

WetSpass-M Modern

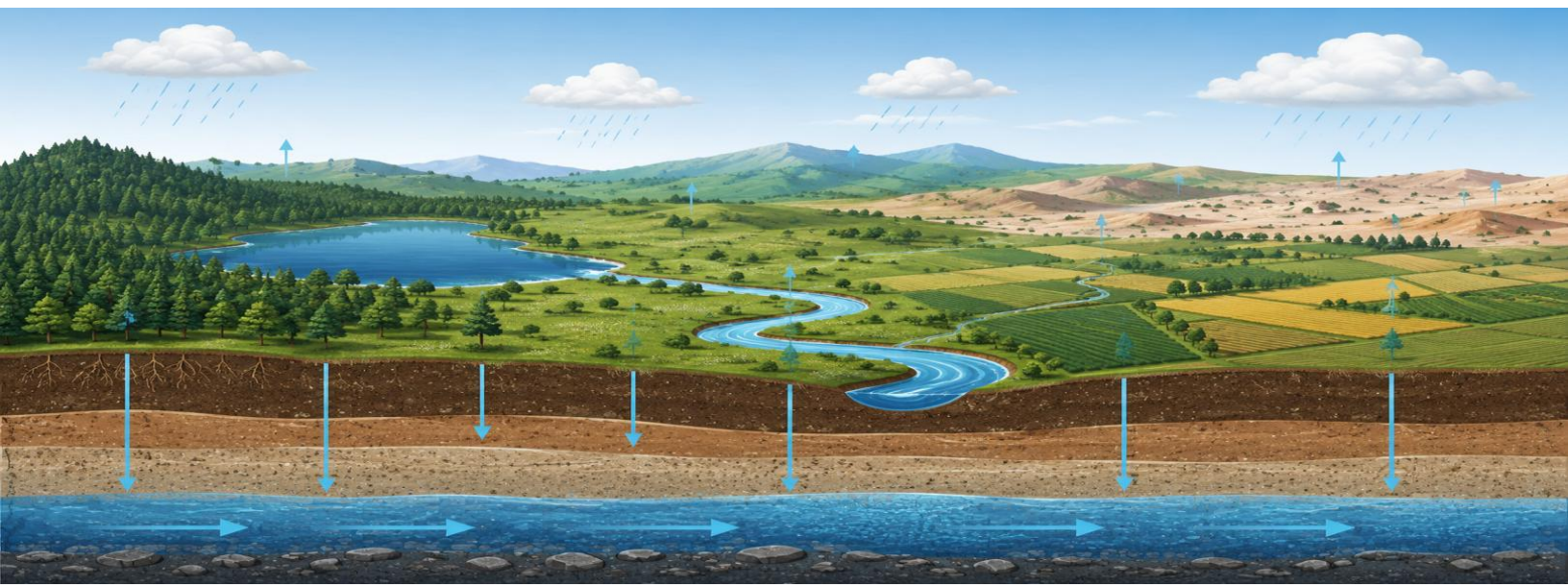
User Guide



Version 2.1.0

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Preface

This document is the user guide for WetSpass-M Modern, a modernization of the original WetSpass-M 2016 model developed by K. Abdollahi, I. Bashir, and O. Batelaan at the Vrije Universiteit Brussel. WetSpass-M is one of the most widely used spatially distributed water-balance models for estimating groundwater recharge at catchment and basin scale, particularly in data-scarce regions where simpler lumped models are insufficient and full physically based models are impractical. WetSpass-M Modern preserves the original model's physics, equations, and lookup-table structure; what it changes is the way the soil column is treated over time, the way the annual mass balance is defined, and the way the model is delivered to the user.

The improvements documented in this manual are:

- **A dynamic soil-water bucket** replacing the original quasi-steady-state assumption. Soil moisture is carried as an explicit state variable from one month to the next, so the seasonal redistribution of water through the root zone is preserved. This matters most in seasonally concentrated rainfall regimes — monsoonal, Mediterranean, semi-arid, and arid climates — where the original assumption of monthly reset can distort the seasonal timing of recharge and the dry-season supply for evapotranspiration.
- **An ET cap consistent with mass balance.** Soil-derived evapotranspiration is capped at the water physically available after runoff ($P - SR$), not at rainfall alone. This prevents the model from producing negative recharge on high-runoff cells and ensures the catchment-scale balance closes.
- **A separate diagnostic for groundwater-fed ET.** Transpiration and evaporation drawn from a shallow water table are computed explicitly and reported as `Cell_gw_discharge`, outside the precipitation balance, instead of being folded back into AET where they would double-count water in the closure test.
- **Integration with QGIS via GeoTIFF I/O.** Inputs and outputs are GeoTIFF rasters. The plugin runs inside QGIS, uses QGIS's own raster and vector libraries, and writes outputs that can be inspected, symbolised, and analysed directly in the QGIS map canvas. Legacy ASCII `.asc` grids are still accepted for backward compatibility.
- **Robust checkpointing and resume for long runs.** The workflow saves its state after every completed month and after every completed spin-up cycle. A power loss, an external drive disconnection, or an unexpected shutdown no longer means starting over — the next time the plugin is opened, the Run tab offers a Resume run button that continues from the last completed month. Only one month of computation is ever at risk.
- **A Focused Recharge module** for streambed infiltration along ephemeral and intermittent stream networks, with a user-selectable combine method for diffusive and focused recharge and a climate-zone-based physical cap derived from mean annual precipitation.
- **A Crop outputs to boundary tool** that replaces the failing QGIS `gdal:rasterize` "Mask rasters" workflow. It presents a file-selection dialog so you choose exactly which rasters to crop, auto-reprojects the boundary vector to each raster's CRS, retains edge pixels, and writes cropped copies to a separate folder without modifying the originals.

The manual assumes you are familiar with QGIS, raster GIS concepts, and basic hydrology (rainfall, runoff, evapotranspiration, recharge). If you are new to any of those, work through the Quick Start in Chapter 3 first — it walks you from a clean QGIS install to a valid annual water balance in about five

minutes using the sample data. Consult the Physics and equations chapter only when you need to understand a specific flux or make a calibration decision. The Troubleshooting chapter at the end collects the errors most commonly reported by users, together with their causes and fixes.

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1. Introduction and scope

1.1 What WetSpass-M Modern does

WetSpass-M Modern computes, on a regular grid and at monthly time steps:

- Interception by vegetation.
- Surface runoff, split by land-cover fraction.
- Actual evapotranspiration (transpiration + soil evaporation + open-water evaporation + impervious-surface evaporation).
- Diffuse recharge to the saturated zone.
- (Optionally) focused recharge along ephemeral stream networks.

The output is a set of GeoTIFF rasters at monthly, seasonal, and annual resolution, together with a text summary file (`Simulated.tbl`), a convergence report (`spinup_convergence.csv`), and a run report (`RunSummary.txt` plus `_run_metadata.json`).

1.2 Who should use it

The model is designed for:

- Regional groundwater recharge estimation.
- Water-balance studies at catchment to basin scale.
- Long-term average annual and seasonal water budgets.
- Climate-change impact assessment (via substituting future climate inputs).
- Land-use change scenario analysis (via substituting land-use maps).

It is not designed for event-scale flood modelling, sub-monthly routing, or transient groundwater simulation. For those, use a physically-based rainfall-runoff model coupled to a groundwater model.

