

Water, hygiene, sanitation and microbial control



Conceptual visualization — water quality and hygiene depend on maintainable treatment equipment, sampling, isolation and verified return to service.

Move from water recycling alone to complete management of sanitary quality, uses, liquid waste and microbial contamination.

Mastery objectives

- trace water from source to verified potable use and identify every quality barrier
- separate hydraulic availability from microbial and chemical acceptability
- calculate reserve, treatment throughput and contamination-recovery time with explicit assumptions
- design sampling, isolation and return-to-service evidence for a degraded water loop

1. Recovered water is not automatically potable water

A loop can recover a large fraction of water while salts, organic compounds or microorganisms remain. The sanitary chain combines separation, filtration, chemical or catalytic treatment, disinfection and monitoring. Success is not only mass efficiency: water must meet the specification of the use for which it is released.

2. Separate water qualities reduce unnecessary treatment energy

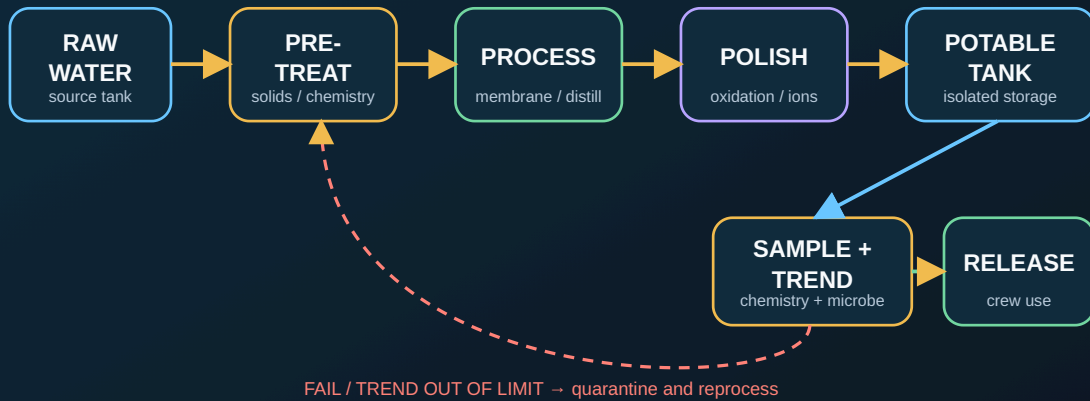
Not every function needs the same water quality. Drinking and food preparation require the strictest control, while technical cleaning, rinsing or some industrial processes may accept a different grade. Clearly separated networks avoid over-treating every liter, provided cross-connections and backflow are prevented.

3. Microbiology: prevent biofilm from becoming a system failure

Pipes, tanks and wet surfaces can support microbial communities and biofilms. Biofilm can degrade water quality, bias sensors and increase pressure drop. Control combines compatible materials, circulation, disinfection, sampling and the ability to clean or replace affected sections.

Water assurance train

Treatment is incomplete until sampling, trend review and release authority close the loop



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Water is released only after treatment and verification; storage quantity alone is not proof of potability. Pedagogical synthesis by Delta-Sierra from the primary sources cited in this course; schematic, not to scale.

4. Human hygiene is a health problem and a water-budget problem

Washing, toilets and clothing create large flows with different contaminants. Procedures must limit consumption without degrading skin health, sleep or infection prevention. Hygiene therefore connects medicine, psychology and water-loop sizing.

5. Sanitation and liquid waste streams

Urine, graywater, condensate and laboratory effluent should not be mixed without considering how each contaminates the recovery process. Every stream is characterized before choosing recovery, separate treatment, storage or controlled disposal. Laboratory chemicals may make a stream incompatible with biological processing.

6. Quality control: measure enough to make a decision

Conductivity, organic carbon, pH, disinfectant residual and microbiological assays answer different questions. A settlement defines frequency, thresholds, confirmation methods and the response when sensors disagree. An out-of-limit value must lead to quarantine or reprocessing decisions rather than becoming only a logged alarm.

7. Sanitary barriers: prevent contamination from flowing back

A crewed water network is not only a sequence of filters. Taps, showers, laboratories, crop systems and maintenance equipment can drive contaminants upstream if pressure relationships or check valves are poorly controlled. Design therefore needs backflow barriers, separation between clean and technical uses, and explicit rules for where treated water may re-enter circulation. Water can be chemically acceptable and still become microbiologically problematic when biofilms establish in piping. Monitoring should combine online measurements with sampling and clear criteria for isolating a suspect volume.

8. Sanitation: close loops without mixing every hazard

Greywater, urine, solid waste and laboratory effluent do not share the same composition or risk. Mixing them too early can complicate treatment and make failures harder to diagnose. A settlement can preserve distinct streams until an appropriate process transforms them, which can also improve nutrient recovery. Sanitation must be coupled to energy: distillation, oxidation and heating consume power and reject heat. Degraded mode should define the minimum water quality needed for drinking, cooking, hygiene, medical cleaning and crop protection.

9. Microbiological event: isolate, sample and correct the cause

When abnormal microbial growth is detected, simply increasing disinfectant concentration is not enough. Operators need to map affected branches, check temperatures and stagnation, find the failed barrier and preserve samples before cleaning. An aggressive intervention can hide the cause while damaging membranes, seals or sensors. Return to service then requires flushing,

chemical checks, microbiological analysis and enhanced monitoring. The event should produce a lasting correction such as removing a stagnation zone, changing recirculation frequency, replacing a material or improving sampling.

10. Worked example: makeup water at 98% recovery

If six people together produce 30 L/day of recoverable water and 98% is actually recovered, nominal loss is $30 \times 0.02 = 0.60$ L/day. Over 500 days the makeup requirement is already 300 L. At 95% recovery the loss becomes 1.5 L/day, or 750 L over the same period. Three percentage points therefore add 450 L of logistics in this example.

Calculated case study: separating gross water demand from makeup water

TEACHING ASSUMPTION — Four people each use 8 L of water per day in a simplified boundary combining drinking and hygiene. The period is 30 days, overall recovery is 90%, and a 20% reserve is added to makeup water.

Let n be the number of people; q demand in L/(person·day); d duration in days; r the dimensionless recovery fraction; and V volume in litres.

Gross demand: $V_{\text{gross}} = n \times q \times d = 4 \times 8 \times 30 = 960$ L. Makeup without reserve: $V_{\text{makeup}} = V_{\text{gross}} \times (1 - r) = 960 \times 0.10 = 96$ L. With a 20% reserve: $96 \times 1.20 = 115.2$ L.

The logistics-relevant number is therefore not simply 960 L: in this simplified model the loop reduces makeup to about 115 L including reserve. Real designs separate potable water, hygiene, urine, condensate and process streams because their qualities and recovery efficiencies differ.

11. Exercise

Draw a system separating potable water, technical water, graywater and urine. Inject microbial contamination into one tank and describe isolation, sampling, treatment, return to service and medical communication.

12. Reasoned solution

Separate the suspect tank from the potable network, preserve a verified reserve for vital use, sample before disinfection, then test upstream and downstream branches to locate the failed barrier. Return to service is justified only after treatment, flushing and results confirm the defined acceptance criteria.

13. Validation mini-project

Design the sanitary plan for a twelve-person habitat: water balances, quality by use, microbial surveillance, cleaning, special effluent, emergency reserves and an out-of-specification water procedure.

Water safety is a chain of controlled qualities, not a single recycling percentage

A Mars settlement cannot treat “water” as one homogeneous inventory. Drinking water, food-preparation water, hygiene water, technical rinse water, condensate, urine, laboratory effluent and crop-loop water carry different contaminants and require different barriers. The first engineering task is therefore to draw the streams, identify where they may connect, and decide what quality is required at each use point. Only after that map exists does a recovery percentage become meaningful.

Closed-loop thinking changes the logistics question. Gross demand describes how much water passes through human and technical activities, while makeup water describes what must be replaced after recovery losses. Those two numbers can differ by an order of magnitude in a high-recovery system, yet the lower makeup figure must never hide the fact that treatment equipment still processes the much larger gross flow. Pumps, membranes, tanks, sensors and microbial controls are sized by throughput and peak conditions as well as by losses.

