The Water Resilience Handbook

A Permaculture-Inspired Guide to Landscape Water Management

Mariam Marzouk

The
Water Resilience Handbook

A Permaculture-Inspired Guide to Landscape Water Management

Mariam Marzouk
MSc. Soil and Water Sciences candidate, Agroecology concentration

A Brief Note on Permaculture

Permaculture is the design philosophy focused on creating and maintaining resilient, equitable living systems. This includes food production systems, human settlements, and all other systems necessary to support human livelihood and well-being.

TABLE OF CONTENTS

Introduction 1

Background 2
- Water, Production, and Ecosystems 2
- Water and Society 4
- Global State of Water Systems. 5
- State of Water Systems in the US 6
- Towards a Paradigm Shift in Water Management 7

Principles of Water Management 9
- Slow, soak, and spread water flows 9
- Let slope and gravity do the work 11
- Irrigate efficiently 12
- Choose the right crops. 14
- Keep the soil covered by integrating trees and perennials 15

Water Management for the Garden, Farm, and Landscape 17
- Climate and Water Interactions 17
- Soil and Climate Interactions 19
- Calculating Water Needs 22
- Calculating Landscape Water Catchment Volumes 23
- Earthworks for Rainwater Harvest, Storage, and Use 24
- Feeding the Soil to Rehydrate the Land 29
- Efficient Irrigation Methods 30

Navigating an Uncertain Future 32
- From Floods to Fertility 32
- Drought Planning and Resilience 32

Connecting the Dots 34
- Sewage and Wastewater Management 34
- Aquaculture 35

Case Studies 37
- Wastewater-Fed Aquaculture in Kolkata, India 37
- Vegetated Swale and Sustainable Drainage Systems in Coventry, UK. 38
- Keyline Water Management and Perennial Polycultures in Wisconsin, USA. 39
- Dryland Water Management in Al Baydha, Saudi Arabia 40

Conclusions. 42

Sources. 44

INTRODUCTION

Water. This vital resource underlies nearly every aspect of our lives, yet it is often taken for granted until we can no longer afford to do so. When things seem to be going fine, it is easy to get careless about water management. For example, for the past few decades, many regions around the world have been pumping up their groundwater as though these reserves were never-ending. Unfortunately, this could not be further from the truth, and today many of the planet's major aquifers are being drained faster than they can be replenished[1,2]. As a result, global agricultural production, not to mention human livelihoods, are increasingly at risk. In the US alone, where 60% of irrigation relies on groundwater[3], the country's largest aquifer supporting a fifth of total agricultural production is expected to be 70% depleted within 50 years[4][5].

The accelerating climate crisis is exacerbating these issues even further, causing more frequent and severe droughts, floods, storms, and unpredictable precipitation patterns in many areas worldwide[6]. Although the future of global irrigation demands under climate change is uncertain, overall global water demand is predicted to increase by 55% over the next three decades[7]. At the same time, our shrinking water resources are increasingly threatened by pollution, wasteful use, and mismanagement. These facts call for a shift in the ways we think about and use water—the literal lifeblood of our ecosystems, societies, and economies. We need to change our relationship to water, and that's what this handbook is about.

Local action is an important part of addressing our growing water challenges, despite their global scale. Thus, this handbook focuses on what individuals and communities can do to increase their water resilience. Specifically, it addresses gardeners, land managers, small farmers, community leaders, local policymakers, and other stakeholders interested in learning more about ways to strengthen their water systems across the garden, farm, and landscape levels. By explaining how to:

1. harvest and store rainwater
2. use the landscape itself to rehydrate the land
3. more efficiently manage wastewater / runoff
4. make the most efficient use of the water resource

this handbook serves as an introductory resource for sustainable water management.

BACKGROUND

As the foundation of all life systems, water is intimately related to the health of our ecosystems and societies. Thus, water resilience is a crucial foundation of any sustainable system. But what exactly is water resilience? The concept of water resilience can be summarized as the ability of water systems to withstand and efficiently recover from water-related shocks (such as nutrient pollution, drought, or flooding) so that they can continue to meet our water needs[8]. When our water systems lack resilience, we witness many cascading impacts to everything from agricultural production to social stability.

Understanding big-picture connections related to water is crucial before one can dive into how to increase water resilience locally. With a clear overview of what the main challenges are, individuals and communities are better equipped to address them. Many of the challenges outlined in this section occur at much larger scales (often national, sometimes global) than can be grappled with locally. Several of these issues are further complicated by economic and political factors that are beyond an individual's power to control. However, by understanding these issues, addressing them head-on, and holding decision-makers and leaders accountable, we can help secure lasting water resilience now and into the future.

Water, Production, and Ecosystems

Let's start by analyzing water's relationship to food production. Perhaps the most obvious way water impacts production is through yield, as declines in either water quality or quantity generally have adverse effects on yield. For example, water with a high concentration of salts (a particularly pronounced issue in arid regions) can stunt plant growth, as can limited water availability during key reproductive growth stages. Where aquifer depletion is compounded by increasingly frequent and severe drought due to climate change, crop production is expected to decrease, especially in arid regions or areas with limited water availability[9]. These effects are already being felt in the American Southwest, which is currently experiencing a decades-long drought—the worst in over 12 centuries[10].

These conditions are continuing to have many negative impacts in the region, including increasingly stressed water supplies, more intense wildfires, impaired farmer livelihoods, and suppressed economic growth[11]. A widespread response has been an increase in government subsidies that incentive more efficient irrigation technology to help save water, but unfortunately this has led to increased—instead of decreased—aquifer depletion[12]. This happens because subsidizing efficient irrigation technologies in groundwater-stressed areas motivates producers to increase production, which results in increased aquifer water withdrawals.

Aside from insufficient water quantity, water quality can also have an impact on food production. Specifically, groundwater contamination is a growing global problem, especially since much of irrigation relies on groundwater. Contamination is often a result of agricultural, urban, and industrial activity resulting in a cocktail of contaminants including heavy metals, persistent pollutants, pesticides, nitrates, and hydrocarbons [13]. More recently, even radioactive waste from hydraulic fracking has been making its way into some watersheds[14].

A particularly problematic contaminant is plastic pollution—which is fast becoming one of the top problems of the century. Microplastics can now be found in nearly every environment on earth, in the human body, and of course in water systems, including groundwater[15,16,17]. Although the full gamut of effects is yet unknown, several disturbing trends have emerged, including adverse impacts on human health, ecosystem integrity, and even crop production and food security[18,19].

Several studies have found that irrigation with contaminated groundwater can lead to the accumulation of toxins in grains and vegetables[13], which could affect human health. Contaminated groundwater also degrades soils, farmland, and ecosystems more generally, an effect that is especially pronounced in arid areas with high rates of evaporation. While low precipitation in arid areas may limit the leaching of soil contaminants *into* groundwater, any contaminants, including salts, that do make their way into the soil will become more concentrated over time due to high evaporation. Overall, water's impacts on agriculture inevitably cascade beyond food production and spill over into the realms of human and ecosystem health.

The health of ecosystems is inextricably linked to the water systems supporting them. Aquatic ecosystems, such as ponds and rivers, are perhaps where this is most obvious, as they often have limited buffering capacity. This means that even small disturbances can have outsize effects[20]. Given the interconnected nature of ecosystems, however, negative impacts in one area often trickle down into other areas as well. For example, agricultural wastewater flowing into streams and rivers can cause eutrophication—a condition where excess nutrients increase algal production, causing (potentially toxic) algal blooms that eventually deplete the water's oxygen, killing fish and other species. Left unchecked, eutrophication can go on to cause major disruptions to the environment, human health, and economic activities[21].

One of the most compelling examples of this is the Gulf of Mexico oxygen minimum zone (OMZ), also known as the "dead zone". Covering 6700 square miles, an area the size of New Hampshire, this oxygen-depleted zone is one of the world's largest—and costliest. A 2020 report by the Union of Concerned Scientists estimated that this dead zone causes up to $2.4 billion in damage to fisheries and marine ecosystems annually. The root cause is eutrophication driven by agricultural pollution flowing into the Gulf from the Mississippi River—a problem likely to worsen as temperatures rise (promoting faster algal growth) due to climate change[22]. This type of agricultural pollution is primarily caused by leaching, erosion, and runoff losses of nitrogen and phosphorus. These nutrients are key to agricultural production but also result in eutrophication when used in excess. In this way, poor water management that disrupts nutrient cycling on a farm in Minnesota can affect downstream communities as far away as Louisiana and beyond.

Another way water affects ecosystems (and thus societies and economies) is through its interactions with the soil food web. In flourishing ecosystems, water is the critical resource supporting billions of diverse soil microorganisms. These microorganisms create the rich, fertile soil high in organic matter that is the bedrock of resilient production systems. Balanced, well-managed water systems are key, as soils that are too dry or too wet lead to several issues. On one extreme, dry, parched soil is an inhospitable environment for soil life and is much more susceptible to wind erosion and compaction. Compaction decreases water infiltration, drying out the soil even further in a negative feedback loop. Overly dry conditions also increase plant water stress, which can have significant impacts on yield[23].

On the other extreme when soils are too wet for too long, or waterlogged, the soil environment may become anaerobic, with too little oxygen to meet the metabolic needs of plant species and conditions that lead to shifts in microbial communities. Such soils are also more easily washed away and may suffer nutrient losses through leaching and runoff. Learning how to managed these extremes of wetness and dryness is becoming increasingly important today, as flood and drought regimes become more common in many areas due to climate change[24,25]. With the right approach, soil moisture can be effectively managed to support resilient production systems.

Water and Society

Given water's critical role in supporting resilient food production systems and ecosystems more broadly, our societies and economies clearly cannot be stable without sound water management. An important threat to sound water management at the community level, aside from climate change, is the growing privatization of the water resource[26]. This is because privatization transfers water rights, ownership, and control from the public to the hands of corporate interests[27], thus dispossessing citizens and limiting or preventing them from being able to control, access, and manage their water. In essence, water privatization turns a fundamental human right into a commodity and privilege that many cannot afford.

The Flint water crisis in Michigan is a pertinent example of current issues in water management in the US. In Flint, infrastructural, political, and environmental justice failures resulted in years of lead exposure and poisoning[28]. Even years later, these same failures continued to prevent many local residents—a primarily low-income and Black community—from accessing safe and clean water, forcing them instead to rely on expensive bottled water for everything from drinking to showering. Despite their polluted water, residents often paid around $200 per month in water bills. Meanwhile, two hours away from Flint, the corporate multinational Nestlé pays Michigan only $200 per year to pump and bottle millions of gallons of fresh, clean water, which it then resells to Michigan (and other Midwestern) residents[29,30]. Unfortunately, such cases are far from rare, as a 2016 Reuters report estimated that close to 3000 areas across the US suffer from contaminated water at rates far higher than those at the peak of the Flint crisis[31].

At the same time, water privatization continues to increase globally, particularly in the Global South but also more recently in the US and Europe. This concerning trend has tremendous impacts for land managers and farmers. The acute drought in the American Southwest is a prime example. While Californian farmers struggled to irrigate their crops, Nestlé drained millions of gallons of water—25 times as much as the corporation is legally entitled to—from the state's San Bernardino Forest to sell as bottled water[32]. Corporate behavior of this nature is not uncommon and is notoriously difficult to stop[33], helped by the sector's reliance on predatory marketing schemes and powerful lobbying groups[34,35].

This has been particularly evident in the case of Standing Rock and the Dakota Access Pipeline (DAPL), which gained international attention in 2016. For years, DAPL backers lobbied extensively to secure approval for the oil pipeline that would threaten indigenous water rights, safety, and governance, in blatant violation of the US treaty with the Standing Rock Sioux tribe[36,37,38]. Despite a years-long legal battle, the DAPL has been operational since 2017—a testament to the deep influence of the lobbying industry. Corporate lobbying groups have even gone as far as drafting legislation to criminalize grassroots protests against similar projects[39]..

Ultimately, water resilience and ecosystem integrity are deeply intertwined with water justice[40,41], which in turn is foundational to a community's development, self-sufficiency, and autonomy. To achieve water resilience, it is important to understand how climate change and economic policy interact with the water resource to affect food production and society at both the global and local scales.

Global State of Water Systems

Overall, the situation of the global state of water systems is dire. Around the world, communities are facing increasing aquifer depletion[3], water pollution, more erratic precipitation patterns[7], and reduced water sovereignty due to current economic policies[42], all of which are exacerbated by the compounding effects of the climate crisis. The effects of these issues are often very unevenly distributed. For example, in terms of water quality, low-income and otherwise marginalized groups often suffer the highest rates of water pollution and lack of access to clean water[43].

Examining the issue of aquifer depletion more closely, we find that in many regions "groundwater reserves have been depleted to the extent that well yields have decreased, pumping costs have risen, water quality has deteriorated, aquatic ecosystems have been damaged, and land has irreversibly subsided"[44]. Currently, little is being done to address aquifer depletion on a wider scale. The few interventions that do exist often focus on technological innovations to save water, despite the limited or even negative impacts of such interventions on watershed sustainability.

For example, drip irrigation is widely touted as a solution to water scarcity, despite the lack of conclusive scientific evidence supporting drip irrigation as a water saving device beyond the plot level[45]. Also, advancing technology has allowed wells to be drilled deeper, which is often done in response to falling water tables. However, deeper wells are a temporary and unsustainable “stop-gap solution” that only exacerbates the problem of aquifer depletion in the long-term[46]. In fact, technological advances often lead to higher resource consumption, not less, in a phenomenon more broadly known as Jevon’s Paradox[47,48].

Compounded by the effects of the climate crisis and increasing demand, decreasing supplies of water are well-poised to become a major source of conflict[49,50]. In fact, political instability is already the reality in many parts of the world as diminishing water supplies and mismanagement fuel growing interstate tensions and conflict[51,52,53, 54]. Economic factors often play a major role as well. The recent Cochabamba “Water War” in Bolivia is a noteworthy example of a collision between economic policy and water access. In the early 2000s, mass protests spread across the country in reaction to decades of economic policy favoring water privatization. These protests fundamentally reshaped Bolivian society and reformed water governance in the country, largely restoring the status of water from a commodity to a human right[55]. These events underscore not only the intertwined nature of economics and water, but also the critical role activism can play in defending and restoring water sovereignty. This is true in the US as well, as it was not until widespread and prolonged activism became impossible to ignore in Flint and Standing Rock that governments began responding to the crises[56,57].

State of Water Systems in the US

The US also suffers many of the same challenges that confront global water resilience, including the impacts of the fast-accelerating climate crisis, water scarcity, pollution, and mismanagement. The fragmentation of the country’s laws into federal, state, and local levels often complicates issues further. For example, although the federal government does not regulate rainwater harvesting, many states heavily restrict rainwater harvesting and use. This is in part a relic of old water rights laws operating on a “first come, first serve” basis that essentially privatize the rain itself[58].

Obstacles to the productive use of rainwater by individuals are situated more broadly in a context which frequently disregards the productive potential of rainwater. For instance, rainwater is often mixed with sewage in stormwater drainage systems instead of being diverted for productive use or storage.

Aside from the wasted potential of rainwater, other cases of water mismanagement illustrate several missed opportunities to improve water use and management. The counter-productive governmental response to the over-pumping of groundwater through subsidies has already been discussed. In addition, water-hungry crops are often grown in water-stressed regions, such as the case of cotton in the American South and Southwest, one of the region's most important (and thirstiest) crops. Federal subsidies keeping the cotton industry afloat illustrate how policy often aggravates problems instead of solving them. In this case, the Southwest is in the midst of a historic drought compounded by alarming rates of groundwater depletion, which unsustainable cotton production will only exacerbate[59].

In the US, the main tools we have to tackle issues of water quality, quantity, and access are often framed in terms of Best Management Practices (BMPs) and government regulations. While useful, both these institutional tools fall short in several important ways. First, BMPs tend to focus primarily on prescribing biophysical water interventions that do not typically address the socioeconomic and political dimensions of water resilience. More specifically, BMPs address aspects such as nutrient pollution and efficient irrigation, but often fail to account for the economic reality of many growers. For example, as around 40% of agricultural land in the US is leased[60], many farmers cannot necessarily afford to implement long-term environmental initiatives when they may not be around to reap the benefits.

Second, BMPs also ignore how growing water privatization threatens the long-term viability of many farming operations, as seen in the case of Nestlé over-pumping California's aquifers while farmers faced water shortages. This is an area where governmental policies can even worsen the problem, in part due to corporate influence on legislation[61,62].

Third—and perhaps most importantly—BMPs and governmental regulations as they currently are framed and implemented typically fail to emphasize one of the most powerful tools we have for achieving water resilience: using the landscape itself to harvest, store, and manage rainwater flows.

