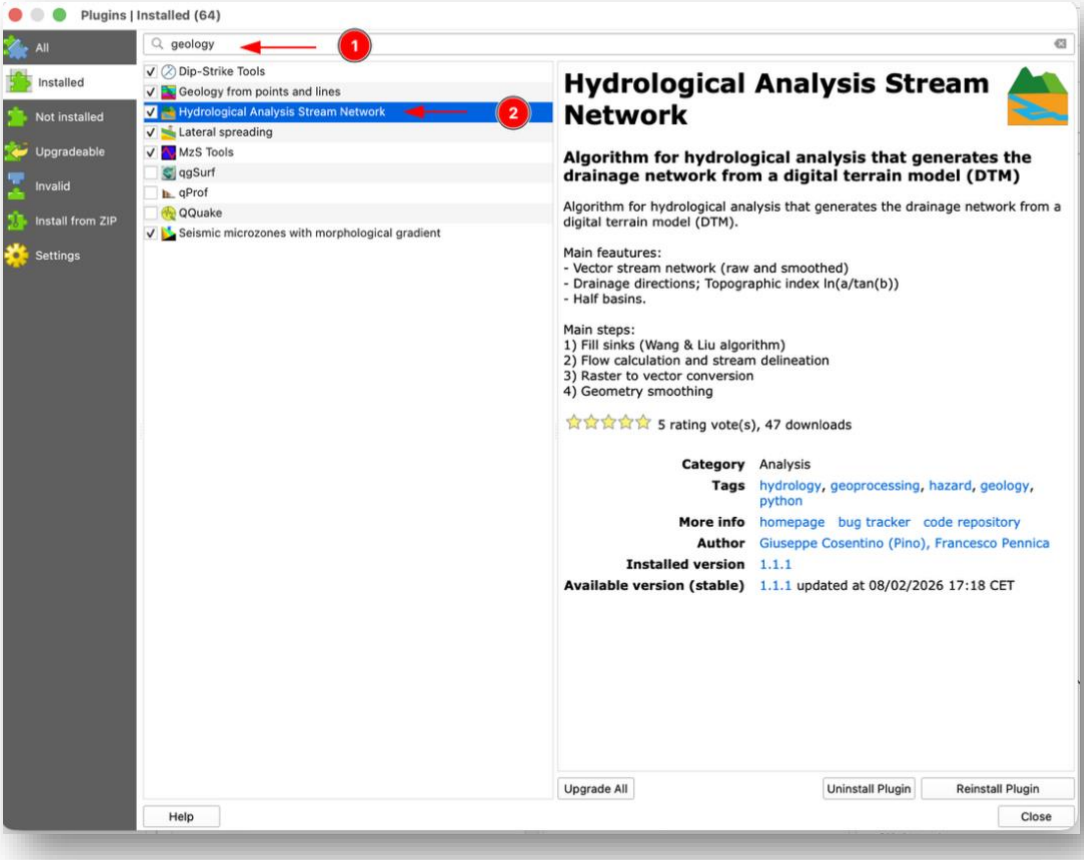

Figure 2. Plugin search and installation

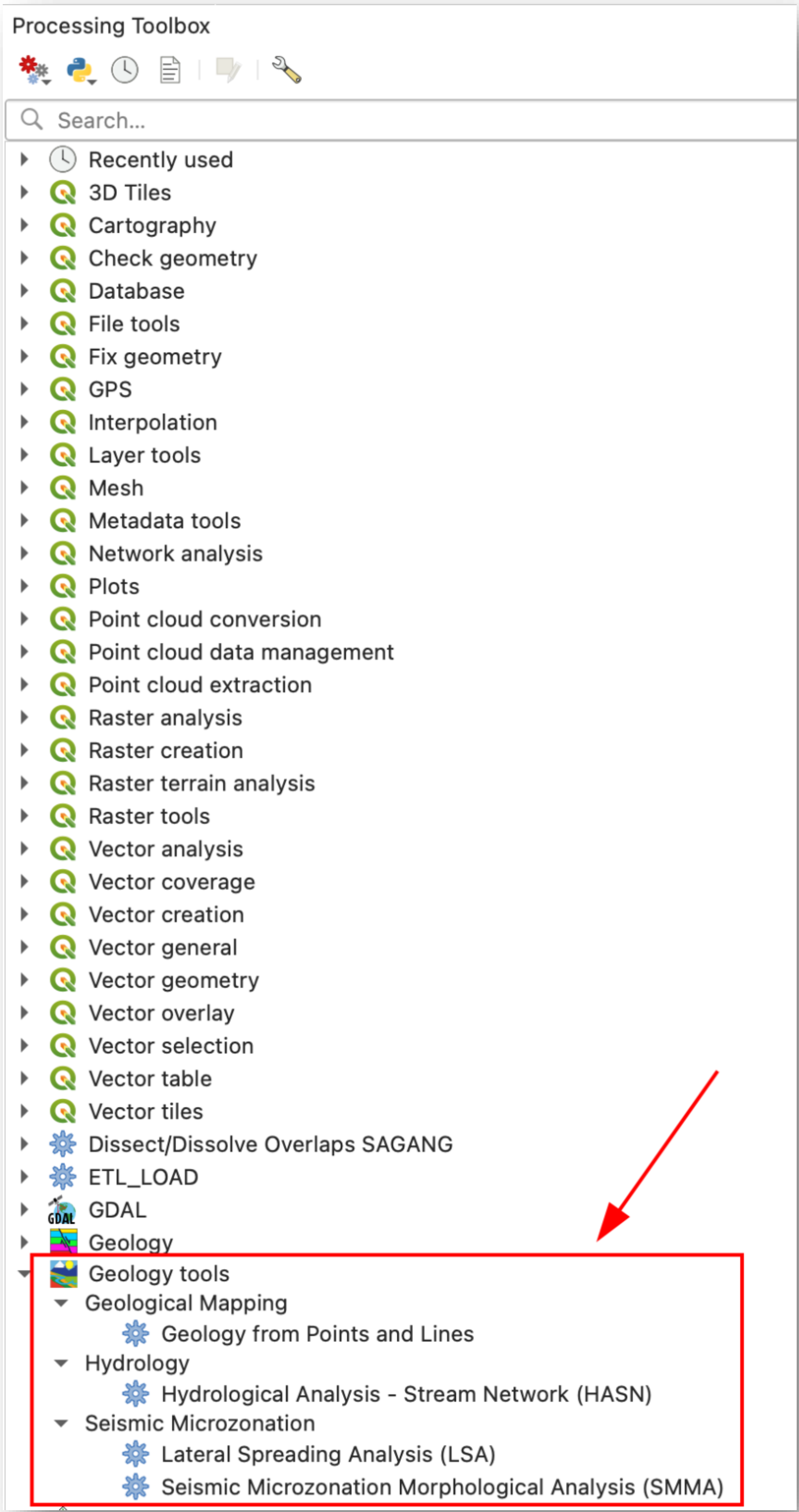

Figure 3. QGIS processing

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1 Geology Mapping

1.1 Geology from points and lines

This QGIS plugin incorporates a GIS methodology for generating topologically correct geological maps from vector point data (centroids with geological attributes) and linear data (geological boundaries). The process involves: converting lines into polygons, spatial join with centroids for attribute inheritance, and topological verification to ensure the absence of gaps, overlaps, and duplicates (Figure 4 Algorithm icon).

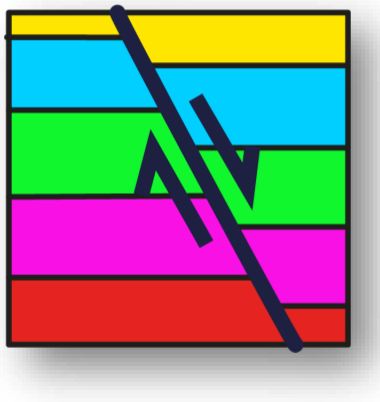

Figure 4. Algorithm icon

Workflow Overview:

- Prepare line data: Draw geological contact lines that intersect or touch to form closed polygons (geological unit boundaries).
- Add point data: Place points inside each polygon with geological attributes such as formation codes, lithology, age, etc.

Run algorithm: The tool will automatically:

- Clean duplicate geometries from points and lines
- Create polygons from the line network
- Transfer geological attributes from points to polygons
- Generate geological contact lines
- Produce topologically clean outputs

Input Parameters:

- **Points with Geological Information**: Point layer containing geological attributes (typically centroids of units) Each point should be located within a distinct geological polygon. Points must have attribute fields with geological information.
- **Geological Attribute Field**: The field containing the primary geological classification can be formation code, lithology, stratigraphic unit, etc. This attribute will be transferred from the Point to Polygons

- **Line Drawing (Geological Contacts):**
  - Line layer representing boundaries between geological units. Lines should form a network of closed polygons. Gaps or overlaps may cause processing errors
- **Vertex Tolerance:**
  - Distance threshold for removing duplicate vertices (in map units) Default: 0.000001 (suitable for decimal degrees). Adjust based on coordinate system and required precision
- **Spatial Predicate:**
  - Intersects: Point touches or is inside polygon (most common)
  - Contains: Polygon completely contains point
  - Within: Point is completely within polygon
  - Overlaps: Geometries share some but not all points

Figure 5 form of the plugin.

