Maintenance Friendly Water Systems

Design and Construction in Rural, Mountainous Ethiopia

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This document describes Maintenance Friendly design: an approach to rural gravity-fed water systems optimised for the people who will operate and repair them, rather than for ease of construction. It covers the problems that recur in conventional designs, the model developed in response, the Distributed Storage system, its limitations, and the construction practices durability depends on.

Typical terrain: steep, dispersed settlement, water points kilometres apart.

1. Maintenance Friendly design

Maintenance Friendly design starts from one practical question: who will run this system day to day, and repair it when it breaks, years after it's commissioned, with the skills and tools reasonably available?

Most engineering optimises for performance at commissioning. Maintenance Friendly design optimizes for what comes after, in the hands of locally trained operators[1]. Every choice of design and construction presented below stems from that one priority: the spring rules, the distribution box, the water point itself.

A community water agent at work. Every Maintenance Friendly choice is made so this person can manage the system

A comparison between the standard scheme (Central Reservoir) and maintenance friendly scheme (Distributed Storage) is presented below. Both models of rural gravity-fed water systems operate with the same type of access for the water users: water is paid for as a bulk fee, not metered per liter, which keeps the system simple and accessible. However a bulk fee also means there is no direct cost attached to leaving a tap open (no direct individual incentive to save water, creating a collective problem if not respected), a fact that shapes almost every maintenance friendly design choices that follows.

[1] While this approach shares some similarity with DBOT (Design-Build-Operate-Transfer), in that both think about operation from the design and construction stage onward, it differs in substance: there is no private concessionaire, no profit-recovery period, and no handover of a finished asset at a fixed contract end. What is transferred here is design and supervision capability itself, to government, on an ongoing basis rather than at a single contractual milestone.

2. The standard scheme: Central Reservoir system

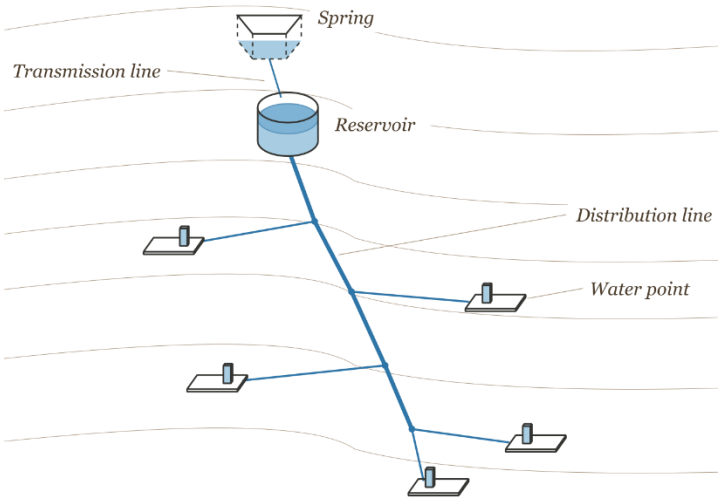
2.1 Central Reservoir system description

A typical rural gravity-fed water network, called here the Central Reservoir system, runs from a spring to several community water points.

From the spring, a **transmission line** carries water to a central reservoir, built upstream of the first water point. This line only has to carry the 24-hour average demand, so it can run at a lower diameter and cost less per meter to build.

The **distribution line** runs from the reservoir outlet through a series of tees, each one branching off to a water point. Most of a community's daily demand happens in a 6 to 10 hour window, so the distribution line has to carry 2.4 to 4 times more flow than the transmission line above it, even though both lines move the same total volume per day.

Water points sit roughly 500 meters apart. A typical scheme serves 6 to 8 of them; larger ones reach 30 or more, with 30 kilometers of pipe end to end.



The Central Reservoir system: one shared reservoir, one distribution line, tees branching to each water point.

2.2. Central Reservoir system limitations

In mountainous rural areas, the Central Reservoir system has five characteristic shortcomings.

First, because every water point relies on a single shared reservoir, any pipe damage or leak along the distribution line drains the system completely and cuts off access, at least for upstream users. This frequently triggers conflict and tampering. For instance, communities near the spring, who view themselves as its rightful owners[2], resent watching water flow past without serving them and frequently cut into the mainline to tap water directly.