Towards a Paradigm Shift in Water Management

Given the insufficient capacity of BMPs and governmental regulation to maintain water access and manage it wisely, the untapped potential of rainwater, the growing scarcity and pollution of groundwater[63], the threatened state of water sovereignty, and the compounding effects of the climate crisis on all these factors, a paradigm shift is necessary to address these issues. To achieve water resilience, it is vital that we radically rethink our relationship to the water resource.

Both material (biophysical) and immaterial (sociopolitical and economic) changes are necessary for lasting, effective improvements in water management. The example of

Bolivia, where citizens banded together to hold the government accountable in terms of securing water rights, illustrates how activism can help catalyze top-down policy changes at the state and federal levels of government. However, such initiatives often take time and may become diluted in the policy-making process, possibly reducing their efficacy and reliability. For that reason, the top-down approach alone is insufficient to secure individual and community water resilience.

Instead, concurrent with top-down change, bottom-up approaches are needed at the smaller scale of the individual, community, and local government. These initiatives may have a higher chance of success at smaller scales, where there are often fewer competing interests. Also, community awareness can help influence local laws for better water management without waiting for state or federal policy changes to materialize—which is especially useful in cases of poor governance. Accordingly, this handbook mainly focuses on the bottom-up interventions that communities can undertake to strengthen their local water resilience.

PRINCIPLES OF WATER MANAGEMENT[1]

Although specific *practices* often vary depending on context (climate, soil type, scale of operation, etc.), there are a few water management *principles* that generally hold across contexts and are the basis from which practices are derived[64]. These principles can be easily remembered using the acronym **SLICK**, which stands for

> **S**low, soak, and spread water flows.
> **L**et slope and gravity do the work.
> **I**rrigate efficiently.
> **C**hoose the right crops.
> **K**eep the soil covered by integrating trees and perennials.

The following pages discuss each of these principles in more detail.

<u>Slow, Soak, and Spread Water Flows</u>

This principle focuses on reducing the erosive potential of water flows, for example from heavy rains or runoff. The goal is to maximize the productive use of the water resource before it leaves the system, which can involve earthworks to create more "winding" paths for water and slower seepage of water throughout the landscape. Slowing water down helps reduce soil erosion and all its associated issues, including negative impacts on downstream water quality due to nutrient pollution, sedimentation, and turbidity. Slower flows also give the landscape a better chance to soak up water into the soil for productive use and storage. Over time, this can help re-hydrate the landscape and recharge local aquifers.

While slowing water down helps it soak into the ground, sometimes additional steps are needed to aid this natural process. For example, landscapes with hard clay pans or compacted soil have low water infiltration. On the opposite extreme, sandy soils may have excessively high water infiltration and correspondingly very low water holding capacity, meaning that water just "runs right through" these soils. In both cases, remediation measures, such as increasing soil organic matter and others described in greater detail in the next section, must be taken before the land can reach its full soil moisture regulation potential [65].

In some cases, it may be desirable to stop water flows completely for storage in temporary or permanent catchments, such as in small dams, ponds, or reservoirs. These can be rainwater catchments or catchments that store water from diversions of small streams and rivers.

1 This information has been assembled mainly through the author's own exposure to soil and water management through graduate study and permaculture education, including courses and other material based on *Permaculture: A Designer's Manual*, by Bill Mollison.

Slowing down water can also help make it easier to manage and spread to where it is most needed. For example, in steep landscapes with many ridges and valleys, the ridges are often the driest areas of the landscape because gravity forces water to take the shortest path down, running off the ridges towards the valleys. This is not always a problem, but if your land is located on a ridge, or if you live in an area susceptible to gully erosion, it can become an issue. Certain techniques, such as keyline design, can help redirect water to the ridges to rehydrate these parts of the landscape[66]. Such techniques will be described in more detail in later pages.

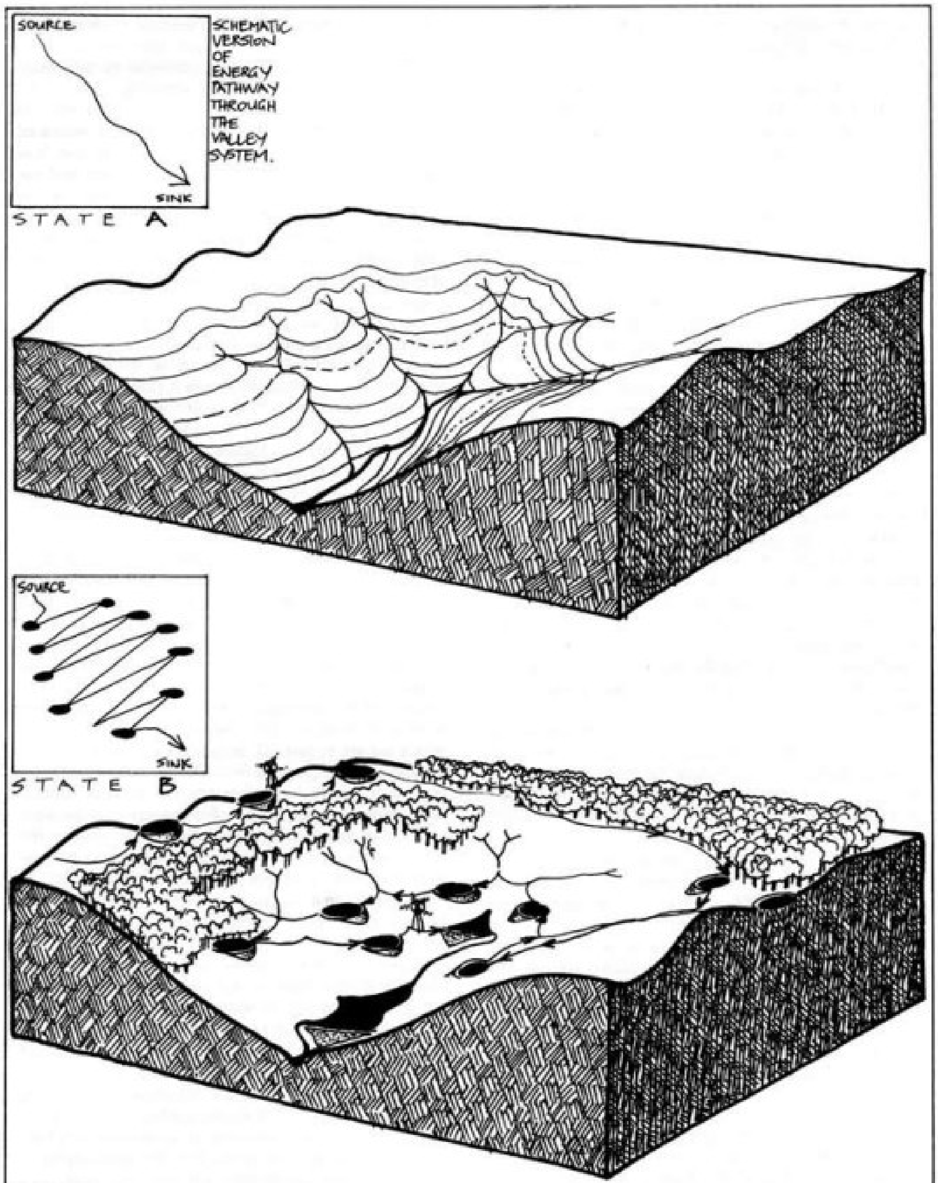


FIGURE 2.1
DESIGNING TO CATCH AND STORE ENERGY.
The designer's work is to set up useful energy storages in a landscape or building (proceeding from State A to State B). Such storages, available for increasing yields, are called resources.

Winding Water Flows
Compare State A (top) to State B (bottom). State B shows how creating a more "winding" path for water increases its productive potential before it leaves the system.

FIGURE 1

Let Slope and Gravity do the Work

Slope is one of the most important, yet commonly underutilized, land features to account for when designing resilient water management systems. Because of gravity, water always runs at right angle to contour, a fact that can be used to your advantage. This is true even on most "flat" land, since even land that appears flat often has a slight grade that can be productively used.

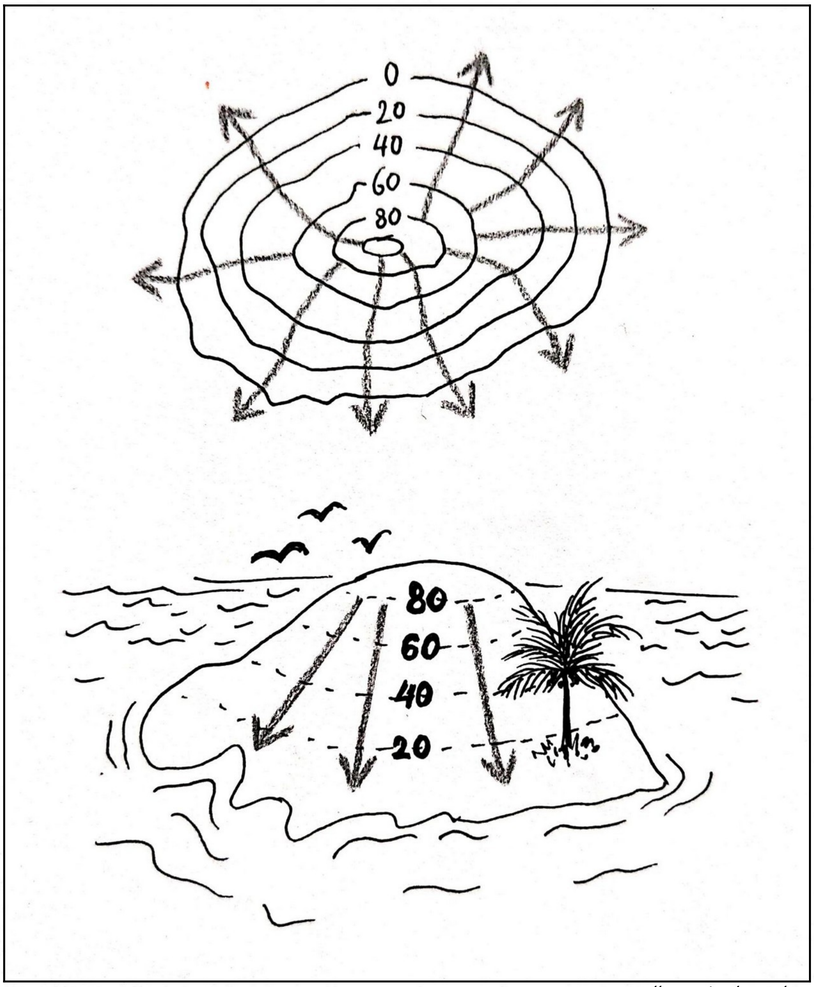


Illustration by author

Water & Contour
Top view and side view of the contours on a small island. The arrows illustrate how water always runs at right angle to contour.

FIGURE 2

Areas with moderate slopes often present many opportunities for passive water catchment and distribution. However, doing so first requires one to identify two important areas in the landscape: the "longest, highest contour line" and the keypoint[64]. The longest contour line at the highest possible elevation is often the best place to start slowing the flow of water before it has a chance to cause erosion downslope. The keypoint is a point just downhill from the inflection point, which is the point where the landscape switches from convex to concave.

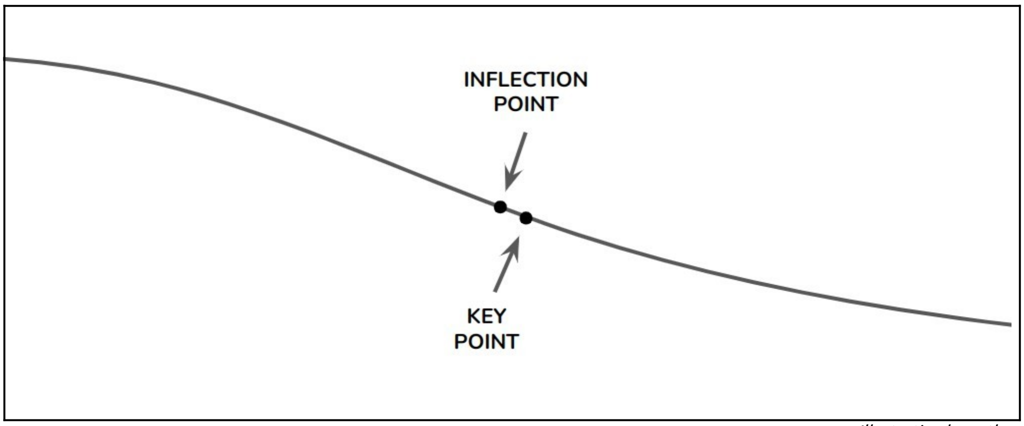


Illustration by author

The Keypoint
The inflection point marks the switch from convex to concave. The keypoint is just below the inflection point.

FIGURE 3

The keypoint is often the best place to begin initial water capture and storage—for example using a small dam—with enough potential energy to create head pressure for maximal downstream water use. Above the keypoint, the land is angled too sharply to maximize water capture, whereas below the keypoint, there is less potential energy available (due to the lower elevation) to generate head pressure. High head pressure is useful for energy generation, irrigation, and for having running water in general, such as from a tap or faucet. That being said, site and soil analyses are crucial to ensuring that keypoint water catchments are able to meet water needs without introducing safety hazards downslope. For example, keypoint water catchments would be unsafe to install on sites with soils prone to slips and slumps. On flatter landscapes, insufficient elevation gradients can mean less potential for generating head pressure, so other catchment strategies will be needed. Gravity can still be taken advantage of, however, by installing rainwater catchment tanks high above the ground, similar to water towers in urban areas.

Excessively steep slopes also require appropriate management to prevent soil erosion and maximize water resilience. Often, such slopes need to be permanently covered with perennial vegetation, for example forested, to remain stable and prevent landslides[67].

Irrigate Efficiently

Although efficient irrigation methods alone often are not enough to meet water-saving goals, they can be a crucial component of a multi-pronged water-saving strategy[45]. All else being equal, a system with more efficient irrigation will outperform a system without.

When choosing an irrigation system, all sources of water should be considered and passive irrigation strategies should be prioritized. For example, contour farming helps increase passive irrigation in water-limited areas by productively using runoff that would otherwise be lost to the environment. One way to do this is to use swales to irrigate orchards, perhaps interplanted with row crops. Primarily a tree-growing system, swales are level ditches dug on-contour with productive trees and shrubs planted on the berm to both make use of collected water and stabilize the mound. (This is in contrast to the more commonly known “landscaping swales” that consist of grassy drainage ditches.)

Since water always flows at right angle to contour, rainwater collected in the swale slowly seeps into the soil at an angle, forming a sub-surface “water bubble” which grows over time over successive rain events, eventually recharging the groundwater[64]. According to the USDA, compared to farming without regard to contour, contour farming increases water infiltration and can help decrease soil erosion by up to 50%[68].

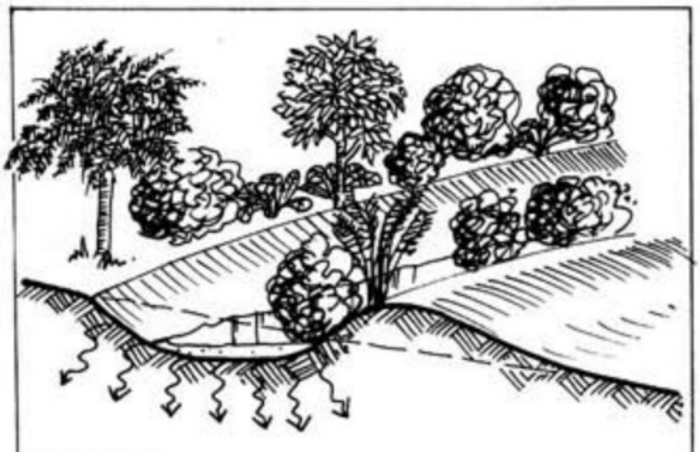


FIGURE 7.23
Swales on contour do not flow; they first stop and then infiltrate overland flow. Swales on hillsides are part of access or production systems.

A Swale
This figure illustrates how runoff can be intercepted by a tree-planted swale for both productive use and groundwater recharge.

FIGURE 4

Aside from passive irrigation, greywater can also help more efficiently meet irrigation demands. Where possible, greywater should be used to maximize productive water recycling. As an additional benefit beyond saving water, greywater frequently has higher nutrient concentrations which can help meet plant nutrient needs. Though greywater may also carry a higher contaminant and salt load, this can be mitigated both at the source (e.g. biodegradable soaps can help reduce contaminant load) and by first routing the greywater through biological filtration systems such as reed beds—although these will also reduce nutrient concentration, which may reduce the fertility benefits of greywater.