Microbiology turns the water system into a living operational environment. Warm wet surfaces, stagnation, roughness, nutrients and dead legs can allow microorganisms to attach and form biofilms. A biofilm can alter water quality, protect organisms from disinfectant, foul sensors, increase hydraulic resistance and make a contamination event persistent even after bulk water

tests improve. Prevention therefore depends on geometry, material compatibility, flushing, temperature management, sanitation procedures and trend monitoring, not on one disinfectant measurement.

Sanitary resilience also requires separation between normal and abnormal states. When a sample is out of specification, the crew needs a known sequence: protect a verified potable reserve, isolate the suspect branch, preserve samples, identify the affected boundary, apply a compatible corrective action, flush or replace contaminated components when needed, and demonstrate recovery with independent checks. “Add more disinfectant” is not a complete incident response because it may suppress symptoms without removing the initiating cause.

Human hygiene belongs inside this engineering model. Reducing shower or laundry water can save resources, but excessive restriction can create skin problems, infection risks, poor sleep, odor, morale loss and extra cleaning burdens elsewhere. The right design treats hygiene as a health function with measurable water demand, contamination load and fallback modes. A settlement that closes its water loop while making daily life medically or socially unsustainable has not solved the real problem.

From source to mouth: the twelve control ideas a crew must understand

1. Map every stream before combining any streams

A useful water-flow diagram begins at generation points rather than at the treatment plant. Crew metabolism, cooking, washing, humidity condensate, toilets, laboratories, crop systems and maintenance each produce water with a characteristic contamination profile. The map should show normal destination, storage buffer, treatment path, sampling points, valves and any cross-connection that could send a lower-quality stream toward a higher-quality network. This makes hidden common-cause paths visible before they become incidents.

Operators then attach quantities to the diagram: average flow, credible peak flow, expected solids or chemical load, required product quality and the amount that can be temporarily stored. A stream that is small in daily volume can still dominate hazard if it contains solvents,

concentrated salts or biological material that damages the main recovery process. Conversely, a large relatively clean condensate stream may deserve a simpler path. Stream mapping is therefore both hydraulic accounting and risk segregation.

2. Define water quality by use, not by a single universal label

Potable water requires the strongest assurance because failure immediately affects crew health. Technical water may tolerate a different mineral content or microbial specification if it never contacts food, drinking systems or sensitive equipment. Crop irrigation can have yet another quality envelope because nutrients, salts and plant pathogens matter differently. Separating these classes avoids spending maximum treatment energy on every litre while still protecting the uses that need the strictest control.

The separation only works if interfaces are physically and procedurally credible. Connectors, hose fittings, labels, software displays and maintenance instructions should make it difficult to route technical water into the potable network by mistake. Backflow protection and pressure relationships matter as much as color coding. A quality class is not a name printed on a tank; it is an enforced boundary maintained through hardware, operations and verification.

3. Use multiple barriers because no single treatment step answers every hazard

Particle removal, adsorption, oxidation, catalytic processing, membrane separation, disinfection and final polishing address different contaminant families. The design should state what each barrier is expected to remove or control and what measurement demonstrates that the barrier is still working. If the system relies on several barriers in series, one degraded stage may be tolerable for a limited period only when downstream capacity and monitoring can cover the loss.

This barrier logic also prevents false confidence in a “good” bulk parameter. Low turbidity does not prove absence of dissolved organics, and acceptable conductivity does not prove microbiological safety. The crew should know which indicators are screening tools, which are direct measurements, and which require confirmation by a different method. The objective is not to maximize the number of sensors but to create enough independent evidence to make a defensible release decision.

4. Greywater recovery depends on what the crew puts into the drain

Greywater from washing can contain surfactants, skin oils, fibres, cleaning agents and microorganisms. Its treatability is therefore partly controlled upstream by the products approved for use in the habitat. A detergent chosen only for terrestrial cleaning performance may foul a membrane, interfere with a sensor or create persistent foam in a recovery loop. Procurement policy becomes a water-system design variable.

Because greywater production varies with crew routines, peak storage and treatment capacity need attention. A large laundry event can create a short high-flow period even if daily average volume is moderate. Buffer tanks can decouple generation from treatment, but long residence times can encourage microbial growth. The buffer is useful only when its volume, mixing, temperature and cleaning strategy are part of the operating concept.

5. Urine and concentrated sanitary streams should be treated as chemistry-rich resources

Urine contains a high dissolved load and can change chemically during storage. Precipitation, odor compounds, biological activity and scaling can complicate recovery equipment. The engineering question is not simply how much water can be extracted, but how the remaining concentrate is managed and whether useful nutrients or chemicals can be recovered without contaminating other loops.

A robust system keeps the concentrate boundary explicit. Maintenance personnel need to know where salts accumulate, which surfaces require inspection, how lines are flushed, and what happens if recovery is temporarily unavailable. Emergency storage capacity may be essential because forcing a problematic concentrate through degraded equipment can turn a local failure into a plant-wide contamination event.

6. Hygiene demand is both a human-factors budget and a contamination source term

Water allocation for hand washing, body cleaning, oral hygiene, toilets and clothing should be based on health and operability, not on an arbitrary desire to minimize litres. Different tasks have different minimum acceptable service levels. During a shortage, the crew can prioritize hand hygiene and clinical cleaning while reducing lower-priority uses, but those degraded modes need to be designed in advance with suitable products and procedures.

The downstream consequence must also be counted. A “dry” cleaning product can reduce water use yet introduce volatile chemicals or solid waste. Reusable textiles may save packaging but increase laundry demand. Hygiene architecture is therefore a cross-system trade among water, air quality, waste, power, crew time and medical risk. A credible budget names those exchanges instead of optimizing one subsystem in isolation.

7. Biofilm prevention starts with geometry and operating discipline

Dead legs, seldom-used branches, rough internal surfaces and low-flow zones create conditions where disinfectant residuals can decay and attached growth can establish itself. Designers should minimize unnecessary stagnant volume and provide ways to flush, sample or isolate branches. The crew should know which outlets must be exercised periodically and which tank or line temperatures make growth more likely.

Once established, a biofilm can release organisms intermittently, producing confusing test results. A single clean sample after disinfection may therefore be insufficient evidence that the system has recovered. Trend data, repeated samples, upstream/downstream comparisons and inspection of vulnerable hardware may be needed. Microbial control is a reliability program with spatial memory, not a one-time laboratory test.

8. Sampling plans must match the question being asked

A sample taken at the treatment outlet answers a different question from a sample taken at a distant tap after several metres of distribution piping. The first may demonstrate treatment performance while the second tests the condition of the network and point of use. Incident sampling should intentionally bracket the suspected boundary so the team can identify where quality changes.

Sampling itself can contaminate the sample. Containers, valves, handling technique, flushing time and storage temperature influence the result. Procedures should distinguish routine trend samples from confirmatory samples that may drive major operational decisions. When the consequence is high, an independent method or replicate can reduce the chance that a handling error causes either an unnecessary shutdown or an unsafe release.

9. Storage is an operational buffer and a sanitary component

Tanks give the crew time to decouple production, treatment and demand. A verified potable reserve can keep vital consumption independent of a temporary treatment outage, while a separate quarantine tank can hold uncertain product until testing is complete. The useful reserve is the volume that can actually be delivered under the failure being considered, not the geometric capacity printed on a drawing.

Tanks also require mixing, level measurement, vent management and a cleaning concept. Sediment or biological growth can accumulate in regions that normal circulation does not reach. If a tank cannot be inspected or sanitized, its long-term reliability depends entirely on assumptions that become harder to verify over years of operation. Maintainability should therefore influence tank shape, access and sensor placement from the start.

10. Backflow and cross-connection control protect the hierarchy of quality

A hose connected for maintenance can temporarily defeat a carefully designed sanitary architecture. Pressure transients can then drive contaminated liquid backward into a clean branch. Hardware backflow preventers, air gaps where practical, isolation valves and controlled connection procedures reduce this risk. The most dangerous configuration is often an unusual maintenance setup rather than normal operation.

Configuration control matters because temporary connections tend to become invisible once the immediate job is finished. The work record should identify what was connected, when it was removed and which post-maintenance flush or sample is required. A sanitary boundary is preserved through configuration discipline just as an electrical safety boundary is preserved through lockout and verification.