Second, storage is shared across communities that are far apart[3], with no practical way to coordinate daily use among them. This lack of coordination triggers a vicious cycle of preemptive consumption: in practice, one community leaves its taps open overnight, causing the reservoir to run dry by morning; every other community then responds by leaving its own taps open too, trying to catch whatever trickle the spring still provides, most of which is wasted overnight.

Third, local faucets are rated for a maximum of 60 meters head, and it is rare for more than three water points to fit within that elevation difference in steep terrain. Standard design usually leaves this unresolved: the solution requires a break-pressure tank fitted with a float valve, a component that is difficult to procure and even harder to maintain in a rural setting.

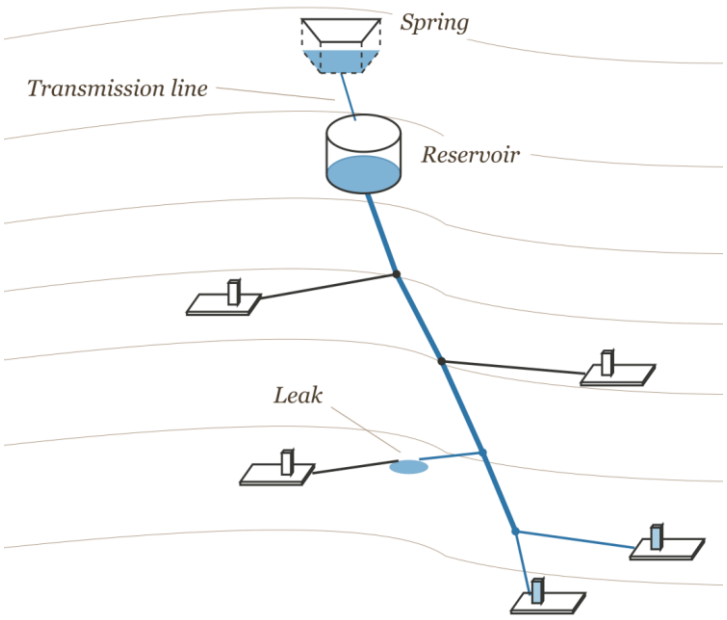
[2] This sense of ownership carries real weight in the community, though it is not reflected in Ethiopian law, where water from a spring is a common good managed by the government.

[3] In a small network of 6 to 8 water points, the distance between the first and last often exceeds 4 kilometers.

Fourth, in steep terrain, getting every water point to deliver water simultaneously requires precise pipe sizing to balance head loss against elevation at every point. That level of precision is impossible to achieve with the tools and skills available in rural Ethiopia.

Fifth, the simultaneous demand across many water points drives up required flow, which in turn requires a larger pipe diameter[4]. Larger pipes cost more to buy and far more to repair, sometimes requiring welding that is beyond what either a community or a Woreda Water Office can manage.

Fundamentally, this model suffers from the impracticability of managing the commons, driven by the impossibility of inter-community coordination and unachievable equity in water distribution.

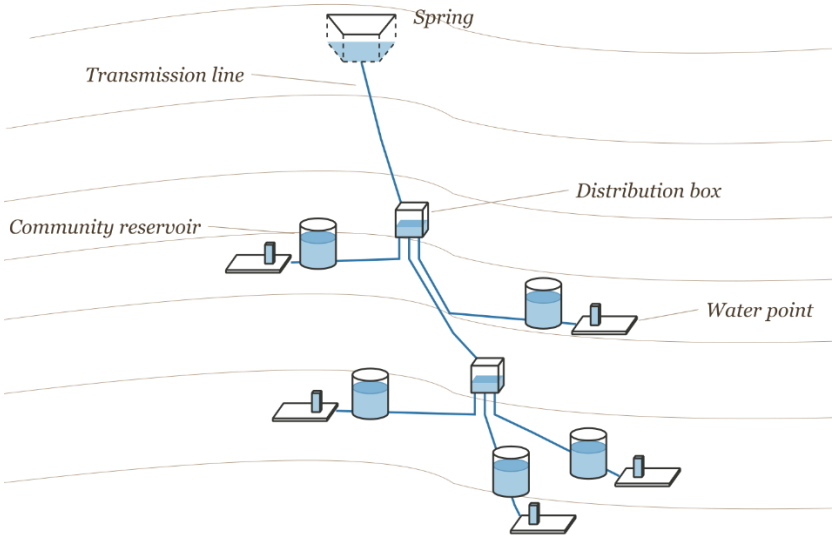


A single leak on one branch drains the reservoir and leaves the two water points above the break dry.

