Natural Strategies for Managing Excess Water in Rio de Janeiro

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Introduction

Flooding and drought represent serious challenges for a society, and by extension, its government. Rio de Janeiro, Brazil is the most vulnerable city in South America to climatic change, where precipitation and flooding have already trended upward during the past decade, especially in the extreme indexes. Climatic changes over the course of the next three decades will provide even more severe and longer dry seasons with increasing temperatures coupled with increasing intensities of precipitation during the wet seasons.

The average temperature in Rio De Janeiro is expected to rise one degree Celsius by 2020, and 3.4 degrees by 2080, resulting in more heat waves, more flooding, more landslides, and more disease. Other dangers are a local greenhouse effect and increased sea level, which is expected to rise between 37cm and 82 cm over the next 65 years (Barros, 2015).

These spatial and temporal changes in precipitation and sea level, driven by climate change, have exacerbated flash flooding and mudslides in the mountainous regions of the rapidly urbanizing city, paralleled by exponential increases in flooding related damage to infrastructure and loss of life. Predicted future climatic changes underscore the pressing need for the city of Rio De Janeiro to proactively seek sustainable and efficacious solutions to help mitigate future loss of life and property.

http://a57.foxnews.com/images.foxnews.com/content/fox-news/world/2014/01/16/violent-storm-sweeps-over-rio-de-janeiro-flooding-streets-and-stoking-mudslides/jcr_content/par/featured-media/media-0.jpg?ve=1
Human Factors

Water availability, pollution, and sanitation access disparities throughout Brazil are common, especially in the heavily populated southeast regions of the country. A high number of Rio De Janeiro’s impoverished population live in urban slums without any access to piped water or sanitation. Despite Brazil’s status as owner of nearly 20% of the world’s water supply, water is scarce in San Paulo, just 412 Km east of Rio De Janeiro, and gradually worsens inland and towards northeast areas of the country.

Other key differences are apparent in figures for national water coverage (82.5%), wastewater (48.6%) and real wastewater treatment (39%). The lack of wastewater treatment means that pollutants are discharged directly into the water or processed in unregulated septic tanks, with serious consequences for water quality, and consequently, for the well-being of the population (Barros, 2015).

Team

Our team views Rio De Janeiro’s vulnerability to future climatic trends – coupled with its already low share of treated wastewater and sanitation access as a towering opportunity to argue immediately for better design development and implementation. Our initial offering here is a set of novel design principles gleaned from some of the most water-variability resilient and adaptable plants, animals and microorganisms found in the Mato Grasso tropical dry forest ecoregion (World Wildlife Foundation).
We’d like to thank these amazing and awe-inspiring species for their hard-earned insights and wisdom:

Our Goal

The task at hand is to better manage excess water and mitigate flooding in Rio De Janeiro. To assist all stakeholders in this endeavor, our team has assembled a set of specific structural, behavioral and functional principles we learned from these champion adapters to help guide and assist the future decisions and actions of project design leads. We have identified the convergence of 6 structural components with corresponding behavioral functions demonstrated in nature to contribute to the effective management of excess water:

- Hollow sponges capture and release water
- Waterproof barriers protect from inundation
- Flexible cylinders direct water flow
- Chambers temporarily store water
- Pressurized channels regulate water flow
- Gravity channels facilitate water flow

How to Use this Document:

Nature handles surplus water using an impressive variety of sustainable strategies. What might humans learn from nature about how to best mitigate excess water challenges in the human built environment? Using biomimicry as a lens to help translate nature’s genius, we present fifteen champion organisms with diverse, optimized water management strategies. Mechanisms range in scale from macro, to meso, to micro; and in scope from form, to process, to ecosystem. We take a deep dive into nature’s brilliant strategies and translate them into their core lessons, applicable to human design.

Water management stakeholders should use this document to gain inspiration for novel, sustainable, successful, biomimetic solutions to the challenge of managing excess water. Our menu of nature’s strategies and structures can be combined a la carte, to create novel, winning, customizable solutions.
We envision a semi-permanent, 100+ year, static, infrastructure-level solution that fits seamlessly into the unique climatic, geographic, cultural, social, and political contextual needs of Rio De Janeiro; one that will be embraced by the local government regulators, the citizens they represent, and the countless other species who share the wealth of this incredibly diverse and rich ecosystem. To achieve the highest standards of sustainability and harmony for the benefit of all living beings, we have established the following aspirations to inform and inspire the design team on its journey:

- Rio De Janeiro is a rapidly urbanizing area with high population growth. The design should be built from the bottom up, be self-organizing, and combine modular and nested components to allow for rapid response to the effects of gradual climate change, intermittent natural disasters, and exponential population growth.
- Nature evolves by keeping what works and adding to it. To function optimally, the solution will need to evolve to survive as well. Incorporating a decentralized model for managing excess water, with built in redundancy, will allow for improved resilience to inevitable change.
- The optimal design should take advantage of recurring cyclical phenomena including local and global water and biogeochemical nutrient cycles. It should assess and react to input and feedback at both short term and long term intervals. On a political scale, an integrally cooperative relationship network should bridge all municipalities to better assist the solution to serve both the people and natural ecosystems of Rio De Janeiro.
- Our design solution should fit form to function with elegance and efficiency to meet multiple needs while minimizing energy use, optimizing local resources, and eliminating waste.

