Chapter 1

Introduction

WATER IS A VALUABLE RESOURCE — perhaps the most valuable resource we have — and the collection and use of rainfall has been a part of human history for thousands of years. However, in recent decades, the collection and use of rainwater has diminished greatly due to cost reductions in groundwater drilling and the increased prevalence of municipal centralized water systems. Despite the benefits that have come with these developments, the increased ease of access has also facilitated poor design (or really, a complete lack of design), which has subsequently led to an incredibly wasteful use of both water and water-energy in our modern-day homes and cities.

In developed countries, nearly all communities treat water with indifference, as an infinite resource and/or as a liability. We shed water from our roofs and direct it straight to the storm sewer (leading to floods and sewer overflows), then we turn on the sprinkler to water our lawn. We don't ever consider the energy cost and implications of the water that flows freely from the faucets. We drain groundwater aquifers; we discard nutrient-rich water (perfect for feeding plants and biology) directly into the sewer system; and, perhaps most telling of all, we defecate into water that has been processed or cleaned to drinking standards before flushing it away.

Added to the above, research into water affordability (Mack and Wrase, 2017) indicates that rising municipal supply water rates (attributed to aging infrastructure, water quality, sanitation, and climate change, among other things) could mean that in the next five years the number of US households who find municipal water utility bills unaffordable could triple — to more than 35%. Nevermind that the cost of replacing aging municipal water infrastructure in the US alone is estimated to be over $1 trillion dollars in the next 20 years (AWWA, 2012).

As current water-supply infrastructure continues to age, glaciers melt, and groundwater aquifers diminish, governments, municipalities, and individuals are starting to realize that capturing and storing rainwater is critical to sustainable, economic, and resilient human habitat.

If we wish to create a resilient future, changing our relationship with water is one of the most important things we can do as individuals and as a community, and it starts right outside our back door.

Water Supply, Security, and Sustainability

Are you trying to provide domestic water to your home and see rainwater as your most cost-effective option? Are you concerned about the resilience of your existing water supply and looking for a backup system (for instance, lack of trust in your municipal water system, or perhaps your groundwater well is dying)? Do you value sustainability and see rainwater harvesting as great way to reduce your resource and energy use? Or perhaps your local municipality has made it illegal to use treated municipal water for non-essential needs such as irrigation, and you require a RWH system to water your garden.

Essential Rainwater Harvesting: A Guide to Home-Scale System Design covers all aspects of RWH system design for your home, whether your goal is water supply, water security, or environmental sustainability. We've distilled years of experience and independent research into a step-by-step approach that includes design thinking, goal setting, system planning, site assessment, calculations, and material selection and sizing for roofs, gutters, downspouts, storage tanks, filtration, and pumps — with special considerations for cold climates.

However, in our consultancy practice, our clients are often looking for more than a simple rooftop harvesting system. They want homes and homesteads that leverage and interact with the environment, producing their own energy and food, harvesting and storing water, cycling nutrients, and restoring the surrounding ecosystems.

Although this rainwater harvesting book is focused on the essentials of designing a rooftop rainwater harvesting system for a house, the upfront consideration of how rainwater capture and storage fits into the broader water and resiliency planning for a property is a crucial first step in the design process. As such, here we present a few brief considerations for full-property water security, resilience, and overall sustainability.

Resilient Systems and Properties

> Where sustainability aims to put the world back into balance, resilience looks for ways to manage an imbalanced world.
>
> — Andrew Zolli, co-author of *Resilience: Why Things Bounce Back.*

Resilience is the outcome that results when a system includes redundancy and is:

- Efficient
- Productive
- Appropriate
- Interconnected

A system is a set of interacting or interdependent component parts forming a complex/intricate whole. The components that make up your rainwater supply are a system. The elements that are put together to provide for your shelter, water, waste, and food needs can be thought of as a system, e.g. our homes are systems. Our neighborhoods and our cities are also systems. Everywhere you look, systems are nested within systems, and it's really just a question of where you draw the boundary.