3. Distributed Storage system

3.1 Distributed Storage system advantages

The Distributed Storage system answers the Central Reservoir model's challenges through self-distributing flow control and decentralized water storage across the network. At the heart of this model is a distribution box, installed at key junctions on the network. The box splits incoming flow between its outlets in fixed proportions[5]. Downstream of each box, water is stored near the community it serves.



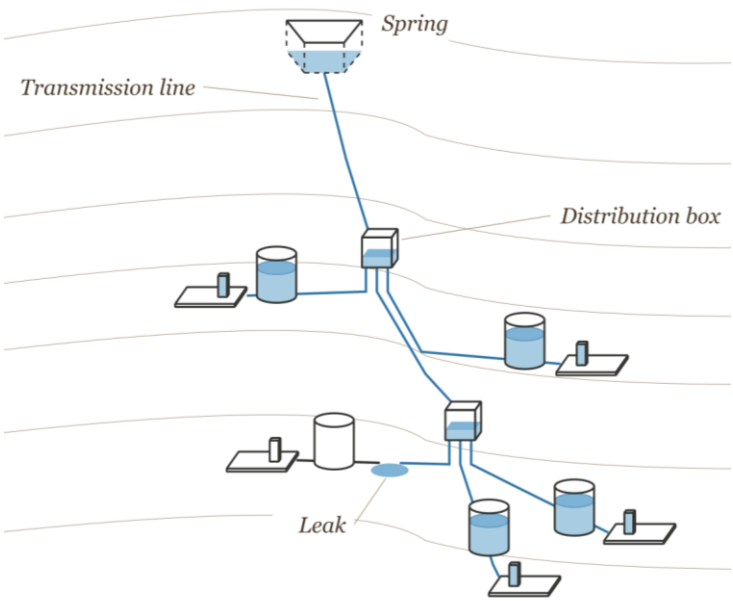
The distribution box splits incoming flow between its outlets in a fixed proportion based on needs.

[4] This effect becomes significant once a network exceeds about 10 water points.

[5] The split ratio is fixed by the size of each outlet: a wider outlet takes a proportionally larger share of the flow. The designer sets each outlet's diameter to match what its community actually needs, using a simple proportion calculation, the rule of three.

This addresses each of the Central Reservoir system's limitations, for the following reasons:

First, because each water point depends on its own local storage, a pipe damage or leak on a secondary line below a distribution box affects only the community on that line. The rest of the network remains unaffected, meaning there is no network-wide breakdown, less potential for conflict between upstream and downstream users, and more time to repair the damage safely, without an entire network waiting on it.



The same leak, in the same place, on Distributed Storage network: only that one community loses water. The other four are functioning normally

Second, decentralized storage solves the problem of managing the commons by giving each community sole responsibility for its own storage, rather than relying on one reservoir that no one is responsible for: if it leaves its taps open overnight, it has no water in the morning; if it closes them, it has plenty. That direct consequence gives water point committees a clear reason to enforce closing rules, and small, close-knit communities generally enforce them well.

Third, decentralized storage prevents the high static pressure that damages faucets and usually requires a break-pressure tank. Because storage is placed near to each community rather than far uphill in one central reservoir, water points stay under low pressure and cost-effective low pressure pipes can run even down steep slopes, eliminating the need for break-pressure tank or control valve anywhere in the network.

