Plan for Growth, Build in Stages

Modularity and incremental development of water delivery systems

PACE Execution • Working white paper • Draft 4 • November 2, 2026

Abstract

Water systems must serve populations whose size, location, purchasing behavior, and service expectations change over time. Forecasts are necessary, but building immediately for a distant forecast can leave an operator with extensive assets, limited sales, high maintenance obligations, and poor water turnover. This paper proposes an alternative: master-plan the full system, deliver a complete and financially supported first phase, and expand through standardized modules as measured demand justifies investment. Modularity applies to source development, pumping, solar generation, treatment, storage, structural supports, distribution, and customer connections. Its purpose is to make growth affordable while preserving service quality. Factory fabrication and interchangeable components support that purpose; they are part of a broader strategy for matching capital commitments to demonstrated needs.

1. From infrastructure targets to functioning service

The central sizing problem is not simply how many people live within a proposed service area. It is how many will use the service, how much they will purchase, where and when they will need it, and whether revenue and committed subsidies can sustain delivery. Population growth, migration, seasonal incomes, competing water sources, connection costs, and confidence in reliability can all change the relationship between population and demand.

A grant can finance infrastructure faster than an operator can establish a customer base. Where funding rewards installed capacity or projected beneficiaries more heavily than sustained service, there is an incentive to build for optimistic future uptake. The resulting system may look complete on a construction schedule while remaining incomplete as a service: the source, tank, and mains exist, but household connections, customer acquisition, or operating finance are missing.

This is a proposed explanation of a recurring implementation problem, not a claim that all funders use these incentives or that beneficiary reporting is wholly unregulated. Established frameworks exist. The WHO/UNICEF Joint Monitoring Programme, for example, defines safely managed drinking water through accessibility on premises, availability when needed, and freedom from contamination. Project reporting should complement such service measures with verifiable operational and commercial data. [1]

At minimum, distinguish the population potentially reachable; households and institutions physically connected; active purchasing accounts; people actually using the service; and people receiving the intended quality and continuity. A customer account and a consumer are different units: one paying account can serve several people. Neither a design population nor a connection count establishes actual consumption or safe service.

The first phase should therefore be a complete service to an achievable initial market. Where on-premise connections are the intended model, their installation and commissioning belong in the phase budget.

Expansion should increase the number of people receiving a reliable service, rather than merely enlarge the population described as potentially served.

2. Incrementalism as an investment strategy

The Freakonomics episode “In Praise of Incrementalism” provides an accessible introduction to progress through accumulated improvements. Its discussions of cities, saving, and performance improvement emphasize the consequences of repeated decisions and small gains. That perspective is useful here, although the episode does not itself establish an optimal water-system investment strategy. [2]

Water-sector research provides a more direct analytical foundation. Basupi and Kapelan examine flexible distribution-system design under uncertain future demand. Erfani, Pachos, and Harou develop a multistage real-options approach to water-supply capacity expansion under uncertain climate conditions. These studies address different planning settings, but both place value on adapting investments as uncertainty resolves. Their results should not be treated as measured savings for the schemes proposed here. [3,4]

The applicable economic concept is the value of flexibility: preserving an affordable future choice can be preferable to committing immediately to one forecast. A modular system makes that choice practical. Standardized expansion interfaces, reserved sites, accessible connections, and approved configurations reduce the cost and disruption of responding to new information.

Incremental development still requires an overall plan. Otherwise, small investments can accumulate into an incompatible system. The master plan should identify likely growth corridors, source constraints, future pressure zones, ultimate structural limits, and the sequence of upgrades. It should also distinguish investments that are expensive to change later from equipment that can be added economically.

Land, rights of way, certain foundations, and difficult road crossings may justify provision for future capacity from the outset. Additional tanks, solar racks, treatment units, and some distribution branches can often be staged. The decision is asset-specific: compare the cost of unused early capacity with the expected cost of later expansion, disruption, and service risk.

3. Complete phases, measured expansion

A practical development sequence starts with a serviceable core and expands through defined decision points. Before construction, establish a demand baseline and scenarios rather than a single growth prediction. Include anticipated connection uptake, measured purchases where available, affordability, seasonal demand, institutional users, source yield, and non-revenue water.