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Saltmarsh Ecosystem
Smooth Cordgrass
(Spartina alterniflora)

ADP: Use meandering and dendritically branching water channels lined with a spongy substrate that is populated with densely packed, vertically arranged, stiff, hollow, tapered cylindrical rods 1-1.5 cm in base diameter, standing slightly taller than maximum water depth. In response to excess water, this arrangement will decelerate, absorb, and gradually release water; filter nutrients and pollutants; allow sedimentation of suspended material; attenuate waves; and thereby mitigate damage from flooding.

Summary of Strategy/Mechanism:
The coastal saltmarsh ecosystem, largely through the contributions of the ecosystem engineering Spartina cord grasses, mitigates flooding with a multifunctional approach. This strategy includes:

- Deceleration of water through channel meandering and branching, which are dependent on the density of vegetation (Kearney and Fagherazzi 2016)
- Absorption of water (water-logging) and gradual release using a spongy peat layer several feet thick, composed of slowly decomposing vegetation and silty mud atop a sandy aquifer (Knott et al 1987; Wilson et al 2011)
- Attenuation of wave energy by interference from marsh vegetation, especially Spartina (Möller et al 2014)
- Prevention of eutrophication by excess nutrient filtration through sedimentation (phosphorous) and/or bacterial, vegetative metabolic activity (Vernberg 1993)
- Filtration of heavy metals, toxins, pathogens out of the water into the peat. Can remain trapped in sediment or be metabolized by bacteria and vegetation (Vernberg 1993)
- Mitigation of erosion through entrapment of eroded soil through siltation due to vegetation, detritus, and roots creating surface area and decreasing water velocity locally (Peralta et al 2008)

Quotes from Primary Literature:
“Salt marshes…assist in flood and erosion control; lessen the effects of stormwater surges; and improve water quality by filtering pollutants, excess nutrients, and disease-causing microorganisms.” - Vernberg 1993

“It is widely recognized that wetlands play an important role in the hydrological cycle, influencing groundwater recharge, low flows, evaporation, and floods… especially flood risk reduction” - Acreman and Holden 2013

“The geometry of tidal channel networks in salt marshes controls the flow of water, nutrients, sediment and biota… Vegetation has been observed to influence the branching and meandering characteristics of tidal channels… positive feedback between vegetation and network geometry.” - Kearney and Fagherazzi 2016

“Spartina… an ecosystem engineer… able to reduce current velocity… stiff canopies have a larger capacity to trap sediment than do flexible ones” - Peralta et al 2008

Application Ideas:
➢ City-wide drainage/sewer system/water treatment to alleviate flooding damage through systems approach including meandering, branched channels with absorptive, filtering qualities to slow storm water runoff, filter contaminants and pollutants that wash into the runoff, and prevent soil erosion.
➢ Roof-top rain capture/temporary storage system to delay runoff and mitigate surges of runoff in during heavy precipitation events.
➢ Drainage along highways to prevent flooding roadways
➢ As a coastal buffer to prevent beach erosion and storm damage from tropical cyclones.
Rubber Tree Roots
(Hevea brasiliensis)

ADP: Numerous large-diameter surface-level aqueducts extend horizontally in 360 degrees from the central axis of a vertical repository. Running the length of each aqueduct are a multitude of smaller-diameter contributories infiltrating into the ground. Surface aqueducts expeditiously extract water into the repository whenever present; as shallow water is gradually depleted, uptake shifts to smaller-diameter ducts penetrating the ground.

Summary of Strategy/Mechanism:
A predominantly horizontal root network extending 150% of the average tree branch length changes its allocation of resources in response to water conditions in the soil profile. When shallow water is plentiful, shallow roots with large xylem vessels hyper-responsive to rainfall expeditiously extract water mostly from the top 30 cm. As shallow water is gradually depleted, uptake shifts to finer root structures at deeper levels.

Quotes from Primary Literature:
"Rubber trees extracted their water mostly from the top 30 cm and less from below 70 cm of the soil profile during the late rainy season when soil water was plentiful. During the late dry season, as the moisture in the middle soil layers (30–70 cm) was gradually depleted, the depth of water uptake shifted to deeper soil levels. The proportion of water uptake from the shallow soil layer (<30 cm) increased markedly after the most recent rainfall in the late dry season and the early rainy season (varying between 65% and 71%), indicating significant plasticity in sources of water uptake in this dimorphic-rooted species. This ability to take up a large proportion of shallow soil water after rainfall is likely the key feature enabling rubber trees to thrive through the period of greatest water demand. Our results suggest that rubber trees are able to adjust the allocation of resources and thus acclimate to the spatiotemporal changes to water conditions in the soil profile." - Liu W, Li J, Lu H, Wang P, Luo Q, Liu W, Li H.

Application Ideas:
➢ Micro, Macro or Mesoscale excess water management system
➢ Portable sump pump
**Acuminate Leaf Apex**  
(Trees of lowland tropical rainforest in South Brazil)

**ADP:** Water runs along the span of a symmetrical, elliptic, smooth channel groove with sides curving concavely or inward, then tapering towards a long, fine, narrow point tip which curls downwards where it drips off, thereby facilitating the rapid discharge and evaporation of water while reducing the size of droplets falling to prevent erosion below.