1.3 Model type

Two operating modes are available:

- **Dynamic bucket mode (default).** Soil moisture is an explicit state carried from month to month. Mass balance: $P = AET + SR + R + \Delta S$. At the annual scale, after spin-up, $\Delta S \approx 0$.
- **WetSpass-M 2016 compatibility mode.** Soil moisture is reset to zero every month ($\Delta S \equiv 0$). This reproduces the original 2016 physics exactly and is intended for validation against legacy results.

1.4 What changed from the 2016 original

Aspect	WetSpaas-M 2016	WetSpaas-M Modern
Soil moisture	Reset every month ($\Delta S = 0$)	Dynamic bucket, carried forward
ET cap	At rainfall	At (rainfall – runoff)
Groundwater-fed ET	Folded into AET	Reported separately as Cell_gw_discharge
Time integration	Monthly, one pass	Monthly, spin-up + reported pass
I/O	ASCII grids	GeoTIFF with ASCII fallback
Aggregation	Simple sum	Nodata-preserving sum
Environment	Standalone GUI	QGIS plugin
Combine of diffusive + focused	N/A	User-selectable, with climate cap
Boundary cropping	Manual in GIS	Built-in, with file-selection dialog

1.5 What is new in 2.1.0

This version, 2.1.0, adds three substantial capabilities on top of the 2.0.5 release:

- A **Crop outputs to boundary** tool that replaces the failing QGIS `gdal:rasterize` workflow with a robust `rasterio`-based implementation and a file-selection dialog.
- A **climate-zone-based physical cap** on total recharge, derived automatically from mean annual precipitation and the standard reference table.
- A **user-selectable combine method** for diffusive and focused recharge — addition, replace-by-max, or focused-over-diffusive — with a Preview button that reports what a given cap would do before any file is written.

The release also fixes three defects in the focused-recharge engine that had been producing physically impossible recharge values and blocking runs with broadcast and rasterization errors. Diffusive recharge remains untouched: it is produced by the same workflow, with the same equations and the same spin-up logic as version 2.0.5.

2. Installation

2.1 Requirements

- QGIS 3.28 or newer (tested through 3.44 and listed for QGIS 4.x via `qgisMaximumVersion=4.99`).
- Python 3.9 or newer (comes bundled with QGIS).
- Python packages: `numpy`, `rasterio`, `geopandas`. The first two are commonly available in QGIS's Python environment. `geopandas` may need to be installed separately for the crop tool.

2.2 Installing the plugin

Locate your QGIS plugin directory:

- **Windows:** `%APPDATA%\QGIS\QGIS3\profiles\default\python\plugins\`
- **Linux:** `~/local/share/QGIS/QGIS3/profiles/default/python/plugins/`
- **macOS:** `~/Library/Application Support/QGIS/QGIS3/profiles/default/python/plugins/`

Copy the entire `wetpass_modern` folder into that directory.

Open QGIS. Go to **Plugins** → **Manage and Install Plugins** → **Installed**. You should see **WetSpass-M Modern** listed. Ensure its checkbox is ticked.

A toolbar icon and a **WetSpass-M Modern** menu entry appear. If the icon is missing, verify that `icon.png` is present in the plugin folder.

2.3 Verifying dependencies

If `rasterio` is missing:

- **Windows:** open the OSGeo4W shell (installed with QGIS) and run: `pip install rasterio`
- **Linux / macOS:** use the same Python interpreter QGIS uses; run: `pip install --user rasterio`

If `geopandas` is missing (required for the crop tool):

Text: `pip install geopandas`

2.4 Shipping the user guide

The Help tab looks for this PDF in the plugin folder. Place it at:

text

`wetpass_modern/help/WetSpassM_UserGuide.pdf`

If it is not present, the Help tab shows a message with the expected path, but the quick-reference material remains available.

3. Quick start in five minutes

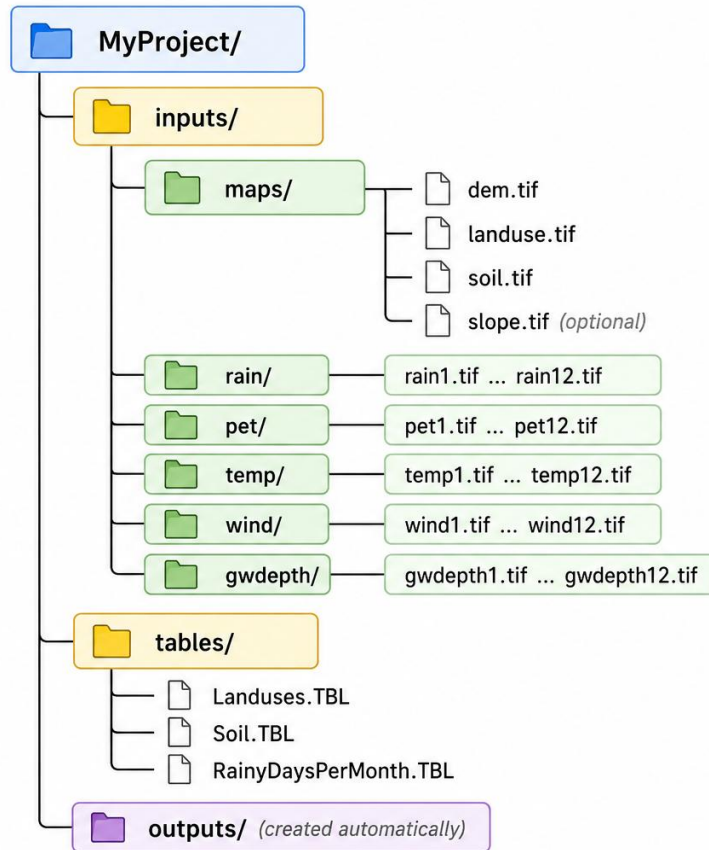
This is the fastest path from zero to a valid annual water balance. Details for each step follow in later chapters.

1. Prepare your input folder using the standard layout shown in section 4.
2. Open the plugin: **WetSpass-M Modern** → **Open**.
3. **Inputs tab**. Set the working directory. Click **Auto-load**. Confirm the DEM, land use, and soil paths are filled.
4. **Check Inputs tab**. Press **Check Inputs**. Every row should be green. Fix any red rows before continuing.
5. **Parameters tab**. Leave the defaults ($LP = 0.85$, $Alfa = 1.5$) unless you have local calibration data.
6. **Run tab**. Set the output directory. Leave **Spin-up cycles** = 2 and **Compatibility mode** = **OFF**.
7. Press **Run**. Watch the Progress tab. The workflow reports convergence after each spin-up cycle and exits early when the bucket is stable. If you are satisfied that the bucket has converged and do not want to wait for the spinner count, press **Skip to final cycle**.
8. **Water Balance tab**. Click **Load from output folder**. The closure error should be close to zero.
9. (Optional) **Focused Recharge tab**. Click **Recompute from inputs**, run focused recharge, then click **Combine** → **Total recharge**.
10. (Optional) **Crop outputs to boundary**. Click the button on the tools row, tick the rasters you want, and confirm.

4. Input data requirements

4.1 Standard folder layout

All inputs live inside the working directory. The recommended layout is:



The **Auto-load** button in the plugin scans this layout and fills the paths for you.