11. Treatment capacity must handle peaks and degraded modes, not only daily averages

Average litres per day can hide short periods when many crew members wash, a laboratory releases a batch, or a crop operation produces a large drain flow. If the processor cannot accept the peak, storage must absorb it without overflowing or creating excessive residence time. The design should therefore pair throughput calculations with buffer-volume calculations and operational scheduling.

Degraded capacity deserves the same treatment. If one pump, membrane train or sterilization stage is unavailable, can the crew reduce nonessential demand, reroute a cleaner stream, or operate the remaining train at a safe duty cycle? A recovery system becomes resilient when procedures connect physical capacity with priority rules rather than assuming every component is continuously available.

12. Release criteria turn measurements into a controlled decision

The final question is not whether a value “looks normal” but whether the product meets a defined release condition. The plan should state which parameters must be within bounds, whether a confirmatory sample is required after corrective action, who has authority to release the water, and what volume remains quarantined until the decision is made. This prevents social pressure or supply anxiety from quietly lowering standards during an incident.

Release criteria should also define what happens when evidence disagrees. A chemical sensor can look acceptable while a microbiological sample is suspect; two samples can conflict because one was contaminated during handling. The procedure should prescribe escalation, repeat testing and preservation of a safe reserve. Uncertainty is managed explicitly rather than resolved by optimism.

Water calculation laboratory: gross demand, makeup and sanitary reserve

Formula 1 — gross demand, recovered volume and makeup requirement

$$V_{\text{makeup}} = n \times q \times d \times (1 - r)$$

Starting question

How much new water must the settlement supply after accounting for the fraction recovered by the loop?

Read aloud

Read: “makeup volume equals crew number times per-person daily demand times duration times one minus recovery fraction.”

Symbols, pronunciation and meaning

n is crew size; q is gross water use per person per day; d is duration; r is the recovered fraction expressed between 0

and 1; V_{makeup} is replacement volume.

Units

If q is in L/(person·day) and d is in days, the result is litres. The recovery fraction has no unit.

Origin and status of values

Crew size and demand are mission inputs or measured operating data. Recovery should come from demonstrated performance across the selected boundary, not from a marketing peak value.

Why this operation

First multiply people, demand and days to obtain gross throughput. Multiplying by the unrecovered fraction isolates the portion that must be replaced.

Substitution and calculation

For 12 people using 9 L/(person·day) over 30 days at $r = 0.95$: gross demand = $12 \times 9 \times 30 = 3,240$ L; unrecovered fraction = 0.05; makeup = $3,240 \times 0.05 = 162$ L.

Calculator entry

Enter $12 \times 9 \times 30 \times (1 - 0.95)$. Keep parentheses around $1 - r$ so the recovery fraction is subtracted before multiplication.

Mental estimate

Five percent of roughly 3,200 L is roughly 160 L, so 162 L is plausible.

Independent check

Recovered volume is $3,240 - 162 = 3,078$ L. Adding recovered volume and makeup returns the gross 3,240 L boundary.

Physical or operational interpretation

The loop still processes thousands of litres even though logistics only replace 162 L in this simplified period. Treatment capacity and imported makeup therefore answer different design questions.

Plain-English translation

In ordinary language: a high-recovery system can greatly reduce imported water, but it does not eliminate the large internal flow that must remain clean and operable.

Variation / sensitivity

At 90% recovery the same case requires 324 L, exactly twice the makeup at 95%. A few percentage points near high recovery can strongly change logistics.

Limit / assumption

This teaching equation ignores water embedded in food, special laboratory use, leaks, tank heels and variable recovery by stream. Real balances separate those terms and carry reserve.

What this does not prove

The makeup equation is only a bookkeeping balance across the chosen water boundary. It does not demonstrate potability, microbial control, processor throughput, tank deliverability or independence of the recovery hardware from the makeup source.

Boundary case to test

Test the recovery fraction itself: $r = 0$ must return the full gross demand as makeup, while $r = 1$ drives this idealized makeup term to zero. Values below 0 or above 1 are invalid; even $r = 1$ would not eliminate leaks, purges or other losses omitted from this simplified boundary.

Formula 2 — usable buffer time before a potable reserve reaches its minimum

$$t_{\text{buffer}} = (V_{\text{available}} - V_{\text{minimum}}) / Q_{\text{essential}}$$

Starting question

How long can essential potable demand be supplied while the main treatment path is isolated?

Read aloud

Read: “buffer time equals available reserve minus protected minimum reserve, divided by essential consumption rate.”

Symbols, pronunciation and meaning

$V_{\text{available}}$ is deliverable potable volume; V_{minimum} is the reserve that operators refuse to consume during the current event; $Q_{\text{essential}}$ is essential demand rate; t_{buffer} is time available.

Units

If volumes are litres and Q is litres per hour, time is hours.

Origin and status of values

Available volume comes from verified tank level and deliverability. Essential demand comes from the degraded-

mode consumption plan, not the normal daily average.

Why this operation

Subtracting protects the minimum reserve. Division by the essential flow converts usable volume into time available for diagnosis and recovery.

Substitution and calculation

If 420 L are deliverable, 120 L must remain protected and essential demand is 25 L/h, usable volume = 300 L and $t = 300 / 25 = 12$ h.

Calculator entry

Enter $(420 - 120) \div 25$.

Mental estimate

Three hundred litres at about twenty-five litres per hour should last about twelve hours.

Independent check

Multiply $12 \text{ h} \times 25 \text{ L/h} = 300 \text{ L}$ and add the protected 120 L to recover the initial 420 L.

Physical or operational interpretation

The result is a decision clock: corrective work that cannot restore a safe source within twelve hours needs another supply path or stricter demand reduction.

Plain-English translation

The crew has about twelve hours of usable potable buffer before reaching the protected minimum in this simplified scenario.

Variation / sensitivity

If demand rises to 40 L/h, the same usable reserve lasts only 7.5 h. If another tank adds 100 L, time extends by 4 h at 25 L/h.

Limit / assumption

The calculation assumes the reserve remains potable and physically deliverable. A common-cause contamination or pump failure can invalidate the nominal tank volume.

What this does not prove

Buffer time is a timing estimate, not proof that the stored water remains potable or that pumps, valves and power can actually deliver it. A contaminated tank or unavailable transfer path can make nominal stored volume unusable.

Boundary case to test

Set $V_{\text{available}}$ equal to V_{minimum} : usable buffer must become exactly zero. If $V_{\text{available}}$ is smaller, the negative result is an alarm that the protected reserve has already been violated. $Q_{\text{essential}}$ must stay positive; a zero denominator is not infinite real autonomy but a different operating state with no modeled demand.

Operational cases: how water problems propagate through a settlement

A positive microbial result at one distant tap

The crew should resist the temptation to disinfect the entire settlement immediately. A distant point-of-use result can originate in the treatment plant, the distribution branch, the tap hardware or the sampling act itself. Operators first protect consumers, switch the affected zone to a verified source if necessary, and take bracketing samples upstream and downstream. Flow history, temperature and recent maintenance help identify whether stagnation or a disturbed biofilm is plausible.

If upstream samples remain clean while repeated point-of-use samples fail, the corrective action can stay local. If multiple branches show the same trend, the boundary expands. This staged reasoning preserves scarce disinfectant, avoids unnecessary shutdowns and builds evidence about the actual failure mechanism. After cleaning or component replacement, recovery requires repeated acceptable results under representative flow, not just one sample taken immediately after a strong flush.

A greywater processor loses half of its nominal capacity

The first response is not automatically to shut down hygiene. The crew compares expected generation with remaining processor throughput and buffer storage. Laundry can be deferred, shower schedules adjusted, and some low-priority cleaning shifted to methods that create less liquid. High-priority hand and clinical hygiene remain protected because their health value is disproportionate to their water volume.

Operators also watch buffer residence time. Slowing generation can be helpful, but simply storing warm nutrient-rich greywater for many days can create a microbiological problem that outlasts the processor repair. The degraded plan therefore combines demand reduction, storage limits, treatment priority and a trigger for more severe restrictions if repair slips beyond the calculated buffer.

A laboratory solvent is accidentally sent toward the recovery loop

Chemical compatibility determines the response. The affected stream should be isolated before it reaches components that could be damaged or before it contaminates a large mixed inventory. The team records the chemical identity, estimated quantity, time and route, then checks which adsorbents, membranes, sensors or catalysts are vulnerable. A small volume can justify discarding or quarantining a larger batch if the consequence of contaminating critical treatment hardware is greater than the cost of losing water.