**Summary of Strategy/Mechanism:**

Water runs along the veins of a simple, symmetrical, elliptic leaf with sides curving concavely or inward, then tapering to a long, fine, narrow point tip. The tip curls downwards, allowing water to rapidly drip off. This form reduces the need for investment in support structures and assists drainage of the leaf blade, thereby aiding the drying of the leaf surface, and reduces the size of droplets falling from leaves and prevents splash erosion at the plant base.

**Quotes from Primary Literature:**

"Drip tips, or the acuminate apices of leaves, are a common feature of understory plants in the humid tropics (Richards 1996). Perhaps the most persistent hypothesis for their function is that they facilitate the rapid channeling of water from leaves, which decreases the drying time for the leaf surface." (Stahl 1893, Lighthoby 1885)

"Drip tips also reduce the size of droplets falling from leaves, which may help minimize soil disturbance beneath a plant (Williamson 1981, Williamson et al. 1983, Rebelo & Williamson 1996)." - Ivey CT, Desilva N.

"Leaves of many species of plants in the rain and cloud forest have long, narrow tips which curl downwards. Water runs along the veins of a leaf to the tip where it rapidly drips off, hence the name "drip-tip." Drip-tips may be a leaf adaptation to quickly shed water, a suggestion previously made by Jungner (1891) and supported by Stahl (1893)." - Lightbody JP.

**Application Ideas:**

- Water drainage and diversion system.
- Road and roofing grooves grid-designed to evenly disperse and divert water runoff, preventing overflow and standing water.
- Mesoscale: canal system stores power gathered from Venturi effect as water channels through constricted section of channel.
- Splash-less water streams. Applications include a myriad of designs such as sinks, tubs, gardens and mud rooms.

![Biological Strategy Illustration](https://www.shutterstock.com/video/clip-4568192-stock-footage-water-drips-on-leaves-slow-motion.html)

![Abstracted Design Principle](https://www.shutterstock.com/video/clip-4568192-stock-footage-water-drips-on-leaves-slow-motion.html)
Absorb and Direct Liquids

Green Bristlegrass
(Setaria viridis)

ADP: Numerous, conical structures with increasing radial measurements surrounded by microscopic grooves along a surface allow for the creation of strong Laplace pressure and a natural “film” of water as the channels are filled, reducing natural resistance and effectively pulling water to a collection point regardless of angle of inclination or the effects of gravity.

Summary of Strategy/Mechanism:

The process for water collection used by Green Bristlegrass follows four stages: condensation, coalescence, transportation, and collection. The sources of its water collection comes from many forms of condensation but the primary sources are fog and rain. This adaptation allows it to have a more localized root structure, pulling water from the air and holding on to excess water.

Micro-sized barbs collect and trap water droplets and funnel them into microgrooves. These microgrooves create a “film” of water that reduces resistance to flow and guide water in a specific direction. This allows a force known as “Laplace Pressure,” a pressure created by a graduating circular or conical shape, to move the water along the stem regardless of the angle that the grass blades are pointed in. This allows the water to essentially defy gravity by removing the water droplet’s gravity from the equation. The water is then collected through absorption.

Quotes from Primary Literature:

"Moisture first condenses at the tip of the barb, and then micro-droplets move directionally from the tip to the base of the barb to coalesce into a droplet. Next, the big droplet is transported with coalescing small droplets or asymmetric growing between the barbs along the green bristlegrass bristle, and finally water is collected at the bottom of the bristle. The big droplet realizes the coalescence and transport process by “step over” the barbs with asymmetric growth and TCL (three phase contact line). The special structure of green bristlegrass with oriented barbs, aligned microgrooves and whole conical structure assist droplets to be directionally transported from the top to the bottom.”

(Xue, 2014)

Application Ideas:

- Microscopic, conical shapes with microgrooves are placed along increasing radii legs of water towers, allowing them to draw water vertically to fill artificial aquifers.
- Periodically placed tubules covered in Laplace pressure causing cones draw water deep into ground that is unable to absorb water otherwise.
- Microgrooves along the bottom of a boat, allowing a film of captured water to reduce resistance.

Biological Strategy Illustration

Abstracted Design Principle

Pressure pulls the water regardless of angle or gravity

Water is “caught” by the barbs, structures diffuse water, removes gravity and is passed to the micro channels for collection

Water enters the micro channels forming a film which lowers resistance, allowing Laplace pressure to draw the water

Water is emptied from the channels via continued Laplace pressure into a collector
Sea Squirt (Ascidiae)

Manage and Filter Liquids

ADP: A banded, flexible, two cylinder container manages the flow of a liquid through a combination of tiny bristles beating in unison and rapid contraction and expansion to create force. The liquid is drawn in through a large opening and held temporarily in the primary cylinder where the bristles push it into the second chamber for expulsion from a smaller opening.