Outputs:

- Geological Polygons: Final polygon layer with geological attributes from points
- One polygon per Geological Unit
- Inherits all attributes from the point layer
- Line layer representing boundaries between different geological units

Intermediate Outputs:

- Clean Points: Point layer after duplicate removal
- Intermediate Polygons: Polygons before attribute joining
- Line Segments: Individual line segments of contacts

Useful for quality control and troubleshooting

Best Practices:

Line Preparation:

- Ensure all lines connect properly to form closed polygons
- Use snapping tools to avoid small gaps between lines
- Check for and fix geometry errors before processing
- The lines can also overlap to ensure the closure of the polygon

Point Placement:

- Place exactly one point per geological polygon
- Points should be well inside polygons (not near boundaries)
- Ensure points have valid geological attribute values
- Check for missing or null attribute values

Coordinate Systems:

- Use projected coordinate systems for accurate topology
- Adjust vertex tolerance based on coordinate system units
- For geographic coordinates (degrees): use very small tolerance (0.000001)
- For projected coordinates (meters): use appropriate tolerance (0.001-0.01)

Quality Control:

- Check intermediate outputs if results are unexpected
- Verify that polygons were created successfully
- Ensure all polygons received attributes from points
- Inspect contact lines for proper attribute assignment

Troubleshooting:

No polygons created:

- Check that lines form closed polygons without gaps
- Verify line endpoints snap together properly
- Look for self-intersecting or overlapping lines
- Polygons missing attributes:
- Ensure each polygon contains exactly one point

Check spatial predicate setting (try "Intersects")

- Verify points are actually inside polygons
- Multiple polygons with same attributes: This may be intentional (same geological unit in multiple areas) Or may indicate duplicate or misplaced points

Technical Notes:

- Algorithm preserves all attributes from input point layer
- Processing uses QGIS native algorithms for maximum compatibility
- Temporary outputs are stored unless specified otherwise
- Final outputs are topologically clean and ready for GIS analysis

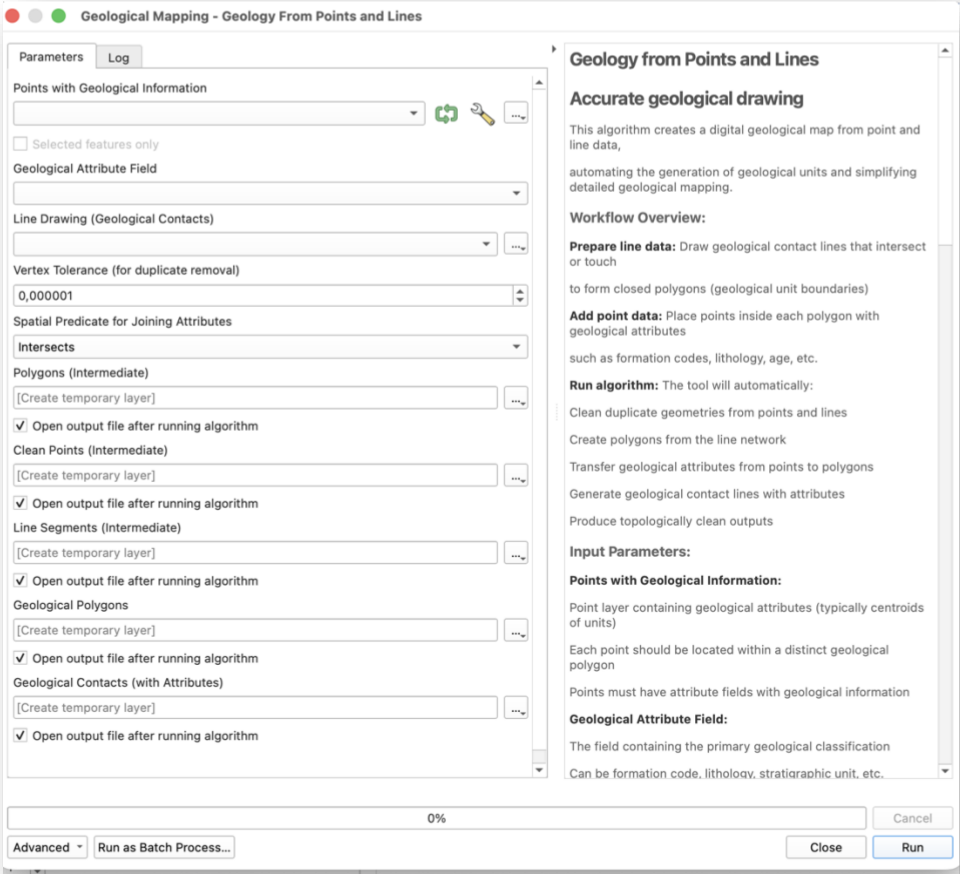

Figure 5. Form Geology Point and Line

References:

- Repository code: https://github.com/pinogcosentino/Geology-from-points-and-lines/tree/1.0
- Giuseppe Cosentino. (2025). QGIS TOOL FOR GEOLOGY FROM POINTS AND LINES (2.0). Zenodo. https://doi.org/10.5281/zenodo.14629465
- QGIS Development Team. (2026). *QGIS Geographic Information System* (versione 3.44). QGIS Association. URL: https://www.qgis.org
- QGIS plugin Builder http://g-sherman.github.io/Qgis-Plugin-Builder/

2 Hydrology

2.1 Hydrological Analysis Stream Network (HASN)

The study of the structure and properties of a watershed's drainage network encompassing both permanent and ephemeral elements such as rivers, streams, brooks, and artificial channel forms an essential foundation for modern hydrological analysis. This systematic characterization goes beyond mere morphological description; it provides the fundamental interpretative framework for: 1) understanding hydrological processes at the watershed scale, 2) accurately modelling surface and subsurface water flow, and 3) quantifying hydrological responses to extreme meteorological events.

To achieve optimal results in terms of precision and scientific robustness, this study adopted an **integrated geoprocessing approach**, synergistically leveraging the complementary strengths of algorithms available in the **GRASS GIS** and **SAGA GIS** environments. This hybrid strategy enabled:

• Maximizing reliability through cross-validation of results from different algorithms

• Optimizing performance by using the most efficient and validated tool for each study phase

• Enriching the analysis by combining well-established methodologies from the open-source hydrological community

The systematic integration of GRASS libraries known for stability in basic hydrological derivation algorithms and SAGA libraries excellent for advanced morphometric analysis and DTM pre-processing represented the optimal methodological choice to ensure both scientific rigor and the completeness of the results obtained.

Relationship

These elements are not isolated, but form part of a logical processing chain, which is illustrated in Figure 6:

1. **Drainage Directions** are calculated from the **DTM**. This represents, for each cell of the DTM, towards which adjacent cell (among the 8 possible) the water would flow. It is the first and most critical output of hydrological analysis based on a DTM. All other layers (network, basins, indices) are derived from this layer.
2. The **Specific Contributing Area (a)** is derived from the Drainage Directions.
3. By combining a and the local **Slope (β)** from the DTM, the Topographic Index (more precisely, the **Topographic Wetness Index - TWI**) is calculated. This is a central index in hydrological modelling. It quantifies an area's propensity to generate surface runoff or saturation.
    - **a**: Specific contributing area (upstream catchment area per unit contour width). Indicates how much water arrives.
    - **tan(β)**: Local slope. Indicates the drainage capacity of the soil.

The index combines two opposing forces:

- **Water convergence (a**): The larger 'a' is, the more water arrives at the point, increasing the probability of saturation.
- **Drainage capacity (tanβ):** The larger 'tanβ' is (steep slope), the faster the water drains away, reducing saturation.

Therefore, a HIGH value of the index ln(a/tanβ) indicates:

- **Conditions of potential saturation**: Landscape points where a lot of water converges from upstream ('a' large) on a gentle slope ('tanβ' small).
- **High probability of generating surface runoff**: When the soil is saturated, even a small amount of additional rainfall cannot infiltrate and generates immediate surface runoff.
- **Zones of moisture accumulation**: Areas such as valley bottoms, concavities, and foot slopes.

A LOW value of the index indicates:

- **Dry conditions**: Locations on steep slopes ('tanβ' large) or ridges ('a' small), where water drains quickly or does not converge.
- **High infiltration capacity**: The soil tends to remain unsaturated.

Practical Applications:

The index is used to map:

- Areas prone to saturation and waterlogging (wetlands, riparian zones).
- Source areas for surface runoff during rainfall events.
- The spatial variability of soil moisture within a catchment.
- The potential location of erosion processes or mass movements (landslides triggered by saturation).

4. By applying a critical area threshold to the Contributing Area, the **Stream Network** is generated (first as a raster, then vectorised and smoothed).
5. Using the Stream Network as a guide, the main basin is subdivided into **Half Basins** (or sub-basins). These are the drainage areas relative to each segment of the river network. They represent the "tiles" with a homogeneous hydrological response. They are the computational units in many semi-distributed hydrological models (e.g., HEC-HMS, SWAT), allowing for the aggregation of parameters such as land use, soil type, and precipitation.