This case shows why laboratory drains deserve explicit routing and why maintenance bypasses need configuration control. Water conservation is not the only objective. Sometimes the safest resource decision is to sacrifice a limited contaminated volume to protect the much larger clean loop and the treatment capability that the settlement cannot readily replace.

A disinfectant sensor suddenly reports zero residual

A zero reading can mean genuine loss of protection, sensor failure, wiring trouble, calibration drift or a sample-point problem. Operators compare independent evidence before making a large chemical adjustment. They can check a second method, inspect recent dosing trends, verify flow and review whether a tank turnover or maintenance activity changed conditions. During uncertainty, potable release can be constrained while a verified reserve supports essential use.

If the sensor is wrong, blindly increasing dose may create an out-of-specification chemical condition. If the zero is real, delaying action may allow growth. The response therefore separates detection, confirmation and control. This is a general principle of remote settlement operations: never let one unverified instrument both diagnose the problem and command an irreversible corrective action.

A potable tank must be opened for maintenance

Opening a sanitary boundary converts a normally closed component into a contamination-sensitive worksite. The team defines cleanliness controls, tools, protective clothing, temporary covers, environmental conditions and the post-maintenance sanitation plan before the hatch is opened. Parts that contact potable water are protected from dust and from tools used on other fluid systems.

After closure, mechanical leak checks are not enough. The return-to-service sequence should restore flow, flush or sanitize as required, and verify the appropriate quality parameters before the tank is released. Configuration records capture what was changed. This protects the crew from a common maintenance trap: fixing the mechanical defect while quietly introducing a sanitary one.

A settlement grows from twelve to twenty people

Crew growth increases gross water throughput, but the stress is not uniform. Potable demand, toilet use, hygiene peaks and laundry batches may rise at different times. A processor that had comfortable average capacity can become constrained during peaks, while tank turnover becomes faster and storage margins shrink. Expansion planning therefore revisits each stream rather than scaling one total number by a population ratio.

The new occupancy also changes emergency reserve duration. The same 600 L tank provides fewer person-days of essential supply. If the architecture relies on a reserve to cover maintenance outages, the growth decision must include either more storage, higher repair readiness, lower degraded-mode demand or additional treatment redundancy. Population is an engineering parameter, not merely a habitation count.

Sanitary water drills with worked reasoning

Exercise 1 — Separate gross demand from imported makeup

A crew of 8 uses a gross 10 L per person per day for 20 days. Overall recovery across the chosen boundary is 92%. Calculate gross throughput and nominal makeup, then explain why treatment equipment cannot be sized from the makeup number alone.

► Reveal the reasoned solution

Exercise 2 — Find the suspected contamination boundary

Routine samples are acceptable at the treatment outlet and first two taps but repeatedly fail at the final branch after a rarely used hose connection. State the next three actions.

- ▶ Reveal the reasoned solution

Exercise 3 — Choose a degraded hygiene strategy

Greywater processing capacity falls to 60% for 48 hours. Which uses would you reduce first, and which would you protect?

- ▶ Reveal the reasoned solution

Exercise 4 — Protect a potable reserve

A verified tank contains 500 L. The operating plan protects 140 L as untouchable emergency reserve. Essential degraded demand is 30 L/h. Calculate usable buffer time.

- ▶ Reveal the reasoned solution

Exercise 5 — Respond to conflicting sensor evidence

Online conductivity is normal, but a microbial screening result is suspect. Can the crew release the water solely because conductivity is acceptable?

- ▶ Reveal the reasoned solution

Exercise 6 — Evaluate a cross-connection risk

A maintenance team proposes using the same portable pump alternately for technical rinse water and potable transfer. Identify the design concern and propose a safer arrangement.

- ▶ Reveal the reasoned solution

Exercise 7 — Plan tank maintenance

List the sanitary steps that belong before, during and after opening a potable-water tank.

- ▶ Reveal the reasoned solution

Exercise 8 — Scale a system for population growth

A twelve-person habitat becomes an eighteen-person habitat while treatment hardware remains unchanged. What four quantities would you recalculate before approving occupancy?

► Reveal the reasoned solution

Water incidents: diagnosis, isolation and sanitary recovery

Commissioning a new potable branch after construction

Before a new branch can serve drinking water, the team treats construction debris, lubricants, cleaning products and stagnant test water as possible contaminants. Mechanical pressure testing is only one part of commissioning. The line is flushed through a controlled route, sanitary treatment is applied when appropriate to the materials, and samples are taken at locations that demonstrate both the source and the new distal point. Valve positions and backflow devices are verified against the as-built configuration rather than assumed from the drawing.

The release decision also checks that the branch can be maintained. Sampling access, isolation capability and flushing flow must be practical after surrounding equipment is installed. A branch that is clean on day one but cannot later be isolated or sanitized becomes a long-term vulnerability. Commissioning therefore validates both present quality and future operability.

A membrane train shows gradual pressure increase

A rising pressure drop can indicate fouling, scaling, blocked prefilters, valve position error or sensor drift. Operators compare differential pressure with flow, feed quality and recent cleaning history before forcing the pump to work harder. Increasing pressure without diagnosis may accelerate damage or compact deposits that are harder to remove. If parallel capacity exists, the affected train can be isolated while product quality and total throughput remain protected.

The crew records the condition at the point of intervention because maintenance results are diagnostic evidence. If cleaning restores performance only briefly, the upstream chemistry or pretreatment may be the true cause. Reliability improves when the team asks why fouling returned rather than treating each pressure rise as an isolated maintenance task.

A tank level reading disagrees with water-accounting estimates

Inventory mismatch can come from a level-sensor fault, unrecorded transfer, leak, trapped volume, density assumption or a boundary error in the accounting model. The response compares independent measurements and valve history before declaring a water loss. A manual or alternate level check, pump runtime and downstream tank change can help reconstruct where the volume actually moved.

This matters because unnecessary emergency conservation can burden the crew, while a real leak left unexplained can consume reserve silently. Water accounting is therefore a diagnostic tool as well as a logistics table. Reconciliation rules should define how much unexplained difference is acceptable before operators stop transfers and investigate.

A sanitation chemical becomes unavailable

The settlement should know which sanitation functions depend on that specific chemical and which have qualified alternatives. Switching products is not trivial because material compatibility, required contact conditions, downstream removal and sensor interference may differ. The team prioritizes the remaining stock for the highest-consequence applications while using mechanical cleaning, heat or another validated method where suitable.

Procurement records should identify substitute products before the shortage occurs. A closed-loop habitat that depends on one imported disinfectant without an alternate procedure has a hidden consumable dependency. The response may also trigger local production research, but immediate operations rely on already demonstrated methods rather than experimental chemistry.

Crop-loop water shows a rising salt trend

A crop system can accumulate salts even while total water recovery looks excellent. Operators review nutrient dosing, plant uptake, evaporation, reject streams and any blending with other water qualities. Simply sending the high-salt water back into the potable loop can increase treatment burden or damage a process not designed for that load. A controlled purge may be necessary even though it reduces headline closure.

The useful engineering question is where the salts ultimately go. If they can be separated and recovered as nutrients, the purge becomes a resource stream. If not, storage or disposal must appear in the mass balance. Closing the water loop while allowing dissolved solids to

accumulate indefinitely is not a physically closed system.

A crew member develops repeated skin irritation during conservation mode

The medical and water teams investigate hygiene products, rinse quality, clothing practices, humidity and the conservation procedure itself. The problem may indicate that the degraded hygiene plan saves water by creating a health burden elsewhere. Adjusting hand and body-cleaning priorities can use more water while still keeping total demand below normal through reductions in laundry or discretionary rinsing.

The event should update the conservation plan rather than be treated as individual preference. Habitability is part of mission reliability. If a water-shortage mode cannot be sustained for the duration assumed in the contingency analysis, the reserve calculation is optimistic even when the litres are mathematically correct.

A quarantine tank approaches capacity during a long investigation

Operators decide whether additional uncertain product can be diverted to another compatible tank, whether low-risk technical use is permitted before potable release, or whether generation must be reduced. Mixing batches can destroy diagnostic information by combining water from different time periods or treatment states. The tank inventory should preserve enough separation to support root-cause analysis.