Resilience is the capacity for a system to adapt (and, we would argue, to continue to thrive) in the face of change or disruption. It's an excellent complement to sustainability, and arguably you can't have resilience without sustainability. However, we like to present and think about systems in terms of their resilience because, fundamentally, for many of our clients and students, their primary motivation for taking action is to increase their personal resilience.

To design a system that is resilient, the design must include redundancy and be efficient, productive, appropriate, and interconnected.

To expand on these resiliency characteristics, in Table 1.1 we present design choices and examples for each characteristic for a resilient property and contrast these against design choices for most modest modern-day homes (i.e. a fragile property).

Table 1.1: A resilient property vs most modern day design.

	Resilient Property	Modern-Day Design
Efficiency	**Focus is on maximizing efficiency.** • Reduction and resource efficiency is the first priority. • Designs are enduring, repairable, solid state, and low tech, where possible.	**Unlimited resource mentality.** • No consideration of quantity of resources used. • Energy and fossil fuel used to make up for design shortcomings. • Design is low quality; elements within the system are disposable, with planned obsolescence.
Productiveness	**The home and occupants collect resources and produce abundantly.** • Home and/or occupants are producers of some or all of their energy, water, and food needs. • Ecological services and products are recognized, valued, and encouraged.	**The home and occupants are merely consumers.** • Constant external inputs required for all needs, including energy, water, and food. • No consideration of ecological yields.
Appropri-ateness	**Energy and water appropriate for end-use.*** • Energy density appropriate to end-use. • Water quality appropriate to end-use. • Gravity used, where possible.	**Energy and water not always appropriate for end-use.*** • No consideration of energy density or appropriate water quality. • Fossil fuel used to make up for design shortcomings.
Interconnectedness	**Design is cyclical and very connected.** • Waste is recycled. • Everything is used multiple times. • Every element has multiple functions and is supported by other elements. • Feedback influences occupants' behavior resulting in beneficial course correction.	**Design is linear and unconnected.** • Waste is sent away. • Single-use mentality. • Designed obsolescence. • Requires constant external inputs. • Lack of integration. • No feedback, and occupants unaware of the consequences of their actions.
Redundancy	**Redundancy is key.** • Backup/alternative plans in place for heat, power, water, and food. • Storage in place for energy, water, and food. • Long-term thinking.	**No redundancy.** • Critical systems have no backup. • Complete dependence on constant, ongoing external inputs. • Short-term thinking.

*Think of how inappropriate it is to cut butter with a chainsaw. The same idea applies to heating your home with natural gas, or using drinking-quality water to flush a toilet. These are poor matches of end-use with energy density or water quality.

The property illustrated in Figure 1.1 is an example of a resilient property located in a cold climate. Note that you can apply the same resiliency characteristics to each individual sub-system for water, energy, and food.

The Water Systems

Efficient: All fixtures high-efficiency/low-volume; water is reused to reduce irrigation and toilet flushing volumes. Gutters and roof designed to prevent rainwater losses. Water-wise landscaping.
Productive: All water captured (building and landscape) and stored for use. Water employed to grow abundant plant and animal life.
Appropriate: Highest-quality filter located at drinking water tap. Greywater used for toilet flushing and irrigation. Rain used for irrigation.
Interconnected: Wastewater is a resource, and nutrients from wastewater are used to grow plants and soil both in the greenhouse and in the landscape. Monitors in place for water usage, rain forecasts, and storage volumes.
Include Redundancy: Water storage designed for appropriate low-rainfall conditions. Backup plan in place.

The Energy Systems

Efficient: High-insulation walls and windows and careful design of the building envelope. Energy-efficient lighting and appliances.
Productive: House oriented to capture passive solar energy. Careful design and selection of glazing. Attached greenhouse provides supplemental heating. Solar photovoltaics for electricity and solar thermal for hot water.
Appropriate: Passive solar gain as primary heating source, biomass as backup heating, photovoltaic electricity used for high-energy demands, solar thermal used for domestic hot water and ancillary space heat. Irrigation is provided passively (using gravity vs being pumped).
Interconnected: Heat-recovery ventilator used to pre-heat intake air. Warm, stale air from the house cycled to the greenhouse. Excess heat energy from the greywater captured in greenhouse.