On the other hand, the groundwater resource should often only be used as a last resort. This is because, unless aquifers are being replenished faster than or at the same rate as they are being drained (a distant goal in many areas), relying on groundwater for irrigation will only serve to hasten aquifer depletion in the long-term. Regardless of the water source used, care should be taken to irrigate in ways that minimize water loss through evaporation, runoff, or other leaks in the system. Also, any water overflows that do occur from chosen irrigation strategies should ideally be rerouted for productive use elsewhere in the system. This is especially crucial in severely water-limited environments, such as in drought-prone, arid, or semi-arid areas.

Many efficient irrigation techniques, ranging from lower to higher tech solutions, exist. Usually, the “best” method will depend on the context, including climatic and soil factors, financial resources, and labor capabilities. Drip and sub-surface drip irrigation are two of the more well-known irrigation methods that minimize evaporative water loss (though they may generate plastic pollution), while precision irrigation systems using moisture sensors can help prevent over or under-irrigation.

Another lower tech solution is clay pot, or olla, irrigation. This remarkably efficient ancient irrigation system was and is traditionally used for agricultural production in arid regions. It consists of burying porous clay pots in the soil, filling them with water, and topping them up as needed. This allows water to be delivered directly to plant roots via auto-regulatory seepage, meeting crop water needs while minimizing water loss by drainage and evaporation. Case studies analyzing the efficiency of olla irrigation found up to 30-60% water savings compared to other irrigation methods, including drip irrigation [69,70].

Readers interested in a more comprehensive overview of how traditional ecological knowledge informs low-tech irrigation strategies (and agroecosystem management more generally) are referred to the book, *Lo-TEK Design by Radical Indigenism*, by Julia Watson.

Choose the Right Crops

The importance of choosing context-appropriate crops (i.e., “the right crop for the right place”) cannot be understated. Cropping and water use patterns in the American West, which is currently experiencing its worst (and anthropogenically exacerbated) drought in recent history, illustrates the critical nature of those choices. Although Western residents face water restrictions and are encouraged to limit water usage, both residential and commercial water use together only account for an estimated 14% of total annual water consumption. On the other hand, irrigated agriculture—mainly alfalfa and haylage used to feed cattle—accounts for the remaining 86%[71]. These crops are draining the region’s already over-stressed water supplies in a stark example of how land use decisions (and dietary choices) can have a profound impact on natural resources. In this case, crop choices are only one part of unsustainable beef production and consumption (i.e., producing beef with irrigated feed crops grown in water-scarce regions).

In general, hardy, native species are often better adapted to local climatic and soil conditions, and thus may be a more water-efficient crop choice compared to species without these evolutionary advantages. However, current access to hardy native species may be limited for many landowners, who must rely on non-native species. When non-native crops are desired, care should be taken to choose species that display similar adaptations or come from similar climatic zones as native plants.

As an example, many arid areas in Australia used to be covered in deep-rooted perennial species which helped maintain the water balance and prevent soil salinification. These plants' deep roots helped keep the water table (and its salts) at a low enough level to prevent salt build up in the upper layers of soil. When colonizers replaced the well-adapted native vegetation with mal-adapted, shallow-rooted annual species, the water balance was massively disrupted and soil salinity increased over time as the water table and its salts encroached upwards through the soil[72].

Aside from illustrating the advantages of native species, this example also highlights the importance of deep-rooted perennial species to irrigated agriculture[2], especially in arid contexts vulnerable to soil salinity[73]. This management strategy can work in tandem with planting drought-tolerant crops and keeping the soil covered to minimize evaporation, which is the theme of the next water management principle.

Keep the Soil Covered by Integrating Trees and Perennials

One of the main benefits of keeping the soil covered is that covered soil is less susceptible to erosion, which also helps preserve downstream water quality. Other benefits include lower soil evaporation rates and cooler soil temperatures, which is especially useful in hot or arid climates. More generally, vegetative soil covers can help create a more moderate soil microclimate better buffered against temperature extremes compared to bare soil.

Mulches are one way to keep the soil covered. Organic mulches (from on-farm plant waste or residues) can help add carbon to the soil, which can help increase soil water infiltration and retention capacity over time as soil organic matter builds in the soil and improves its structure[74]. One challenge with organic mulches is that they may require more careful management to avoid accidentally introducing diseases, weed seeds, or other pests. Plastic mulches are often used but should be minimized or avoided because they can ultimately lead to soil degradation, water repellency, and pollution in the long-term[46,47,75].

2 Although alfalfa is a deep-rooted perennial, its long growing season and high water demand (necessary to achieve high yields) make it unsuitable as a production crop in arid and/or water-stressed regions.

Another way to keep the soil covered is by integrating trees and perennial species into the landscape. Perhaps more than any other method, perennial integration offers the most long-term benefits that increasingly strengthen water resilience over time. Trees and other deep-rooted species help improve soil structure by increasing porosity and supporting a diverse soil microbiome, both of which increase soil water infiltration and retention[76,77]. Once established, perennial plants act as a living mulch, while trees can increase soil fertility by passively “mulching” the ground with their leaf litter, especially legume trees and shrubs. Additionally, they can be pruned periodically for more traditional mulch applications and to manage water usage[78].

Trees and perennial vegetation also help to clean and filter water flows. This helps manage water quality within an agroecosystem, and is also beneficial for biologically “treating” and cleaning any water flows leaving the system. For example, riparian buffer strips can be used to preserve the water quality of streams and rivers near the farm or landscape being managed[79].

As permanent soil covers, trees and perennials also shade the soil and keep it several degrees cooler during hotter months, helping reduce both evaporation and plant heat stress. Although the increased plant biomass means increased transpiration, this water loss is typically more than offset by the other benefits provided, especially in mature, established systems[80]. In fact, on a bigger scale, trees and forests more generally are critical components of the water cycle that facilitate both precipitation and groundwater recharge[81].

That being said, trees and perennials may increase water consumption during establishment, so a strategic combination of mulching, perennials, and trees (along with judicious species selection and water management) can help build water resilience over time within a water-limited context.

Climate and Water Interactions

The first step to devising an effective water management plan is having a thorough understanding of how climatic factors interact with water in the landscape. Climate, generally defined as the prevailing weather conditions (mainly moisture and temperature levels) over long periods of time in a region, is affected by several major factors. These factors are easily remembered with the acronym, Climate (“climb it”) Ladder, which stands for

Latitude
Altitude and topography
Distance from oceans or large water bodies
Direction of winds
East / West coasts
Rain and precipitation

While a thorough analysis of how each of the climatic factors interacts with each other to affect water management is beyond the scope of this handbook, here a few general useful rules to remember:

Latitude
Aside from affecting day-length, latitudes closer to the equator tend to be hotter and wetter, while latitudes further away from the equator tend to be cooler and drier. This is important to remember because temperate zones will necessitate different management strategies compared to the tropics or drylands.

Altitude and topography
A rule of thumb about altitude is that every 100 meters of elevation increase roughly equates to between 0.5-1 degrees of latitude change (further away from the equator), although day-length stays the same[82,83]. This means that temperatures at high latitudes are generally cooler, which can lead to lower evaporation rates and the possibility of growing cooler climate crops. (However, because pressure also decreases with altitude, evaporation rates may increase when the effect of lower pressure outweighs the effect of lower temperature.)
Topographically, valleys often have their own micro-climates. For example, elevated or shaded valleys can have cooling and sheltering effects, which can reduce evaporative water losses because of the lower temperatures and decreased winds. Slope orientation also matters, with sun-facing slopes (south-facing in the northern hemisphere) being warmer than opposite slopes.

Distance from oceans or large water bodies

Oceans and other large bodies of water (such as the Great Lakes) provide moderating or buffering effects to the environment in what is known as the maritime effect. Near large bodies of water, temperatures tend to be milder and vary less throughout the year compared to regions that are further inland. Inland areas are affected by the continental effect and experience more extreme high and low temperatures throughout the year. The maritime effect also contributes to a more humid climate with higher rates of precipitation throughout the year.

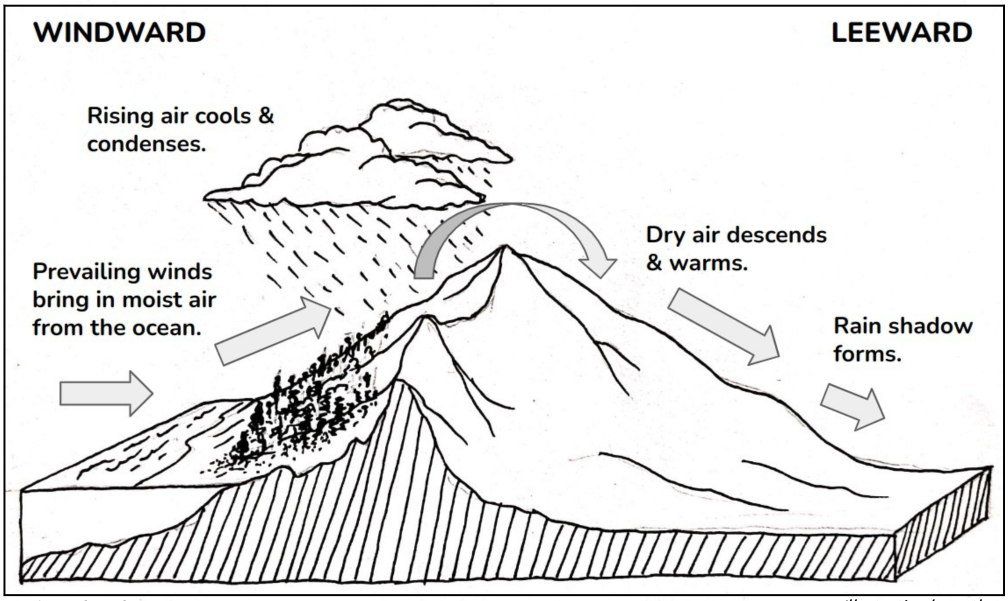
Direction of winds

The direction of locally prevailing winds can affect seasonal rain cycles, but can also be an important factor to account for when thinking about how to mitigate wind stress on plants and animals. Crops under high wind stress experience higher rates of water loss and lower yields, which can be mitigated with the strategic integration and placement of wind breaks[84, 85].

East / West coasts

Aside from locally prevailing winds, the Coriolis effect causes predictable global wind cycles that affect local weather, especially coastal precipitation patterns[86]. Of the three prevailing global wind belts (the Polar Easterlies, the Westerlies, and the trade winds), the Westerlies, between latitudes 30 and 60, are the main wind belt affecting regional climates and coastal variations in the US. The Westerlies blow warm, moist air from west to east, resulting in wetter environments on the windward west coast and drier environments inland. This effect is especially pronounced because of the Sierra Nevada mountain range. The mountains trap most of the wind's moisture (in the form of precipitation) on the windward side, leaving the air that flows over the mountains leeward much drier, hence the rain shadow desert in the Western US.

Similar wind patterns also affect precipitation on the East coast, although the Eastern US remains much wetter than the West in part due to its topography and absence of a rain shadow. Generally, due to climate change, the West is predicted to get drier while the East will get wetter[87].



Rain Shadow *Illustration by author*
This illustration shows how rain shadows, and rain shadow deserts, form.

FIGURE 5

Rain and precipitation
While rain is one of the major components of precipitation, other contributors can include snow melt, hail, fog, dew, and surface condensation[64]. Despite being potentially significant sources of water, these types of precipitation are often under-measured and underappreciated compared to rain, so they are important to account for when designing a water management plan.

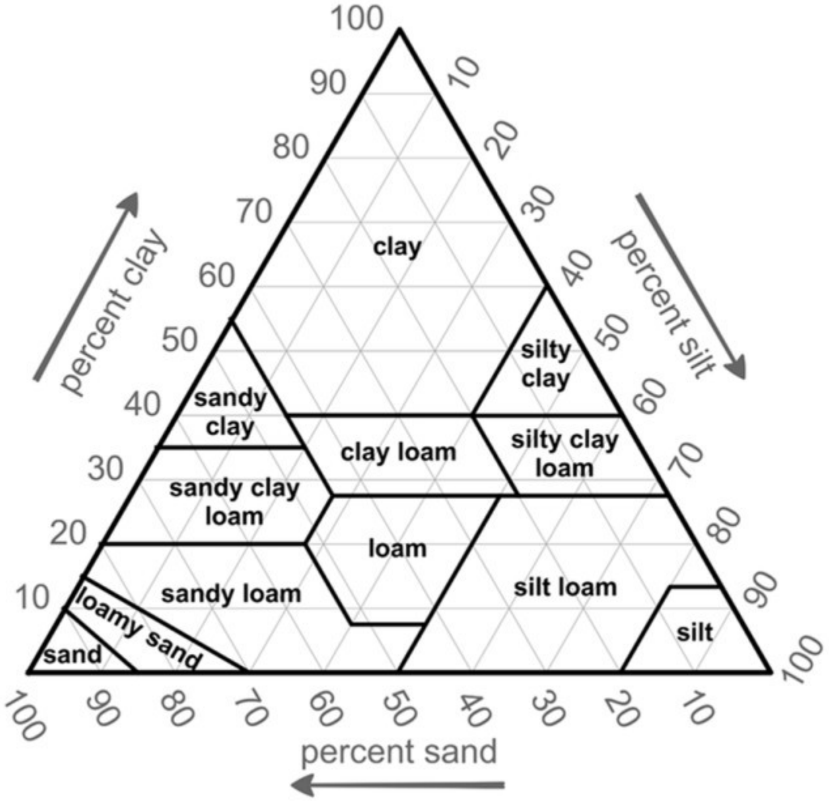
Soil and Water Interactions

Aside from the influence of climate, soil plays a major role in water management. Seemingly subtle differences in soil texture and structure can be the deciding factor of whether the landscape is frequently ponded and muddy or parched and dry. Soil type can also determine what types of earthworks are possible on a site. This is because each soil type behaves differently, including variations in drainage, nutrient cycling, and aggregation. For example, a high clay fraction is desirable when building small earth dams, but can be detrimental (if unamended) for growing certain crops due to poor drainage. Slope, soil, and climate can also interact to make certain earthworks not only difficult, but even dangerous in certain contexts. For example, on steep slopes under high rainfall conditions, installing swales to increase soil water moisture could lead to catastrophic landslides[88,89].

Costly and sometimes lethal design mistakes are much more easily avoided with a thorough understanding of how soil, climate, and water interact within a landscape. A key component of these interactions is soil texture, which is primarily determined by the size and proportion of soil mineral particles. Sand is made up of the biggest, coarsest particles, silt is made of smaller particles, and clay is made of the smallest particles. The texture class of a soil can be determined by soil sampling, with one of the easiest and most accessible methods, aside from hand feel estimates, being the “jar method”, outlined below[90].

The Jar Method

1. Choose several distinct points in the landscape to get a more comprehensive overview of the soil texture in the area.
2. At each point, dig down a few inches beyond the organic matter layer and collect between a cup or two cups of soil.
3. Remove any rocks, pebbles, or roots, and crush aggregates (soil clumps) so that the soil sample is more uniform.
4. Place each sample in a jar and add enough water to cover the soil by a few inches.
5. Optional: Add a tablespoon of Borax or Calgon to help settle out clay particles[91].
6. Shake the jars vigorously for a few minutes to help break down any remaining aggregates.
7. Place the jars on a level surface and allow the contents to settle undisturbed for a few days.
8. Sand will settle out first, followed by silt, and finally clay. Some organic matter may remain suspended in the water, but this can be ignored.
9. Use a ruler to measure the height of each layer and calculate the relative proportion of each.
10. Match up the calculated proportions to the soil texture triangle to determine the soil texture.



Soil Texture Triangle
Using the measured layers from the jar method, match up the calculated proportions to the soil texture triangle to determine soil texture. The total should add up to 100.

FIGURE 6

The main benefit of the jar method is that it is an easy way to gain a rough approximation of a site's soil type. Soil labs can provide more accurate soil assessments for a fee and should be considered when a high degree of accuracy is desired. Beyond soil texture, other soil features can interact and have important hydrological consequences. For example, spodic horizons in sandy soils may cause poor drainage, despite the sandy soil texture. Soil maps, widely available online, can also help to understand the broader soil characteristics of a region. For example, the USDA provides a convenient soil survey tool at https://websoilsurvey.sc.egov.usda.gov/ .

Depending on soil texture, various amendments may be needed to achieve desired management goals. Generally, physical interventions are applied first, followed by chemical and finally biological amendments. For example, compacted soil pans with high acidity may first be deep-ripped, then amended with lime to lower acidity, and finally compost or other organic amendments may be added to increase organic matter content[92].

An alternative (or concurrent) strategy, especially useful on smaller scales or in resource-limited contexts, is to "build up" above the poor soil. For example, raised beds can be used to help improve drainage around crops planted on poorly draining soil, although this method can be expensive over large acreages. In most contexts, working to steadily build organic matter will help improve soil structure in the long-term, thus strengthening water resilience.