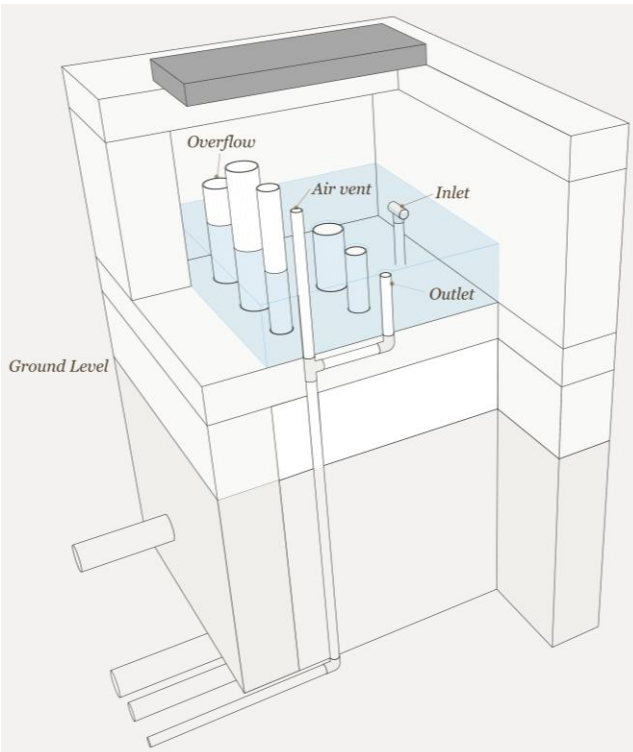
Fourth, sizing the network no longer means balancing head loss against elevation across the whole system simultaneously. Instead each box's outlets are sized using a simple proportional calculation, ensuring every branch receives its fair share of the flow regardless of terrain. As a result, the complex system-wide hydraulic design is reduced to a single, straightforward pipe calculation between each distribution box and its corresponding water point.

Fifth, because storage happens locally rather than centrally, every pipe in the network only ever carries the 24-hour average demand, rather than the peak demand of a shared distribution line. Every pipe in a Distributed Storage network can therefore be sized like a transmission line: smaller diameter, cheaper to buy, and easier to maintain or repair with local rural resources than large-diameter distribution pipe required by a Central Reservoir network.

The two models, side by side:

Feature	Central Reservoir	Distributed Storage
Impact of a pipe leak	Whole network dry	Only that branch dry
Storage management	Shared, uncoordinated preemptive consumption	Local, sole responsibility of each community
Pressure at taps	High static head, requires break-pressure systems	Always kept very low
Sizing method	Complex network-wide head loss balancing required	Simple proportion at each box and single pipe hydraulics
Pipe size & flow	Peak demand, large diameter (expensive and hard to repair)	24-hour average flow, small diameter pipes (cheaper and easier to repair)

The distribution box, in details:



The distribution box splitting flow in proportion to outlets diameter.

Free-Flow Distribution: Where the number of users is limited and the spring's yield is abundant, Free-Flow Distribution (in essence a distributed storage system with no storage) is the preferred choice as water points run continuously, with no reservoir and no tap at either end. The distribution box's fixed proportional split is the only regulation the system needs: nothing downstream has to open, close, or break, which makes it easier to maintain than any tap-fitted water point. It also gives a higher level of service, with water that is always available and with no limit on alternative uses such as watering livestock. In areas with less water to spare, a mixed network is a good compromise, some water points closed with a community reservoir, others left free-flow where needs are higher.

3.2. Limitations of the Distributed Storage system

The Distributed Storage system costs less to build than the Central Reservoir system in low-density or steep terrain. However, in flat, densely populated areas, a Central Reservoir system with metered volumetric billing remains more suitable, being both cheaper to build in that setting and better matched to cost recovery.

The solution to this is to combine both systems into a single scheme, in which a Distributed Storage system covers the upstream, steep and rural section of a network, whilst a metered Central Reservoir system covers the downstream town on flatter ground.

Flat terrain also poses a challenge: whilst breaking pressure at every distribution box is an advantage in steep terrain, in flat areas, this head lost at each box leaves less pressure to reach downstream water points. The solution used in the field so far is to build the distribution box directly on top of the community reservoir, which to adds heads to increase the pressure.

A distribution box built on top of the reservoir: one structure instead of two, close to the people who use it.

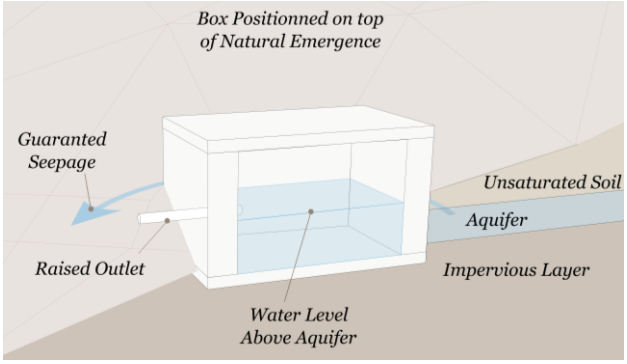
Finally, the Distributed Storage system is also more sensitive to negative pressure and air blocks than the Central Reservoir system, owing to the numerous distribution boxes which each introduce a sensitive pipe segment. Mitigating negative pressure requires careful pipe route selection and sometimes the installation of air vents. Air block mitigation demands particular care in the first few meters downstream of a structure, but can be alleviated by raising the distribution box on top of the community reservoir.