The first phase should include the entire chain required to deliver water: source, energy, pumping, treatment, storage, distribution, usable connections, metering, operating staff, and maintenance arrangements. For the PACE proposition, this supports the principle of completing on-premise connections within each funded service area. A phase is complete when its intended customers can use the service, not when the upstream equipment has been installed. [5]

Expansion decisions should combine several indicators:

- Demand: active accounts, purchased volume, connection waiting lists, and sustained peak requirements.
- Service: pressure, continuity, water quality, complaints, and capacity constraints observed during demanding conditions.

- Source and assets: seasonal yield, drawdown, pumping performance, tank turnover, and remaining equipment capacity.
- Finance: cash collected, operating expenditure, maintenance reserves, arrears, and the funding available for the next phase.

Thresholds should be set during design and reviewed using actual operating data. A short demand spike should not automatically trigger permanent expansion. Conversely, known lead times mean procurement may need to begin before existing capacity is exhausted. The objective is timely investment supported by evidence.

Two practitioner accounts illustrate why this matters. One concerns a substantial water investment whose consumption and collections reportedly fell far below expectations. The other concerns a network reportedly designed around on-premise connections without funding to deliver those connections. Both describe a gap between installed infrastructure and a functioning customer service. They are hypotheses for case-study investigation, not independently verified findings; the author's recalled project details appear in the editorial note at the end.

Selecting the first service area

The first phase requires explicit decision criteria of its own. Population density, settlement pattern, and the location of likely customers should inform where service begins. Average population density across a large administrative area can conceal compact settlements separated by substantial distances. Planning should therefore examine household locations, potential connections per kilometer of distribution, expected purchased volume per kilometer, and the distance and elevation between customers and the source. Population density is an input to this assessment; the density of actual or reasonably expected demand is the more direct operating consideration.

The master plan should distinguish the authorized service territory, the area intended for eventual service, and the boundary of the first funded phase. These boundaries need not coincide. The first-phase boundary should identify the specific households and institutions to be connected, the infrastructure needed to serve them, and the interfaces for later expansion. It should be defined through multidisciplinary review with the operator, relevant authorities, and affected communities, and documented spatially rather than left as a broad beneficiary estimate.

Candidate first-phase areas should be compared against a consistent set of criteria:

- Service need: current water quality, reliability, access difficulties, and the consequences of delayed service.
- Demand concentration: settlement density, likely connection uptake, seasonal use, and expected purchased volume along the proposed network.
- Technical feasibility: source capacity, topography, pressure requirements, water turnover, access, land availability, and feasible construction routes.
- Financial support: the cost of complete connections, expected collections, operating and maintenance obligations, and committed affordability support.
- Operational readiness: staffing, practical skills, supervision, access for inspection and repair, and the complexity of operating the proposed phase.
- Expansion value: whether the initial assets and boundary support logical, affordable extensions without stranding infrastructure or obstructing later service.

Criteria and their relative importance should be agreed before selecting the preferred area. A scoring matrix can make tradeoffs visible, but it should not substitute for engineering judgment or turn uncertain demand estimates into apparent precision. Basic feasibility and service requirements should be treated as prerequisites. Compare the remaining alternatives under plausible uptake scenarios and explain why the

selected boundary offers a complete, manageable first phase. The densest or most affluent settlement should not automatically win: service need, committed support, and the pathway to less concentrated areas also belong in the decision.

Building operator capacity through successive phases

Phased development also provides a practical way to build operator capacity. A smaller initial system gives a team repeated experience with the full service cycle: producing and treating water, maintaining pressure and continuity, reading meters, collecting revenue, inspecting assets, responding to faults, managing spares, and communicating with customers. Standardized equipment and recurring procedures make these repetitions transferable to later phases.

The principle is progressive responsibility matched to demonstrated capability. Operators bring differing levels of experience, and the initial scope should reflect that experience, available supervision, and local support. Simpler initial configurations can provide a manageable setting for practice and improvement while still meeting the same water-quality and service requirements expected of the expanded system.

Each phase should therefore include an operating-capacity plan alongside the engineering and financial plans. Provide practical training, supervised commissioning, written procedures, essential tools, reliable records, and access to technical assistance. Review performance across representative operating conditions, including fault response and seasonal changes where relevant. Useful evidence includes consistent treatment and monitoring records, timely preventive maintenance, reconciled meter and collection records, appropriate handling of alarms, and the ability to diagnose and escalate problems.