Summary of Strategy/Mechanism:

Sea squirts have two large pores on their bodies, one for the purpose of sucking in water and the other to allow them to expel it. The water is drawn into the sea squirt’s body as a means of gathering both food and oxygen, and when it has gleaned these through the gill slits in its pharynx, it then pushes the water back out. This expulsion of water is also used as a defense mechanism when the Sea Squirt is threatened with predation.

Water is drawn in through the first pore into a main cylinder where tiny, fast-moving hairs called cilia beat in unison to continue moving the water while it is filtered of oxygen and food particles by mucus membranes. The remaining water is then pushed out of the second and smaller of the two pores through powerful contractions of the bands of muscle fibers in the sea squirt’s body.

Quotes from Primary Literature:

"The sea squirt's body is made up of two cylinders. Water drawn into the main cylinder through the uppermost opening is filtered to extract food and oxygen, then escapes through the lateral cylinder. The small size of the lateral opening causes a rapid jet of water which carries the sea squirt's waste well beyond the incoming water current." (Foy and Oxford Scientific Films 1982:23)

"Sea squirts have two body openings: one for taking water in and one for pumping, or squirting, water out. The water-intake opening leads to a large chamber that takes up most of the inside of the sea squirt and is lined with slits. Seawater, which contains food particles and oxygen, is drawn into the large chamber and then is pumped into a second chamber. The slits are small enough to keep the food particles inside the first chamber, which leads to the digestive system. After entering the second chamber, the water is pumped out of the animal through the exit hole.” (Grizmek, 2005)

Application Ideas:

- Draining temporary mires or swamps that form due to greater than anticipated rain. Design allows for filtering out non-liquid materials.
- Pump for cold water locations as the inner bristled gears could move solidified liquids such as ice.

Biological Strategy Illustration

Abstracted Design Principle
**Summary of Strategy/Mechanism:**

Hagfish produce copious slime when disturbed. Glands on their sides release the contents of mucin cells and thread cells into the water through pores that open to the outside (Böni et al 2016). When exposed to seawater, mucin vesicles rupture through an influx of calcium ions and subsequent inflow of water through aquaporins in the mucin vesicle membranes (Herr et al 2016). Mucin (glycoproteins) expands through interactions with water.

Long, impressively skeined thread filaments from the thread cells spontaneously release themselves from their thread chambers as water interacts to dissolve the glue-like substance that stabilizes them. The expanding mucin globs spontaneously bind to themselves and to the narrow (1-3 micron) thread filaments, further unfurling them, helping to extend them to their full lengths, up to 34 cm (Böcker et al 2016).

The thread filaments and mucin make an interconnected mesh that interacts synergistically to form a dilute, slimy mass that entrains large volumes of water (Winegard and Fudge 2010). Water is not trapped/absorbed, but is slowed down extensively through interactions with the microscopic pores/spaces between the fibers (Fudge et al 2005). This strategy/mechanism acts at the meso scale. Just 35 milligrams of hagfish slime gland exudate makes more than a liter of water-entraining slime in less than 100 ms. This process is fast and the resulting slime holds 26,000 its dry weight in water (Fudge et al 2009).

**Quotes from Primary Literature:**

“Hagfish slime is 99.996% seawater, 0.0015% mucin and 0.002% threads…. it is almost three orders of magnitude more dilute than typical mucus secretions…. a very fine three-dimensional sieve that can trap water over short timescales, but over longer timescales simply slows it down.” (Fudge et al 2005)

“…hagfish slime deployment occurs via the following sequence of events: (1) expulsion of the slime exudate into convectively mixing seawater results in the swelling and subsequent elongation of mucin vesicles to form mucin strands, (2) these elongated mucin strands attach to the thread skeins, (3) the mucin strands transmit the hydrodynamic forces of mixing to the thread skeins, thereby initiating unraveling, and (4) entanglement of the threads and mucin strands results in the complete unraveling of thread skeins. The whole slime is therefore a highly complex network of mucin strands, slime threads and seawater…. to yield a complex network capable of the viscous entrainment of water.” (Winegard and Fudge 2010)

“Hi Deb - thanks for reaching out… As for HFS working with freshwater, it’s not impossible. The slime works pretty well in freshwater, and you wouldn’t use real slime for such an application anyway, so you could potentially engineer a synthetic version to work in FW. Synthetic slime is something we’re actively working in my lab. Hope that’s useful. -D” (Fudge DS 2017, personal communication)

**Application Ideas:**

- Automatically deployable slime net can slow the movement of water during storm events, delaying the impact of runoff. Triggered by presence of water - released on roof top surfaces for example - fibrous and glycoprotein components. Cheaper than green roof. Little bit of the exudate goes a long way. Rain triggered sprinkler system launches it.
- Net of slime could slow or temporarily hold water below ground under pavement/sidewalks/parking lots.
- Could be employed on areas with steep slopes to slow storm runoff.
Manage Excess Water

Leaf Venation

ADP: Large-diameter primary channels form a geometrically organized grid composed of multiple, redundant closed loops that intake excess water via gravity through numerous, evenly dispersed portals. Branching off and enveloped within these loops are smaller channels forming more tightly-knit loops. These secondary channels are position below the primaries, at a 2:1 diameter, length and loop circumference ratio. As and when excess water entering the portals builds critical pressures within the system, valves in the secondary channels open into many smaller, evenly dispersed, free-ending channels.