Fig. 1.1: *A model of a resilient property located in a cold climate. The water, energy, and food systems include redundancy and can be described as efficient, productive, appropriate, and interconnected.* Credit: Verge Permaculture/S. Andrei

Monitoring systems in place for energy production and storage.
Include Redundancy: Grid-tied power for backup electricity. Heating provided by three sources: passive solar, active solar, and biomass.

The Food Systems

Efficient: Local food and seasonal food prioritized. When in abundance, food grown onsite is harvested, preserved, and stored for later use.
Productive: Perennial forest gardening, annual vegetable production, and four-season production in the attached greenhouse. Micro-livestock systems (such as chickens) for eggs and meat. Biodiverse and abundant plant and animal life grown not only for the occupants, but to support surrounding ecosystems.
Appropriate: Food that supplies the occupants is grown with appropriate energy (human-scale vs large manufacturing-scale) and appropriate water (local and captured water vs imported water). Gardens designed for passive irrigation instead of pumped irrigation.
Interconnected: Food scraps, plant, and others wastes are cycled to create compost, soil, and/or to feed micro-livestock.
Include Redundancy: Not purely reliant on industrialized food system. Occupants grow some of their own food and support the local food economy as much as possible.

If your motivation is resilience, you'll want to keep these characteristics in mind as you are designing your RWH system, but also particularly as you consider your RWH system in the context of full-property water security and overall property design.

Order of Design Priorities

For a property to be truly sustainable and resilient, its occupants must have a safe and dependable supply of water, along with protection from the dangers of drought, flooding, and erosion. Recognizing the management of water — a source of life, and source of risk — as central to the success of an environmentally integrated system, it is always the first consideration when we design any property.

There are many elements to consider related to water when in the early design stages: potential water sources (municipal water, groundwater, surface water, rainwater, etc.), watershed management, landscape water retention/diversion/distribution, land-shaping (ponds, swales, collection, drains), infiltration, overflow management, storm water, water reuse, septic, and more.

In practice, we most often see homeowners purchase property, build a house, then try and figure out how to manage and supply water to that structure. The correct order of design priorities (water first, infrastructure next) is completely missed in most modern-day design. To most successfully achieve sustainability or resilience, water planning must be a priority in the *initial* design stages. An understanding of how volumes can be minimized/optimized, where water will come from, where it might be stored, and where it will go should be considered before even starting out on the design and placement of any building.

Water-Harvesting Earthworks

If the scope of your project is larger than a simple rooftop RWH system, and you (1) want your home integrated within a lush, biodiverse environment that restores fertile soil, sustains plants, wildlife, and humans, and you'd (2) like your property to be drought-proof and/or minimize the risk of fire, then you'll absolutely want to consider how your rooftop RWH system fits in as part of a much larger integrated water design.

One of the ways we do this in our consultancy practice is by thinking of the landscape and soils surrounding the home as the primary water *storage* system. We can enhance and improve water infiltration and storage with careful consideration of property elevations and any appropriate water-harvesting earthworks such as rain gardens, swales, diversion drains, ponds, etc.

Our favorite resources for planning and designing landscape water-harvesting earthworks are included in the Resources section at the back of this book.

Improving Soil Water-Holding Capacity

Whether rain falls directly on the ground, or is directed to landscape from tank overflows or water reuse strategies, if the ground surrounding your home is hard and compacted, the water will not infiltrate and will be virtually ineffective. Therefore, when it comes to landscape hydration for supporting biology, gardens, food production, or ecosystem services in general, your best bet is to make sure that the soil on the property is healthy and has high water-holding capacity.

How to do this? Well, soil water-holding capacity increases significantly with even a slight increase in soil carbon content. A 1% increase in soil carbon on your property will store an additional 168,000 liters/hectare (17,960 US gal/acre) (Jones, 2010). This also makes soil storage the most cost-effective way to increase your overall property water stores. Consider that to store this same volume of water in tanks would cost you anywhere from $30,000–$70,000 in infrastructure.

Because carbon content increases when you support soil biology and soil health, there are three primary practices for increasing the water-holding capacity of your land:

1. Keep the soil covered (no bare soil) with living plants, year-around if possible.
2. Maximize diversity in crops and plant species.
3. Avoid the use of synthetic fertilizers, fungicides, insecticides, and herbicides.