4. Non-negotiable practices

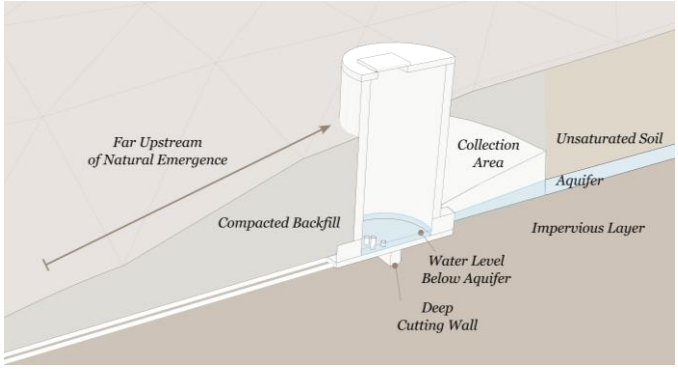
This section covers a set of practices that are well understood in principle, not new innovation, yet which are skipped constantly in the field, mostly because they are seen as too basic to document and implement carefully.

Durable spring capping: Designed for water table drawdown

The common mistake in spring capping is treating the emergence like a small dam: building a structure right at the point where the aquifer naturally surfaces, and raising the water level inside it high enough to reach the outlet pipe. This approach guarantees that the water will find another way out, either below the dam or through a separate natural outlet, since water in natural ground will always find the path of least resistance.



Treated as a dam: *water raised above the impervious layer finds its way around the wall.*



Treated as drainage: *the trench is the easiest path available, so the water takes it always*

What an uninspected spring box looks like inside: root growth left to develop unchecked

Instead, a spring box has to be designed and built as a drainage structure that gives the water a preferential path to follow, rather than a wall that traps it. This requires excavating deep enough to draw down the water table, while tapping strictly into the aquifer itself and keeping surface runoff from behind the structure out entirely.

To be maintainable, a spring box needs to be:

- visitable, for example with a hinged metal door with a lock, since a sealed door guarantees no one from the community will ever open it for inspection.
- cleanable, with an operable washout and overflow, sized to carry away all the excess water so the spring is never under pressure.

- protected with a fence to keep animals out of the spring close perimeter, with contour ditches around to route contaminated runoff away from the structure entirely.

Cost effective and durable reservoir: Constructed with standard metal mold

A custom-sized reservoir demands real, advanced skill to build, since it needs to resist water pressure and stay watertight over years of use. Using a standard reservoir mold guarantees that performance using the skills actually available on site. It is cost effective to build and result in extremely durable community reservoir.

> *Each distributed community reservoir consists of a thin reinforced concrete shell, thoroughly vibrated and cast in one of three fixed sizes, covering the range a rural community actually needs.*

A reservoir under construction in its metal mold.

Monolithic concrete water points: design for ergonomics.

Water points are built using monolithic reinforced concrete rather than masonry, since a plastered surface erodes under continuous water flow. They are designed around actual daily usage: spilled water drains through a pipe set below the faucets, so it never splashes across the apron, and feeds a cattle trough instead. A washing table, built at waist height, lets women do laundry without bending over a basin on the ground.

A water point in use: drainage below the taps going to the cattle trough, wash table at waist height.

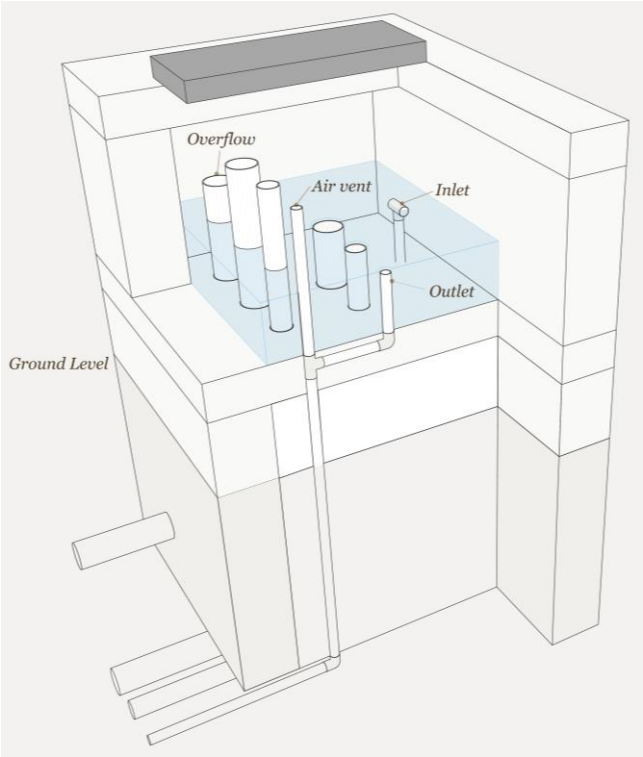
5. Maintenance-Friendly approach, applied