Expansion should account for the team's demonstrated capacity and the additional workload it will create. Where gaps remain, the response may be targeted training, additional staffing, simpler controls, or stronger technical support. Urgent service needs may justify expansion with that support in place rather than waiting for every skill to be developed internally. The intended progression is that physical capacity, customer demand, operating capability, and financial resources grow together.

4. Cash flow is part of system design

An oversized scheme imposes obligations immediately. Operators must inspect longer networks, read more meters, maintain more assets, manage treatment, and respond to failures even when sales remain small. Capital expenditure may be grant-funded, but operating expenditure and capital maintenance expenditure continue after construction.

A useful management measure is cash available after routine operating costs and an explicit provision for major maintenance. Collections, rather than invoices alone, determine the cash available to pay staff, buy chemicals, repair equipment, and retain essential spares. A scheme that appears affordable only because it postpones maintenance has not demonstrated sustainable operation.

For a simplified planning model:

Operating cash margin = cash collected from water sales + reliable operating support − routine operating cash costs − maintenance reserve contribution.

This measure should be tracked separately from expansion expenditure, debt service, and other financing flows. A sound operating business can have negative total cash flow during a funded expansion. Equally, a positive bank balance produced by an unspent construction grant does not demonstrate a viable operating service.

Research on business liquidity supports attention to cash management without supplying a universal profitability timetable. Afrifa's study of UK small and medium-sized enterprises examines relationships among working capital, cash flow, and performance. JPMorgan Chase Institute research finds an association between irregular cash-flow patterns and higher business exit rates. These are useful adjacent findings, not causal proof that a particular water scheme will succeed if it reaches a specified margin. [6,7]

The proposed objective is to establish a financially supported operating base early and test the incremental economics of each expansion. Where tariffs cannot cover socially necessary service, a dependable subsidy is part of the financing model. Positive operating cash flow must not become a reason to exclude households unable to pay; affordability support should be explicit and funded.

No universal rule establishes that significant income begins in year five. The more defensible point is that adoption and operational improvement take time. A multiyear funding framework can accommodate that process better than a construction deadline that assumes customers will appear immediately.

5. Hydraulic right-sizing protects water quality

Oversizing affects more than cost. A large pipe or tank operated at low demand can retain water for longer periods. EPA guidance identifies oversized infrastructure, low use, and dead ends among conditions associated with excessive water age and loss of disinfectant residual. Stagnation can create additional water-quality management burdens. [8,9]

The geometry is straightforward: stored pipe volume increases with the square of its internal diameter. A one-kilometer pipe with a 100-millimeter internal diameter contains approximately 7.85 cubic meters; one with a 75-millimeter internal diameter contains approximately 4.42 cubic meters. The larger pipe holds about 78 percent more water. At the same through-flow, its idealized displacement time increases correspondingly. This illustration is not a pipe-sizing recommendation: actual residence times depend on network topology, flow reversals, mixing, and demand patterns.

Free chlorine decays as it reacts; it does not have a single fixed expiration time. Higher water age, temperature, and chlorine demand can reduce residual before water reaches consumers. A low residual signals reduced protection and requires investigation, but does not by itself prove that the water is contaminated. Nor does all consumed chlorine become combined chlorine. Taste, odor, and disinfection by-products depend on chemistry and operating conditions; increasing the dose alone may leave the underlying residence-time problem unresolved.

Storage should be operated for the demand actually being served. Where permitted by the design, adjusting operating levels can improve turnover. Such changes must retain required treatment contact time, pressure, emergency reserves, and acceptable pump cycling. Tank layout, mixing, temperature, and the location of treatment also matter. [8,9]

Distribution expansion should be modeled for each stage, including the different demand patterns of communal taps and on-premise connections. Extended-period hydraulic and water-quality analysis can test pressure, water age, and residual management as customer uptake changes. Flushing remains an operating tool, but recurring flushing consumes water, chemicals, and labor; its costs belong in the lifecycle comparison.

