GIS & Remote Sensing Workflow for Rainfall Network Design

Adaptive Spatial Structuring, Diagnostics, and Scientific Recursion

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Goal

This seminar develops a **scientifically grounded workflow** for designing physiographically stratified rainfall networks in low mountain regions (e.g. the Burgwald, Germany).

Rather than optimising station locations directly, the course emphasises:

- spatial structure before optimisation,
- explicit separation of structure, process, and context,
- reproducible spatial analysis,
- and validation through **diagnostic reasoning**, not model perfection.

The workflow combines **literature-driven design**, **GIS-based spatial structuring**, and **selective quantitative diagnostics**.

Course Structure

- **Total sessions:** ~10 × 3 h
- **Core workflow modules:** Sessions 1–6
- **Advanced / toolkit modules:** Sessions 7–10 (project-specific)

Each session contains: - 1 h instructor input, - guided implementation, - structured discussion and reflexion.

Introduction: From Conceptual Design to Calculation

Rainfall network design is not a purely technical optimisation problem. It is a **scientific design task** that links:

- landscape structure,
- physical processes,
- and measurement constraints.

In the first phase of the course (Tasks *First Design* and *Resources & Pitch*), the following were developed:

- conceptual network layouts,
- deployment rationales (physiographic, information-gain, hydrological),
- resource plans and feasibility assessments,
- an initial literature base using **benchmark observatories**.

The technical modules that follow **do not invent completely new questions**. They **operationalise, adapt and test** these design ideas using spatial data and reproducible workflows.

> **Adaptive redesign**
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> In response to the evolving projects, the module plan was **adapted rather than replaced**. The workflow was reordered to ensure that spatial structure and process assumptions are made explicit *prior to* interpolation or optimisation.

Module 0 – Concept & Evidence Scan

Status: completed in Tasks *First Design* and *Resources & Pitch*

Goal: Establish a **literature-anchored design rationale** before technical work.

Core elements

- Review of benchmark rain-gauge networks and observatories.
- Classification by dominant rationale:
  - physiographic stratification,
  - information-gain optimisation,
  - hydrological coupling.
- Conceptual Burgwald network:
  - 20 stations,

  - explicit station roles (Backbone, Infill, P–Q, Open–Wood, Event-Scout),
  - data and resource plan,
  - initial literature justification.

> **Key idea**
>
> Defines ***what should be built*** and ***why***. All following modules answer ***how***.

Module 1 – Project Organisation & FAIR Data Retrieval

Goal: Build a reproducible project skeleton consistent with Module 0.

Technical scope

- R project setup (`renv`, `here`, `targets`)
- FAIR principles (Findable, Accessible, Interoperable, Reusable)
- Targeted datasets:
  - DEM / DGM → terrain, landforms, drainage
  - CORINE / ATKIS → structural & physiographic context
  - RADOLAN, DWD gauges → precipitation fields and point data
  - Sentinel-2 → structural layers (canopy/open), not full RS modelling

> **Key idea**
>
> Data selection is not purely technical.
> It is **biased by process assumptions** and directly constrains the interpretation of the project results.

Module 2 – Geodata Preprocessing as Process Modelling

Goal: Derive **process-relevant base variables**, not just cleaned inputs.

Technical scope

- Raster/vector handling (`terra`, `sf`, `stars`)
- Morphometry:
  - slope, aspect, curvature / convexity
  - landform classification (ridge / slope / valley)
- Hydrological pre-structuring:

  - flow direction, flow accumulation
  - watershed and sub-catchment delineation

- Functional land-cover simplification (forest/open, canopy density)

> **Key idea**
>
> This step reframes preprocessing as **process modelling at the first order**.
> Consequently, all **scale decisions** made here become part of the scientific argument and must be revisited explicitly.

Module 3 – Wind Fields & Luv–Lee Annotation

Goal: Provide atmospheric **context**, not full atmospheric modelling.

Technical scope

- Wind data (DWD stations, ERA5 / COSMO)
- Dominant wind directions (seasonal / aggregated)
- Aspect × wind → Luv/Lee annotation

> **Key idea**
>
> This module introduces key **conceptual constraints**.
> Variables such as *Luv/Lee* are treated as **annotation layers**, not as clustering variables.
> They support **interpretation and diagnostics across segments**, but do not define the spatial segmentation itself.

Module 4 – Spatial Structuring & Stratification (Core Module)

Goal: Reduce spatial complexity **before** interpolation or optimisation.

Technical scope

- Tile-based structural pre-analysis
- Adaptive spatial units:
  - `supercells` (Nowosad ecosystem)
  - optional simple clustering (e.g. `kmeans`)
- Focus on:
  - spatial coherence,

  - reproducibility,
  - process plausibility.

Key idea

This module marks a **shift in emphasis**.
Rather than pursuing exhaustive cluster-validity optimisation (e.g. silhouette scores), the focus is placed on **interpretability**, **stability**, and **process plausibility**.
As a consequence, the workflow requires a **renewed and more critical engagement with the literature** to reassess methodological assumptions and design choices.