Alternative layouts are also recognised (maps/ + tables/, Inputs/Maps/ + Inputs/Tables/, and Maps/ + Tables/). The Check Inputs tab tells you which layout it detected.

4.2 Grid alignment

All raster inputs must share exactly the same grid as the DEM: CRS, pixel size, origin, width, and height. Resolution alone is not enough — two 30 m grids with different origins are still misaligned.

To align rasters in QGIS: **Raster** → **Projections** → **Warp**. Set the target CRS and extent to the DEM, use bilinear for continuous variables (rain, temperature, wind, PET, gwdepth) and nearest for categorical variables (land use, soil).

The Check Inputs tab runs this alignment test automatically.

4.3 Raster formats

GeoTIFF is preferred. Legacy ASCII `.asc` grids are accepted for backward compatibility. Output is always GeoTIFF.

4.4 Units

Variable	Unit	Typical range
Rainfall	mm/month	0 – 500
PET	mm/month	0 – 300
Temperature	°C	–30 – 45
Wind speed	m/s	0 – 15
Groundwater depth	m below surface	0 – 200
DEM	m	project-dependent
Slope	percent	0 – 100

All fluxes are monthly totals, not intensities. Do not supply daily rates.

4.5 Monthly file naming

The model expects a 12-file pattern per climate variable:

text

```
rain1.tif ... rain12.tif
pet1.tif ... pet12.tif
temp1.tif ... temp12.tif
wind1.tif ... wind12.tif
gwdepth1.tif ... gwdepth12.tif
```

Prefixes are configurable on the Settings tab.

4.6 Lookup tables

Three tables are read from `inputs/tables/`.

Landuses.TBL — tab-delimited. One row per land-use class code.

Column	Meaning
1	Land-use code (integer)
4	Vegetated fraction (0–1)
5	Bare-soil fraction (0–1)

6	Impervious fraction (0–1)
7	Open-water fraction (0–1)
8	Rooting depth (m)
9	Leaf area index (LAI)
10	Minimum stomatal resistance (s/m)
11	Vegetation roughness height z_0 (m)
13	Land-use factor for runoff coefficient
14	Aerodynamic resistance at 1 m/s wind (s/m)

Soil.TBL

Column	Meaning
1	Soil code
3	Field capacity (fraction)
4	Wilting point (fraction)
6	Residual water content (fraction)
7	Soil moisture parameter a
8	Evaporation depth (m)
9	Tension height at air-entry (m)
12	Soil factor for runoff coefficient
13	Saturated Hydraulic Conductivity (K_s in m/s)

RainyDaysPerMonth.TBL — Two columns: month number (1–12), mean number of rainy days per month.

4.7 Optional inputs

- Snow cover (snowcover1.tif ... snowcover12.tif): fraction 0–1. Enable on the Run tab.
- Irrigation (irrig1.tif ... irrig12.tif): additional water applied to the soil.
- LAI per month in inputs/maps/LAI/.

5. Tab-by-tab reference

5.1 Inputs tab

Sets the working directory and the primary rasters. The Auto-load button scans the standard folder layout and fills the paths automatically.

Fields:

- **Working Directory** — root of the project, contains `inputs/` and `outputs/`.
- **DEM map, Land use map, Soil map, Slope map** — paths to the static rasters. If Slope is left empty and "Create slope map from DEM directly" is ticked, the model computes slope internally.
- **Project boundary shapefile** — polygon used by the Crop outputs to boundary tool.
- **No of time steps** — usually 12 for a full year.
- **Starting / Final time step** — usually 1 and 12.
- **Initial discharge** — initial surface and subsurface flow values for the surface-water interaction option. Only used if the model is configured with basin area > 0.

5.2 Check Inputs tab

Runs a full validation:

- Every required lookup table exists and has enough columns.
- Every monthly raster exists for every requested month.
- Every raster shares the DEM's CRS, transform, width, and height.

Results are colour-coded. Red rows block the run — fix them first. Orange rows (grid mismatch) are warnings that usually indicate the model will produce garbage, so they should be fixed too.

Only explicit Check Inputs clicks write to the run log. Auto-checks triggered by switching tabs stay silent, so the log is not filled with duplicate lines.

5.3 Settings tab

Configures file-name prefixes for each variable. If your files are named `precip1.tif` instead of `rain1.tif`, change the prefix here. Also configures the nodata value (default -9999).

5.4 Parameters tab

Calibration coefficients.

Parameter	Default	Notes
"a" interception	4.5 mm/day	Interception threshold
Alfa	1.5	Priestley-Taylor coefficient
LP	0.85	Soil-moisture limitation
Average intensity	4 mm/h	Used in runoff formula
Slope factor	0.4	Weight in runoff coefficient
Land-use factor	0.3	Weight in runoff coefficient
Soil factor	0.3	Weight in runoff coefficient
Basin area	10 km ²	For surface-water interaction
"x" coefficient	0.5	Surface-water interaction
Beta	0.75	Baseflow coefficient
Contribution factor	0.5	Recharge contribution

5.5 Output Period tab

Choose which temporal aggregations to write:

- **Monthly** — 12 files per variable.
- **Seasonal** — wet-season and dry-season files.
- **Annual** — one file per variable.

Season definitions are preloaded for several climate regions; the Ethiopian preset uses Kiremt (June–September) as wet season and the rest as dry season.

5.6 Run tab

- **Output Directory** — where rasters and reports go.
- **Model version** — compatibility mode checkbox (see section 12).
- **Spin-up cycles** — number of extra warm-up passes before the reported pass (see section 7). Default 2.
- **Save final soil moisture** — writes `soilwater_storage_initial.tif` for use as the starting state in future runs.
- **Reset soil moisture state** — deletes the state file, forcing the next run to start from a dry profile.
- **Enable automatic checkpointing** — writes a checkpoint after every completed month, so a power loss or drive disconnection resumes where it stopped.

- **Create simulation file** — writes `Simulated.tbl` with per-month mean fluxes.
- **Include snow processes** — enables the snow module.

5.7 Progress tab

Live log and progress bar. Controls:

- **Skip to final cycle** — abandons the remaining spin-up cycles and jumps straight to the final output cycle. Use this once the bucket has essentially converged and you do not want to wait for the spinner count. The current cycle finishes cleanly, then the workflow moves to the final pass.
- **Pause** — stops at the next block write and saves a checkpoint. The next run can resume from it.
- **Cancel** — stops at the next block write without saving a checkpoint. Partial output remains on disk until the next fresh run.
- **Close dialog** — hides the window; the run continues in the background.

5.8 Results tab

Choose which intermediate rasters to keep on disk. By default the model keeps monthly recharge and AET rasters; the rest are deleted after aggregation to save space.

5.9 Water Balance tab

See section 11.

5.10 Focused Recharge tab

See section 9.

5.11 Crop outputs to boundary

See section 10.

5.12 About tab

Scientific justification, equations, references. See section 6 for a summary.

5.13 Help tab

Opens this PDF and provides a quick-reference of the workflow, output folder structure, and common errors.

5.14 Calibration tab

Reads an observed CSV and the run's `Simulated.tbl`, computes NSE, KGE, PBIAS, R^2 , RMSE, and MAE, and displays a time-series comparison. See Chapter 13 for a full explanation of the metrics and a recommended calibration workflow.