Capacity planning therefore includes investigation duration, not only normal process flow. A quarantine volume that holds one routine sample period may be inadequate for a multi-day incident. The system needs a strategy for prolonged uncertainty without forcing premature release or dumping valuable water blindly.

A pipe repair requires a temporary bypass around treatment

Temporary bypasses are high-risk configurations because they can defeat sanitary barriers that are normally automatic. The work package states exactly which quality can flow through the bypass, what downstream uses are prohibited, how the temporary hose or pipe is cleaned, and which valves must be locked or tagged. Visual markings and independent verification reduce the chance that another operator assumes the system is in normal configuration.

After repair, the bypass is removed, normal barrier sequence is restored, and post-maintenance samples confirm that no lower-quality water reached protected branches. Configuration control closes the incident; simply repairing the broken pipe is not enough.

A remote sampling result is delayed while the potable reserve shrinks

The crew must balance evidence quality with resource time. The release plan can define whether a rapid local screening method is sufficient for provisional restricted use while a slower confirmatory result is pending. The decision depends on hazard, treatment history and reserve state, not on impatience. Some uses may remain prohibited even if limited technical consumption is allowed.

This is where predeclared decision authority matters. Operators should not invent lower acceptance standards because the tank is getting empty. Instead, the contingency architecture should provide another verified source, a reduced-demand plan or a clearly justified provisional criterion developed before the emergency.

Long-term trend shows slowly declining recovery efficiency

A one-percent decline may not trigger an alarm, yet over months it can materially increase makeup demand and indicate membrane aging, leakage, fouling or changed crew usage. Trend review separates measurement drift from real loss by reconciling multiple meters and process performance. Maintenance can then be scheduled before reserve requirements grow unexpectedly.

The lesson is that high closure needs statistical attention. The difference between ninety-eight and ninety-six percent can double the unrecovered fraction. Small percentage changes near the top of the scale deserve operational interpretation rather than being dismissed as rounding noise.

Water-system design dossier: sanitary verification and long-duration operation

Design dossier — separate potable availability from treatment availability

A settlement can have a healthy treatment plant and still lack deliverable potable water if a distribution pump, valve group or tank outlet is unavailable. Conversely, treatment can be down while a verified reserve keeps consumption safe. Reliability accounting should therefore represent production, storage and delivery as separate functions. The crew dashboard can show how many hours of potable service remain under each relevant failure, not merely whether the processor itself is “green.”

This functional view changes spare-part priorities. A small outlet valve or level sensor can become as mission-critical as a large membrane assembly if it is the only path to the reserve. The design dossier should list such hidden single points and show the manual or redundant route that preserves water access during maintenance.

Design dossier — manage water quality after long stagnation

A branch that remains unused for weeks can differ substantially from a continuously circulated line. Disinfectant residual may decay, temperature may drift and attached growth can develop even though the central tank remains within specification. Long-idle branches therefore need a restart procedure that can include flushing, sampling or controlled recirculation before the outlet returns to potable service.

The required action depends on branch volume, material, previous history and hazard consequence. The important principle is that “isolated and untouched” is not automatically equivalent to “preserved.” Storage and stagnation are physical states that affect quality over time.

Design dossier — use maintenance windows to preserve sanitary redundancy

Water-system maintenance should be scheduled against reserve level, alternate treatment capacity, crew demand and the probability of overlapping work. Taking two nominally redundant trains out of service for convenience can erase the very redundancy that protects a contamination event. Work permits can include a sanitary availability check before valves are opened.

If a second anomaly occurs during maintenance, operators need an abort point that leaves the system in a stable configuration. This may mean reinstalling a cleaned module, closing a bypass or restoring one train before continuing diagnosis. Maintenance sequencing is therefore part of sanitary resilience, not an afterthought.

Design dossier — instrument uncertainty belongs in the alarm threshold

A sensor threshold should not be chosen without considering measurement accuracy, drift and process variability. If normal variation is close to the alarm limit, the crew will face frequent ambiguous events and may learn to ignore alerts. If the threshold is too loose, a real deterioration can progress before action. Trending and confirmatory methods can create an intermediate warning state rather than forcing every deviation into an immediate shutdown.

The control plan should record calibration interval, known interferences and what secondary evidence is required for release decisions. Instrument engineering and sanitary policy meet at the threshold.

Design dossier — plan for cleaning water and cleaning waste

Cleaning a tank, membrane or pipe consumes water and produces a concentrated waste stream. That volume must appear in the balance, particularly during a contamination event when repeated cleaning can consume reserve quickly. The waste may contain disinfectant, biofilm debris or chemicals that should not be routed straight back to the normal recovery process.

A mature procedure identifies the source of cleaning water, maximum expected volume, temporary storage destination and criteria for returning the equipment to service. Maintenance water is part of life-support logistics, not an invisible utility.

Design dossier — verify the emergency water plan by drill

A tabletop calculation can show twelve hours of potable buffer, yet an actual drill may reveal that transferring from the reserve tank requires a hose stored behind other equipment, a pump that shares the failed bus, or a sampling step that takes longer than expected. Periodic drills should exercise the full path from declaring an out-of-specification condition to delivering verified water under degraded conditions.

Timing, crew workload and configuration errors from the drill feed back into reserve sizing and procedure design. A reserve is credible only when the crew can access and manage it through the same failure that motivated the reserve.

Final synthesis for mission qualification

Final synthesis — define what “water-secure” means for the settlement

A water-secure settlement is not one that reports a high recycling percentage. It is one that can identify each water quality, preserve a verified potable reserve, isolate contamination without losing the whole network, continue essential hygiene in degraded mode, repair treatment equipment without destroying sanitary barriers, and demonstrate return to service with independent evidence. The design review should therefore ask for time-to-consequence under treatment loss, distribution loss and contamination, then show the hardware and procedure that buys recovery time in each case. This closes the gap between chemistry, microbiology, logistics and human habitability: water security is a system capability whose proof is the ability to keep people healthy while a credible fault is being diagnosed and corrected.

Qualification notes

Qualification note — preserve margin above the mathematical minimum

A final water design should retain operating margin above the calculated minimum reserve because real consumption, sampling delay and recovery performance fluctuate. The acceptance review should therefore compare expected, degraded and worst-reasonable cases rather than approve a tank volume that works only when every assumption lands exactly on its nominal value. Margin is what converts a correct equation into an operable system.

Interactive beginner glossary

These terms are written to stand alone in a tooltip: a beginner should not need another technical dictionary to understand the first sentence.

- potable water — Water released for drinking and food preparation after the required sanitary checks have been satisfied.
- makeup water — New water added to replace the fraction lost from a recovery loop.
- gross demand — The total water passing through activities before recovery is subtracted.
- greywater — Wastewater from washing or similar uses that is less contaminated than toilet waste but still requires controlled treatment.
- sanitary stream — A water or wastewater flow whose contamination and health implications require defined handling rules.
- barrier — A treatment or physical control that blocks, removes or reduces a specified hazard.
- biofilm — A community of microorganisms attached to a wet surface and embedded in protective material they produce.
- dead leg — A poorly flushed branch or pocket of piping where water can remain stagnant.
- disinfectant residual — The measurable amount of active disinfectant remaining in water after dosing and reactions.
- cross-connection — A connection through which lower-quality fluid could reach a cleaner system.
- backflow — Reverse movement of fluid into a system from which it should remain separated.
- quarantine tank — Storage used to hold uncertain or out-of-specification water until a release decision is made.
- release criterion — A defined condition that must be satisfied before water is authorized for its intended use.
- sampling point — A designed location where a representative water sample can be collected.
- confirmatory test — A second measurement or method used to check an important initial result.
- throughput — The amount of fluid a process receives or treats during a stated time.
- peak flow — The highest relevant short-duration flow that equipment or storage must accommodate.
- residence time — How long water remains in a tank, pipe or process volume before leaving it.
- sanitation — Controlled cleaning and treatment intended to reduce contamination to an acceptable state.