Workflow Geoprocessing

Step 1: Fill Sinks (Wang & Liu Algorithm)

Aim: To create a hydrologically correct DTM (Digital Terrain Model), without depressions that would artificially block the flow of water.

Raw DTMs (especially LiDAR or high-resolution ones) contain thousands of small depressions, many of which are measurement errors or artefacts, not true endorheic basins. The Wang & Liu algorithm is an efficient and accurate "Fill & Raise" method. It identifies all depressions (sinks). For each depression, it finds the lowest outlet point (spill point) on its boundary. It fills the depression up to the height of the outlet point.

Output: Raster filled DTM

Step 2: Flow Calculation and Stream Delineation

Purpose: To calculate the water flow path and identify the cells that form the river network.

2a. Flow Direction: For each cell of the *filled DTM*, the direction towards the adjacent cell with the steepest downward slope is determined. For this purpose, the GRASS *r. watershed* algorithm was used. GRASS does not limit itself to simple D8 (where for each cell, its elevation is compared to that of its 8 neighbours (D8), slopes are calculated, and the steepest downslope direction is identified). Instead, it uses a flow search algorithm that considers a broader window to determine the flow direction towards the farthest downslope cell, not just the adjacent one.

Output: Drainage direction raster (*flow direction)*

2b. Flow Accumulation: For each cell, the total number of upstream cells that drain into it is calculated. Each cell contributes a value of 1 (or an area value). The result is a map representing the drainage volume.

Output: TWI raster (*flow accumulation*).

2c. Stream Delineation: A contributing area threshold (default 100 m^2) is applied to the flow accumulation raster. Cells with an accumulation value exceeding this threshold are classified as part of the river channel.

Output: Delineate streams raster (*streams*).

Step 3: Raster to Vector Conversion

Purpose: To transform the raster (grid-based) representation of the network into more manageable vector lines (polylines) for *GIS* analysis and cartography.

Process: The GRASS algorithm (*r.to.vect)* traces lines by following adjacent cells classified as channels in the stream raster.

Output: A vector layer LineString type.

The resulting network has a *stair-case pattern*, as it follows the grid of raster cells. It is geometrically precise but visually and hydraulically unrealistic; therefore, the operation described in Step 4 was performed.

Step 4: Geometry Smoothing

Purpose: To improve the cartographic and hydraulic realism of the vector network by smoothing the right angles. Smoothing is a generalisation operation. The plugin provides two parameters: a smoothing offset (default value 0.25) and a parameter controlling the number of iterations. Smoothing must be applied with moderation to avoid excessively altering the real channel position (e.g., making it crossroads or boundaries). Consequently, both the *raw* version (for analysis) and the *smoothed* version (for visualisation and cartographic representation) have been retained.

Schema algorithm plugin (Figure 6).

All layers generated by the plugin are the analytical building blocks that transform a simple elevation model (DTM) into a functional representation of a landscape's hydrological behaviour, essential for modelling, planning, and risk management.