Calculating Water Needs

Calculating annual water needs will help determine the kinds of interventions needed onsite to meet projected water demands. Although this handbook mainly focuses on water management at the farm and landscape scales, it is worth mentioning that similar approaches can be used to meet domestic water use needs. For example, according to the WHO, a person needs between 50 and 100 liters of water per day to meet basic needs[93]. This equates to between 18300 and 37000 liters, or between 4840 and 9800 gallons annually. To meet, or at least partially meet, these needs from rainwater harvesting and storage, water demands, roof catchment areas (plus other available catchment volumes), and annual precipitation averages can be used to roughly calculate the amount of water that can be harvested and the size of the tanks or catchments needed to store it.

Similar calculations can be made for crop and livestock water needs, bearing in mind that the climate itself, as well as the growth stage of the crop, will affect water needs. Suppose, for example, that a certain crop needs an inch (25 mm) of water per day in a very hot and dry climate. This means that the crop needs an inch of water available in its root zone over the entire area it is grown. Thus, if the crop covers 1 acre, it would need around 27,000 gallons of water per day, as follows:

1 acre = 6,272,640 square inches
(6,272,640 square inches) x (1 inch / day) = 6,272,640 cubic inches / day
(6,272,640 cubic inches) / (231 cubic inches per gallon) = 27,154 gallons / day (102,790 liters / day)

This does *not* mean, however, that the crop needs 27,000 gallons of water supplied to it everyday by rain or irrigation. The crop could be irrigated 3 inches every 3 days, for example, allowing it to use 1 inch per day[94]. Or, a deficit irrigation strategy could be used, depending on the crop and context. Alternatively, soil moisture may be high enough to allow the crop to be irrigated even less frequently, since the crop's water needs would be supplied in part from stored soil moisture.

Therefore, calculating crop and animal water needs provides a useful starting point for understanding water demands and whether those demands can be realistically met in a particular climate and under certain management strategies. This type of calculation also highlights the importance of choosing the right crops for the right environment—that is, the climate, soil type, and general water availability of the region.

<u>Calculating Landscape Water Catchment Volume[64]</u>

In tandem with calculating crop water needs, the landscape's total water catchment volume can be calculated to gain a broad overview of how the landscape itself can be used to meet water demands without stressing groundwater resources. This calculation is also useful for designing in safety measures for extreme rain events.

Because water always moves at right angle to contour, the potential maximum catchment area of a site can be calculated using a contour map. Regional contour maps are widely available online. As an example, consider Figure 7 below showing a catchment area map for a site outlined in red[95]. In this example, water moves at a right angle down from the high points in the landscape, in this case into the site itself. Depending on the topography surrounding the site, the catchment area may be much larger or smaller.

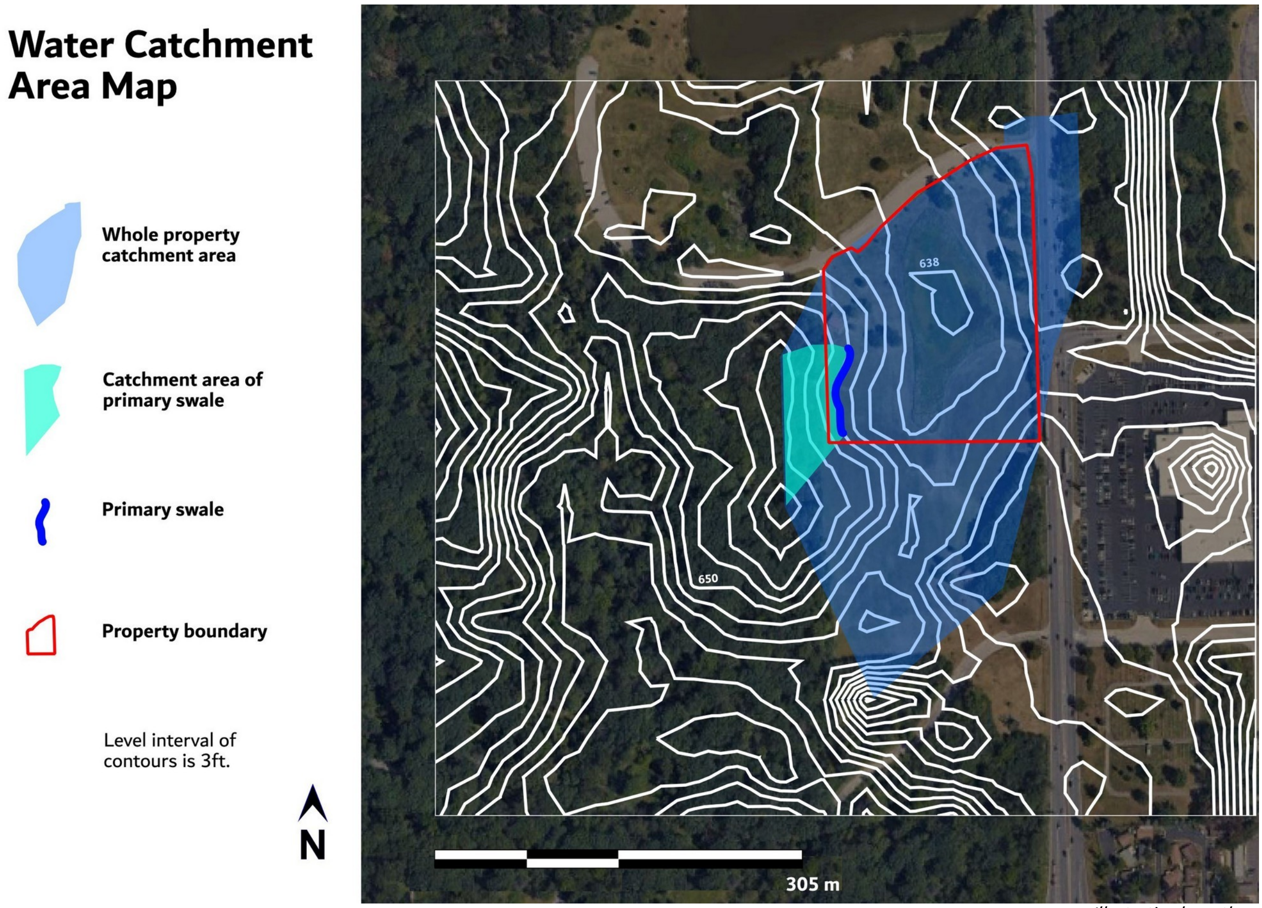


Illustration by author

Water Catchment Area Map
The contours for this particular map were generated using the free online tool, http://contourmapcreator.urgr8.ch/ .

FIGURE 7

After the catchment area of the entire site is delineated and its area is computed, it becomes easier to picture which water harvesting features and earthworks may be useful for the site, and where their placement makes the most sense.

From the entire site's catchment area, smaller catchment areas for planned major water catchment features, such as dams or swales, can be computed. For example, in Figure 7, a smaller catchment area for the primary swale is shown in turquoise (which is part of the entire site's catchment area, shown in blue).

The catchment volumes for these areas can then be calculated using historic precipitation records. For this calculation, it is assumed that the ground is already 100% saturated so that any additional water will behave as runoff. Then, the maximum 24-hour rain event is multiplied by the catchment area to calculate the amount of water potentially caught by the site over 24 hours. (The maximum rain occurrence is used, along with the 100% saturation assumption, so that water can be safely managed in the event of extreme rain events.)

The potential catchment volume can then be divided by 24 to obtain the hourly rate of water flow. The hourly rate can be divided by 60 to obtain water flow per minute. The water flow per minute, in turn, can be further divided by 60 to obtain water flow per second. Finally, the flow per second should be over-calculated for safety.

For example, an earth dam's catchment area of 1200 feet squared receiving a maximum 24-hour rain of 24 inches (2 feet) will have a catchment volume of 2400 feet cubed (about 18,000 gallons) over 24 hours. The hourly rate of water the dam may have to handle is 2400 / 24 = 100 cubic feet per hour, which is about 1.7 cubic feet per minute, or 0.028 cubic feet (about 0.2 gallons) per second. This per second flow could then be over-calculated by 50% for safety, leading to a final per second flow of 0.3 gallons.

This calculation can help determine the appropriate size of catchments, their water storage potential, and the size of their overflow features (such as spillways or overflow pipes) for the safe management of water flows.

Earthworks for Rainwater Harvest, Storage, and Use

Water resilience is strengthened by water conservation, which can be done by productively managing runoff and capturing water flows so that they have a chance to spread, soak into, and rehydrate the landscape. Managing water in this way creates opportunities for increased productivity. For example, water-harvesting swales can add productive tree systems to the landscape. In general, catchments should be placed as high as safely possible in the landscape for maximum head pressure. From there, water can work its way down and be directed to where it is needed. A good rule to remember is that water moves down for free, but moving it upwards costs energy.

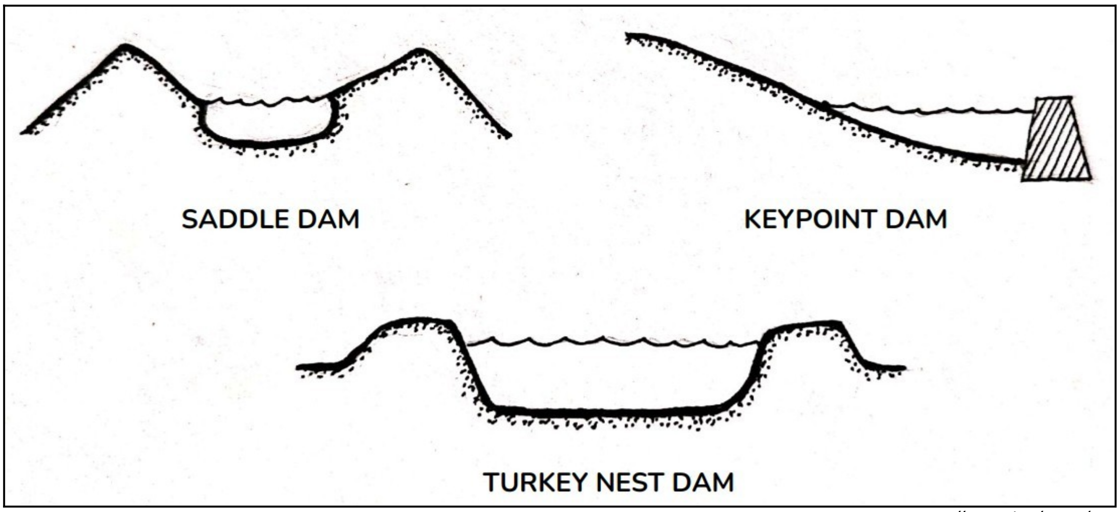
In water-limited contexts, such as in many arid or semi-arid regions, water conservation will likely be the main priority. In humid landscapes where water is not a limiting factor, redirecting water flows for productive use might be of higher priority than conserving water. Such areas often already have enough—and sometimes too much—water, so emphasis may instead be placed on using that water productively and safely redirecting surplus overflows into local watersheds without causing pollution.

When water conservation is the priority, soil evaluation is the first step to determining what kinds of water-conserving earthworks are most appropriate for the site. What follows is a brief overview of the main kinds of earthworks useful for water conservation, along with a description of the soils and topographical features appropriate for their installation. For more information on the various earthworks listed here, including installation and maintenance instructions, the reader is referred to the resources numbered here and in the following sections[96, 97, 64].

Water Storage: Dams, Ponds, and Cisterns

The goal with dams is to harvest and store rainwater for later use. Dams are an example of surface storage, where the goal is to hold water above the soil surface (instead of allowing it to percolate downwards for "deep storage" in aquifers). There are many different types of dams, each appropriate for various topographies and climates. For example, saddle dams can be placed in a ridgeline between two peaks to capture water high in the landscape. Keypoint dams, on the other hand, are located at or just below the keypoint in a valley and are useful for starting other water catchment systems downslope. For instance, a keypoint dam might overflow into a series of swales, which eventually overflow into a pond much farther downslope.

Yet another option, particularly useful for flat land, are turkey nest dams. Often functioning as earthen storage tanks, turkey nest dams consist of an excavated circle with earthen walls. Dams can be constructed out of the earth itself, which can be a low-cost and environmentally friendly option (if appropriate soil is available onsite), or they can be made from stone or concrete. For earth dams, a high clay content in the soil is necessary for stability and impermeability, and the clay fraction should be non-swelling to prevent cracking[98,99]. When suitable soil is not available onsite, earth dams can be constructed by mixing in offsite clays or other amendments necessary to achieve the desired soil type.



Types of Dams *Illustration by author*

The illustrations above depict cross-sections of a few different types of dams. While saddle dams and keypoint dams can start gravity-fed systems downslope, turkey nest dams on flat land may need to be connected to a pump to move water where needed.

FIGURE 8

In terms of climatic considerations, dams should generally be narrower and deeper in dry, hot climates, whereas they can be shallower and wider in humid climates. This is because dams can experience high evaporative water losses, which is of greater concern in hot and dry climates compared to wetter ones. In drylands, the smaller surface area of the water in narrower and deeper dams results in less evaporation, especially when combined with other strategies such as shading.

It can be prudent to consult local experts before investing in a dam project, as even a small dam constructed incorrectly can become an expensive, possibly illegal, and potentially dangerous mistake. A well-constructed and properly permitted dam, on the other hand, is an investment that can provide many cascading long-term benefits in terms of increased water resilience, fertility, and productivity.

In contrast to dams, which rely on walls to hold back and store water, ponds are usually sub-surface excavations that essentially store water in a large hole. They can be either natural or man-made. As with dams, a high clay content in the soil will ensure greater water retention and storage capability.

Finally, cisterns differ from both ponds and dams in that they are waterproof structures, or tanks, for storing water. Cisterns can be useful additions to the landscape in terms of water storage, both at the small scale such as using rain barrels in the garden, and at larger scales, such as collecting rainwater in concrete tanks to meet cattle water needs.

Water Interception: Swales, Terraces, and Keyline Design
While soil for dam construction needs to have a high clay content and be heavily compacted for stability and impermeability, the opposite is true for swales. As mentioned in a previous section, swales are level, contoured ditches that intercept runoff. Thus, swales can be particularly useful in drylands, which tend to produce more runoff in comparison to humid landscapes. By slowing down water flow and decreasing its erosive potential, swales can help prevent gully erosion in prone landscapes. Also, in comparison to the labor and cost that dams may require, swales are generally easier and more affordable to install, making them a particularly cost-effective water-harvesting tool.

Every time it rains, the growing water lens forming under the swale slowly seeps through the soil and helps support vegetation down-slope of the swale. Over years, swales will eventually fill up with soil enriched in organic matter as tree litter and other trapped organic material build up and decompose in the trench (turning the swale into a terrace). By that time, the runoff from many successive rain events will have been captured and slowly infiltrated into the ground beneath, rehydrating the landscape.

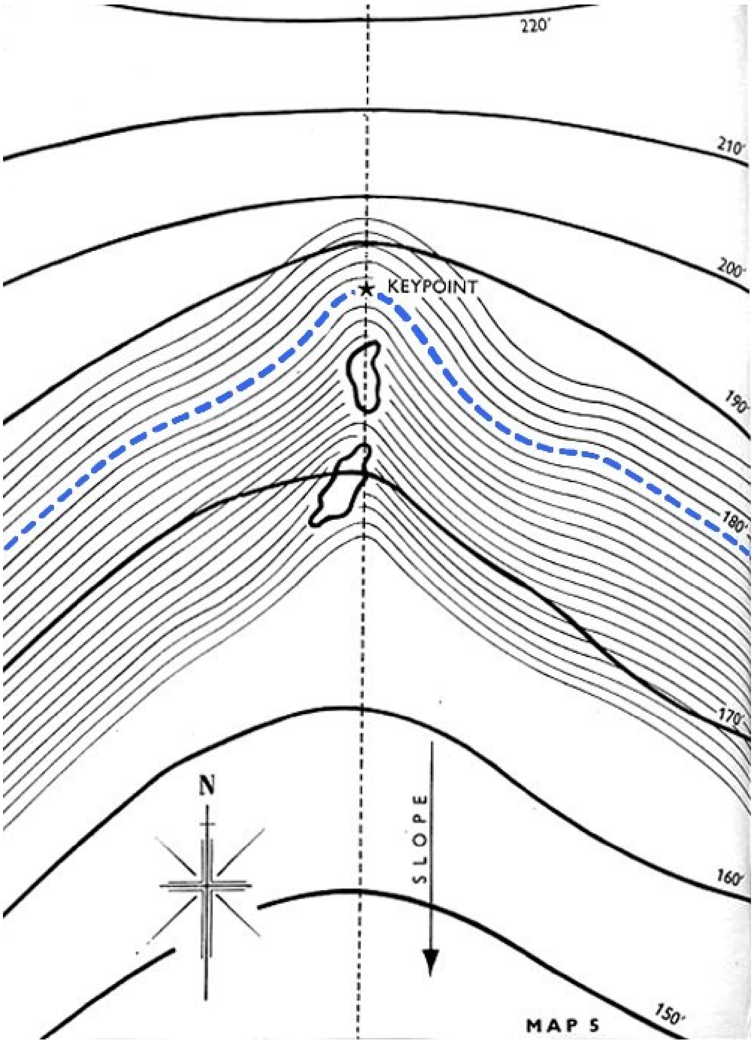
Trees and woody shrubs are an integral component of swales, both because they help stabilize the berm and because they make productive use of some of the captured runoff. The goal with swales, in contrast to dams, is to intercept water flows for eventual deep storage in local aquifers. For this to occur, soils need to be moderately well-draining and relatively uncompacted.