- potabilization — The set of treatment and verification steps used to make water suitable for drinking.
- concentrate — The smaller stream in which salts or other contaminants become more concentrated after recovery.
- fouling — Performance loss caused by material accumulating on a membrane, surface, sensor or process component.
- buffer volume — Stored capacity that separates short-term generation or demand from process throughput.
- essential demand — The reduced water use that must still be supplied to protect health and critical operations during a degraded mode.
- quality class — A defined water category linked to the requirements of a particular use.
- trend monitoring — Repeated measurements used to detect gradual change rather than relying on a single result.
- isolation valve — A valve used to separate one branch or component from the rest of the fluid network.
- sanitary boundary — The physical and procedural separation that protects a clean water system from contamination.
- out of specification — A measured condition that falls outside the approved acceptance range.
- return to service — The controlled process of verifying a repaired or sanitized system before normal use resumes.

Operational review checklist

- Draw every normal and abnormal water stream, including temporary maintenance connections.
- State the required quality at each use point and the evidence that proves it.
- Keep gross throughput separate from makeup logistics in calculations.
- Verify peak treatment flow and buffer storage, not only daily averages.
- Provide a deliverable potable reserve that remains independent of the most credible treatment outage.
- Minimize dead legs and identify branches requiring periodic flushing or exercise.
- Control products placed into greywater so they remain compatible with downstream treatment.

- Define how urine concentrate and special laboratory effluent are isolated and stored.
- Use sampling locations that can bracket an incident boundary.
- Require independent confirmation when one measurement could trigger a major irreversible action.
- Protect potable equipment during maintenance with explicit cleanliness and post-work release steps.
- Design backflow prevention and connection hardware so quality classes cannot be casually mixed.
- Predefine degraded hygiene priorities that protect hand, food and clinical sanitation.
- Keep a response sequence for microbial events: protect, isolate, sample, diagnose, correct, verify.
- Recalculate reserve duration and processor margins whenever crew size or operating pattern changes.

Engineering calculation studio: make the water system auditable from first principles

The following calculations do not replace microbiological procedures, laboratory validation or mission-specific standards. Their purpose is to make the physical bookkeeping visible. Every value that is not a measured or sourced property is explicitly a teaching assumption so that the student can recompute the result rather than memorize it.

Formula A – daily gross water demand

Question. Before recycling is considered, how much water does a group require during one day?

Intuition. If one person needs a certain quantity in a day, a group needs that quantity once for each person.

$$Q_{\text{day}} = N \times q$$

Read aloud. “Q day equals N multiplied by q.”

- **Q_{day}**: total gross water demand, for example in litres per day.
- **N**: number of people, a simple count.
- **q**: gross demand per person per day, for example litres per person per day.

Why multiplication? The unit check shows it: persons × L/(person·day) = L/day. The word “person” cancels.

Teaching calculation. Assume N = 30 and q = 35 L/(person·day). Line 1: 30 × 35 = 1,050. Line 2: Q_{day} = 1,050 L/day. A calculator entry is simply 30 × 35.

Mental check. 30 × 30 = 900 and 30 × 5 = 150; 900 + 150 = 1,050, so the result is plausible.

Interpretation. This is gross demand before any recovery. It does not tell us how much must be imported or extracted locally.

Limit. Real demand varies with hygiene policy, food preparation, maintenance, medical events and process loads; a single per-person value is a planning simplification.

Formula B – concentration after successive independent removal steps

Question. If several treatment stages each remove a fraction of a constituent, what concentration remains after all stages?

Intuition. Each stage acts on what survived the previous stage. Therefore the surviving fractions multiply; their efficiencies are not simply added.

$$C_n = C_0 \times \prod (1 - \eta_i)$$

Read aloud. “ C_n equals C_0 multiplied by the product of one minus η_i .” The capital pi, Π , means multiply every listed factor.

- C_0 : starting concentration.
- C_n : concentration after n modeled stages.
- η_i (“eta i ”): fractional removal efficiency of stage i , from 0 to 1.

Teaching calculation. Use an illustrative indicator concentration of 100 arbitrary concentration units, with two independent modeled stages removing 90% and 80%. Surviving fractions are 0.10 and 0.20. Line 1: $100 \times 0.10 = 10$. Line 2: $10 \times 0.20 = 2$. Thus $C_n = 2$ in the same concentration unit.

Unit check. Concentration $\times$ dimensionless $\times$ dimensionless remains concentration.

Mental check. After a 90% removal, only one tenth remains. Removing 80% of that leaves one fifth of the remainder, so two units from one hundred is consistent.

Limit. This simple product assumes the stated efficiencies apply to the same constituent under the actual operating conditions and treats stages as separable. It is not proof of potability or sterilization.

Formula C – contaminant or solute mass flow

Question. How much mass of a dissolved or suspended constituent passes a point per unit time?

Intuition. Concentration tells us mass per volume. Volumetric flow tells us volume per time. Multiplying them gives mass per time.

$$\dot{m} = C \times Q$$

Read aloud. “Mass flow rate equals concentration multiplied by volumetric flow rate.”

- $\dot{m}$ (“m dot”): constituent mass flow rate, such as grams per hour.
- C : concentration, such as grams per litre.
- Q : volumetric flow, such as litres per hour.

Teaching calculation. If a process stream carries an illustrative $C = 0.8$ g/L at $Q = 25$ L/h, then $\dot{m} = 0.8 \times 25 = 20$ g/h.

Unit check. g/L $\times$ L/h = g/h; litres cancel.

Independent check. Divide 20 g/h by 25 L/h: 0.8 g/L, recovering the starting concentration.

Interpretation. This converts a concentration measurement into a loading rate useful for sizing collection, treatment or inventory accounting.

Limit. It assumes concentration and flow represent the same stream and time interval. Pulses and poor mixing can make a single sample unrepresentative.

Formula D – reserve volume from a critical flow and required duration

Question. What minimum usable reserve volume corresponds to a known essential flow for a specified time?

Intuition. A flow is a quantity used each unit of time. Multiplying by time gives the total quantity consumed.

$$V_{\text{buffer}} = Q_{\text{crit}} \times t$$

Read aloud. “Buffer volume equals critical flow multiplied by time.”

- **V_buffer:** usable reserve volume.
- **Q_crit:** essential consumption or delivery rate.
- **t:** protected duration.

Teaching calculation. Assume an essential water demand of 240 L/day and a design exercise requiring 5 days of protected supply. $V_{\text{buffer}} = 240 \times 5 = 1,200 \text{ L}$.

Calculator check. $240 \times 5 = 1200$. Reverse check: $1,200/240 = 5 \text{ days}$.

Interpretation. This is usable volume. Tank geometric volume may need to be larger because unusable heel, isolation rules and quality segregation can reduce accessible water.

Limit. The relation does not include replenishment during the event or changing demand; both should be modeled separately when they matter.

Formula E – concentration after mixing two compatible streams

Question. If two compatible water volumes with different concentrations are mixed, what is the ideal mixed concentration?

Intuition. First compute the amount of constituent carried by each volume, add those amounts, then divide by the new total volume.

$$C_{\text{mix}} = (C_1V_1 + C_2V_2) / (V_1 + V_2)$$

Read aloud. “C mix equals C one V one plus C two V two, divided by V one plus V two.”

Teaching calculation. Take 40 L at 2 mg/L and 60 L at 8 mg/L. Constituent mass from stream 1: $2 \times 40 = 80$ mg. Stream 2: $8 \times 60 = 480$ mg. Total = 560 mg. Total volume = 100 L. $C_{\text{mix}} = 560/100 = 5.6$ mg/L.

Bounds check. For positive volumes, the mixture must lie between 2 and 8 mg/L. 5.6 satisfies that condition.

Limit. This ideal mass balance assumes additive volumes, conserved constituent and genuine mixing. Reactions, precipitation, adsorption or phase separation invalidate the simple model.

Formula F – hydraulic residence time

Question. How long, on average in an idealized well-mixed volume, does fluid remain inside a vessel?

Intuition. If a vessel contains a certain volume and flow removes one vessel-volume every so many hours, volume divided by flow gives the characteristic time.

$$\tau = V / Q$$

Read aloud. “Tau equals volume divided by volumetric flow.”

- τ (“tau”): idealized residence time.
- V : active liquid volume.
- Q : through-flow rate.

Teaching calculation. For $V = 300$ L and $Q = 50$ L/h, $\tau = 300/50 = 6$ h.

Unit check. $\text{L} \div (\text{L/h}) = \text{h}$.