Module 5 – Scientific Recursion (Re-Entry Loop)

Goal: Enforce an explicit **scientific recursion**:
projects must now be **re-aligned, refined, and justified** based on accumulated insights.

This module introduces a deliberate **loop in the workflow**.
Instead of progressing forward, all groups are required to **re-enter their own project logic**.

The intention is to make explicit what ideally should have happened iteratively from the start: the continuous adaptation of methods to concepts, not the other way around.

Scientific Recursion

Over the past weeks, students have: - implemented substantial technical workflows, - explored multiple methodological templates, - generated concrete spatial structures, strata, and candidate designs.

What has often *not* happened sufficiently is the **recursive alignment** between: - conceptual intent, - methodological choices, - and scientific justification.

This module therefore enforces that alignment **retroactively and explicitly**.

Scientific Recursion

Each group must now refine its project by:

- revisiting the original concept and design intent,
- adapting the workflow where necessary (simplification, re-weighting, omission),
- justifying these adaptations with **literature and own argumentation**,
- explaining why the resulting workflow is *appropriate for their specific project.*

The provided workflow and examples are to be treated as **exemplary scaffolding**, not as a blueprint to be reproduced.

What this module demands

- A clear statement of **what was changed** and **why**.
- Explicit references that support or contradict earlier assumptions.
- Recognition that technical completeness does **not** imply scientific adequacy.
- Acceptance that refinement often means **removing** methods, not adding more.

> **Key idea**
>
> A scientifically grounded, internally consistent project design that: - reflects informed methodological choices, - acknowledges limitations and alternatives, - and demonstrates ownership over the workflow.
> This recursion marks the transition from **method execution** to **scientific authorship**.

Module 6 – Interpolation, Mapping & Diagnostic Validation

Goal: Use interpolation and mapping as **diagnostic tools** to evaluate spatial structuring and process assumptions — not to construct a "true" precipitation field.

Conceptual framing

Interpolation is deliberately positioned **after** spatial structuring and stratification. Its role is not optimisation, but **testing**:

- Do the chosen spatial units and strata explain systematic deviations?
- Where do interpolated fields perform consistently well or poorly — and why?

Technical scope

Interpolation inputs

- RADOLAN precipitation products, *or*
- simple gauge-based approaches (IDW, basic Kriging).

Evaluation strategy

- Extract precipitation time series at:
  - existing gauges,
  - planned or hypothetical station locations.
- Analyse residuals and differences by:
  - spatial strata and segments,
  - landforms (ridge / slope / valley),

  - annotation layers (e.g. Luv/Lee),
  - catchments and sub-catchments.

Mapping & visual diagnostics

- Cartographic tools: `tmap`, `ggplot2`, `mapview`
- Core overlays:
  - segmentation and physiographic strata,
  - landforms and drainage networks,
  - interpolated precipitation fields,
  - spatial residual patterns.

Maps are treated as **analytical artefacts**, not presentation products: they are used to identify structural consistency, mismatches, and process-related patterns.

> **Key idea**
>
> Interpolation functions as a **stress test**. The question is not whether an interpolated field looks smooth or accurate, but whether **the chosen spatial structuring helps explain where and why interpolation fails**.

Suggested Timeline

Session	Theme	Module(s)	Format
1	Concept & Evidence	Module 0	Discussion + design review
2	Project & Data Infrastructure	Module 1	Setup + guided workflow
3	Preprocessing & Landforms	Module 2	Analysis + maps
4	Spatial Structuring	Module 4	Segmentation workshop
5	Wind Context & Interpretation	Module 3	Annotation + discussion
6	Scientific Recursion	Module 5	Literature-based redesign
7	Diagnostic Validation	Module 6	Interpolation + residuals
8–10	Workshops & Refinement	Advanced modules	Project-specific deep dives

> ⚠ Original Schedule vs. Adaptive Workflow
>
> ### Summary Table

Original Module	Original Focus	Adaptive Role Now	Status
Module 0	Implicit literature review	Explicit concept & evidence scan	Central
Module 1	Project setup & data	FAIR, reproducible implementation base	Active
Module 2	Preprocessing	First-order process modelling	Active
Module 3	Wind fields	Contextual annotation (Luv/Lee etc.)	Active
Module 4	Structuring & clustering	Core spatial backbone (segmentation & strata)	Active
Cross-cutting	Iterative scientific reflection	Explicit Scientific Recursion (Module 5)	Central
Interpolation	Field generation	Diagnostic / validation instrument (Module 6)	Limited
Visualization	Mapping	Analytical diagnostics, not presentation	Integrated

Key Take-Home Messages

- **Structure precedes interpolation.**
- **Interpolation serves validation, not truth.**
- **Spatial decisions imply scale decisions.**
- **Adaptive workflows require renewed literature engagement.**
- **Scientific recursion is part of the method, not an afterthought.**