The Maintenance Friendly approach asks who will run this system day to day, and repair it when it breaks, years after commissioning. Every technical choice in this approach, from how to distribute water, how to store it, and how to make it easier to access, is made with that question in mind. The Distributed Storage system, adapted specifically for the rural, mountainous context, answers these questions, with trade-offs of its own, and a set of non-negotiable practices that no clever design choice can replace.

This mindset starts from the first sketch of the network, not as an afterthought once the system is already built, and does not rely on unusual materials or rare skills. This is Maintenance Friendly design and construction.

Annex A: Distribution Box

The Distribution Box is the structure that makes passive self-distribution possible, by splitting the upstream flow according to fixed proportion. Rather than relying on manual valves or complex hydraulic balancing, it splits the upstream flow according to fixed proportions, so each branch automatically receives its exact share of water, regardless of upstream flow variations or downstream demand.



Cutaway of a distribution box: inlet tee at outlet height, outlets cut to a single level, flow splitting in proportion to outlet diameter.

A distribution box splits flow between outlets using vertical PVC pipes, each cut to exactly the same height, working as a crest weir. Because it is a crest, the flow over each pipe depends on its perimeter, not its cross-sectional area. This has a real practical advantage: a 50mm outlet carries double the flow of a 25mm outlet, not four times, the way ordinary pipe sizing would work. This is also roughly how a community water agent judges it, just by looking at the two pipes side by side, whereas nobody in the field can look at a Hazen-Williams-driven pipe selection and see the logic in it.

Sizing outlets to match each community's share of the flow uses a simple proportional formula. Since every outlet sits at the same level, discharge is a function of diameter alone, and the ratio between two outlets' diameters sets the ratio between their flows. This is a simple rule of three: multiply the total design flow by each community's share, then choose diameters whose ratio best matches it.

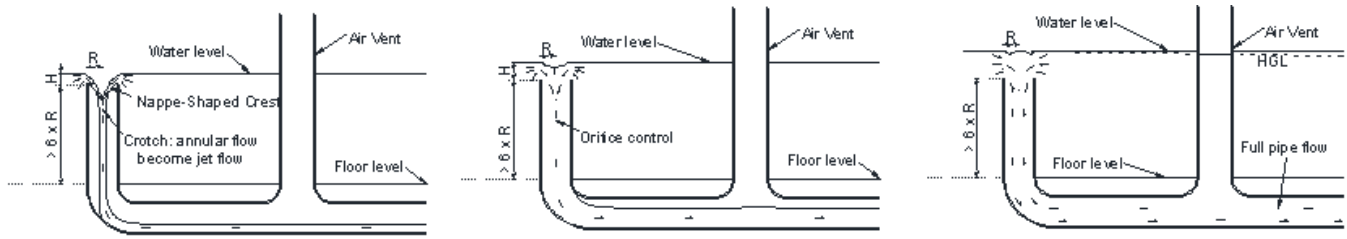
Three things break the proportional split, and the box's construction exists specifically to prevent each one.

Turbulence at the inlet is the first. Water entering above the surface splashes and disturbs it. Water entering too low drags air in with it, and the resulting bubbles disturb the surface. The inlet pipe is fitted with a tee, placed exactly at outlet height, at the water surface itself, to channel the incoming flow's speed away from the outlets, so that water arrives at the right level without disturbance to outlet crest flow.

Uneven outlet levels are the second, and the easiest to get wrong on site. Construction supervision calls for checking every outlet level with a spirit level, within 1 mm of each other, then a visual check that the crest flow looks identical at every outlet, this is a necessary best practice.