However, swales generally do not work as well on soils that drain too quickly, such as excessively sandy soils, since these soils often produce little to no runoff to capture in the first place. Swales work best on moderate slopes and should not be installed on severely sloping land, which could be destabilized by excessive water retention. A versatile tool, swales can be as small as ridges a few inches in width in the garden, or as large as feet-wide hollows in “flat” lands. The appropriate placement, length, and depth of swales will vary according to topography, soil type, and climate[96].

In contrast to dams and swales, terraces perform yet another function in the landscape. While dams store water above the landscape and swales help to rehydrate the soils below, terraces are primarily a tool for crop production, although they can also help prevent soil erosion and increase water infiltration when properly managed[100]. Terraces are essentially flat “benches” dug into the landscape that provide a level surface for growing crops. This can be especially useful in hilly landscapes, although care must be taken to avoid destabilizing slopes with high soil saturation.

Yet another useful tool for productively intercepting water flows is keyline design, developed by the Australian engineer P.A. Yeomans in the 1950s[101]. Although keyline utilizes contour to intercept runoff and increase water infiltration like swales, keyline is primarily a subsoiling technique used to redistribute water in the landscape to where it is most needed.

The first step to creating a keyline design is to understand the land's topography and where water naturally collects throughout the landscape. Contour maps can be a useful tool for this process. Next, keypoints (i.e., where slope transitions from convex to concave) in the landscape are identified. From the keypoint, a keyline is created by tracing out the level contour extending from both sides of the keypoint. After the keyline is delineated, subsoiling begins, which consists of ripping the subsoil in rows parallel to the keyline. (In contrast to swales, which follow the land's contours, keyline subsoiling ignores all but the keyline's contour line.)



Reprinted from http://tcpermaculture.com/site/2015/05/04/an-introduction-to-keyline/

Example of Keyline Design
The keyline is the contour line running through the keypoint, shown in the blue dashed line. Notice how subsequent rows are parallel to the keyline, rather than following the land's contours.

FIGURE 9

While any plow could technically be used for this process, Yeomans developed a specialized plow for keyline that minimizes soil disturbance. Yeomans' plow also needs less power to pull compared to traditional plows, making its usage more accessible to smaller scale land managers[102]. The effect of this landscaping technique is to prevent water from taking the shortest path downhill, instead slowing its flow and allowing it to sink into the soil along the subsoiled rows. This hydrates the ridges which would otherwise be the driest parts of the landscape. Aside from helping to rehydrate the landscape, keyline can be a useful management tool to help divert water from where it is unwanted towards more productive use. Finally, by harnessing runoff, decreasing water's erosive potential, relieving soil compaction, and hydrating drier regions, keyline design can be a valuable strategy to help mitigate both flood and drought.

Feeding the Soil to Rehydrate the Land

Along with installing earthworks to help more efficiently manage water, "feeding the soil" can go a long way towards improving the landscape's ability to store and productively use water flows. More specifically, any practice that improves soil health often also improves the soil's ability to regulate moisture levels. This is because healthy soils—characterized by a diverse and thriving microbial population supporting high soil organic matter—have a higher water infiltration and retention capacity[103, 104, 105]. There are many ways to improve soil health for increased water resilience, with practices generally falling into three categories:

1. Maximizing diverse soil cover
2. Managing nutrients effectively
3. Minimizing soil pollution

These categories, which can be remembered as "Triple M", are described in more detail below.

Maximizing diverse soil cover
Maximizing soil cover, such as by minimizing tillage, ensures minimal disturbance to the soil, which helps preserve the integrity of the soil food web. Diverse soil cover is important because higher plant diversity correlates with greater microbial diversity, which is important for soil health and crop productivity[106, 107]. Many practices can help maximize diverse soil cover, including cover cropping, integrating perennials and trees, longer and more diverse crop rotations, and companion planting.

Managing nutrients effectively
Safeguarding soil health means safeguarding the integrity of nutrient cycling. Healthy soils more effectively cycle nutrients, which means nutrients stay in the system to keep it functioning instead of being lost to the environment (where they become both an economic and environmental problem)[108].

To manage nutrients effectively, the source, timing, and placement of fertilizers (including manures) and soil amendments should match plant needs to decrease the potential of nutrient losses and pollution. For example, a well-managed integration of nitrogen fixers can provide nitrogen at the root zone of crop plants to reduce external nutrient inputs and hopefully minimize nutrient losses. Also, practices that increase soil carbon such as mulching, retaining residues, and composting can help promote microbial activity and increase soil organic matter. Using these methods, care must be taken to maintain favorable carbon to nitrogen (C:N) ratios, as doing so will help preserve long-term soil fertility.

Minimizing soil pollution

In this context, minimizing pollution refers to minimizing the use of any materials which may be harmful or toxic to soil biota. This includes certain pesticides, herbicides, fungicides, industrial pollutants, and emerging contaminants which are known to have a detrimental impact on the soil microbiome[109, 110].

Efficient Irrigation Methods

As efficient irrigation has already been discussed, this section serves to reiterate and highlight some of the main ideas to remember when choosing an irrigation system. The ultimate ideal in efficient irrigation is when no irrigation is needed at all. In such a system, the agroecosystem self-regulates its own hydrology to support plant needs. Established “food forests” are one example of such a system. A food forest is an agroecosystem planted to mimic a natural forest’s multi-layered structure but using primarily edible species. Just like a natural forest needs no irrigation and few (if any) external inputs, well-established, mature food forests are similarly self-regulating[111, 112].

Such systems need time to mature, however, and may be more difficult to establish in some contexts compared to others. Thus, this ideal may instead be more useful as a guiding principle of what to aim for when designing efficient irrigation systems.
As outlined previously, passive irrigation strategies should be maximized, and the water resource should be recycled as much as possible within the system. Passive irrigation is primarily achieved by designing crop systems to intercept and productively use runoff wherever possible, for example using contour farming or keyline design. Water-storing earthworks can also help supplement plant water needs, which is especially useful in areas with less frequently occurring rain and runoff events.

There are several ways to recycle the water resource. As previously mentioned, greywater irrigation systems are one way to increase water recycling. In humid landscapes with abundant or over-abundant water, excess water flows can be captured and productively rerouted for irrigation, instead of simply draining the water away into local watersheds. For example, in would-be water-logged landscapes fitted with drain tiles, it may be possible to redirect the drained waters to storage tanks to meet irrigation demands.

In particularly water-limited environments, irrigation methods that minimize evaporative water loss should be prioritized, while in humid landscapes where evaporation is less of a concern, there may be more flexibility in choosing which irrigation strategies to use. Finally, although the “best” irrigation system will depend on contextual needs and limitations, working to create hydrologically self-regulatory landscapes that are less reliant on irrigation will ultimately bolster water resilience far more than systems that are not self-sustaining.

From Floods to Fertility

With the mounting and compounding challenges of climate change, political instability, and resource depletion, the future can seem very uncertain and entirely out of our control. However, even if certain catastrophic events cannot be avoided entirely, with the right planning and preparation, their destructive capacity can often be mitigated or even used productively. For example, investing in flood-resilient infrastructure can help harness the potential of otherwise destructive flooding events. This can be especially useful in regions that are transitioning to flood and drought regimes. In such areas, harnessed and stored floodwaters can help meet crop water demands during periods of drought.

Another way to manage floods is with wetlands. Wetlands have historically acted as natural buffering systems against storms and flooding. In addition to offering flood protection, wetlands regulate surface water quality and quantity, replenish and sustain groundwater levels, and even help maintain stream flow in drier regions[113, 114, 115]. Despite these valuable services, an estimated 90% of the earth's wetlands have been destroyed or degraded, severely handicapping our ability to productively manage floods[116]. Thus, rehabilitating the wetlands in our landscapes or constructing new ones can go a long way towards restoring our ability to use floods to our advantage.

In drylands where rainfall often comes in concentrated bursts only once or a few times per year, water can cause flash floods and then almost entirely evaporate, leaving little moisture to sustain animals, crops, or human livelihoods. One way to harness this water is to use sand dams to prevent immediate evaporation and instead allow the water to soak into the land for long-term storage and use during dry periods.

Sand dams are a rainwater harvesting system that mainly consists of a reinforced wall built across a seasonal riverbed. Over time, sand and silt collect behind the wall every time it rains, allowing for subsoil water infiltration and storage behind the dam wall. Because water is stored in the soil itself, it is less prone to evaporative loss. Sand dams have been particularly successful in East African drylands, where their use has been documented to mitigate drought, speed up drought recovery, and increase crop yields and farmer incomes[117, 118]. Thus, sand dams are a promising tool for both managing flood and drought in dryland agroecosystems.

Drought Planning and Resilience

Although the effects of drought may not be entirely unavoidable, they can be mitigated with proper planning. Managing landscapes, farms, and gardens to conserve water use and store excess flows is one of the best long-term strategies for grappling with water limitations. The principles and practices outlined in this handbook provide a starting point for how to design and manage such landscapes. Specifically, having infrastructure in place ready to harness rainwater (both for short-term storage in catchments and long-term deep storage in the soil and in aquifers) will ensure greater water availability during dry periods.

Over time, this kind of holistic water management can increase water resilience and drought resistance. This is because, as once-dry landscapes accumulate and conserve more water, they become able to sustain more trees and vegetation. On bigger scales, permanent and widespread vegetation, particularly trees, can help to “break out” of drought cycles and even promote rain, starting a positive feedback loop where increasing moisture decreases aridity[119].

In fact, due to the key role forests play in regulating the global water cycle, deforestation is a major cause of desertification, a growing problem where once-verdant landscapes degrade into barren desert[120]. Thus, protecting our remaining forests, planting new ones, and integrating agroforestry can help reverse desertification, decrease drought, and strengthen water resilience[121, 122]. The key is to start with “getting water right”. When the integrity of our water systems is preserved, everything else falls into place. Otherwise, if we do not prioritize water resilience, our well-meaning efforts may actually worsen problems. For example, a team of researchers found that large-scale afforestation in Southwest China actually had a negative impact on the region’s already stressed water supplies, highlighting the importance of holistic water management[123].

A water management system increases in resilience as the beneficial connections between various elements in the system increase. Ideally, the elements in a garden or farm should all serve the need(s) of some other element(s), thus bolstering the symbiotic self-sufficiency of the system as a whole. For example, a series of swales could overflow into a pond, which itself may overflow into a local watershed. On smaller scales, such as in a garden, a swale might overflow into a rain garden—a small depressed area in the landscape that collects rain and runoff to nourish (ideally productive) vegetation.

Designing in functional redundancy, a core component of resilience, is another way to increase the beneficial connections within a system[124]. In essence, functional redundancy describes a situation where each critical function is performed by more than one element, so that there is always a “back up”. For example, a system in which irrigation needs can be met in multiple ways, such as from rainfall, harnessed runoff, and small dams, is much more resilient than a system relying on one method alone, such as rain or an underground aquifer. In the latter case, the system may fail if the rains are late or if groundwater levels fall too much. For that reason, it is a good idea to make sure all essential functions in a system are backed up by more than one element.

At the same time, elements should be multi-functional whenever possible, with each element serving multiple functions, thus increasing a system’s overall efficiency. Swales are one such example, as they provide multiple functions including mitigating soil erosion, harnessing runoff, supporting production, increasing organic matter, and rehydrating the landscape.

In that vein, the following subsections will describe a few ways to increase beneficial connections (and decouple problematic ones) with the overall goal of strengthening water resilience.

Sewage and Wastewater Management

As previously mentioned, pollution is a major threat to our water systems, with local watersheds in many areas becoming increasingly and sometimes dangerously polluted. One reason for this is the decoupling of nutrient cycles from farm to plate. Specifically, nutrients are removed from the land with each harvest, trucked sometimes thousands of miles away, and ultimately discarded in the form of human waste. While some regions process and productively use this waste to fertilize pastures, many cities discharge it as sewage (often, but not always, after treatment) into local watersheds from combined sewer and stormwater systems[125]. (Even when sewage is processed separately from stormwater, it is often sent to landfills which can contaminate groundwater over time.)

Aside from the fact that this process is costly and energy-intensive, there are several problems with this approach. For one, this process wastes a lot of water, both at the outset when potable water is used for flushing, and further downstream, especially in combined sewer systems. Combined sewer systems combine rainwater (which could be diverted for productive use) with sewage, which is especially problematic in water-scarce areas. Another major issue is that combined sewer systems often overflow when overwhelmed by high stormwater flows. This results in untreated sewage and industrial waste being discharged into local water bodies, which presents a major health hazard and pollution risk[126]. To protect local water bodies in areas with combined sewer systems, communities and individuals can help mitigate overflow risk by decreasing runoff into the sewer system. This can be done by harvesting rainwater, establishing rain gardens, and otherwise managing the garden to productively use rainwater flows (and decrease runoff) as much as possible.

Also, dry sanitation systems, such as composting toilets and urine diversion systems, are in many cases a viable alternative to traditional sewage management systems that also provide several benefits. A major benefit, especially in arid or water-stressed areas, is that they do not require water. Another benefit is that they help to recouple nutrient cycles. Specifically, safe and proper management of human waste helps return harvested nutrients back to the land, preventing soil nutrient depletion over time[127, 128]. Finally, properly managed dry sanitation systems are much less likely to pollute water bodies because they generally function in isolation from them. That being said, local regulations and cultural norms currently limit the implementation of these kinds of alternative sanitation systems, especially in the US.

Another innovative approach is to recycle wastewater flows for use in aquaculture and agricultural production systems, which will be further explored in the following sections.

Aquaculture

Aquaculture is an aquatic production system, producing a potentially wide variety of organisms, including fish, mollusks, crustaceans, algae, aquatic plants, and more. When strategically integrated into a larger production system, aquaculture can help support and provide benefits to many other components. For example, aside from producing fish, a fish pond can supply high-nutrient water for irrigation of fruit trees planted nearby.

Aquaculture systems are naturally very dynamic and biodiverse. They can be more-or-less unmanaged, passive systems, functioning as wetlands in the landscape. Such systems can help buffer against storms and flooding, as well as help clean water flows and runoff to avoid polluting local watersheds. Or, in addition to these benefits, aquaculture systems can be intensely managed for production as an important source of farm income.

Aquaculture systems can also help clean and productively use wastewater flows[129]. One example is to have a configuration with ponds connected in series, with each pond taking inputs from the one before it and producing output to flow into the pond next in the series[64]. In such a system, wastewater (whether from urban sewage or from farm waste) can first be routed to a sewage lagoon, before feeding into a secondary lagoon that supports insect production. The insect lagoon then flows into a shrimp production system, which flows into a shellfish and small fish pond, before finally flowing into a larger fish or predator fish pond. Connecting the ponds in series helps to first filter out large detritus, then smaller detritus, and finally the nutrients themselves. Along the way, biofiltering plant species planted at pond edges (or aquatic plants in the ponds themselves) can aid in the purification process.

Key to the optimal functioning of this system is the careful management of the raw wastewater in the first step, when it is fed into the sewage lagoon. The sewage lagoon may consist of one or more wastewater stabilization ponds (WSP) that help clean the water by filtering out large debris and suspended solids, sedimentation, and disinfection. The WSPs themselves are shallow anaerobic or facultative basins that break down organic matter through algal and bacterial activity. Sunlight, in combination with the shallow depth of WSPs, naturally disinfects pathogenic micro-organisms, making WSP one of the most cost-effective wastewater treatment options for removing pathogens, including fecal coliforms and E. Coli[130, 131].

Research analyzing the efficacy of WSP across several countries has found that 2-4 weeks of retention time in WSPs is enough to almost completely eradicate pathogenic bacteria and viruses, with sunlight exposure being the most important factor in disinfection[130]. In areas with low sunlight, disinfection rates can be improved by using shallower basins (although this will increase the area required for the WSPs), increasing residence times, or both.