6. Physics and equations

6.1 Water balance at a cell, per month

The model partitions precipitation into four fluxes and one storage change:

$$P = AET + SR + R + \Delta S$$

where:

- **P** = precipitation (rainfall plus snowmelt)
- **AET** = actual evapotranspiration to the atmosphere
- **SR** = surface runoff
- **R** = recharge to the saturated zone
- **ΔS** = change in soil-water storage during the month

6.2 Interception

$$\begin{aligned} a_{aai} &= a \cdot LAI \\ Va &= P - (1 - 1/\exp(0.463 - LAI)) \\ DIT &= a_{aai} - a_{aai} / (1 + Va / a_{aai}) \\ I_{total} &= vegarea \cdot P \cdot (1 - \exp(-DIT \cdot nr / P)) \\ I_{total} &= \min(I_{total}, PET) \\ I &= I_{total} - (0.04 + 0.067 \cdot LAI) \end{aligned}$$

where **nr** is the number of rainy days in the month, **a** is the interception parameter (default 4.5 mm/day), and **vegarea** is the vegetated fraction of the cell.

The factor $(0.04 + 0.067 \cdot LAI)$ splits total interception into a portion that evaporates directly (which is the flux **I** that enters AET) and a remainder that drips back to the soil.

6.3 Surface runoff

Runoff is computed with a modified runoff-coefficient method:

text

$$\begin{aligned} C_{per} &= w_{lu} \cdot LU_factor + w_{soil} \cdot Soil_factor + w_{slope} \cdot slope / (10 + slope) \\ C_{imp} &= 0.09 \cdot \exp(2.4 \cdot (imp + ow)) \\ C_{wp} &= (1 - imp - ow) \cdot C_{per} + (imp + ow) \cdot C_{imp} \\ C_{sr} &= (C_{wp} \cdot Pd) / (C_{wp} \cdot Pd - I_{coef} \cdot C_{wp} + I_{coef}) \text{ if } I_{coef} < Pd \\ &\quad C_{wp} \text{ otherwise} \\ Q &= Ch \cdot C_{sr} \cdot (P - I_{total}) \end{aligned}$$

where $Pd = P / nr$ is the average daily rainfall, $I_{coef} = 24 / I_{avg}$ is the inverse of the average rainfall intensity, and **Ch** is a soil-moisture-driven runoff modifier.

6.4 Actual evapotranspiration

AET is the total flux of water from the land surface to the atmosphere. It combines six physically distinct components:

$$\text{AET} = \text{I} + \text{E_transp} + \text{E_bare} + \text{E_imperv} + \text{E_gw} + \text{E_ow}$$

where:

- **I** = interception that evaporates directly from vegetation surfaces
- **E_transp** = transpiration from soil moisture in the root zone
- **E_bare** = evaporation from bare soil
- **E_imperv** = evaporation from impervious surfaces
- **E_gw** = transpiration and evaporation drawn from a shallow water table
- **E_ow** = evaporation from open water bodies

The soil-derived components are computed with a soil-moisture limitation:

$$\text{E_transp} = \text{PET_veg} \cdot (1 - a \cdot (\text{awc} / \text{PET_veg})) \cdot \text{evap_rate}$$

$$\text{E_bare} = \text{PET} \cdot (1 - a \cdot (\text{awc} / \text{PET})) \cdot \text{evap_rate}$$

where **awc** is available water capacity plus soil storage, and **a** is the soil moisture parameter from Soil.TBL.

In dynamic mode, the soil-water supply is **S_prev + P - I - SR - E_imperv**, not just the current month's rainfall. This is the key difference from 2016: the bucket carries moisture forward so that a wet month can supply transpiration in a subsequent dry month. The groundwater-fed component (**E_gw**) is computed separately and reported in the diagnostic raster **Cell_gw_discharge**. This raster is provided for interpretation — it tells you how much of the total AET was drawn from the water table rather than from the soil column. **It is already included inside AET**, so it must not be subtracted a second time in the closure equation.

6.5 Recharge

Recharge is the overflow from the soil bucket:

$$\text{S_max} = (\text{fc} - \text{wp}) \cdot \text{rootdepth} \cdot 1000 \quad [\text{mm}]$$

$$\text{A} = \text{S_prev} + \text{P} - \text{I} - \text{SR} - \text{E_imperv}$$

$$\text{E_s} = \min(\text{E_s_potential}, \text{A}) \quad [\text{tp} + \text{bare}]$$

$$\text{S_new} = \text{clamp}(\text{A} - \text{E_s}, 0, \text{S_max})$$

$$\text{R} = \max(0, \text{A} - \text{E_s} - \text{S_max})$$

fc and **wp** come from Soil.TBL, **rootdepth** from Landuses.TBL.

6.6 Snowmelt

Snow is tracked as snow water equivalent (SWE):

$$\text{SWE} = \text{SWE_prev} + \text{P} / (1.61 - 1.35 \cdot \text{T} + 1)$$

$$\text{Cm} = \text{melt factor if } \text{T} > \text{base temperature, else } 0$$

$$\text{Melt} = \min(\text{Cm} \cdot \text{degree_days} \cdot \text{T}, \text{SWE})$$

$$\text{SWE} = \text{SWE} - \text{Melt}$$

degree_days is read from DegreeDaysPerMonth.TBL.

7. Spin-up and convergence

7.1 Why spin-up is needed

Because soil moisture is now a state variable, the model needs to run the same 12 monthly input maps several times before the bucket reaches a repeating annual cycle: S at the start of year N equals S at the start of year N + 1 at every cell.

Only then does the reported year have a well-defined mass balance and a ΔS that can be compared against P.

7.2 Recommended spin-up counts

Climate	Cycles
Maritime temperate	1
Continental / Mediterranean	2
Monsoon (Ethiopia, India, West Africa)	2–3
Arid / semi-arid	3–5
Default (may auto stop on spin up convergence)	7

The spinner on the Run tab sets extra warm-up passes before the reported pass. Set to 7 (default) → 8 passes total.

7.3 Automatic convergence check

After every spin-up cycle the workflow computes:

mean |S_end – S_start| [mm/yr]

If this falls below a tolerance, the bucket has converged and the remaining warm-up cycles are skipped automatically. The default tolerance is:

tolerance = max(1.0 mm, 0.5% × mean annual P)

For P = 1170 mm/yr, the tolerance is 5.86 mm/yr. A 5% margin is applied on top, so values within 5% of the tolerance also count as converged. This prevents the workflow from running an extra cycle when the residual is sitting on the numerical noise floor.

7.4 Convergence report

Every run that has at least one spin-up cycle writes `spinup_convergence.csv`:

```
Spin-up convergence report
mean_annual_P_mm,1171.6800
```

```

tolerance_mm,5.8584
tolerance_frac,0.005000
converged_after_cycle,3
cycle,mean_abs_dS_mm,mean_dS_mm,pct_of_P,tol_mm,converged
1,47.210314,41.305442,4.031023,5.858400,no
2,8.417295,7.441808,0.718202,5.858400,no
3,1.208741,0.918376,0.103163,5.858400,yes

```

Interpretation:

- `mean_abs_dS_mm` — the convergence metric for that pass.
- `pct_of_P` — the metric as a fraction of mean annual P.
- `converged` — yes if the metric fell below the tolerance (with margin).