Submerged outlets are the third. If the water level rises past H = 0.2 × D, the outlet stops behaving as a crest weir, flow shifts to orifice control and eventually full pipe flow, and the split stops being proportional to diameter. A reference table of minimum outlet diameter for a given flow is part of the design methodology, and the designer checks every outlet against it for dry-season flow, the season where an exact split matters most. In the rainy season, when every outlet is running with water to spare, some loss of precision is an acceptable trade.

As inlet flow rises, the outlet passes through three regimes. Only the first keeps the split proportional to diameter.



Crest control
Split proportional to diameter.

Orifice control
Split no longer proportional.

Full pipe flow
Split bases on downstream pipeline

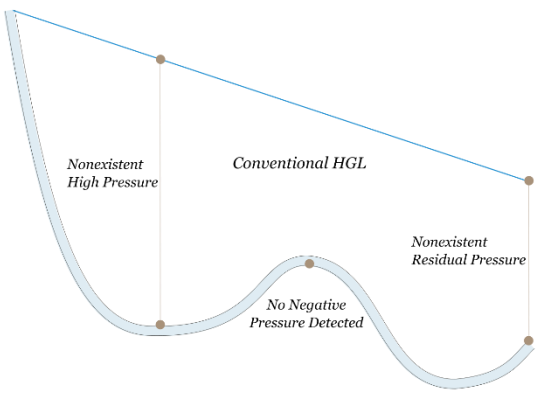
Full construction steps, box dimensions, foundation, and casting sequence are documented in PROCEED's distribution box construction methodology (MF4-M40).

In flat terrain, and wherever air-block sensitivity is a concern, building the distribution box directly on top of the reservoir instead of as a separate structure recovers the head a standalone box would otherwise lose to atmospheric pressure at that point. That extra head helps the line reach water points further down where there is little elevation to spare, and gives enough pressure right at the start of the line that a small bump in the terrain is far less likely to let a small air pocket block the flow. It keeps this dual structure right near the community rather than having a box far away where it is easily overlooked. Full construction details for the combined structure are in PROCEED's reservoir DB construction methodology (MF4-M51).

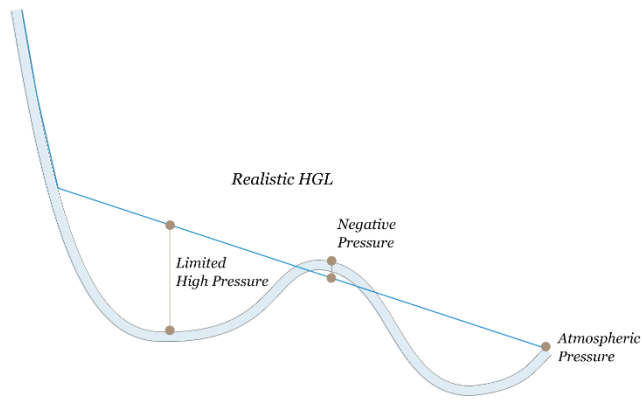
Annex B: Design Software

Commercial hydraulic design tools are built around pressure networks: many nodes, connected in loops or branches, assumed to run full and under positive pressure throughout. This suits a Central Reservoir system well, and it is possible to model the transmission line from spring to reservoir, with enough manual tweaking. However, these tools stop working once a network has tens of transmission-type lines, one for every distribution box branch. Commercial tools have no built-in concept of a distribution box, so each line needs its own manual workaround, which becomes rapidly impractical.

The main challenge, however, is physical, not just a matter of scale. A pipe sized for transmission flow, with a reasonable safety margin above the spring's dry-season yield, does not necessarily run full everywhere. At a high point along its route, it can run into negative pressure, which pushes on pipe integrity and creates a risk of contaminant ingress. If adapting pipeline size cannot solve it, an air vent placed at that high point prevents the siphon from forming at all, admitting air the moment pressure becomes negative. Conventional hydraulic calculation assumes full-pipe flow throughout and does not model properly this, which makes it physically wrong.