In addition to more sustainably, efficiently, and cost-effectively manage wastewater, wastewater-fed aquaculture systems can be an important economic asset. For example, the fish can be sold at the market, or it can be further processed and sold as organic fertilizer. The larger fish ponds can help meet irrigation water demands of various trees and crops, which may themselves be a food source for other animals on the farm that produced the wastewater in the first place. Thus, aquaculture systems can help create a “closed loop” system where both water resilience and the resilience of the overall production system more generally is bolstered.

Though these systems have a lot to offer, they are also sufficiently complex to pose a risk if improperly managed. Thus, interested readers are referred to *Wastewater Management Through Aquaculture* by B. B. Jana, R. N. Mandal, and P. Jayasankar for more information on constructing, maintaining, and optimizing such systems.
A real-world example of a wastewater-fed aquaculture and agricultural production system of this kind is explored in the following section.

CASE STUDIES

This section presents four case studies from around the globe exploring real-world applications of some of the water management techniques outlined in this handbook.

Case Study #1: Wastewater-Fed Aquaculture in Kolkata, India

Wastewater-fed aquaculture used to be relatively common around the world, but has been in decline in recent years due to increasing urbanization, decreasing availability of peri-urban land, and growing industrial contamination of domestic wastewaters[132]. Today, only one large-scale, formal system of this kind remains, and it is located in Kolkata, India. Known as the East Kolkata Wetlands (EKW), this system is the largest natural sewage treatment works in the world, and has been designated a "wetland of international importance" by Ramsar, the Intergovernmental Convention on Wetlands, for its ingenious use of urban wastewater to support fish and agricultural production [133].

The EKW consists of a complex system of both natural and man-made wetlands, including ponds, canals, marshes, and agricultural areas. The way the system works is that domestic wastewater feeds into the EKW via a complex network of underground drains and canals. Ponds are initially filled with black, anaerobic wastewater, which sits for a few weeks until plankton develop, creating aerobic conditions. At this stage, the ponds look green due to the plankton buildup. Fish fingerlings are then stocked to feed on the plankton. Meanwhile, plankton levels are maintained by allowing smaller flows of nutrient-rich wastewater to enter the ponds[132].

According to government data, the EKW naturally processes and treats around 75% of the city's domestic wastewater, which amounts to millions of liters of wastewater per day[134]. Covering 12,500 hectares (around 30,900 acres), the EKW provides "about 150 tons of fresh vegetables daily, as well as some 10,500 tons of table fish per year, the latter providing livelihoods for about 50,000 people directly and as many again indirectly"[135].

A major challenge to preserving the integrity of the EKW has been rapidly growing urbanization and industrial pollution in the area. For the time-being, however, the EKW remains a remarkable example of a wastewater-fed production system that is cost-effective, efficient, and resilient. Thus, this model offers a potential blueprint for similar systems which can be implemented on smaller scales, for example on local farms or in rural communities.

Case Study #2: Vegetated Swale and Sustainable Drainage Systems in Coventry, UK

While there are numerous examples of successful swale systems around the world, many of these occur in dryland areas where the primary goal is to infiltrate rainwater and runoff to soak it into the landscape and support production. Swales are less common in humid or temperate climates, as these areas tend to be less water-limited. This case study is an interesting example of a swale installed and studied in a temperate climate (Cfb Köppen climatic classification) in the UK, and thus offers insight into the potential performance of swales in wetter climates.

The vegetated swale in this case study is part of an experimental site established in 2005, located at the Center for Agroecology, Water and Resilience, which is part of Coventry University. The area's land use is defined as "rural mixed with small peri-urban areas associated with roads, highways, car parks and other civil engineering related infrastructure, as well as small villages". Notably, the site includes other natural water management infrastructure of which the swale is only one part, such as "a reed bed, rain gardens and large green areas promoting infiltration and bioretention hydrological processes"[136].

The swale in this case study is located on land with about 1-1.5% slope, and is 45.0 m long by 1.1 m wide at the bottom. It has a trapezoidal cross-section and consists of layers of soil and vegetation. The swale handles a catchment area of about 375.0 m^2, with overflows managed via two small pipes that discharge into a local river. Over the course of its lifetime and with little maintenance, this swale has evolved into an emerging wetland that is more-or-less self-regulating. Specifically, research spanning 3 years and 19 storm events has found that the swale infiltrates water (or empties temporarily ponded water) at an average rate of 2.52 mm per hour, which is close to the emptying rates recommended by stormwater management manuals.

Long-term field monitoring has shown that the swale supports "rich biodiversity, such as local plant species and a varied range of pollinator insects". Temperature data also showed that such swales can behave as thermal regulators in the landscape, providing warmer temperatures in winter and cooler temperatures in the summer.

During the 3 years of monitoring, one flooding issue was recorded and one hydraulic failure was identified. Intense rain events, especially if they frequently occur successively, increase the risk of flooding, especially in areas that may already have high soil moisture content (such as in humid climates). An important caveat to this case study is that, although the swale incorporated biodiverse vegetation, it did not include trees on the berm, which could have provided further stabilization effects and potentially decreased flooding risks due to the productive use of water by the trees as well as their roots helping to hold the structure together.

Case Study #3: Keyline Water Management and Perennial Polycultures in Wisconsin, USA

One of the most compelling and well-known examples of large-scale keyline water management in the US is Mark Shepherd's New Forest Farm in southwestern Wisconsin. Originally a conventional row crop farm, New Forest Farm has since been converted into a productive, perennial agricultural operation "using oak savanna, successional brushland and eastern woodlands as the ecological models"[137].

The farm's 106 acres of production is very diverse and includes tree nuts, fruit, fungi, medicinal plants, integrated annual species, and animals. Contour planting and agroforestry are extensively used throughout the farm, helping to preserve and improve soil health, which in turn improves the farm's production and water resilience. At the heart of the farm's success is Mark Shepherd's water management model, which is a modified version of Yeoman's keyline design.

Specifically, Shepherd has adapted Yeoman's techniques to better suit Wisconsin's climate, weather patterns, and soils. For example, as Yeoman developed his methods in Australia, he did not account for variables such as rapid snowmelt, rain occurring on frozen ground, or rain on snow events, which are common in the northern US and Canada. Unmodified for this context, small surface furrows and subsoiler rip lines may not adequately harness available water—and this water may be the only moisture a site receives over an entire season[138]. Thus, Shepherd adapted keyline water management to account for these variables and harness runoff more completely, retain water where needed, and control water flows throughout the farm.

Complementing the keyline design of the farm is a strategically integrated network of ponds, swales, and other water features. Shepherd more fully outlines the farm's structure, operations, and water management in a series of online interviews conducted by the Savanna Institute, the leading agroforestry and perennial agriculture organization in the midwestern US[139,140, 141].

For a more in-depth look at his modified keyline water management techniques and how they can be applied at and adapted to different scales and various climates, the reader is referred to Mark Shepherd's book, *Water for Any Farm*. For more on how farmers across the US having been using perennial polycultures and diverse soil covers to increase their soil and water resilience, the reader is referred to the documentary, *Living Soil*, produced by the Soil Health institute[142].

Case Study #4: Dryland Water Management in Al Baydha, Saudi Arabia

For thousands of years, indigenous land management systems helped preserve fertility in the Mecca region of Saudi Arabia. In the 1950s, however, these systems were abolished, resulting in desertification that destroyed in a few decades the fertility that had been cultivated over millennia. In a cyclic downwards spiral, local tribes were forced to rely on imported feed to feed their animals—which they were only able to afford by cutting down their trees to sell as firewood. Along with mismanaged grazing, this widespread deforestation sped up the desertification of the region, resulting in a "degraded, desolate, and dehydrated landscape"[143].

In an attempt to rehabilitate the region, the Al Baydha project was started in 2010 with support from the Saudi government. The project was directed by Neal Spackman, an internationally renowned pioneer in arid and coastal agroecologies. The Al Baydha region has a very harsh and unforgiving climate, with rainfall averages of 60 mm (2.36 inches) per year and summer temperatures as high as 50°C (122°F). At the start of the project, ecological degradation was so severe that there was practically no soil or water onsite, and very limited biological capital to work with. The main tools available were "mountains and stone, sunlight, dust, and floods". Although the seasonal mountainous desert flooding in the region can be dangerous, these floodwaters are the "only sustainable source of water in the region", and were thus of central importance to the project.

The main goal of the project was to slow down floodwaters coming down the mountains to allow them to sink into and rehydrate the landscape of wadis and floodplains. This would create a buildup of soil moisture that would serve as the foundation for silvopastoral systems: a "savanna-oriented agroecology for reestablishing sustainable grazing patterns while providing resilience through tree crops".

For three years, local tribesmen worked with Spackman to design and implement water-harvesting features into the mountainous landscape. Silt traps, small dams, and rock terraces were installed based on traditional Incan and Nabataean water management systems. Only four rain events occurred over those first three years, although each provided crucial feedback for how to iterate, adapt, and improve the system's design and approach. In 2012, the first trees were planted, with over 4000 planted by 2015. Species selection was based on a combination of what would provide ecological and economic value. To nurture the trees until they were established, drip irrigation was used until 2016. By that time, around 20,000 cubic meters of water had been used to irrigate the trees, but an estimated 50,000 cubic meters had infiltrated into the ground—resulting in a net water savings while increasing the land's fertility and productivity.

The real test of the viability of the project was in 2016, when irrigation was stopped completely. This was done in part due to lack of funding, but also because it was crucial to find out whether the agroforestry systems and approaches used were truly sustainable for this climate, and thus ecologically scalable to similar regions. For the next two years, almost no rain fell and many trees desiccated and died, but the rain finally came at the end of 2018 and again in 2019. Since then, the site has flourished without irrigation or other inputs, relying entirely on the harvested seasonal floodwaters for sustenance. The land has turned into a dryland savanna, which has seen the return of wild bees, an increase in bird, lizard, and insect populations, and growing plant biodiversity, all of which are helping to support local production.

The project is a “living template” with broad implications not only for the entire coastal region of the Arabian peninsula, which has an almost identical geography and climate to Al Baydha, but also for similarly arid regions worldwide, such as in the American West and Southwest. The dryland water management strategies used in this project can potentially form the backbone of rural circular economies, all while helping to increase water resilience, “reverse desertification, increase biodiversity, create soil, sequester carbon, increases freshwater resources, and drastically augment the land’s ability to foster life”.

To learn more about this project, the reader is referred to the video documentary, *The Story of Al Baydha: A Regenerative Agriculture in the Saudi Desert*, available on YouTube.

CONCLUSIONS

Water flows over a politically, socioeconomically, and ecologically complex landscape. Thus, it is crucial to combine coordinated political action with individual and community efforts to build and achieve lasting water resilience. This is especially true as climate change accelerates and ecological degradation continues to threaten our water resources. The first step is to explore how political and economic decisions affect water status, as well as how communities around the world have come together to hold their leaders accountable for securing water rights.

In tandem with addressing this complex landscape of interacting factors, water management principles and practices can be applied and used to help build water resilience at the garden, farm, and landscape levels. Successfully navigating the future will require innovative approaches to conserve and productively use our water resources, such as harnessing floodwaters for productive use and using wetlands to buffer against storm surges. Equally important is connecting other areas of water use, such as sewage management and aquaculture, to general water management in our landscapes to create more resilient systems overall.

For additional inspiration and "proof-of-concept" of the water management strategies outlined in this handbook, several case studies from diverse regions around the world have been explored.

Strengthening water resilience (and water management more generally) is a topic of considerable depth. By its very nature, managing water is interdisciplinary, converging across and affecting all dimensions of life. Thus, for nearly every major topic introduced in this handbook, entire books have been written that more fully explore and detail implications and applications. For the interested reader, here is a brief list of books that may offer additional insight and knowledge:

<u>Sustainable Agroecosystem and Water Systems Design</u>
Gaia's Garden by Toby Hemenway
Lo-TEK Design by Radical Indigenism by Julia Watson
Permaculture: A Designer's Manual by Bill Mollison

<u>Earthworks for Water Management</u>
Water for any Farm by Mark Shepherd
The Permaculture Earthworks Handbook by Douglas Barnes

<u>Alternative Sanitation and Waste Management</u>
The Humanure Handbook by Joseph Jenkins
Wastewater Management Through Aquaculture by B. B. Jana, R. N. Mandal, & P. Jayasankar

Policy, Economy, Activism, and Resource Management
Making Public in a Privatized World by David McDonald
Occupying Schools, Occupying Land by Rebecca Tarlau
The Wealth of Communities by Charlie Pye-Smith & Grazia Borrini-Feyerabend

Some key challenges to lasting water resilience are poor governance, water privatization, ecological degradation, and climate change. Imagine what transformations might take place in the desiccating American West, for instance, if government subsidies moved beyond focusing on efficient irrigation and instead considered holistic dryland water management strategies such as those outlined in the Al Baydha project? Fortunately, we already have examples of how to combine political action with sound ecological management. The aforementioned *Living Soil* film, for example, explores how a government-funded cost-share program was implemented to increase farmer adoption of cover crops, which improved the soil and water resilience of the area. The main challenge is in scaling up such initiatives and spreading them far and wide.

The author's hope is that, equipped with the information in this handbook, the reader will be able to better understand the interconnected nature of policy, economy, ecology, and water—and thus the importance of political participation for long-term change. Equally crucial is the expanded understanding of how to increase water resilience locally by using the landscape itself to productively harness water flows. Finally, as an introductory resource, this handbook aims to point the reader in the right direction in terms of what questions to ask about water management and where to begin looking for the answers.

SOURCES

1. A. S. Richey *et al.*, "Quantifying renewable groundwater stress with GRACE," *Water Resources Research*, vol. 51, no. 7, pp. 5217–5238, Jul. 2015, doi: 10.1002/2015wr017349.
2. J. S. Famiglietti, "The global groundwater crisis," *Nature Climate Change*, vol. 4, no. 11, pp. 945–948, Oct. 2014, doi: 10.1038/nclimate2425.
3. B. R. Scanlon *et al.*, "Groundwater depletion and sustainability of irrigation in the US High Plains and Central Valley," *Proceedings of the National Academy of Sciences*, vol. 109, no. 24, pp. 9320–9325, Jun. 2012, doi: 10.1073/pnas.1200311109.
4. D. R. Steward, P. J. Bruss, X. Yang, S. A. Staggenborg, S. M. Welch, and M. D. Apley, "Tapping unsustainable groundwater stores for agricultural production in the High Plains Aquifer of Kansas, projections to 2110," *Proceedings of the National Academy of Sciences*, vol. 110, no. 37, pp. E3477–E3486, Aug. 2013, doi: 10.1073/pnas.1220351110.
5. J. B. Little, "Saving the Ogallala Aquifer," *Scientific American*, vol. 19, no. 1, pp. 32–39, Mar. 2009, doi: 10.1038/scientificamericanearth0309-32.
6. R. McSweeney, "Explainer: What the new IPCC report says about extreme weather and climate change," *Carbon Brief*, Aug. 10, 2021.
7. H. Pltonykova, S. Koeppel, F. Bernardini, S. Tiefenauer-Linardon, and L. de Strasser, "The United Nations World Water Development Report 2020: Water and Climate Change.," *UN Water*, pp. 22–23, 2020.
8. Å. Johannessen and C. Wamsler, "What does resilience mean for urban water services?," *Ecology and Society*, vol. 22, no. 1, 2017, doi: 10.5751/es-08870-220101.
9. Y. Kang, S. Khan, and X. Ma, "Climate change impacts on crop yield, crop water productivity and food security – A review," *Progress in Natural Science*, vol. 19, no. 12, pp. 1665–1674, Dec. 2009, doi: 10.1016/j.pnsc.2009.08.001. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1002007109002810
10. A. P. Williams, B. I. Cook, and J. E. Smerdon, "Rapid intensification of the emerging southwestern North American megadrought in 2020–2021," *Nature Climate Change*, vol. 12, no. 3, Feb. 2022, doi: 10.1038/s41558-022-01290-z.
11. E. Kerr, "Brutal Drought Depresses Agriculture, Thwarting U.S. and Texas Economies," 2012 [Online]. Available: https://www.dallasfed.org/~/media/documents/research/swe/2012/swe1204c.pdf. [Accessed: Sep. 09, 2022]
12. M. R. Sanderson and V. Hughes, "Race to the Bottom (of the Well): Groundwater in an Agricultural Production Treadmill," *Social Problems*, vol. 66, no. 3, pp. 392–410, Jun. 2018, doi: 10.1093/socpro/spy011.
13. P. Li, D. Karunanidhi, T. Subramani, and K. Srinivasamoorthy, "Sources and Consequences of Groundwater Contamination," *Archives of Environmental Contamination and Toxicology*, vol. 80, no. 1, pp. 1–10, Jan. 2021, doi: 10.1007/s00244-020-00805-z.
14. V. J. Brown, "Radionuclides in Fracking Wastewater: Managing a ToxicBlend," *Environmental Health Perspectives*, vol. 122, no. 2, Feb. 2014, doi: 10.1289/ehp.122-a50.
15. Technology Networks, "Microplastics Found in Every Human Tissue Studied," *Applied Sciences from Technology Networks*, Aug. 2020. [Online]. Available: https://www.technologynetworks.com/applied-sciences/news/microplastics-found-in-every-human-tissue-studied-338672. [Accessed: Sep. 15, 2022]
16. X. Lim, "Microplastics are everywhere — but are they harmful?," *Nature*, vol. 593, no. 7857, pp. 22–25, May 2021, doi: 10.1038/d41586-021-01143-3. [Online]. Available: https://www.nature.com/articles/d41586-021-01143-3

17. S. Samandra *et al.*, “Microplastic contamination of an unconfined groundwater aquifer in Victoria, Australia,” *Science of The Total Environment*, vol. 802, p. 149727, Jan. 2022, doi: 10.1016/j.scitotenv.2021.149727.