6. Applying modularity across the system

Sources and boreholes

Preserve realistic pumping options when developing a source. Borehole and casing dimensions, pump clearance, access for rehabilitation, and sanitary protection can be expensive to change later. A larger drilled hole with an appropriately designed casing may preserve upgrade options, but the proposed ten-inch hole and six-inch casing are examples, not universal specifications. Geology, annular space, gravel packing, sealing, sustainable yield, water quality, and local requirements govern the design. More pump capacity cannot overcome an inadequate source.

Storage, head, and structural supports

Factory-made column segments, bolted interfaces, bracing, and tank platforms can form a repeatable structural family. Fabrication in jigs, controlled welding, inspection, and hot-dip galvanizing after fabrication offer a way to reduce inconsistent field work. Installation then centers on foundations, alignment, approved connections, and documented acceptance checks. This carries forward the standardization logic of the earlier PACE pump and structures papers. [5,10,11]

A triangular plan allows neighboring storage bays to share supports. In a simple chain of edge-sharing triangles, the first bay uses three support locations; each added bay adds one support location and two plan edges. Thus n bays use n + 2 support locations and 2n + 1 distinct plan edges. These counts describe geometry, not the complete bill of materials or structural capacity. Shared supports receive greater loads, and bracing, foundations, platforms, and access still require design.

The appropriate description is modular expansion with shared components and declining average support count per bay—not exponential growth. The marginal cost may be lower than constructing another independent tower, but savings require a complete engineered and priced comparison.

Height can also be an expansion dimension when the structural family and original foundations are designed for approved future configurations. Raising the operating water level by three meters adds approximately 29.4 kilopascals of static pressure. Whether this permits service to more distant or higher customers depends on friction losses, topography, minimum and maximum pressures, pumping capability, and source capacity.

Height increases require a designed lifting and reconstruction method, temporary stability provisions, and service-continuity arrangements. Adding segments is not automatically safe, and increasing height does not inherently increase stability. Ordinary telecommunications sections are precedents for manufacturing and assembly; their suitability for elevated water loads must be established separately. Directly embedding tower sections in concrete likewise requires a designed foundation and corrosion detail, rather than an assumed substitution for reinforcing steel.

Treatment and equipment spaces

Treatment can expand through additional validated units or parallel trains where the process permits. Buildings can preserve space and connections for future filters, dosing equipment, or contact capacity. Expansion must account for throughput, contact time, chemical storage, backwashing, maintenance access, and process reliability.

Electrical rooms may accommodate substantial capacity growth within an initial footprint if clearances, ventilation, cable routes, and equipment arrangement are planned. Geometry still matters: a three-meter-square room has nine square meters of floor area, while an equilateral triangle with three-meter sides has approximately 3.90 square meters. Triangular modules can combine into larger spaces, but equipment requirements should determine the useful shape.

Solar generation and standardized racks

Solar arrays illustrate repeatable expansion particularly well. The proposed module is a ten-position rack arranged as five columns by two rows, with panels in portrait orientation: their long dimension follows the slope, and their short edges lie uphill and downhill. Adjustable mounting provisions can accommodate an approved range of panel dimensions and loads. A nominal wattage does not define physical interchangeability.

One position can hold a secured, electrically isolated spare. At an illustrative 350 watts per panel, nine connected panels provide 3.15 kilowatts of nameplate capacity; the tenth is inventory, not generating capacity. Adding racks adds both active capacity and spares. This is a maintenance strategy, not automatic electrical redundancy. Compatibility, storage exposure, replacement testing, and safe isolation still require attention.

Mechanical rack boundaries need not define electrical strings. Series and parallel arrangements must meet the selected controller's voltage, current, and power limits under expected temperatures. Parallel strings may extend useful production during lower irradiance, subject to the pumping and source constraints. They do not guarantee a proportional increase in delivered water.

Grundfos documentation lists a 300-volt DC maximum for the referenced SQFlex range. A nominal operating voltage near that ceiling is not sufficient protection: cold-weather open-circuit voltage must remain within the applicable limit. RSI drives and SQFlex control equipment serve different motor arrangements and must not be treated as interchangeable. A later pump upgrade may reuse a compatible rack while requiring a different electrical design. [12]

Rack height and access should support safe cleaning, drainage, security, and maintenance. Elevation alone cannot prevent damage from thrown objects. Standardizing the rack should simplify installation while allowing site-specific wind, foundation, electrical, and security requirements.