Hydrological Analysis Stream Network - QGIS Plugin

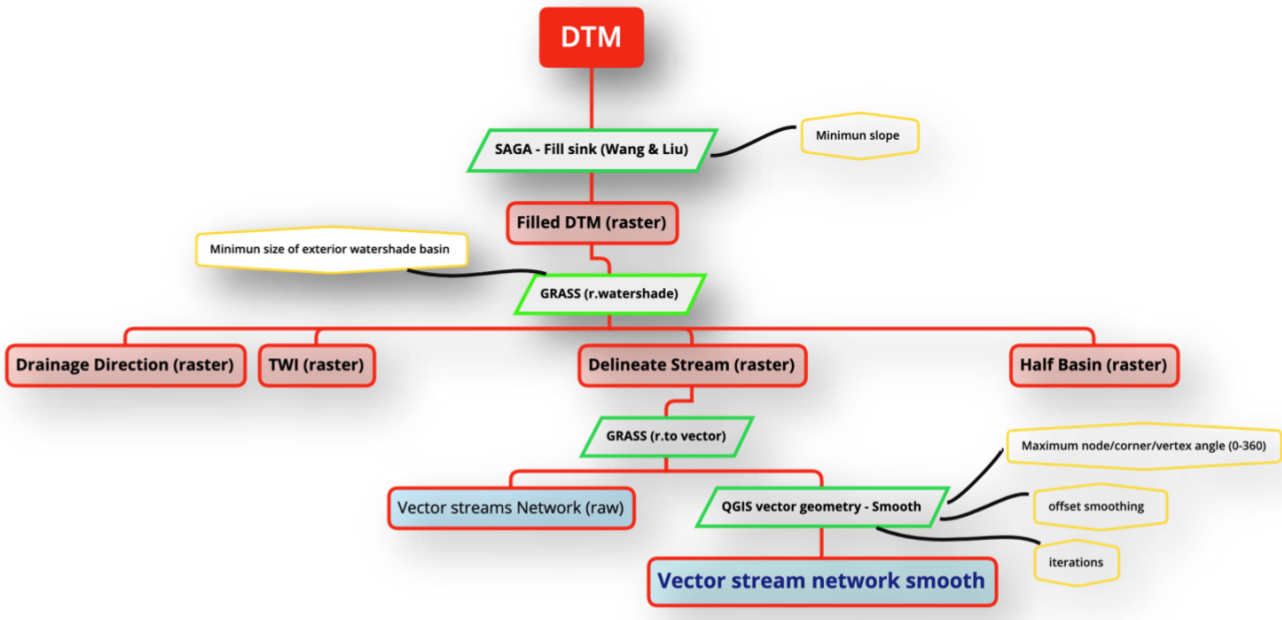

Figure 6. Algorithm Schema

Best Practices:

Input Data Preparation:

- Use high-quality DTM with minimal artifacts
- Ensure DTM is in projected coordinates (not geographic)
- Remove or interpolate No Data values if present
- Consider pre-processing with Gaussian filter for noisy data

Parameter Selection:

- Start with default minimum basin size, adjust based on results
- For detailed networks: use lower threshold (25-50 cells)
- For main channels only: use higher threshold (200-500 cells)
- Consider DTM resolution when setting basin size

Quality Control:

- Visually inspect filled DTM for artifacts
- Compare stream network with topographic maps or imagery
- Check for unrealistic stream patterns
- Validate drainage directions in complex terrain

Performance Optimization:

- Clip DTM to study area before processing
- Consider resampling very high-resolution DTMs
- Processing time increases with DTM size
- GRASS algorithms may require significant memory

Limitations and Considerations:

- Flat areas may produce unrealistic flow patterns
- DTM artifacts can propagate through the analysis
- Stream extraction is sensitive to basin size threshold
- Human-modified terrain (roads, dams) may affect results
- Requires GRASS GIS and SAGA GIS plugins to be installed and functional

Applications:

- Watershed and sub-watershed delineation
- Stream order classification (Strahler, Shreve)
- Flood hazard mapping
- Erosion susceptibility assessment
- Hydrological model parameterization
- Riparian zone identification
- Environmental impact assessment

References:

- Wang, L., & Liu, H. (2006). An efficient method for identifying and filling surface depressions in digital elevation models.

- Metz, M., et al. (2011). Efficient extraction of drainage networks from massive, radar-based elevation models.

- GRASS Development Team (2023). r. watershed module documentation.

- Repository code: https://github.com/pinogcosentino/Hydrological-Analysis-Stream-Network

- Cosentino, G., & Pennica, F. (2026). Hydrological Analysis Stream Network - QGIS Plugin (1.1). Zenodo. https://doi.org/10.5281/zenodo.18254583

QGIS Development Team. (2026). *QGIS Geographic Information System* (versione 3.44). QGIS Association. URL: https://www.qgis.org

3 Seismic Microzonation

3.1 Lateral Spreading Analysis (LSA) for Seismic Microzonation (SM)

Lateral spreading (Figure 7) is a term used in geotechnical and earthquake engineering. It refers to the horizontal movement of soil or rock, often occurring during an earthquake. This phenomenon typically happens in areas with loose, saturated soils, and it can cause significant ground deformation, impacting structures, pipelines, and other infrastructure. Lateral spreading usually occurs when:

- There is a liquefaction of loose, water-saturated soils.
- The ground surface slopes gently.