Summary of Strategy/Mechanism:

Hydraulic conductance is the measure of ease with which water can move through pore spaces. Leaf vein systems form an integrated network composed of closed loops and free ending veins which provide for optimal hydraulic conductance and water dispersion in response to fluctuating flow or damage to any vein. This compensatory function results in a highly efficient and resilient water management strategy that distributes water and equalizes pressures evenly throughout the system in times of water excess.

Xylem cells form long tubular veins that transport water from the roots to the leaves. The number of loops and free ending veins in the leaf determine its vein length per unit area (VLA). Higher VLA’s increase hydraulic conductance, and grow to the fourth power of diameter. Increasingly thicker veins, therefore, have exponentially greater water transport capacity and mechanical resistance. Total leaf vein density is another critical determinant of hydraulic conductivity, as it also establishes water reserve potentials across the leaf by reducing the area in between major veins.

Quotes from Primary Literature:

“One basic function of leaf venation is represented by its contribution to the mechanical behavior of a leaf. Venation geometry and density influences mechanical stability... Transport of water and carbohydrates is the other basic function of this system and the transport properties are also influenced by the venation architecture.” - Roth-Nebelsick et al.

“Leaf venation is a pervasive example of a complex biological network, endowing leaves with a transport system and mechanical resilience. Transport networks optimized for efficiency have been shown to be trees, i.e., loopless. However, dicotyledonous leaf venation has a large number of closed loops, which are functional and able to transport fluid in the event of damage to any vein, including the primary veins.” - Sack L et al.

Application Ideas:

➢ Gravity driven water diversion system.
➢ Gravity driven water distribution system.
➢ Gravity driven water regulation system.
➢ Gravity driven water dispersion system.
➢ Information networks
**Black Soldier-Fly Larvae** *(Hermetia illucens)*

**ADP:** Combine multiple tubular and flexible vectors to create vortices that can influence the dynamics of a flowing liquid, allowing the opportunity to control both the current and distribution patterns of particulates.

**Summary of Strategy/Mechanism:**

Soldier black-fly larvae are a ubiquitous organism found in many places across the world. In some locations, the larvae are deposited in streams. The larvae anchor themselves from their posterior to the substratum (rock bed of the stream) with silk. They then dangle in the stream’s currents in an attempt to gather food through the use of their anterior fans.

A colony of black-fly larvae will then work together, syncing their motions up to create vortices around their tails to direct water currents in a way that creates the maximum efficiency for the catching of food. These vortices are small whirlpools that would be insignificant on their own, but within a group they can create noticeable changes in the fluid dynamics.

**Quotes from Primary Literature:**

"Some black-fly larvae that live in shallow, rapid streams have an interesting variation on the device. They are attached at their posteriors and have a pair of food-trapping fans on their anterior ends. A larva twists lengthwise so one fan is uppermost and feeds from material suspended well out in the velocity gradient. The other fan is then lower and a bit downstream; it feeds on material resuspended in the vortices rising behind the body. Upward flow of water in the vortices is further encouraged by a downstream tilt of the body as a whole. Groups of larvae, positioned as they are in nature, don't compete for food but instead enhance each other's feeding efficiency." (Vogel 2003:135)

**Application Ideas:**

- Placement inside pipes and plumbing fixtures to control the turbulence.
- Placement along the sides of aqueducts to help control water directionality and force.
- Placement on the edges of road surfaces to direct excess water off of the roads.

**Biological Strategy Illustration**

[Image: https://asknature.org/strategy/body-shape-and-position-direct-water-current/]

[Image: https://www.wired.com/2013/11/happy-black-fly-day/]

**Abstracted Design Principle**

[Image: Vortex Control ADP]

**Placement and angle of flex in the tubular structures allows multiple small effects to combine and upset normal fluid dynamics.**
**Summary of Strategy/Mechanism:**

Marsh crabs are able to pull water from damp sands to avoid desiccation. Located along the crab’s legs are tufts of stiff hairs known as setae. These hairs are used in the process of drawing water from the damp sands, through a mixture of hydrophilic properties and negative pressure (suction).

When marsh crabs find a patch of suitably damp sand they drive their legs, and thereby the setae, down into the sand. This force, in combination with very high hydrophilic surfaces in the hairs (which resemble soda straws), creates a strong capillary action, whereby the meniscus that forms at the leading edge of liquid bows upwards, urging it forward. In addition, the crabs then create a bellows effect by sucking in air through their branchial chambers. This creates negative pressure (suction) to pull the water into their bodies where it is then passed through their gills membranes and eventually any water that has not been retained is swallowed into the gut for a second opportunity for absorption.