If `converged_after_cycle` equals the spinner value, the bucket was still drifting at the last allowed pass. Add 1–2 cycles and re-run.

When spin-up is set to 0, no spin-up cycle runs and the CSV is not written. The final cycle runs directly from the state stored in `soilwater_storage_initial.tif`.

7.5 Manual verification

Two independent checks confirm convergence:

- In the Water Balance tab, ΔS is close to zero — within the tolerance reported in the Progress log.
- The last row of `spinup_convergence.csv` has `converged = yes`.

If both checks pass, the reported mass balance is trustworthy.

8. Outputs and interpretation

8.1 Output folder structure

outputs/

— Lookups/	static lookup rasters
— Interception_1.tif ... _12.tif	monthly outputs
— Cell_runoff_1.tif ... _12.tif	
— Cell_evapotranspiration_1.tif ...	
— Recharge_diffusive_1.tif ...	
— Recharge_diffusive_annual.tif	annual aggregate
— Recharge_diffusive_wet_season.tif	seasonal (if enabled)
— Recharge_diffusive_dry_season.tif	seasonal (if enabled)
— Recharge_focused_annual.tif	(after Focused Recharge tab)
— Recharge_focused_annual_capped.tif	(optional, if cap enabled)
— Recharge_Total_annual.tif	(after Combine button)
— cropped_to_boundary/	(after Crop button)
— soilwater_storage_initial.tif	bucket state for next run
— soilwater_storage_delta_annual.tif	ΔS over the reported year
— spinup_convergence.csv	spin-up report (when spin-up > 0)
— wetspass_checkpoint.json	resume state (deleted on completion)
— Simulated.tbl	per-month mean fluxes
— RunSummary.txt	human-readable run report
— _run_metadata.json	machine-readable run metadata

8.2 Output variables

Name	Meaning	Units
Interception	Interception of the cell	mm/month
total_Interception	Interception before the $0.04 + 0.067 \cdot \text{LAI}$ factor	mm/month
evap_rate	Evaporative efficiency factor (0–1)	—
Cell_runoff	Runoff of the cell	mm/month
Cell_evapotranspiration	AET of the cell	mm/month
Cell_gw_discharge	Groundwater + open-water part of AET	mm/month
recharge	Diffuse recharge	mm/month
vegrunoff	Runoff in vegetated area	mm/month
barerunoff	Runoff of bare soil	mm/month
imperrunoff	Runoff of impervious area	mm/month
owrunoff	Runoff on open water	mm/month
Cell_actualtranspiration	Total actual transpiration	mm/month
Cell_actual_baresoil_evapo	Evaporation from bare soil	mm/month
Cell_ow_evaporation	Evaporation from open water	mm/month

Name	Meaning	Units
Cell_imper_evaporation	Evaporation from impervious surface	mm/month
Cell_gw_transpiration	Groundwater transpiration	mm/month
Cell_gw_evaporation	Groundwater evaporation	mm/month
penmann_coefficient	Penmann coefficient	—
wb_error	Per-cell water balance closure error	mm/month

8.3 Reading the annual rasters

Annual rasters are the sum of the 12 monthly rasters. For continuous variables (rain, ET, runoff, recharge) this is correct. For state variables (`soilwater_storage`), annual aggregation is not meaningful and the model writes them as monthly snapshots instead.

8.4 Simulated.tbl

Text file with the catchment-mean fluxes per month:

```
TimeStep  AET    Runoff  Interception  Recharge
1         23.4567 12.3456  5.6789      8.9012
2         25.1234 11.2345  6.7890      7.8901
...
```

Useful for calibration against observed annual hydrographs. When a run is resumed, the file is appended to rather than truncated, so months written before the pause are preserved.

9. The Focused Recharge module

9.1 What it computes

Focused recharge is the streambed infiltration along ephemeral or intermittent streams. It is a separate process from diffuse recharge and typically concentrated on a small fraction of the catchment area.

The module:

- Derives a stream network from the DEM (D8 flow accumulation).
- Routes monthly surface runoff downstream.
- Applies an exponential transmission loss on streambed cells.
- Reports the fraction of the network treated as losing vs gaining.
- Applies a climate-zone-based physical cap on the combined total recharge.

9.2 Parameters

- **Stream threshold** — accumulation threshold in cells (typical 500).
- **K_s** — streambed hydraulic conductivity, either from Soil.TBL or a fixed value. Typical clogged values: 1e-7 to 1e-6 m/s.
- **Channel width** — from Strahler order, from a shapefile attribute, or fixed.
- **Losing / gaining threshold** — depth-to-water-table cutoff. Streambed cells with a shallower water table are treated as gaining and skip loss.
- **Flow duration fraction** — fraction of each rainy day during which ephemeral streams actually flow. Typical 0.20–0.40.
- **Maximum infiltration depth** — physical cap, typical 20 mm/day.

9.3 Climate regime

The climate regime is auto-selected from rainfall when you click **Recompute from inputs**:

Mean annual P	Regime
< 300 mm/yr	Arid
300 – 700	Semi-arid
700 – 1200	Mixed / transitional
≥ 1200	Humid

Rainfall is more reliable than depth-to-water-table for this classification, since gwdepth rasters are typically interpolated from sparse borehole observations and can easily be off by tens of metres. The gwdepth-based classifier remains available as a secondary cross-check via the **Auto-detect from gwdepth (secondary)** button.

9.4 Combine methods

When you click **Combine** → **Total recharge**, you choose how the diffusive and focused rasters are combined into a single total recharge raster. The choice matters because the two estimates represent different physical pathways to the water table and therefore need to be combined without double-counting and without discarding a real contribution.

Addition (default). $R_{\text{total}} = R_{\text{diffusive}} + R_{\text{focused}}$. This is correct when the two mechanisms are physically independent pathways, which is the standard WetSpass-M formulation: a water molecule that infiltrates through the soil matrix is counted once by the diffusive model, and a water molecule that reaches a streambed and infiltrates there is counted once by the focused model. Addition is the recommended default for operational studies.

Replace-by-max (conservative). $R_{\text{total}} = \max(R_{\text{diffusive}}, R_{\text{focused}})$. At each cell the larger of the two estimates is kept. This avoids any chance of double-counting, at the cost of a systematic underestimate at every stream cell by $\min(R_{\text{diff}}, R_{\text{foc}})$. Use this only if a reviewer or a legacy comparison requires the conservative assumption, and document the choice.

Focused-over-diffusive. $R_{\text{total}} = R_{\text{focused}}$ on stream cells, $R_{\text{diffusive}}$ elsewhere. Use this only if you believe the diffusive model already includes some streambed loss and you want to replace that component with the focused estimate rather than add to it.

The chosen method is stored in the tab between runs. The log and the summary dialog both report which method was used, so the provenance of any given `Recharge_Total_annual.tif` file is unambiguous.

9.5 Physical cap

The focused-recharge engine can produce extreme values at individual stream cells when upstream runoff is concentrated into a small streambed area. Even with the mass-balance and monthly depth caps that the engine applies internally, the combined total can occasionally exceed what is physically plausible for a given climate. To guard against this, the combine step offers an optional physical cap derived from mean annual precipitation.

Clicking **Recompute from inputs** reads the monthly rainfall rasters, computes mean annual precipitation, classifies it against the standard reference table, and sets the recommended cap to the upper bound of the plausible recharge fraction for the matched zone.