Interpretation. The result helps reason about storage turnover, contact time and how quickly a changed inlet condition can influence a vessel.

Limit. Real tanks can have dead zones, short-circuit paths and imperfect mixing; τ is a characteristic time, not the guaranteed age of every parcel of water.

Formula G – logarithmic reduction as a way to compare orders of magnitude

Question. How can a student express a large reduction in an indicator concentration without writing many zeros?

Intuition. A base-10 logarithm counts powers of ten. A tenfold reduction is 1 log; a hundredfold reduction is 2 log.

$$LR = \log_{10}(C_{\text{before}} / C_{\text{after}})$$

Read aloud. “Log reduction equals the base-ten logarithm of concentration before divided by concentration after.”

Teaching calculation. If an illustrative indicator falls from 10,000 units/mL to 10 units/mL, the ratio is $10,000/10 = 1,000$. Because $1,000 = 10^3$, $LR = 3$.

Reverse check. A 3-log reduction means a thousandfold ratio between before and after in this idealized comparison.

Limit. A log reduction for one measured indicator does not by itself prove removal of every pathogen, toxin or chemical contaminant. Sampling method, detection limit and treatment conditions matter.

Integrated exercise — from people to reserve

A 30-person teaching settlement uses a gross 35 L/(person·day). A modeled recovery system returns 97% of processed water under nominal conditions. First compute gross demand. Then compute nominal make-up. Finally, if the recovery train is assumed unavailable and the emergency policy reduces essential demand to 9 L/(person·day), calculate a five-day emergency reserve.

Solution. Gross demand = $30 \times 35 = 1,050$ L/day. Nominal unrecovered fraction = $1 - 0.97 = 0.03$, so nominal make-up = $1,050 \times 0.03 = 31.5$ L/day. Emergency essential flow = $30 \times 9 = 270$ L/day. Five-day reserve = $270 \times 5 = 1,350$ L usable. These answers address quantity only; quality and equipment availability require separate verification.

Water-loop calculation laboratory: losses accumulate even when recovery looks excellent

A recovery percentage is not a promise of self-sufficiency. The missing fraction must be replaced from stored or locally produced water, and downtime or contamination can dominate the average.

Net make-up water

Question. How much new water must enter a loop each day after recycling?

$$m_{\text{make-up}} = m_{\text{processed}} \times (1 - r)$$

Read aloud. Make-up mass equals the mass processed during the period multiplied by one minus the recovery fraction.

- **m_{make-up}**: replacement water, in kilograms per day.
- **m_{processed}**: water sent through the loop, in kilograms per day.
- **r**: recovered fraction written as a decimal; 98% becomes 0.98.

Teaching scenario. Thirty people and associated hygiene/process loads send 105 kg/day through a modeled loop. At $r = 0.98$: $1 - 0.98 = 0.02$; $105 \times 0.02 = 2.10$ kg/day of make-up. Over 100 days, ignoring downtime and other losses, that is 210 kg.

Unit check. kg/day $\times$ dimensionless fraction = kg/day.

Interpretation. A high percentage can still create a large cumulative supply requirement. This calculation does not prove potable quality, microbiological safety, or equipment availability.

Dilution as a measurement skill, not a recipe

Laboratories often prepare a lower-concentration calibration or teaching solution from a stronger stock. The ideal mixing identity is $C_1V_1 = C_2V_2$. If a harmless tracer stock is 5% and a 20 L teaching batch is required at 0.1%, $V_1 = (0.1/5) \times 20 = 0.4$ L of stock and 19.6 L of diluent. This is a mathematics exercise, not a disinfectant prescription: real sanitation chemistry requires material compatibility, validated concentration ranges, contact time and safety data.

► Exercise — 97% recovery

First-Man incident room: keep a water fault from becoming a settlement-wide exposure

Water safety is not created by one purification device. It is created by barriers that remain understandable when one measurement turns bad. A credible chain separates source collection, pretreatment, primary purification, final disinfection or microbial control, clean storage, distribution and point-of-use monitoring. The purpose of this separation is diagnostic as much as protective: when quality changes, operators need to know where contamination could have entered and which clean volumes can still be trusted.

Source

identify stream and contamination risk

Treat

remove particles, chemicals and microbes

Protect

clean tank, distribution and backflow control

Verify

trend, sample, release and investigate

A bad sample is an event, not automatically a diagnosis

Suppose a routine sample shows an unexpected microbial signal. The immediate questions are where the sample was taken, whether the sampling method itself could have contaminated it, whether online indicators changed at the same time, and which volumes were exposed after the last trusted result. Operators should preserve the sample, repeat using an independent point or method where possible, quarantine suspect water if consequence justifies it, and avoid flushing evidence away before the boundary is understood.

Trend data matter. A gradual increase in total organic load can suggest a different problem from a sudden step after maintenance. A disinfectant residual falling while tank temperature rises is more informative than either value alone. The system should therefore store time-aligned measurements so the investigation can reconstruct what changed first.

Define clean/dirty boundaries before maintenance

Opening a filter housing, replacing a pump or connecting a temporary hose can defeat an otherwise excellent treatment train. Maintenance plans should state which side is clean, which tools are allowed there, how components are sanitised, how air or dust ingress is controlled and what test is required before the line returns to service. On Mars, a “quick bypass” can be especially dangerous because resupply is slow and a contamination event may consume scarce filters, disinfectant and crew time.

Exercise: choose a defensible degraded mode

The main processor still meets flow demand, but a downstream microbial monitor gives repeated high readings. A protected emergency water tank has enough verified potable water for 36 hours. The correct degraded mode is not to keep distributing from the suspect branch merely because production capacity remains high. Shift essential consumption to the protected tank, reduce nonessential use, isolate or quarantine the suspect path, investigate sampling and treatment evidence, and define the test that will justify return to service. The 36-hour stock is therefore a diagnostic and repair clock, not merely inventory.

Operational qualification lab: keep safe water available while evidence is incomplete

A settlement water operator is rarely given a clean textbook fault. The realistic problem is uncertainty: one sensor drifts, a sample is suspect, a pump has just been serviced, one storage tank contains verified water and another contains water whose status is unclear. The operator must protect health without wasting the entire inventory. This laboratory turns the water loop into an auditable chain of barriers, measurements and release decisions.

Start with boundaries. Separate **production capacity** from **potable-water status**. A processor can continue making water while its output is quarantined. Separate **verified storage** from **suspect storage**. Separate the clean distribution branch from hoses, tools and components that have crossed a dirty boundary. These distinctions let the crew keep essential consumption alive while the investigation continues.

Build an evidence map before opening valves

For every tank and branch, record the last trusted sample, online indicators, most recent maintenance, direction of flow and which downstream users consumed water after that point. The map should answer three questions without guesswork: what volume is definitely clean, what volume is definitely suspect, and what volume cannot yet be classified. Unknown is not the same as contaminated, but unknown water should not silently become potable water merely because demand is high.

A teaching incident can begin with a microbial monitor that rises after a filter replacement while conductivity and total flow remain normal. Plausible explanations include a contaminated sample, contamination introduced during maintenance, stagnant water in a branch, or failure of a downstream barrier. The correct response is to preserve evidence, isolate the minimum defensible boundary and obtain an independent check. Flushing the whole network immediately may destroy the evidence and consume scarce water without identifying the cause.

Verified potable reserve time

$$t_{\text{reserve}} = V_{\text{verified}} / \dot{q}_{\text{essential}}$$

1 – Concrete question

How long can the settlement remain on water that is already verified safe while a suspect branch is investigated?

2 – Intuition without symbols

Usable time equals the trusted quantity available divided by how quickly essential users consume it.

3 – Quantities first

Identify only water whose status is verified, then define an emergency consumption rate that excludes postponable uses.

4 – Formula

Reserve time equals verified volume divided by essential volumetric flow.

5 – Read aloud

“t reserve equals V verified divided by q-dot essential.”

6 – Symbols

t_{reserve} is reserve duration; V_{verified} is trusted potable volume; $\dot{q}_{\text{essential}}$ is the emergency potable-water demand rate.

7 – Pronunciation

$\dot{q}$ is read “q dot”; the dot indicates a quantity per unit time.

8 – Units

If V is litres and $\dot{q}$ is litres per hour, the answer is hours.