**Quotes from Primary Literature:**

“Water is acquired by capillary action using hydrophilic setae situated at the base of the walking legs (between the second and third pair) and subsequently transferred to the branchial chambers, where it is absorbed across the gill membranes. Excess water is moved to the mouthparts, swallowed into the foregut, and later gradually absorbed.” (Hughes, 2014)

“Fiddler crabs, and the closely-related ghost crab, O. quadrata, use hydrophilic tufts of setae located at the base of their walking legs to efficiently extract water from damp sand. “ (Allen, 2012)

“The crabs use setal tufts between the second and third pairs of walking legs and branchial chamber suction of up to -43 mmHg to extract sand capillary water, which is absorbed by the gills and/or drunk.” (Thompson, 1989)

**Application Ideas:**

➢ Small straw-like pipes placed in small crawl spaces under homes allowing excess water to be drawn up and into grey water tank reserves.
➢ Pressurized underwater aquifers push or pull water in or out based on osmotic pressure differences.

**Abstracted Design Principle**

- Negative pressure is applied through an expanding bellows
- Many hydrophilic, straw-like setae structures allow capillary action and the applied negative pressure to draw in liquids
- Captured liquids are stored for later use
- Profound capillary action from hydrophilic surfaces draws the water up the channeled setae to create a prominent meniscus

**Biological Strategy Illustration**

[Image of marsh crab diagram]

[Image of marsh crab setae]

[Image of capillary action diagram]
Sphagnum Moss

(Renewable and Evaporate)

ADP: A layer of hollow, wicking, spirally reinforced chambers 20 x 40 microns wide can collect and temporarily store large volumes of water via circular surface pores 10-15 microns in diameter that are open to the environment. Subsequent water loss by evaporation is rapid. The mechanism acts like a super-absorbent, quick-drying, reusable sponge.

Summary of Strategy/Mechanism:

Sphagnum mosses, or peat mosses, are astonishingly absorbent and can hold twenty times their weight in water. Water is attracted to broad, rounded pores (10-15 microns diameter) on the surface of moss leaves. The pores pull the water into strong, fiber-reinforced, hollow, temporary holding chambers called hyaline cells (20 x 40 microns). The chambers have internal spiral thickening to make them more sturdy. Despite the weight of water, they neither burst, nor collapse under the strain. When moisture input ceases, rapid water loss by evaporation follows. Porous cellulose construction results in an extremely light weight material when dry. Hyaline cells have a bonus secondary feature. They bind and store positively charged dissolved nutrients along with water. (Kremer et al 2004; Koch and Barthlott 2009; Trembling earth)

Quotes from Primary Literature:

"Peat moss (Sphagnum)... has a sponge-like surface structure, formed by pores of 10-20 microm in diameter.... Water uptake of up to 20 times of their own dry weight occurs..." (Ennos & Sheffield 2000 in Koch and Barthlott 2009).

"...the sphagnum cells have an incredible ability to hold onto water. The secret here is the existence of the dead cells called the hyalocytes. These cells have walls strengthened with fibers which prevent either the cells collapsing or exploding with stress.... Another unusual property of the peat cells is the ability of their walls to absorb and hold on to nutrients that come in from the rain and surrounding waters.... the cell wall itself has the ability to "bond" ions with a positive charge as well as with nitrogen." (Trembling earth)

Application Ideas:

➢ Roof top water absorption and release prevents run off
➢ Puddle removing street sweeper with mossy rollers to remove road hazard puddles after storms, keep traffic moving
➢ Outdoor cushions for patio furniture
➢ Door mats
➢ Cleaning Sponges

Biological Strategy Illustration

Abstracted Design Principle

https://asknature.org/strategy/internal-perforations-transport-nutrients/#.WPl4iFMrJPM
https://sphagnumsem.wordpress.com/

15
Manage Excess Water

Giant Barrel Cactus
(Echinocactus Platycanthus)

ADP: A malleable sheath encapsulates numerous dilatable vesicles composed of thin, foldable, flexible walls that, in response to excess water in the outer environment, distend to extract it into their pliable cavities and rapidly collapse and shrink only on demand to evacuate.

Summary of Strategy/Mechanism:

Water is stored in collapsible cells with thin, flexible walls that expand and contract as water is transferred in or out. These cell’s walls are also folded and undulated, allowing them to easily and rapidly fit their form to this function. Running through and around these regions are more rigid cortical bundles that provide a compartmentalized structure for the collapsible cells. They are contorted due to shrinkage of the surrounding cells. The collapsible cells lose their water more easily than the surrounding tissues, but gain it more slowly. This strategy provides for the facilitation of water transfer going first to cells more essential to the structure and protection of the plant.

Quotes from Primary Literature:

“Qualitatively, collapsible cells and collapsible parenchyma tissue were observed in seedlings of both species, more often in those subjected to water stress. These tissues were located inside the epidermis, resembling a web of collapsible-cell groups surrounding turgid cells, vascular bundles, and spanned across the pith. Water is mainly stored in the water-storage parenchyma of the cortex within the stems. Cacti have a small surface-volume ratio which allows them to store a maximum of water but with a minimum of transpiration area.” - Rosas U, Zhou RW, Castillo G, Collazo-Ortega M.

“...water-storage cells should have thin, flexible walls that can contract or shrink readily such that the cell’s volume diminishes as water is transferred out. ...In all cacti, cell walls of the inner cortex are especially thin and flexible, but in many cacti there is an additional modification: the walls are folded or undulate, even when young and recently produced by the shoot apical meristem. Because the walls already have folds in them, the cells are presumably set to shrink very easily. These cells have been called collapsible cortex cells.” - Mauseth JD.