***Conventional HGL**: shows very high pressure throughout, and never reveals where the pipe is actually running negative.*

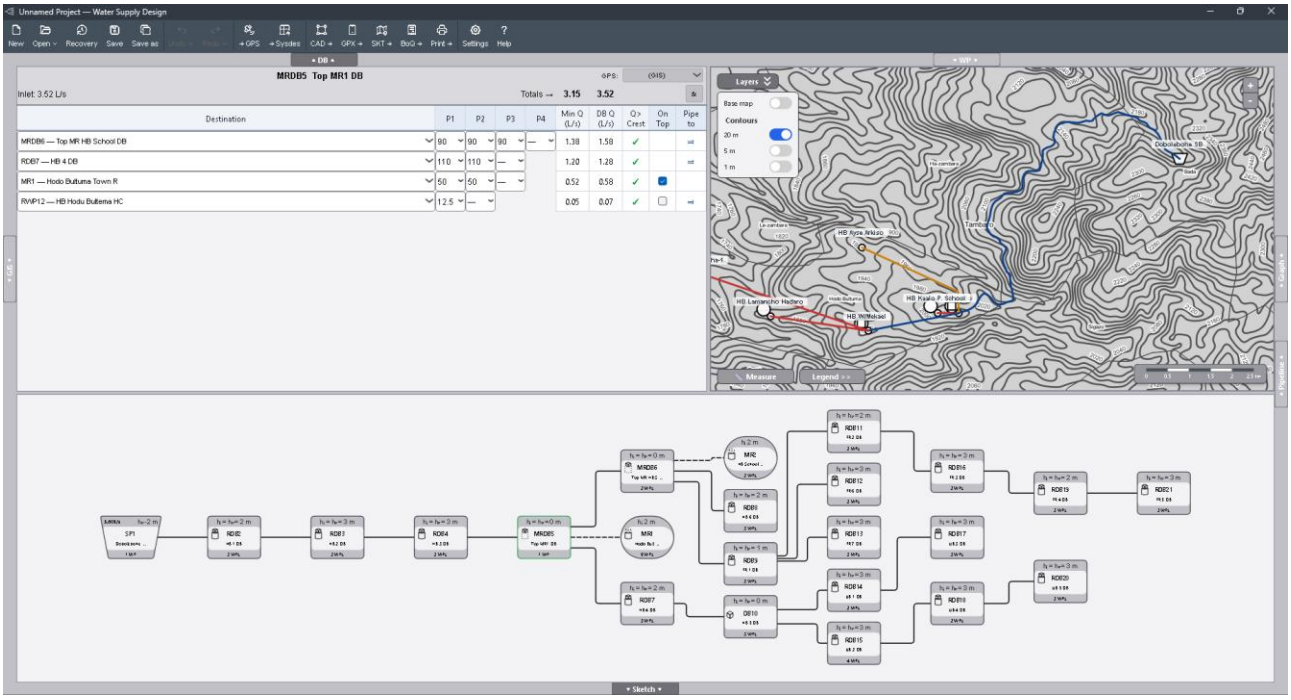


***Realistic HGL**: the same profile, computed backward from atmospheric pressure at the outlet, showing the sections genuinely under negative pressure, and that high pressure was never the real issue.*

Negative pressure isn't a weakness the model introduces. It's a problem that was always there, hidden by the conventional HGL, that the realistic one finally reveals.

The design software used in the Maintenance Friendly approach computes what is called Realistic Hydraulic Grade Line (HGL). Rather than assuming full pipe flow from the spring downward, the calculation starts from atmospheric pressure at the outlet, and works back upstream from there, accounting for negative pressure sections and air vent placement along the way. The result is the actual pressure profile along the pipeline, not the idealised one conventional tools produce.

Beyond this hydraulic engine, the software represents an entire network as a tree: springs at the root, distribution boxes and their outlets branching from them, water points as the leaves. It calculates each box's outlet split directly from outlet pipe diameters, according to the physics described in Annex A. Every pipeline segment gets its own Realistic HGL profile, with automatic checks for negative pressure, pressure exceeding pipe ratings, and insufficient flow at the far end. Elevation comes from GPS waypoints and digital elevation model lookups.



Home screen of the design software showing the repartition of a DB, the first line in the GIS panel and the interactive DB tree

As elevation data drives every one of the calculations, the choice of survey tool matters as much as the hydraulics do. We tested various tools, compared against a total station as the accuracy benchmark: GPS-plus-DEM outperforms both the clinometer, and a handheld GPS's own elevation reading taken alone. A handheld GPS combined with a 5-meter resolution digital elevation model keeps its error under 5 meters at 95% confidence, regardless of how far the survey runs.