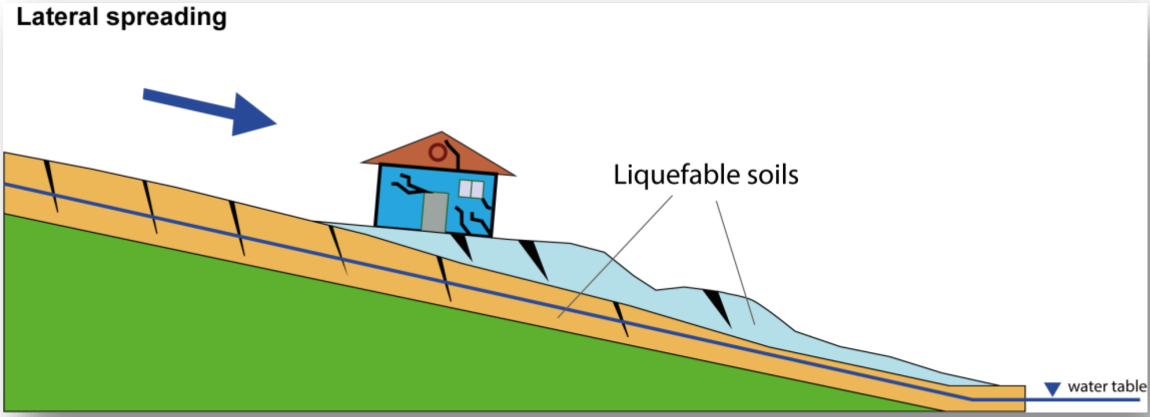

Figure 7. Lateral spreading

There are nearby free faces, like riverbanks or sea cliffs, providing an unconfined direction for the soil to move.

This type of ground failure is especially dangerous because it can lead to the collapse of buildings, bridges, and other critical infrastructure.

This algorithm (Figure 8) classifies terrain susceptibility to lateral spreading phenomena based on liquefaction index (IL) and terrain slope percentage

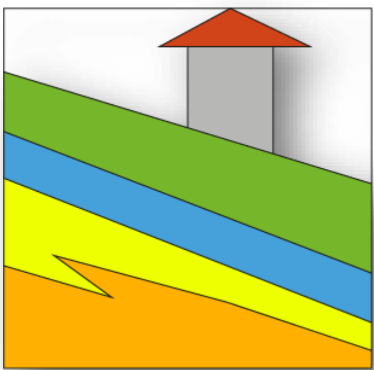

Figure 8. Algorithm icon

Input parameters:

- **Liquefaction Index (IL):** Polygon vector layer containing ***IL*** values from CPT/SPT analysis.
- **Digital Terrain Model (DTM):** Raster layer representing terrain elevation

Output files:

- **Slope %:** Raster layer showing terrain slope in percentage
- Lateral Spreading Zones: **Polygon vector layer** with classified zones; fid: Feature identifier; ***code:*** Numeric zone classification code *(101-104: **RZ**, 201-203: **SZ**, 300: **Z0**)*

Plugin works in QGIS, software open source, and calculates zones subject to lateral spreading (Figure 9):