Application Ideas:

➢ Portable water collecting and mobilizing spheres.
➢ Energy efficient water transport.
➢ Flood prevention pods.

Biological Strategy Illustration

Abstracted Design Principle
Summary of Strategy/Mechanism:

The movement of water through the Red Eyed Tree Frog's skin is a passive process. Their capillaries penetrate much farther into the epidermis than most other organisms, creating channels that allow water to enter the body without utilizing traditional amounts of drinking. These channels, known as AQP5s or aquaporins, are primarily located on the ventral skin of the frogs. Designed for permeability, they are considered “always-open” and freely allow the exchange of water between the frog and the outside world.

In order to avoid dehydration and limit the entry of foreign particles or substances, the aquaporin are able to close or “gate.” This allows them to stop water flow regardless of the osmotic pressure that normally allows water permeation by narrowing or closing the membrane walls. In addition, the gates are able to keep out unwanted ions or hydrogen molecules. This is accomplished by the spinning of water molecules to break down hydrogen bonds to keep the hydrogen from entering the narrow part of the channel. Ions are unable to enter due to their size relative to water molecules.

Quotes from Primary Literature:

“Amphibians do not drink water through their mouth. Instead, they possess a specialized region in the ventral skin that, compared with that of other tetrapods, is highly permeable to water and ions as well as to respiratory gases (1–3). Water movement occurs across plasma membranes of various cells of animals, plants, and microorganisms through specialized water-channel proteins called aquaporins (AQPs). Aquaporins form membrane pores selectively permeable to water and, isoform dependently, to certain small solutes such as glycerol and urea.” (Hasegawa, 2003)

“This penetration of capillaries into the epidermis of the ventral part of the skin permits the absorption of water. Our findings regarding the thickness of the ventral epidermis which is evidently thinner in the grooves (3.7 to 49.6 um) and the places where capillaries are invaginated in the ridges (47 um), confirm the possibility that tree frogs absorb water through the skin of the whole ventral side of their bodies. This is enhanced when tree frogs cling to wet surfaces with their entire ventral side, as observed in the animals kept in a terrarium.” (Goniakowska-Witalinksa)

Application Ideas:

- Filtered drains placed throughout areas around populated locations that have ever expanding smaller tubules according to Murray’s Law, allowing water to be drained and dispersed to reinvigorate soils.
- Pressurized underwater aquifers push or pull water in or out based on osmotic pressure differences.
- Crawl spaces under buildings catch and draw standing water in times of flooding and pull it up into catch tanks through capillary pressure.
Rice (Oryza Sativa L)

ADP: Two expandable, membranous kidney bean-shaped gates manage water flow through a substrate by shrinking to close egress in response to water loss, and expanding to open access in response to water gain. Water permeating the membranes creates internal pressure which causes expansion of the bean shapes and the opposite poles of each to bow away from the central channel axis, opening the waterway. As water drains out of the membranes, internal pressures subside, causing the opposite poles of the bean shapes to shrink and contract back towards the central channel axis, closing the waterway.

Summary of Strategy/Mechanism:

Guard cells are a pair of two cells that surround each stoma opening and function to regulate passage of water and gases in and out of the pore. To open and close, these cells are triggered by one of many possible environmental or chemical signals.

In response to sunlight, guard cells take up potassium from surrounding cells. This increase in solute causes osmotic potential to decrease which induces an influx of water across the guard cell membrane. As the volume of the guard cells increase, they “inflate” into two kidney-bean-like shapes. As they expand, they reveal the stoma opening in the center of the two guard cells. This opening causes evapotranspiration to drive passive vertical water uptake from the soil through narrow cellulose tubular structures. The resulting increased turgor pressure further expands the cells, creating the bowing shape that opens the pores. When the guard cells are most turgid, or swollen, the stomatal opening is largest.

Conversely, in response to high osmotic pressure due to soil water shortage or lack of sunlight, the guard cells shrink to close the pores and thereby prevent water loss. As potassium ions leak out when either pumping ceases or plasmolysis occurs due to excess evapotranspiration, the guard cells then shrink and collapse the pore. When the guard cells have lost water, the cells become flaccid and the stomatal opening closes entirely.

Quotes from Primary Literature:

"Plants react, in principle, to soil-water tension since the uptake of water by the roots is governed by the difference in water potential in the roots and that in the soil surrounding the roots. Most of the reduction in leaf area appears to be the consequence of slowed cell expansion, the closing of stomata and inhibition of photosynthesis." (Outlaw Jr. 2003:503)

"When a guard-cell pair accumulates solutes, the resultant turgor and volume changes cause the guard cells to bow outward because of cell-wall architecture, enlarging the pore between them. This simple explanation belies the underlying complexity of guard-cell turgor regulation and whole-plant responses." (Outlaw Jr. 2003:503)

Application Ideas:

➢ Water-permeable walls that allow water through but close when dry.
➢ Water-permeable roads/flooring that absorb and collect water to be stored underground or diverted without losing structural integrity.
➢ Water gathering roofing material for buildings that collects rainwater to be filtered and used for occupants without losing insulating and protective functionalities.