Reference table for the physical cap:

Climate zone	Mean annual P (mm/yr)	Recharge fraction	Recommended cap (mm/yr)
Arid	100 – 300	1 – 5 %	5 – 15
Semi-arid	300 – 700	5 – 15 %	15 – 100
Humid temperate	700 – 1500	20 – 35 %	150 – 500

Climate zone	Mean annual P (mm/yr)	Recharge fraction	Recommended cap (mm/yr)
Wet tropical	1500 – 3000	30 – 50 %	450 – 1500
Extreme cloud forest / karst	3000 – 5000	40 – 60 %	1200 – 3000

The cap is optional and can be overridden. The recommended value is pre-filled into the override spinbox so you can see the number the plugin is suggesting and either accept it or adjust it.

The **Preview cap effect** button reports, without writing anything to disk, exactly what a given cap would do. It scans the two combine inputs tile-by-tile and reports the number of valid cells, before-cap and after-cap min/mean/max statistics, the number of cells that would be clipped, the mean drop across all cells, the overall max reduction, and a binned distribution of the clipped values by ratio to the cap.

When the cap is enabled and the **Also write capped focused raster** box is ticked, a separate file `Recharge_focused_annual_capped.tif` is written alongside the total. The original `Recharge_focused_annual.tif` is never overwritten.

9.6 Workflow

A typical focused-recharge run proceeds as follows:

1. Run the main (diffusive) model first. The focused engine reads `Cell_runoff_*.tif` from the output folder and cannot proceed without them.
2. Open the Focused Recharge tab.
3. Click **Recompute from inputs**. This computes mean annual precipitation from the monthly rain rasters, auto-selects the climate regime, and fills the recommended physical cap.
4. Configure parameters as needed. The **Auto-detect from gwdepth (secondary)** button is available if you want a cross-check.
5. Press **Run focused recharge**.
6. Optionally press **Preview cap effect** to check how the cap will behave before committing to it.
7. Press **Combine** → **Total recharge** to write `Recharge_Total_annual.tif`.
8. Return to the Water Balance tab and click **Update recharge**.

The workflow is checkpointed after every month, so if the run is interrupted, clicking Run again resumes from the last completed month rather than starting over.

10. Crop outputs to boundary

10.1 What it does

The **Crop outputs to boundary** button on the tools row removes the rectangular "zero collar" that the DEM alone leaves behind by cropping every selected output raster to a polygon boundary. It replaces the failing QGIS `gdal:rasterize` workflow.

10.2 Why it exists

The QGIS "Mask rasters" tool uses `gdal:rasterize` on the command line. It frequently fails with either `ERROR 1: Duplicate argument -ot` or a silent no-output when the boundary polygon's CRS differs from the raster's, or when the two layers do not spatially overlap. WetSpass-M Modern's crop tool bypasses the GDAL command-line layer and uses `rasterio` plus `geopandas`, which handle CRS reprojection and boundary-pixel retention correctly.

10.3 Selection dialog

Clicking the button opens a dialog listing every `.tif` file in the output folder, grouped by variable and period. Tick the ones you want cropped.

Controls:

- **Filter** — type a substring to narrow the list.
- **Select all, Select none, Invert.**
- **Only annual** — ticks only `*_annual.tif`.
- **Only Recharge** — ticks only `Recharge_*.tif`.
- A running counter shows how many of the available rasters are selected.

10.4 Where the output goes

Cropped files are written to a subfolder named `cropped_to_boundary/` inside the source output folder. The originals are never modified, so you can compare cropped and uncropped versions of any file side by side.

10.5 Behaviour

The tool auto-reprojects the boundary vector to each raster's CRS, caching the reprojection per unique CRS. Edge pixels are retained with `all_touched=True`, which is critical for hydrological water-balance closure — discarding edge cells systematically biases catchment-scale recharge. Pixels outside the boundary are set to nodata.

The crop runs on a background thread. The GUI stays responsive while a large folder is being processed, progress is reported in the tab's progress bar, and every file — success or failure — is

logged with its name and the resulting pixel dimensions. A failed file does not stop the rest of the queue.

10.6 Recommended workflow

1. Produce all the rasters you want to keep: diffusive, focused, total, and any annual or seasonal aggregates.
2. Set the project boundary shapefile on the Inputs tab.
3. Click **Crop outputs to boundary**.
4. In the dialog, tick the rasters you want cropped. Typically the annual files plus any seasonal files.
5. Click OK. The originals remain in place; the cropped copies are written to `cropped_to_boundary/`.
6. Load the cropped rasters from `cropped_to_boundary/` into QGIS for visualisation or further analysis.

11. The water balance panel

11.1 Reading the panel

The panel shows the annual average of each flux and the closure error:

Mass balance: $P = AET + SR + R_total + \Delta S$

Closure error = $P - AET - SR - R_total - \Delta S$

The colour of the closure error is green if $|error|$ is within the acceptable band ($< 1\%$ of P), amber if 1–5%, and red above 5%. A green closure on a spun-up run is the strongest evidence that the model has produced a physically consistent water balance.

11.2 What ΔS means

ΔS is the change in stored soil moisture over the reported year. On a converged run it is close to zero — typically under the tolerance of 0.5% of P . If ΔS is larger, the bucket has not yet reached a repeating annual cycle. Increase spin-up cycles by 1 and re-run.

ΔS is not a closure-error correction. It is a real, physical flux that belongs in the balance and would be non-zero even in a perfect model run, because the soil column still accumulates or releases some water during the reported year.

11.3 Focused recharge integration

If you have run the Focused Recharge module, the panel reads `Recharge_focused_annual.tif` and adds it to `R_total`. If you have also produced `Recharge_Total_annual.tif` with the Combine button, the panel reads that file directly. The panel distinguishes these cases in the status line beneath the buttons.

12. Compatibility mode

12.1 What it does

Ticking **WetSpass-M 2016 compatibility mode** on the Run tab disables the dynamic bucket and restores the original physics:

- Soil moisture is reset to zero every month ($\Delta S = 0$ internally).
- Soil-derived ET is capped at rainfall, not at $(P - \text{runoff})$.
- Groundwater-fed ET is folded back into `Cell_evapotranspiration`.
- The recharge-driven ET adjustment is reapplied so that the closure error matches the original 2016 formulation.

12.2 When to use it

Use it to validate the modernized code against a legacy WetSpass-M 2016 installation on identical inputs. Cell-by-cell differences should be at the level of floating-point round-off. If they are larger, the implementation has diverged and should be investigated.

Do not use compatibility mode for operational studies in seasonally concentrated rainfall regimes — you will lose the seasonal redistribution that the bucket provides.

13. Calibration and validation

13.1 What the two words mean in this context

Calibration is the process of adjusting the model's tunable parameters so that its outputs reproduce observed data at a specific site. The parameters that can be calibrated are the ones on the Parameters tab: `a` (interception), `Alfa` (Priestley-Taylor coefficient), `LP` (soil-moisture limitation), `intensity`, `w_slope`, `w_landuse`, `w_soil`, and — if surface-water interaction is enabled — `x`, `Beta`, and `contribution`.

Validation is the process of testing a calibrated model against an *independent* dataset that was not used in the calibration. A model that reproduces its calibration data but fails on independent data is overfitted and should not be used for prediction.