A) **Low Susceptibility Zones (Z0):**

- 2 < Slope% ≤ 5 and 0 < IL≤ 2

B) **Susceptibility Zones (SZ)**

- 0< IL ≤ 2 and 5 < Slope% ≤ 15

- 2< IL ≤ 5 and 2 < Slope% > 5

- 5 < IL ≤ 15 and 2 < Slope% ≤ 5

C) **Respect Zones (RZ)**

- 0< IL ≤ 2 and Slope% > 15

- 2< IL ≤ 5 and Slope% > 5

- 5< IL ≤ 15 and Slope% > 5

- IL >15 and Slope% > 2

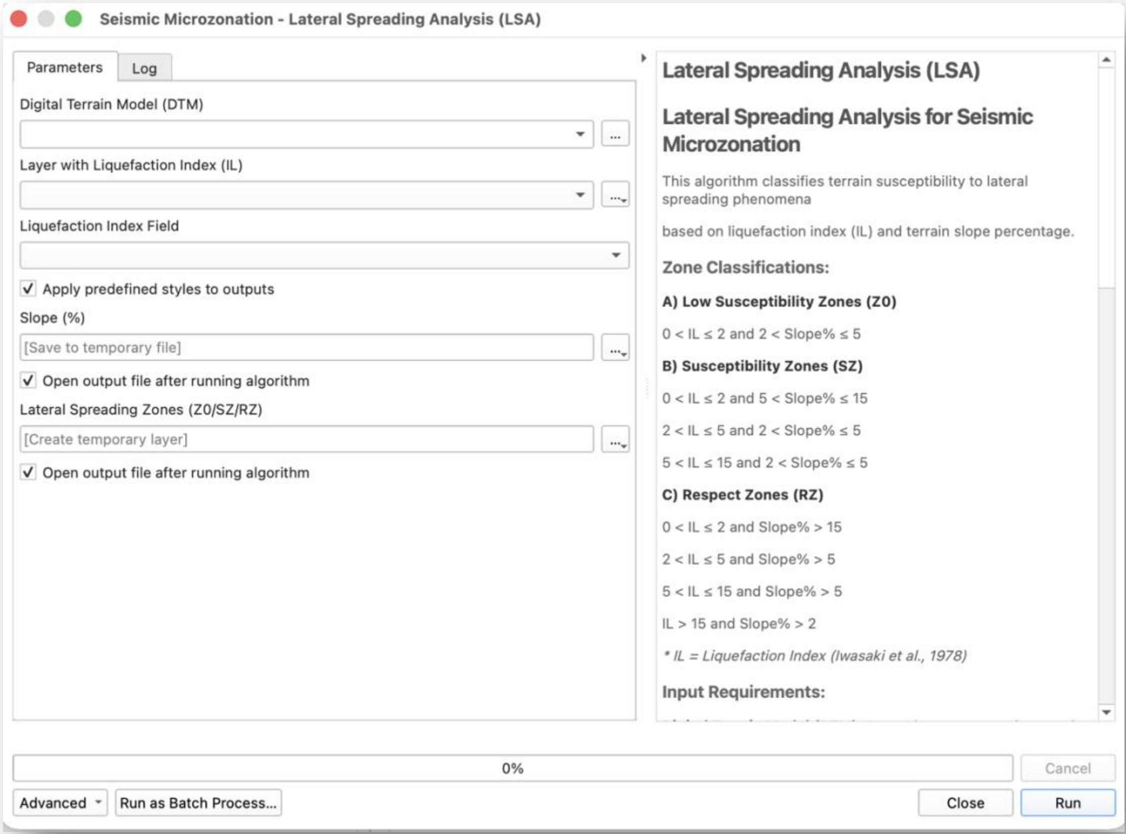

Figure 9. Form for data input and output file

Processing Workflow:

1. Clip DTM to liquefaction analysis area
2. Calculate slope percentage from DTM
3. Convert slope raster to polygons
4. Intersect slope with liquefaction index layer
5. Classify areas based on IL and slope thresholds
6. Merge and organize classified zones
7. Apply visualization styles (optional)

References:

- Italian Seismic Microzonation Guidelines (ICMS, 2008)

- Gli indirizzi per gli studi di microzonazione sismica in Emilia-Romagna per la pianificazione territoriale e urbanistica DGR 476/2021 (e DGR integrativa n. 564/2021) https://ambiente.regione.emilia-romagna.it/it/geologia/sismica/indirizzi-per-studi-microzonazione-sismica

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- Iwasaki, T., et al. (1978). Simplified procedure for assessing soil liquefaction

- Associazione Geotecnica Italiana (AGI). Linee guida per la programmazione ed esecuzione delle indagini geotecniche

- Lancellotta, R. (2012). Geotecnica. (Ed. Zanichelli)

- https://github.com/pinogcosentino/Lateral-spreading-for-seismic-microzonation/tree/0.4

- Cosentino, G., & Pennica, F. (2025). Lateral spreading for seismic microzonation (0.1). Zenodo. https://doi.org/10.5281/zenodo.14719324

- QGIS Development Team. (2026). *QGIS Geographic Information System* (versione 3.44). QGIS Association. URL: https://www.qgis.org

- QGIS plugin Builder http://g-sherman.github.io/Qgis-Plugin-Builder/

3.2 Seismic Zones with morphological gradient (SZMG)

This algorithm identifies areas with slopes exceeding a critical threshold within seismic or geological zones, useful for assessing areas susceptible to topographic amplification or slope instability. (Figure 10)

Figure 10. Algorithm icon

The morphological gradient in seismic areas with slopes ≥15° can influence the propagation of seismic waves, amplify their energy and increase the risks of landslides or ground subsidence. This plugin identifies areas with a morphological gradient with slopes ≥15° within seismic zones (Input vector file) starting from the DTM.

Input Parameters:

- **Digital Terrain Model:** Elevation raster layer (DTM)
- **Geological Seismic Zones:** Polygon layer defining study areas
- **Slope Threshold:** Critical slope angle in degrees (0-90°, default: 15°)

Workflow:

- **DTM Clipping:** The DTM is clipped using the geological vector mask
- **Slope Calculation:** A slope map is generated in degrees
- **Threshold Analysis:** Areas exceeding the slope threshold are isolated
- **Vectorization:** Identified areas are converted to polygons
- **Attribute Join:** Original seismic zone attributes are preserved

Outputs:

- **Slope Map:** Raster layer showing slope in degrees
- **High Slope Zones:** Vector layer of areas exceeding the threshold

References:

- Italian Seismic Microzonation Guidelines (ICMS, 2008)

- QGIS Project (2024). PyQGIS Developer Cookbook

- Repository code: https://github.com/pinogcosentino/Seismic-Zones-with-morphological-gradient-SMG-

- Cosentino, G., & Pennica, F. (2025). Seismic microzones with morphological gradient (0.1). Zenodo. https://doi.org/10.5281/zenodo.14679295