Distribution and future loops

A staged network can reserve corridors and provide engineered, isolated future connection points. As demand develops, additional branches, parallel routes, or loops may relieve bottlenecks and improve continuity. Their locations should follow the master plan and hydraulic model, rather than a universal tee spacing or pipe diameter.

Loops can create useful alternative flow paths, but do not automatically eliminate low-flow areas or water-age problems. Each expansion requires review of demands, pressures, valve arrangements, flushing, and water quality. Unused connection provisions should avoid creating unnecessary stagnant branches. Some trunks should be sized for longer-term needs immediately; other sections can grow economically as demand becomes visible.

7. Established precedents for reusable engineering

The Bailey bridge demonstrates how a demanding structural function can be delivered through interchangeable manufactured parts and approved configurations. The Federal Highway Administration describes transportability, rapid assembly, and adaptation to different spans and loads among the system's requirements. The relevant lesson is that engineering can be embodied in a reusable product family and retained across many installations. [13]

Commercial radio towers offer a related precedent. ROHN markets recurring tower families and factory-fabricated, galvanized components. The engineering of a product family can be reused, while site loads, foundations, and permitted configurations still receive attention. This supports standardization; it does not establish that one tower form is universally least-cost or suitable for water storage. [11]

Westney's discussion of capital-project cost reduction and Fisher, Ramdas, and Ulrich's research on component sharing provide complementary perspectives on standardization. Common parts can reduce repeated design and procurement work, although excessive commonality can impose performance or material penalties. The aim is a small, useful family of compatible components rather than one component forced into every application. [10,14]

Geoffrey Moore's "Crossing the Chasm" offers an additional commercial analogy: adoption requires a complete solution for a defined customer group. Applied here, the implication is to establish dependable service in an achievable initial area and then extend it. This is an analogy from technology marketing, not a timetable or an empirical model of rural water adoption. [15]

8. Funding a progression rather than a construction event

A five-year funding framework is worth testing as an alternative to a single short construction cycle. It could finance the master plan, a complete first phase, early operating support where needed, monitoring, and subsequent capital tranches. Five years is a proposed program structure, not a universal requirement or a promise of profitability.

Later tranches should follow agreed evidence: sustained use, service quality, source performance, financial reporting, maintenance provision, and a credible demand case for expansion. The framework must also fund the monitoring and engineering needed to make those decisions. Operators should not be left carrying an oversized scheme while waiting indefinitely for a donor's next decision.

There are legitimate reasons to build ahead of observed purchases: urgent public-health needs, population displacement, long procurement lead times, indivisible infrastructure, and affordability constraints that suppress current demand. These should be explicit scenarios in the master plan. Incremental development succeeds when it preserves future access and responds promptly, not when it becomes an excuse to defer necessary service.

9. A practical validation program

The proposal should be tested through a limited portfolio with common reporting. Compare staged and conventional alternatives using lifecycle cost, time to functioning service, connection uptake, purchased volume, quality and continuity, cash collected, operating cost, major maintenance, and expansion disruption. Record engineering and manufacturing costs separately so that genuine repetition benefits can be distinguished from subsidy or omitted scope.

For structures, qualify a bounded family of configurations and document fabrication tolerances, inspection, coatings, connections, foundations, and expansion methods. For hydraulics and treatment, validate each phase against the intended service. For solar and pumping, define approved mechanical and electrical combinations. Track replacement-part availability and actual operator workload across the portfolio.

The proposed development model is therefore straightforward: plan the whole service, establish a complete operating base, preserve affordable upgrade paths, and commit additional capital as evidence supports it. Modularity makes incremental growth physically possible. Reliable service and financial discipline make that growth useful.

Editorial note: practitioner cases awaiting verification

The author recalls a Madagascar project costing approximately US$6 million, with consumption and payments around 10 percent of expectations. The comparison periods, forecast denominators, project scope, records, and permission to identify the project have not been verified. These figures are not used as quantitative evidence in this draft.

The author also recalls a Tanzanian well project where planned on-premise connections were not included in the funded scope. This account is not independently verified. The general implementation lesson is to align the service design, funded connections, and operating requirements.

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