Both activities are supported by the **Calibration tab** in the plugin.

13.2 What the Calibration tab does

The Calibration tab reads two inputs:

1. **Observed data** — a CSV or text file with at least two columns: time step (month number) and observed value. The plugin recognises the standard column names `timestep`, `time`, `month`, `date` for the first column, and `observed`, `obs`, `value`, `streamflow`, `runoff` for the second. If your column names differ, use the dropdown in the tab to map them.
2. **Simulated.tbl** — the per-month summary file written by the run itself, located in the output folder.

The tab then reports four goodness-of-fit metrics: NSE, KGE, PBIAS, and R^2 , plus two absolute-error metrics: RMSE and MAE. It also draws a time-series comparison plot and a scatter plot of observed versus simulated values.

13.3 The metrics

NSE (Nash-Sutcliffe Efficiency) is the standard hydrology metric. It ranges from $-\infty$ to 1. Values above 0.75 are considered very good, 0.5 to 0.75 is acceptable, and below 0.5 indicates the model is not capturing the observed variability.

$$\text{NSE} = 1 - \frac{\sum(Q_{\text{obs}} - Q_{\text{sim}})^2}{\sum(Q_{\text{obs}} - Q_{\text{obs_mean}})^2}$$

KGE (Kling-Gupta Efficiency) decomposes the error into three components: correlation, bias, and variability. A KGE of 1 is perfect; values above 0.75 are considered good; values below 0.5 indicate a problem. KGE is often preferable to NSE because it penalises variance errors, not just mean errors.

$$\text{KGE} = 1 - \sqrt{[(r - 1)^2 + (\alpha - 1)^2 + (\beta - 1)^2]}$$

where r is Pearson correlation, α is the ratio of standard deviations, and β is the ratio of means.

PBIAS (Percent Bias) measures systematic over- or under-prediction. A PBIAS of 0 is perfect. Positive values indicate the model over-predicts; negative values indicate it under-predicts. Values within $\pm 10\%$ are usually considered acceptable.

$$\text{PBIAS} = 100 \cdot \Sigma(Q_{\text{sim}} - Q_{\text{obs}}) / \Sigma(Q_{\text{obs}})$$

R² is the squared Pearson correlation coefficient. It measures linear association but does not penalise bias or scale errors, so it should be reported alongside NSE or KGE, not instead of them.

RMSE (Root Mean Square Error) and **MAE (Mean Absolute Error)** are absolute-error metrics in the same units as the observed data. They are useful for reporting but not for cross-site comparison, because their magnitude depends on the scale of the data.

13.4 What to calibrate against

The most common calibration targets in WetSpass-M workflows are:

Target	Source	When to use
Annual streamflow	Gauge records	The standard. The catchment-integrated runoff must match observed discharge.
Monthly streamflow	Gauge records	If monthly data exist. Tests seasonal timing, not just annual totals.
Actual ET	Eddy-covariance flux tower	If you have a flux tower in or near the catchment.
Groundwater levels	Observation wells	Indirect, but useful in heavily monitored basins.
GRACE-derived TWS	Satellite gravimetry	For large basins (> 100,000 km ²). TWS change is a proxy for ΔS + groundwater change.

In most WetSpass-M applications, the calibration target is annual streamflow, and the tunable parameter with the strongest influence is **LP** (soil-moisture limitation), followed by **Alfa**.

13.5 Calibration workflow

A defensible calibration workflow proceeds as follows:

1. **Split your observed record.** Reserve 30–40 % of the record for validation. For a 20-year record, use 12–14 years for calibration and 6–8 years for validation. Do not use the same data for both.
2. **Start from the defaults.** Run the model once with the default parameters and record NSE, KGE, and PBIAS against the calibration period.
3. **Adjust LP first.** LP controls how much of the available soil moisture is lost to ET before recharge begins. Raising LP increases ET and reduces recharge; lowering it does the opposite. Adjust in increments of 0.05.
4. **Adjust Alfa second.** Alfa scales the Priestley-Taylor PET. If your observed ET is systematically too low, raise Alfa; if it is too high, lower it.

5. **Adjust the runoff weights last.** Only if runoff remains badly mismatched after LP and Alfa have been tuned. The three weights (`w_slope`, `w_landuse`, `w_soil`) must sum to approximately 1.0.
6. **Re-run and re-evaluate.** Repeat until the metrics stabilise. Do not tune beyond three or four iterations — the model has limited degrees of freedom, and further adjustment is overfitting.
7. **Validate on the held-out period.** Run the model with the calibrated parameters and compute NSE, KGE, and PBIAS on the validation period. If the validation metrics are much worse than the calibration metrics, you have overfitted and should back off the parameter adjustments.

13.6 Target values

The following ranges are widely used in the hydrological literature as thresholds for a defensible calibration:

Metric	Very good	Acceptable	Poor
NSE	> 0.75	0.50 – 0.75	< 0.50
KGE	> 0.75	0.50 – 0.75	< 0.50
PBIAS	± 10 %	± 10 – 25 %	> ± 25 %

If your calibration does not reach at least the "acceptable" band on the calibration period, the model is not representing the dominant processes at your site. Before tuning further, check:

- Are your inputs correct? A misaligned rainfall raster or a mis-specified land-use table will prevent any calibration from succeeding.
- Is the water balance closing? If the closure error is large, the calibration target is meaningless.
- Is the dominant process actually within the model? WetSpaSS-M is a monthly water-balance model. It does not simulate event-scale flooding, snow-dominated regimes with rain-on-snow events, or strongly karstic systems with rapid conduit flow.

13.7 Validation protocol

A complete validation reports the following:

1. **Held-out period.** Metrics computed on data not used in calibration.
2. **Multi-site validation.** If the model is to be transferred to ungauged basins, validate on several gauges.
3. **Sensitivity analysis.** Vary each calibrated parameter by ± 20 % and report how much the metrics change. If the metrics are highly sensitive to a parameter that has no physical justification for being tuned, the calibration is fragile.
4. **Uncertainty range.** Report the range of parameters that give "acceptable" metrics, not just the single best-fit parameter set. A calibration that is narrow to a single point is usually overfitted.

13.8 Common calibration pitfalls

- **Tuning on the validation period.** This defeats the purpose of validation. Keep the two periods strictly separate.

- **Calibrating against the wrong variable.** If you calibrate runoff against a groundwater-level record, the calibration will be meaningless. Match the calibration target to the appropriate model output.
- **Ignoring the water balance.** A model that reproduces streamflow but has a closure error of 20 % is not a valid calibration, because it means the internal fluxes are wrong even though the outlet is right.
- **Over-tuning.** More than five or six parameter adjustments almost always means overfitting. Report the parameter set that gives the best validation, not the best calibration.
- **Skipping spin-up.** Calibration on a non-converged run is meaningless. Always let the bucket converge before comparing to observations.

14. Troubleshooting

14.1 The Check Inputs tab shows red rows

The tables or rasters listed are missing or malformed. Read the message column — it usually identifies the file path or the missing column.

- Missing file → check the file name spelling.
- Missing column → open the .TBL file and compare to the template.
- Grid mismatch → reproject the raster to the DEM grid.

14.2 "Input rasters are not on the same grid as the DEM"

This means CRS, transform, or size differs. Use **QGIS** → **Raster** → **Projections** → **Warp** to reproject every input to the DEM's grid. Verify the fix with the Check Inputs tab.