18. M. M. A. Allouzi *et al.*, “Micro (nano) plastic pollution: The ecological influence on soil-plant system and human health,” *Science of The Total Environment*, vol. 788, p. 147815, Sep. 2021, doi: 10.1016/j.scitotenv.2021.147815.

19. D. Zhang *et al.*, “Plastic pollution in croplands threatens long-term food security,” *Global Change Biology*, vol. 26, no. 6, pp. 3356–3367, Apr. 2020, doi: 10.1111/gcb.15043.

20. J. O. Goyette, E. M. Bennett, and R. Maranger, “Low buffering capacity and slow recovery of anthropogenic phosphorus pollution in watersheds,” *Nature Geoscience*, vol. 11, no. 12, pp. 921–925, Oct. 2018, doi: 10.1038/s41561-018-0238-x.

21. S. J. Hwang, “Eutrophication and the Ecological Health Risk,” *International Journal of Environmental Research and Public Health*, vol. 17, no. 17, p. 6332, Aug. 2020, doi: 10.3390/ijerph17176332.

22. Union of Concerned Scientists, “Reviving the Dead Zone Solutions to Benefit Both Gulf Coast Fishers and Midwest Farmers,” 2013 [Online]. Available: https://www.ucsusa.org/sites/default/files/2020-05/reviving-the-dead-zone.pdf

23. T. C. Hsiao, E. Fereres, E. Acevedo, and D. W. Henderson, “Water Stress and Dynamics of Growth and Yield of Crop Plants,” *Ecological Studies*, vol. 19, pp. 281–305, 1976, doi: 10.1007/978-3-642-66429-8_18.

24. B. Lehner, P. Döll, J. Alcamo, T. Henrichs, and F. Kaspar, “Estimating the Impact of Global Change on Flood and Drought Risks in Europe: A Continental, Integrated Analysis,” *Climatic Change*, vol. 75, no. 3, pp. 273–299, Apr. 2006, doi: 10.1007/s10584-006-6338-4. [Online]. Available: https://link.springer.com/article/10.1007%2Fs10584-006-6338-4. [Accessed: Oct. 20, 2019]

25. X. He, M. Pan, Z. Wei, E. F. Wood, and J. Sheffield, “A Global Drought and Flood Catalogue from 1950 to 2016,” *Bulletin of the American Meteorological Society*, vol. 101, no. 5, pp. E508–E535, May 2020, doi: 10.1175/BAMS-D-18-0269.1. [Online]. Available: https://journals.ametsoc.org/view/journals/bams/101/5/bams-d-18-0269.1.xml. [Accessed: Jul. 28, 2021]

26. E. Swyngedouw, “Dispossessing H2O: the contested terrain of water privatization,” *Capitalism Nature Socialism*, vol. 16, no. 1, pp. 81–98, Mar. 2005, doi: 10.1080/1045575052000335384.

27. K. J. Bakker, “A Political Ecology of Water Privatization,” *Studies in Political Economy*, vol. 70, no. 1, pp. 35–58, Mar. 2003, doi: 10.1080/07078552.2003.11827129.

28. M. Denchak, “Flint water crisis: Everything you need to know,” *NRDC*, 2018. [Online]. Available: https://www.nrdc.org/stories/flint-water-crisis-everything-you-need-know

29. J. Glenza, “Nestlé pays $200 a year to bottle water near Flint – where water is undrinkable,” *the Guardian*, Sep. 29, 2017. [Online]. Available: https://www.theguardian.com/us-news/2017/sep/29/nestle-pays-200-a-year-to-bottle-water-near-flint-where-water-is-undrinkable

30. N. Blakely, “Seven Years On: The Flint water crisis has yet to conclude,” *Great Lakes Now*, Oct. 27, 2021. [Online]. Available: https://www.greatlakesnow.org/2021/10/seven-years-flint-water-crisis/

31. Special Reports, “Reuters finds lead levels higher than Flint’s in thousands of locales,” *Reuters*, Dec. 19, 2016. [Online]. Available: https://www.reuters.com/investigates/special-report/usa-lead-testing/

32. M. Singh, “Drought-hit California moves to halt Nestlé from taking millions of gallons of water,” *The Guardian*, Apr. 27, 2021. [Online]. Available: https://www.theguardian.com/us-news/2021/apr/27/california-nestle-water-san-bernardino-forest-drought

33. S. Beder, *Suiting Themselves: How Corporations Drive the Global Agenda*. Routledge, 2012.

34. Food and Water Watch, “Take Back the Tap The Big Business Hustle of Bottled Water,” Feb. 2018 [Online]. Available: https://foodandwaterwatch.org/wp-content/uploads/2021/03/rpt_1802_tbttbigwaterhustle-web.pdf

35. C. Winter, “Nestlé Makes Billions Bottling Water It Pays Nearly Nothing For,” *Bloomberg.com*, 2019. [Online]. Available: https://www.bloomberg.com/news/features/2017-09-21/nestl-makes-billions-bottling-water-it-pays-nearly-nothing-for

36. B. Piper and D. McQueen, “How Successful Have Lobbyists Been at Influencing State and National Policy to Further the Completion of the Dakota Access Pipeline, Since the 2008 US Election?,” *Journal of Promotional Communications*, vol. 6, no. 1, 2018.

37. I. Vardi, “How A General-Turned-Oil Lobbyist Helped Push Through The Dakota Access Pipeline,” *HuffPost UK*, Feb. 11, 2019. [Online]. Available: https://www.huffingtonpost.co.uk/entry/dakota-access-pipeline-army-corps-of-engineers-robert-crear_n_5c619dfce4b0eec79b2668de. [Accessed: Sep. 14, 2022]

38. Smithsonian, “Standing Rock Sioux and Dakota Access Pipeline,” *Smithsonian National Museum of the American Indian*, 2015. [Online]. Available: https://americanindian.si.edu/nk360/plains-treaties/dapl

39. N. Lakhani, “Revealed: rightwing US lobbyists help craft slew of anti-protest fossil fuel bills,” *the Guardian*, Sep. 14, 2022. [Online]. Available: https://www.theguardian.com/us-news/2022/sep/14/rightwing-lobbyists-at-heart-of-anti-protest-bills-in-republican-states. [Accessed: Sep. 14, 2022]

40. F. Sultana, “Water justice: why it matters and how to achieve it,” *Water International*, vol. 43, no. 4, pp. 483–493, Apr. 2018, doi: 10.1080/02508060.2018.1458272.

41. M. Z. Zwarteveen and R. Boelens, “Defining, researching and struggling for water justice: some conceptual building blocks for research and action,” *Water International*, vol. 39, no. 2, pp. 143–158, Feb. 2014, doi: 10.1080/02508060.2014.891168.

42. R. Ahlers, “Fixing and Nixing: The Politics of Water Privatization,” *Review of Radical Political Economics*, vol. 42, no. 2, pp. 213–230, Apr. 2010, doi: 10.1177/0486613410368497.

43. P. Mohai, Paul and B.Bryant, “Race, Poverty, and the Environment.” *EPA Journal*, vol. 18, no. 6, 1992.

44. L. F. Konikow and E. Kendy, “Groundwater depletion: A global problem,” *Hydrogeology Journal*, vol. 13, no. 1, pp. 317–320, 2005, doi: 10.1007/s10040-004-0411-8. [Online]. Available: http://www.azul.bdh.org.ar/bdh3/archivos/publications/986998/Leonard_F_Konikow-Bueno.pdf

45. S. van der Kooij, M. Zwarteveen, H. Boesveld, and M. Kuper, “The efficiency of drip irrigation unpacked,” *Agricultural Water Management*, vol. 123, pp. 103–110, May 2013, doi: 10.1016/j.agwat.2013.03.014.

46. D. Perrone and S. Jasechko, “Deeper well drilling an unsustainable stopgap to groundwater depletion,” *Nature Sustainability*, vol. 2, no. 8, pp. 773–782, Jul. 2019, doi: 10.1038/s41893-019-0325-z.

47. L. Sears *et al.*, “Jevons’ Paradox and Efficient Irrigation Technology,” *Sustainability*, vol. 10, no. 5, p. 1590, May 2018, doi: 10.3390/su10051590.

48. J. M. Polimeni, K. Mayumi, M. Giampietro, and B. Alcott, *The Myth of Resource Efficiency*. Routledge, 2015.

49. M. Falkenmark, “Growing water scarcity in agriculture: future challenge to global water security,” *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, vol. 371, no. 2002, p. 20120410, Nov. 2013, doi: 10.1098/rsta.2012.0410.

50. D. K. Kreamer, “The Past, Present, and Future of Water Conflict and International Security,” *Journal of Contemporary Water Research & Education*, vol. 149, no. 1, pp. 87–95, Dec. 2012, doi: 10.1111/j.1936-704x.2012.03130.x.

51. N. Loodin, “Aral Sea: an environmental disaster in twentieth century in Central Asia,” *Modeling Earth Systems and Environment*, vol. 6, Jun. 2020, doi: 10.1007/s40808-020-00837-3.

52. M. I. Weiss, “A perfect storm: the causes and consequences of severe water scarcity, institutional breakdown and conflict in Yemen,” *Water International*, vol. 40, no. 2, pp. 251–272, Jan. 2015, doi: 10.1080/02508060.2015.1004898.

53. S. Folke, “Conflicts over Water and Land in South Indian Agriculture: A Political Economy Perspective,” *Economic and Political Weekly*, vol. 33, no. 7, 1998.

54. A. Swain, “Challenges for water sharing in the Nile basin: changing geo-politics and changing climate,” *Hydrological Sciences Journal*, vol. 56, no. 4, pp. 687–702, Jun. 2011, doi: 10.1080/02626667.2011.577037.

55. D. A. McDonald, *Making public in a privatized world: the struggle for essential services*. London: Zed Books Ltd., 2016, pp. 234–248.

56. B. J. Pauli, *Flint fights back: environmental justice and democracy in the Flint water crisis*. Cambridge, Massachusetts: The Mit Press, 2019.

57. N. Lakhani, "Dakota access pipeline: court strikes down permits in victory for Standing Rock Sioux," *the Guardian*, Mar. 26, 2020. [Online]. Available: https://www.theguardian.com/us-news/2020/mar/25/dakota-access-pipeline-permits-court-standing-rock

58. University of Nevada, Reno, "Western Water Law: Understanding the Doctrine of Prior Appropriation," *Extension | University of Nevada, Reno*. [Online]. Available: https://extension.unr.edu/publication.aspx?PubID=3750

59. A. Lustgarten, N. Sadasivam, and ProPublica, "Holy Crop: How Federal Dollars Have Made America's Drought Crisis Worse," *ProPublica*, May 27, 2015. [Online]. Available: https://projects.propublica.org/killing-the-colorado/story/arizona-cotton-drought-crisis/. [Accessed: Sep. 20, 2022]

60. USDA, "USDA ERS - Farmland Ownership and Tenure," *www.ers.usda.gov*. [Online]. Available: https://www.ers.usda.gov/topics/farm-economy/land-use-land-value-tenure/farmland-ownership-and-tenure/

61. Harvard Law School Forum, "The Corporate Capture of the United States," *Harvard.edu*, 2012. [Online]. Available: https://corpgov.law.harvard.edu/2012/01/05/the-corporate-capture-of-the-united-states/

62. A. Chang, "When Lobbyists Literally Write The Bill," *NPR.org*, Nov. 11, 2013. [Online]. Available: https://www.npr.org/sections/itsallpolitics/2013/11/11/243973620/when-lobbyists-literally-write-the-bill

63. A. Lustgarten, "Injection Wells: The Poison Beneath Us," *https://www.shalepalwv.org/wp-content/uploads/2014/02/Injection-Wells_-The-Poison-Beneath-Us-ProPublica.pdf*, Jan. 23, 2014. [Online]. Available: Injection Wells: The Poison Beneath Us. [Accessed: Sep. 21, 2022]

64. B. Mollison, *Permaculture: A Designer's Manual*. Tagari Publications, 1988.

65. M. Boyle, W. T. Frankenberger, and L. H. Stolzy, "The Influence of Organic Matter on Soil Aggregation and Water Infiltration," *jpa*, vol. 2, no. 4, p. 290, 1989, doi: 10.2134/jpa1989.0290.

66. S. Hill, "Yeomans' Keyline design for sustainable soil, water, agroecosystem and biodiversity conservation: a personal social ecology analysis," *BP Wilson et A. Curtis (éd.), Agriculture for the Australian Environment. Proceedings of the 2002 Fenner Conference, Albury (Australie), Johnstone Centre, Charles Stuart University*, pp. 34–48, 2003.

67. C. O'Loughlin and R. Ziemer, "The importance of root strength and deterioration rates upon edaphic stability in steepland forests," *Proceedings of IUFRO Workshop P. 1.07-00 Ecology of Subalpine Ecosystems as a Key to Management.*, pp. 70–78, 1982.

68. USDA NRCS, "Conservation Choices: Contour Farming," *Usda.gov*, 2021. [Online]. Available: https://www.nrcs.usda.gov/wps/portal/nrcs/detail/null/?cid=nrcseprd414214

69. H. Ansari, M. Naghedifar, and A. Faridhosseini, "Performance evaluation of drip, surface and pitcher irrigation systems: A case study of prevalent urban landscape plant species.," *International Journal of Farming and Allied Science*, vol. 4, pp. 610–620, 2015.

70. H. Malekinezhad, "Comparison of cucumber and watermelon yield and water use in clay pitcher and furrow irrigation methods," *International Journal of Water*, vol. 9, no. 3, p. 275, 2015, doi: 10.1504/ijw.2015.070359.

71. B. D. Richter *et al.*, "Water scarcity and fish imperilment driven by beef production," *Nature Sustainability*, vol. 3, no. 4, pp. 319–328, Apr. 2020, doi: 10.1038/s41893-020-0483-z. [Online]. Available: https://www.nature.com/articles/s41893-020-0483-z

72. H. Lambers, "Introduction, Dryland Salinity: A Key Environmental Issue in Southern Australia," *Plant and Soil*, vol. 257, no. 2, pp. V–VII, Dec. 2003, doi: 10.1023/b:plso.0000003909.80658.d8.

73. G. Singh, N. T. Singh, and I. P. Abrol, "Agroforestry techniques for the rehabilitation of degraded salt-affected lands in India," *Land Degradation and Development*, vol. 5, no. 3, pp. 223–242, Oct. 1994, doi: 10.1002/ldr.3400050306.

74. S. P. Shirish, S. K. Tushar , and A. B. Satish, "Mulching: A Soil and Water Conservation Practice," *Research Journal of Agriculture and Forestry Sciences*, vol. 1, no. 3, pp. 26–29, 2013.

75. Z. Steinmetz *et al.*, "Plastic mulching in agriculture. Trading short-term agronomic benefits for long-term soil degradation?," *Science of The Total Environment*, vol. 550, pp. 690–705, Apr. 2016, doi: 10.1016/j.scitotenv.2016.01.153. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0048969716301528

76. L. Krishnamurthy, P. K. Krishnamurthy, I. Rajagopal, and A. Peralta Solares, "Can agroforestry systems thrive in the drylands? Characteristics of successful agroforestry systems in the arid and semi-arid regions of Latin America," *Agroforestry Systems*, vol. 93, no. 2, pp. 503–513, Nov. 2017, doi: 10.1007/s10457-017-0143-0.

77. H. Breman and J. J. Kessler, "The potential benefits of agroforestry in the Sahel and other semi-arid regions," *European Journal of Agronomy*, vol. 7, no. 1–3, pp. 25–33, Sep. 1997, doi: 10.1016/s1161-0301(97)00035-x.