9 – Convention

Use the same inventory boundary for both numerator and demand. Do not count inaccessible water or water already quarantined.

10 – Why division

Each hour consumes $\dot{q}$ litres; dividing the stock by litres per hour tells how many such hours the stock can support.

11 – Assumptions

The simple calculation assumes constant emergency demand and no replenishment during the interval.

12 – Unit check

$$L \div (L/h) = h.$$

13 – Numerical case

Verified stock: $V_{\text{verified}} = 1,920 \text{ L}$.

Essential demand: $\dot{q}_{\text{essential}} = 80 \text{ L/h}$.

$t_{\text{reserve}} = V_{\text{verified}} / \dot{q}_{\text{essential}}$.

$t_{\text{reserve}} = 1,920 \text{ L} \div 80 \text{ L/h}$.

$t_{\text{reserve}} = 24 \text{ h}$.

14 – Why each operation

No percentage is required: the problem is a stock divided by a rate. The rationed rate belongs in the denominator because higher demand shortens the available time.

15 – Algebra check

Rearranging gives $V = t \times \dot{q}$. Thirty-six hours multiplied by 75 L/h returns 2,700 L.

16 – Mental estimate

75 L/h is 1,800 L/day, so 2,700 L should last about one and a half days. Thirty-six hours matches that estimate.

17 – Interpretation

The crew has a 36-hour diagnostic and repair clock before that protected stock is exhausted.

18 – What it does not prove

It does not prove the suspect loop is contaminated, nor that the protected tank can be used without distribution losses or quality checks.

19 – Sensitivity

If emergency demand rises to 100 L/h, reserve falls to 27 h. Demand discipline therefore creates investigation time.

20 – Practice

Guided exercise. Recompute the verified reserve clock for 1,920 L at an essential demand of 80 L/h.

Detailed guided correction.

1. Use only the verified inventory: 1,920 L.
2. Use the emergency demand rate: 80 L/h.
3. $1,920 \div 80 = 24 \text{ h}$.

4. The verified stock therefore supports 24 hours at that demand, before distribution losses or new verified production are credited.

Autonomous exercise. Create a two-tier demand plan in which essential use is 80 L/h during the first investigation phase and hygiene demand is restored after an independent negative result. Assume the verified stock starts at 1,920 L, phase 1 lasts 6 h, and phase 2 demand is 110 L/h. Determine the total reserve clock.

► Autonomous correction – open after attempting the exercise

21 – Mission decision

Use the reserve clock to choose sampling, repair and escalation deadlines. Do not wait until the tank is nearly empty before deciding whether to reconnect the suspect branch.

Release criteria matter more than reassurance

A branch should return to potable service because predefined evidence has been satisfied, not because the crew is tired of restrictions. The release package can require an acceptable repeat sample from an independent point, confirmation that maintenance steps were completed, absence of contradictory trend data, and a documented flush or sanitation step when applicable. If the evidence does not close the causal question, the system can remain in a conservative degraded mode even when the immediate sample looks better.

Qualification drill

Write a one-page response for a settlement in which a downstream microbial reading rises, a 36-hour verified reserve exists and a greenhouse requests non-potable water. Mark every valve action that could mix clean and suspect inventories. Define the minimum evidence required before each boundary is relaxed. Then explain which data you would preserve for later investigation. The objective is not to “fix the sensor”; it is to preserve health, water and diagnostic information at the same time.

Source context. NASA descriptions of Environmental Control and Life Support Systems and water-recovery work provide real operational context for closed-loop water management; the numerical incident above is explicitly a Delta-Sierra teaching scenario, not an ISS or Mars mission specification. [NASA ECLSS](#). [NASA — Water Recovery Milestone](#).

R61 water assurance case: prove potable-water safety across production, storage, distribution and recovery

A settlement water system is only as safe as the weakest boundary between source, treatment, storage, distribution and human use. A high recovery percentage does not prove microbiological safety, and a clean sample does not prove that an entire network is clean. The operating team therefore needs an assurance case: a structured argument that identifies hazards, barriers, measurements, release criteria and recovery actions for every path by which water can become unsafe.

Use several independent barriers instead of trusting one perfect treatment step

Filtration, chemical or physical disinfection, compatible materials, protected storage, hygienic distribution and surveillance should be treated as complementary barriers. Each barrier controls a different failure mechanism. The operations board should show which barriers are active, which are degraded, and whether any single fault can bypass several barriers at once. A valve alignment error that connects potable and technical water can defeat excellent treatment hardware if the boundary itself is not controlled.

Primary-source bridge — ECLSS. NASA describes water recovery as one part of the coupled life-support architecture. R61 uses that systems view to separate recovery efficiency from potable-water assurance. [Official source](#).

Sampling plans need spatial, temporal and process logic

Sampling only the final outlet can miss contamination trapped in a branch, biofilm developing in a low-flow segment, or a transient event after maintenance. Build a map of representative sampling points: treatment outlet, storage tank, distant distribution endpoint, return loop and any area recently opened to maintenance. Add time logic as well: startup, post-maintenance, after a long stagnant period and after an alarm. A sample is evidence about a place and time; it is not a permanent certificate.

Trend precursor indicators before waiting for a clinical event

Operations should trend conductivity or relevant chemistry, turbidity where meaningful, microbial indicators, tank turnover, disinfectant residual if used, temperature and filter differential pressure. The objective is not to create an enormous laboratory burden but to detect movement away from the qualified envelope early enough that the crew can isolate a branch or switch to reserve water before illness appears. The escalation rule should distinguish warning, investigation and release-stop thresholds.

Protect water reserve from the incident that created the shortage

An emergency reserve is useful only if it is isolated from the same contamination route, power fault or software command that affected the primary loop. At least one reserve path should have a distinct isolation boundary and a clearly verified draw procedure. If reserve tanks share the same contaminated transfer manifold, the settlement may discover too late that nominally redundant inventory has a common cause.

Primary-source bridge — ISS water recovery milestone. NASA's ISS water-recovery reporting demonstrates the importance of closing water loops, while the settlement assurance case adds the operational question of whether the recovered water remains safely releasable after faults and maintenance. [Official source](#).

Incident drill — ambiguous microbial signal after maintenance

A distant potable outlet returns an abnormal microbial indicator twelve hours after work on a nearby valve. A second sample is pending. The defensible response is not to declare the entire settlement contaminated or to dismiss one result. Isolate the smallest justified zone, preserve unaffected reserve, review maintenance boundaries and valve lineup, take confirmatory samples upstream and downstream, and define what evidence will permit reopening. The learning objective is to make the team manage uncertainty without turning uncertainty into either panic or complacency.

Qualification evidence for a water-secure settlement

Before population growth, demonstrate that the crew can detect loss of one barrier, identify the affected boundary, provide safe reserve water, prevent cross-connection during maintenance, trace a suspect batch, and restore the system using explicit release criteria. Water security is

therefore not merely litres per person per day; it is the ability to maintain trustworthy water while the system is imperfect.

Maintenance must preserve the sanitary boundary while the loop is open

Every maintenance procedure should state which surfaces become exposed, which upstream and downstream valves create the isolation boundary, how tools are cleaned, where drained liquid goes, and what post-maintenance flushing or sampling is required. A technician should not have to infer sanitary controls from a generic mechanical work order. The water team and maintenance team should agree on the release criteria before the system is opened, because once the loop is apart operational pressure can encourage shortcuts.

Use a contamination zone map during incident command

When a suspect result appears, mark confirmed clean, suspect and unknown zones on the same network map used for valve control. This helps the commander avoid both over-isolation and under-isolation. The map should evolve with each sample and valve action, preserving time stamps so investigators can later reconstruct exposure. A changing map is often more useful than a single binary alarm because contamination evidence arrives gradually.

Recovery is not complete until normal surveillance is re-established

After a branch is disinfected or flushed, the team should not immediately abandon enhanced sampling. Define a short recovery surveillance period with repeated evidence under normal flow and use. Close the incident only when release criteria remain satisfied, reserve inventory is restored, temporary cross-connections are removed and the operating log matches the final valve configuration.

Sanitation risk crosses people, surfaces, water and waste interfaces; barriers must be maintained at each boundary. Pedagogical synthesis by Delta-Sierra from the primary sources cited in this course; schematic, not to scale.