14.3 Recharge raster is all zeros

Three possible causes:

- The run did not complete — check the Progress log for errors.
- ET consumes all available water — check the Water Balance panel: if AET is close to P, recharge will be near zero. Adjust the LP or LAI parameters.
- The recharge raster was produced by an earlier buggy run — delete `Recharge_diffusive_*.tif` and re-run.

14.4 Closure error is large in the Water Balance panel

In order of likelihood:

- ΔS is large — the bucket has not converged. Increase spin-up cycles.
- Rasters are misaligned — Check Inputs will catch this.
- Compatibility mode was toggled between runs — discard the checkpoint and re-run.

14.5 Checkpoint errors on Resume

If a parameter, spin-up count, or compatibility setting changed after pausing, the checkpoint's parameter hash no longer matches. Click **Discard checkpoint** and start a fresh run.

14.6 Model appears stuck on a spin-up cycle

It is not stuck. Each cycle runs 12 months. Watch the "Month N — block M" lines. The workflow exits early when the bucket converges — look for the CONVERGED line in the Progress log. If you are satisfied with convergence and do not want to wait for the spinner count, press **Skip to final cycle**.

14.7 Power loss or drive disconnection during a run

Automatic checkpointing is on by default. The workflow saves its state after every completed month. When you reopen QGIS:

- The Run tab shows a "Paused run found" banner.
- The main button reads "Resume run" instead of "Run".
- Click Resume run and the workflow picks up at the exact month and block where it stopped.

Only one month of computation is ever at risk.

14.8 "Output device unavailable" warning

The external drive holding the output folder was disconnected. The workflow retried the write a few times and then paused cleanly. Reconnect the drive, then click Resume run on the Run tab. Only the month that was in progress will be recomputed.

14.9 Duplicate "[Check Inputs]" log lines

Fixed as of version 2.0.5. Auto-checks triggered by switching to the Check Inputs tab or changing the working directory no longer write to the run log; only an explicit Check Inputs click does.

14.10 Crop tool: "geopandas is not installed"

Install `geopandas` in QGIS's Python environment. On Windows, open the OSGeo4W Shell and run `pip install geopandas`. On Linux and macOS, use the same Python interpreter QGIS uses.

14.11 Crop tool: "Invalid path — Output directory does not exist"

Set the Output Directory on the Run tab before clicking the crop button.

14.12 Crop tool: some files fail to crop

The log line shows the file name and error. Common causes are the raster being open in QGIS and locked for writing, a boundary shapefile that is not readable, or a corrupted raster. Unload the raster, verify the boundary file, and re-run.

14.13 Focused recharge: "operands could not be broadcast together"

Fixed as of 2.1.0. The soil-derived Ks raster is now resampled to the D8 hydrology grid before use. If you see this on an older version, upgrade.

14.14 Focused recharge: outliers in Recharge_focused_annual.tif

The 2.1.0 engine caps each cell's monthly infiltration at $\text{max_daily_depth_mm} \times \text{flow_days}$ and enforces mass balance at every cell. If you still see large values, either the cap is too loose for your soils, the stream threshold is too low, or the DEM contains an artificial sink or spike. Adjust `max_daily_depth_mm`, `flow_duration_fraction`, or the stream threshold accordingly.

14.15 Combine: "Duplicate argument -ot"

Fixed as of 2.1.0. The width rasterization step no longer passes `-ot` twice.

14.16 Which combine method should I use

For standard WetSpass-M workflows, use **Addition**. Use **Replace-by-max** only if you have a specific reason to be conservative and are aware that it underestimates total recharge. Use **Focused-over-diffusive** only if you believe the diffusive model already includes some streambed loss.

14.17 The capped total looks too low

Check the recommended cap in the Focused Recharge tab. If it is much lower than you expect, click **Recompute from inputs** and verify the mean annual P is correct. Then use **Preview cap effect** to see how many cells are being clipped. If the cap is too aggressive for your catchment, tick **Override with** and enter a higher value.

15. References and acknowledgements

15.1 Original model

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15.3 Evapotranspiration

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15.4 Acknowledgements

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Appendix A — Glossary

AET — Actual evapotranspiration. The sum of transpiration, soil evaporation, open-water evaporation, and impervious-surface evaporation over a period.

Addition (combine) — $R_{\text{total}} = R_{\text{diffusive}} + R_{\text{focused}}$. The default combine method in 2.1.0.

Bucket — A simplified representation of the soil column as a single reservoir of plant-available water.

Climate cap — Upper bound on total recharge, equal to the upper bound of the plausible recharge fraction for the matched climate zone.

Closure error — The residual in the water balance after all fluxes and storage changes are accounted for. Should be close to zero on a well-posed model run.

DEM — Digital elevation model. A raster of land-surface elevations.

Focused recharge — Recharge concentrated on a small fraction of the landscape, typically streambeds and topographic lows, as opposed to diffuse recharge spread over the whole catchment.

Gaining stream — A stream that receives water from the aquifer along its reach.

Losing stream — A stream that loses water to the aquifer along its reach. Losing reaches are the source of focused recharge.

PET — Potential evapotranspiration. The evapotranspiration that would occur if water were freely available.

Replace-by-max (combine) — $R_{\text{total}} = \max(R_{\text{diffusive}}, R_{\text{focused}})$. Conservative alternative that avoids double-counting at the cost of a systematic underestimate.

Spin-up — The process of running a state-tracking model repeatedly on the same inputs until the internal state reaches a repeating cycle.

ΔS — Change in soil-water storage over a period. Zero in quasi-steady-state models; non-zero in dynamic models.

Appendix B — File listing

Filename	Purpose
<code>__init__.py</code>	QGIS plugin entry point
<code>metadata.txt</code>	Plugin metadata
<code>icon.png</code> , <code>icon.ico</code>	Icons
<code>LICENSE.txt</code>	Academic-use license
<code>README.md</code>	Short project README
<code>CHANGELOG.md</code>	Version history
<code>wetpass_plugin.py</code>	Main plugin class
<code>wetpass_provider.py</code>	QGIS Processing provider
<code>wetpass_algorithm.py</code>	QGIS Processing algorithm
<code>core/calculation_engine.py</code>	Core physics
<code>core/workflow.py</code>	Orchestrator with spin-up
<code>core/raster_io.py</code>	Raster I/O with auto-alignment
<code>core/cropper.py</code>	Boundary cropping (new in 2.1.0)
<code>core/focused_recharge.py</code>	Focused recharge engine
<code>core/stream_derivation.py</code>	D8 hydrology, stream network
<code>core/stream_io.py</code>	Vector rasterization
<code>core/run_report.py</code>	Run summary and metadata writers
<code>ui/main_dialog.py</code>	Main GUI
<code>ui/worker.py</code>	Background thread (diffusive)
<code>ui/focused_tab.py</code>	Focused recharge tab
<code>ui/focused_worker.py</code>	Background thread (focused)
<code>ui/water_balance_tab.py</code>	Water balance panel
<code>ui/calibration_tab.py</code>	Calibration panel
<code>ui/boundary_preview.py</code>	Boundary preview widget
<code>ui/tools_menu.py</code>	Tools menu actions
<code>help/WetSpassM_UserGuide.pdf</code>	This document