78. N. A. Jackson, J. S. Wallace, and C. K. Ong, "Tree pruning as a means of controlling water use in an agroforestry system in Kenya," *Forest Ecology and Management*, vol. 126, no. 2, pp. 133–148, Feb. 2000, doi: 10.1016/S0378-1127(99)00096-1. [Online]. Available: https://doi.org/10.1016/S0378-1127(99)00096-1. [Accessed: Aug. 23, 2022]

79. V. Anbumozhi, J. Radhakrishnan, and E. Yamaji, "Impact of riparian buffer zones on water quality and associated management considerations," *Ecological Engineering*, vol. 24, no. 5, pp. 517–523, May 2005, doi: 10.1016/j.ecoleng.2004.01.007.

80. OSU, "Save water by cutting trees?," *College of Earth, Ocean, and Atmospheric Sciences*, Nov. 26, 2019. [Online]. Available: https://ceoas.oregonstate.edu/feature-story/save-water-cutting-trees. [Accessed: Oct. 04, 2022]

81. D. Ellison *et al.*, "Trees, forests and water: Cool insights for a hot world," *Global Environmental Change*, vol. 43, pp. 51–61, Mar. 2017, doi: 10.1016/j.gloenvcha.2017.01.002. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0959378017300134

82. Eric William Danielson, J. Levin, and E. Abrams, *Meteorology*. Boston: Mcgraw-Hill, 2003, p. 389.

83. K. Montgomery, "Variation in Temperature With Altitude and Latitude," *Journal of Geography*, vol. 105, no. 3, pp. 133–135, May 2006, doi: 10.1080/00221340608978675.

84. J. Grace, "3. Plant response to wind," *Agriculture, Ecosystems & Environment*, vol. 22–23, pp. 71–88, Aug. 1988, doi: 10.1016/0167-8809(88)90008-4. [Online]. Available: https://www.sciencedirect.com/science/article/pii/0167880988900084. [Accessed: Sep. 15, 2019]

85. J. P. Privé and N. Allain, "Wind reduces growth and yield but not net leaf photosynthesis of primocane-fruiting red raspberries Rubus idaues in the establishment years," *Canadian Journal of Plant Science*, vol. 80, no. 4, pp. 841–847, Oct. 2000, doi: 10.4141/p99-170.

86. National Geographic, "Wind | National Geographic Society," *education.nationalgeographic.org*. [Online]. Available: https://education.nationalgeographic.org/resource/wind

87. D. R. Easterling *et al.*, "Ch. 7: Precipitation Change in the United States. Climate Science Special Report: Fourth National Climate Assessment, Volume I," *Fourth National Climate Assessment*, 2017, doi: 10.7930/j0h993cc.

88. G. Acharya, T. A. Cochrane, T. Davies, and E. Bowman, "The influence of shallow landslides on sediment supply: A flume-based investigation using sandy soil," *Engineering Geology*, vol. 109, no. 3–4, pp. 161–169, Nov. 2009, doi: 10.1016/j.enggeo.2009.06.008.

89. D. Barnes, "When Swales Can Kill," *www.permaculturereflections.com*, 2014. [Online]. Available: https://www.permaculturereflections.com/when-swales-can-kill/. [Accessed: Oct. 11, 2022]

90. H. Boriyo, "Analyze your garden soil at home with the jar test," *Ag - Community Horticulture/Landscape*, Feb. 2020 [Online]. Available: https://extension.oregonstate.edu/gardening/techniques/analyze-your-garden-soil-home-jar-test. [Accessed: Oct. 11, 2022]

91. "Soil Texture Testing - Two Easy Methods," *The-compost-gardener.com*, 2019. [Online]. Available: https://www.the-compost-gardener.com/soil-texture-testing.html

92. "Deep ripping for soil compaction," *www.agric.wa.gov.au*. [Online]. Available: https://www.agric.wa.gov.au/soil-compaction/deep-ripping-soil-compaction

93. "The Human Right to Water and Sanitation Media brief 1 UN-Water Decade Programme on Advocacy and Communication and Water Supply and Sanitation Collaborative Council" [Online]. Available: https://www.un.org/waterforlifedecade/pdf/human_right_to_water_and_sanitation_media_brief.pdf

94. FAO, "CHAPTER 2: CROP WATER NEEDS," *www.fao.org*. [Online]. Available: https://www.fao.org/3/s2022e/s2022e02.htm

95. Image from one of the author's projects

96. D. Barnes, *The permaculture earthworks handbook : how to design and build swales, dams, ponds, and other water harvesting systems*. Gabriola Island, Bc: New Society Publishers, 2017.

97. D. Doherty, "Design and Construction of Earth Dams," *Appleseed Permaculture*, 2000. [Online]. Available: http://appleseedpermaculture.com/docs/DD_PCA_DamArticle.pdf

98. WEDC Loughborough University, "Small Earth Dams." [Online]. Available: https://www.lboro.ac.uk/orgs/well/resources/technical-briefs/48-small-earth-dams.pdf

99. Agriculture Victoria, "Soil materials for farm dam construction - Agriculture," *Agriculture Victoria*, Jul. 21, 2020. [Online]. Available: https://agriculture.vic.gov.au/farm-management/water/managing-dams/soil-materials-for-farm-dam-construction#h2-1. [Accessed: Oct. 13, 2022]

100. M. Meliho, A. Khattabi, A. Nouira, and C. A. Orlando, "Role of Agricultural Terraces in Flood and Soil Erosion Risks Control in the High Atlas Mountains of Morocco," *Earth*, vol. 2, no. 4, pp. 746–763, Oct. 2021, doi: 10.3390/earth2040044.

101. Percival Alfred Yeomans, *The Challenge of Landscape: The Development and Practice of Keyline*. KEYLINE PUBLISHING PTY. LIMITED, 1958.

102. Keyline Water Management, "Keyline Design - Definitions & Examples," *Keyline Water Management*. [Online]. Available: http://crkeyline.ca/what-is-keyline-design/. [Accessed: Oct. 15, 2022]

103. X. D. Liu, Y. N. Qiao, and G. Y. Zhou, "Controlling action of soil organic matter on soil moisture retention and its availability," *Chinese Journal of Plant Ecology*, vol. 35, no. 12, pp. 1209–1218, Dec. 2011, doi: 10.3724/sp.j.1258.2011.01209.

104. UNL Water, "The connection between soil organic matter and soil water," *UNL Water*, Apr. 13, 2020. [Online]. Available: https://water.unl.edu/article/animal-manure-management/connection-between-soil-organic-matter-and-soil-water

105. Organic Matter Can Improve Your Soil's Water Holding Capacity, "Organic Matter Can Improve Your Soil's Water Holding Capacity," *NRDC*, Dec. 15, 2016. [Online]. Available: https://www.nrdc.org/experts/lara-bryant/organic-matter-can-improve-your-soils-water-holding-capacity

106. H. Ferris and H. Tuomisto, "Unearthing the role of biological diversity in soil health," *Soil Biology and Biochemistry*, vol. 85, pp. 101–109, Jun. 2015, doi: 10.1016/j.soilbio.2015.02.037.

107. D. R. Zak, W. E. Holmes, D. C. White, A. D. Peacock, and D. Tilman, "Plant diversity, soil microbial communities, and ecosystem function: are there any links?," *Ecology*, vol. 84, no. 8, pp. 2042–2050, Aug. 2003, doi: 10.1890/02-0433.

108. K. Tully and R. Ryals, "Nutrient cycling in agroecosystems: Balancing food and environmental objectives," *Agroecology and Sustainable Food Systems*, vol. 41, no. 7, pp. 761–798, Jun. 2017, doi: 10.1080/21683565.2017.1336149.

109. A. Kalia and S. K. Gosal, "Effect of pesticide application on soil microorganisms," *Archives of Agronomy and Soil Science*, vol. 57, no. 6, pp. 569–596, Sep. 2011, doi: 10.1080/03650341003787582.

110. C. Gutiérrez *et al.*, "Effect of soil properties, heavy metals and emerging contaminants in the soil nematodes diversity," *Environmental Pollution*, vol. 213, pp. 184–194, Jun. 2016, doi: 10.1016/j.envpol.2016.02.012.

111. Shelterwood Forest Farm, "The Lost Forest Gardens of Europe," *Shelterwood Forest Farm*. [Online]. Available: https://www.shelterwoodforestfarm.com/blog/the-lost-forest-gardens-of-europe

112. E. J. Wallace, "The Moroccan Food Forest That Inspired an Agricultural Revolution," *Atlas Obscura*, Apr. 01, 2019. [Online]. Available: https://www.atlasobscura.com/articles/what-is-permaculture-food-forests

113. N. O. Uluocha and I. C. Okeke, "Implications of wetlands degradation for water resources management: Lessons from Nigeria," *GeoJournal*, vol. 61, no. 2, pp. 151–154, 2004, doi: 10.1007/s10708-004-2868-3.

114. S. Narayan *et al.*, "The Value of Coastal Wetlands for Flood Damage Reduction in the Northeastern USA," *Scientific Reports*, vol. 7, no. 1, pp. 1–12, Aug. 2017, doi: 10.1038/s41598-017-09269-z. [Online]. Available: https://www.nature.com/articles/s41598-017-09269-z#citeas

115. Y. P. Sheng *et al.*, "Coastal marshes provide valuable protection for coastal communities from storm-induced wave, flood, and structural loss in a changing climate," *Scientific Reports*, vol. 12, no. 1, Feb. 2022, doi: 10.1038/s41598-022-06850-z.

116. R. C. Gardner and C. Finlayson, "Global Wetland Outlook: State of the World's Wetlands and Their Services to People," *papers.ssrn.com*, Oct. 05, 2018. [Online]. Available: https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3261606

117. R. Lasage, J. Aerts, G. C. M. Mutiso, and A. de Vries, "Potential for community based adaptation to droughts: Sand dams in Kitui, Kenya," *Physics and Chemistry of the Earth, Parts A/B/C*, vol. 33, no. 1, pp. 67–73, Jan. 2008, doi: 10.1016/j.pce.2007.04.009. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1474706507000708. [Accessed: Jan. 17, 2022]

118. C. Ryan and P. Elsner, "The potential for sand dams to increase the adaptive capacity of East African drylands to climate change," *Regional Environmental Change*, vol. 16, no. 7, pp. 2087–2096, Mar. 2016, doi: 10.1007/s10113-016-0938-y.

119. B. Locatelli and R. Vignola, "Managing watershed services of tropical forests and plantations: Can meta-analyses help?," *Forest Ecology and Management*, vol. 258, no. 9, pp. 1864–1870, Oct. 2009, doi: 10.1016/j.foreco.2009.01.015.

120. R. Mcsweeney, "Explainer: Desertification and the role of climate change," *Carbon Brief*, Aug. 06, 2019. [Online]. Available: https://www.carbonbrief.org/explainer-desertification-and-the-role-of-climate-change/

121. R. Meier, J. Schwaab, S. I. Seneviratne, M. Sprenger, E. Lewis, and E. L. Davin, "Empirical estimate of forestation-induced precipitation changes in Europe," *Nature Geoscience*, vol. 14, Jul. 2021, doi: 10.1038/s41561-021-00773-6.

122. A. Quandt, H. Neufeldt, and J. T. McCabe, "The role of agroforestry in building livelihood resilience to floods and drought in semiarid Kenya," *Ecology and Society*, vol. 22, no. 3, 2017, doi: 10.5751/es-09461-220310.

123. Y. Xiao, Q. Xiao, and X. Sun, "Ecological Risks Arising from the Impact of Large-scale Afforestation on the Regional Water Supply Balance in Southwest China," *Scientific Reports*, vol. 10, no. 1, Mar. 2020, doi: 10.1038/s41598-020-61108-w.

124. C. R. Biggs *et al.*, "Does functional redundancy affect ecological stability and resilience? A review and meta-analysis," *Ecosphere*, vol. 11, no. 7, Jul. 2020, doi: 10.1002/ecs2.3184.

125. M. Preisner, E. Neverova-Dziopak, and Z. Kowalewski, "Mitigation of eutrophication caused by wastewater discharge: A simulation-based approach," *Ambio*, vol. 50, no. 2, May 2020, doi: 10.1007/s13280-020-01346-4.

126. PennState Extension, "What are Combined Sewer Overflows?," *Penn State Extension*. [Online]. Available: https://extension.psu.edu/what-are-combined-sewer-overflows

127. C. K. Anand and D. S. Apul, “Composting toilets as a sustainable alternative to urban sanitation – A review,” *Waste Management*, vol. 34, no. 2, pp. 329–343, Feb. 2014, doi: 10.1016/j.wasman.2013.10.006. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0956053X13004923

128. J. C. Jenkins, *The Humanure Handbook*, 4th ed. S.L.: Chelsea Green, 2019.

129. B. B. Jana, R. N. Mandal, and P. Jayasankar, *Wastewater Management Through Aquaculture*. Singapore Springer Singapore, 2018.

130. S. Lozano, “An Ecological Design Approach to Wastewater Management,” 2008. [Online]. Available: https://scholarworks.uvm.edu/cgi/viewcontent.cgi?article=1140&context=graddis

131. F. Brissaud, T. Andrianarison, J. L. Brouillet, and B. Picot, “Twenty years’ monitoring of Mèze stabilisation ponds: part II – removal of faecal indicators,” *Water Science and Technology*, vol. 51, no. 12, pp. 33–41, Jun. 2005, doi: 10.2166/wst.2005.0421.

132. S. W. Bunting, J. Pretty, and P. Edwards, “Wastewater-fed aquaculture in the East Kolkata Wetlands, India: anachronism or archetype for resilient ecocultures?,” *Reviews in Aquaculture*, vol. 2, no. 3, pp. 138–153, Aug. 2010, doi: 10.1111/j.1753-5131.2010.01031.x.

133. K. Taylor, “Planning to Preserve the East Kolkata Wetlands,” *dukespace.lib.duke.edu*, Apr. 2008 [Online]. Available: https://dukespace.lib.duke.edu/dspace/handle/10161/535. [Accessed: Oct. 28, 2022]

134. Vidhi Doshi, “Kolkata: the city that eats fish reared on sewage,” *the Guardian*, May 31, 2017. [Online]. Available: https://www.theguardian.com/sustainable-business/2017/jan/25/kolkata-west-bengal-india-cites-fish-farming-sewage-food-demand-real-estate

135. Ramsar, “East Calcutta Wetlands | Ramsar Sites Information Service,” *rsis.ramsar.org*, 2002. [Online]. Available: https://rsis.ramsar.org/ris/1208. [Accessed: Oct. 28, 2022]

136. L. A. Sañudo-Fontaneda *et al.*, “Descriptive Analysis of the Performance of a Vegetated Swale through Long-Term Hydrological Monitoring: A Case Study from Coventry, UK,” *Water*, vol. 12, no. 10, p. 2781, Oct. 2020, doi: 10.3390/w12102781.

137. New Forest Farm, “New Forest Farm,” *New Forest Farm*. [Online]. Available: https://newforestfarm.us/

138. M. Shepherd, “Keyline Design Transforms Farm Water Management,” *EcoFarming Daily*. [Online]. Available: https://www.ecofarmingdaily.com/build-soil/keyline-design-transforms-farm-water-management/. [Accessed: Oct. 31, 2022]

139. Savanna Institute, “New Forest Farm (full interview) - Pioneer Agroforestry Farm Tour Series,” *www.youtube.com*, 2019. [Online]. Available: https://www.youtube.com/watch?v=4y8AndRWfUA&ab_channel=SavannaInstitute. [Accessed: Oct. 31, 2022]

140. Savanna Institute, “Mark Shepard - Pioneer Agroforestry Farm Tour Video Series,” *www.youtube.com*, 2019. [Online]. Available: https://www.youtube.com/watch?v=xBRnPcZ8xUo&ab_channel=SavannaInstitute. [Accessed: Oct. 31, 2022]

141. Savanna Institute, “Our Mission | Savanna Institute,” *www.savannainstitute.org*. [Online]. Available: https://www.savannainstitute.org/our-mission-2/. [Accessed: Oct. 31, 2022]

142. Soil Health Institute, “Living Soil Film,” *www.youtube.com*, 2019. [Online]. Available: https://www.youtube.com/watch?v=ntJouJhLM48&ab_channel=SoilHealthInstitute

143. N. Spackman, “The Story of Al Baydha: A Regenerative Agriculture in the Saudi Desert.” *www.youtube.com*, 2020. [Online]. Available: https://www.youtube.com/watch?v=T39QHprz-x8&t=901s&ab_channel=AlBaydha. [Accessed: Nov. 01, 2022]