Biological Strategy Illustration

Abstracted Design Principle

Water permeating the bean shaped membranes causes expansion and opposite poles to bow away from central axis. When the membranes are most swollen with water, the polar sides of the membrane expand furthest away, fully opening the waterway.
**Summary of Strategy/Mechanism:**

There are more bacterial cells in a teaspoon of soil than there are humans on the whole planet (OhioLine 2010). Bacillus subtilis is a rod-shaped soil bacteria that lives on plant roots and promotes their growth (Vlamakis et al. 2013). Like most bacteria, B. subtilis populations grow within their own gel-like secretions, forming biofilms. The bacteria secrete a sticky matrix of proteins, polysaccharide sugars, and nucleic acids that glue them together into a mat (Cairns et al. 2015). One important protein, called BslA, is secreted by the cells in large quantities. BslA proteins rise to the surface of the matrix, link together, and self-assemble into an organized lattice (Stanley-Wall 2015). The lattice creates a water-repellent barrier that works like a raincoat, shielding the population of bacteria below. Each BslA protein has a region on the outer surface that contains exclusively water-repellent (hydrophobic) amino acids: leucine, isoleucine, and valine. These amino acids create a water-repellent cap on the top of each individual BslA protein (Hobley et al. 2013). The cap's water repellency is not triggered until these BslA proteins reach the surface of the matrix and come into contact with air. Numerous BslA proteins pack together into a continuous waterproof layer that is flexible, elastic, and more water repellent than Teflon (Hobley et al. 2013; Stanley-Wall 2015).

**Quotes from Primary Literature:**

“A defining feature common to biofilms is the production of the extracellular matrix that is typically composed of proteins, exopolysaccharides, and nucleic acids” – Hobley et al. 2013

“Bacillus subtilis biofilm colonies are extremely nonwetting, greatly surpassing the repellency of Teflon toward water” – Hobley et al. 2011

“Assembly of the mature biofilm also requires the presence of the biofilm coat protein called BslA. BslA is essential for both the observed complexity and the extreme hydrophobicity displayed by the mature biofilm” – Cairns et al. 2014

“BslA self-assembles into an organized lattice at an interface. BslA, consists of an unusual, extremely hydrophobic "cap" region” – Hobley et al. 2013

“The mature biofilm exhibits a complex network of intertwined wrinkles and ridges and is highly hydrophobic...” – Cairns et al. 2014

**Application Ideas:**

- Photo paper coating – prevent damage/loss of photo albums/art in floods
- Book paper coating – prevent damage/loss of books/historical documents in floods
- Temporary emergency shelters/tents
- Lining in drainage channels in areas that require fast draining
- Sealant to avoid saturation of wooden decks, docks, fences, pilings to prevent rot.
- Sealant to avoid saturation of mortar
- Lining for car doors to prevent water leaking into car during flood events
Summary of Strategy/Mechanism:

Lichens are a symbiotic relationship in which photosynthetic algae live within a fungal network. The rim lichen, Lecanora conizaeoides, layers rough structures of varying sizes on top of each other to create a jagged, craggy nano-landscape at its surface. The combination of layered roughness and the water repellency of its chemical make up mean this lichen is extremely waterproof (super-hydrophobic). Water beads up and runs off without wetting or penetrating the surface. Water droplets span the gaps in the rough surface and stay suspended on top of the rough peaks. The roughness encourages the beaded water to run off, taking dirt, dust, contaminants, and dissolved pollutants, such as sulfur dioxide, along with it. Gas exchange with the algae (needed for photosynthesis) can occur in the grooves and channels between the rough peaks, underneath the water droplets, even in very wet conditions. This lichen adaptation acts a lot like a waterproof breathable rain coat that keeps it clean and able to still photosynthesize in wet weather. (Shirtcliffe et al 2006, Hauk et al 2008, Koch et al 2008, Katasho et al 2015)

Quotes from Primary Literature:

“Superhydrophobicity… occurs when a surface is both hydrophobic and very rough. The roughness … causes an increase in the angle between a drop of water and the surface…. water tends to bridge the tops of peaks of the roughness…. it tends to follow the Cassie-Baxter model… tends to cause drops of water to roll off more readily.” - Shirtcliffe et al 2006

“The lichen Lecanora conizoides… it is full of hydrophobic pores for gas exchange. The combination is very similar to that of breathable garments, where a super-hydrophobic surface protects a system of small pores from becoming blocked by a film of water. We postulate that the lichen uses this super-hydrophobic breathable surface to allow gas exchange during and soon after rainfall. The super-hydrophobic outer surface may also act to protect the lichen from pollution by reducing direct exposure to rainwater and promoting dust removal.” - Shirtcliffe et al 2006

Application Ideas:

➢ Line channels to redirect water during rain events in areas where rapid draining is required.
➢ Rapid repair patches for damaged, leaking infrastructure (roofs).
➢ Greenhouse film trap moisture within, but allow gases to escape.
➢ Water shoes or boots
➢ Emergency shelter
➢ Antifouling for boat bottoms
➢ Self-cleaning products
References

Acuminate Leaf Apex (pg 8)


Mirror Leaf (pg 9)


Mirror Leaf (pg 9)


Mirror Leaf (pg 9)