Best of all, adhering to these practices not only increases the water-holding capacity of your landscape, it also builds upon and enhances your natural capital and increases your overall sustainability and resilience through increased biodiversity, improved ability to grow nutrient-dense food, and reduced atmospheric carbon content, turning your "footprint" into a positive one.

Learn More

Again, we advise you to remember the importance and benefits of considering your rooftop RWH system as simply a small part of a much larger strategy for full-property water security, sustainability, and resilience. See this as an opportunity to create an integrated natural ecosystem that buffers you against the impacts of disaster while it increases the long-term economic and environmental value of your property.

In addition, changing our relationship with water has enormous implications and a large positive environmental impact when you consider the global crises we are facing with respect to biodiversity loss, food insecurity, and climate change. But going forward, we are going to narrow our focus in this book and keep it to the essentials of rooftop RWH system design.

Make sure you check out the other titles in the *Sustainable Building Essentials* series, and for more information on full-property design, including our favorite books, recommended courses, resources, and blogs on related subjects such as permaculture design, sustainability, soil and soil health, see the Resources and References section at the back of this book.

Design Scenarios

Now that you understand how the RWH system fits (or may fit) within the larger context of water design for your property, it's time to narrow down your RWH design scenario.

Are you in a remote off-grid location? Are you in an existing house in the city? Are you building a new building or retrofitting an existing building? What are your water supply options?

What about your climate? Are you in a cold climate with ground frost in the winter? Is it an arid climate? Are your rainfall patterns uniform throughout the year or does rain come in certain seasons?

Depending on the answers to the above, your RWH system may be simply a small piece of a household water-supply plan, or it may be designed to supply all of your water needs at all times.

There are many permutations of a RWH system, but the three most common household scenarios we see with our clients are:

1. Supplemental supply: rainwater as the secondary system, with a primary system in place.
2. Primary supply: rainwater as the primary system, with secondary system in place.
3. Off-grid supply: rainwater as the primary system, with no secondary system.

In the above scenarios, the primary or secondary system could be a municipal water supply, a groundwater well, gravity-fed or pumped system from surface water on the property, or even trucked-in water.

In Scenario 1, the RWH system is there for specific or supplemental water supply, such as irrigation. Sized usually to only meet specific loads (like toilet flushing), its intended use is either as supplementary supply or as an emergency system, or as both.

In Scenario 2, the RWH system could be designed to meet most (if not all) of the demand over the course of the year, and the secondary system is in place to shave off the peak demands, as well as kicking in in the event of drought or low rainfall. This can be a cost-effective strategy for supplying a majority of your needs with rainwater, especially when a municipal or groundwater supply is already in place.

In Scenario 3, the RWH system must supply all of the demand, all year round. Here, there is a far lower risk tolerance for a zero rain tank balance than in scenario 1 or 2, and this must be factored into the design of the system.

Each of these most-common RWH design scenarios has different functionality and different risk considerations. In the next chapter we'll present typical design considerations and approaches for each. And even if your particular design and usage scenario is not exactly as described above, you should easily be able to apply the presented design thinking and strategizing to your particular needs.

Regulations, Codes, and Standards

Before starting on any RWH project, you must review and understand the local regulations and legal minimum technical requirements. Unfortunately, this is not always straightforward. Depending on where you are in the world, the legal framework for RWH can be clear-cut, complex, contradictory, or — more often than not — quite ambiguous.

Added to this is the fact that significant legislative reform is happening and/or anticipated, particularly in North America, given the increased awareness around water issues and impending shortages.

When investigating and attempting to navigate your current local legal requirements, it is helpful to understand the typical structure of regulations, codes, and standards, and how these relate to one another. First off, there are usually (but not always) regulations such as local laws and by-laws that regulate the rights and allowable uses for captured rainwater. For example, provincial, state, or municipal regulations might stipulate the following:

- Who owns the captured rainwater (the landowner? the government?).
- Conditions and requirements pertaining to rainwater capture and use, if any.
- The minimum applicable technical requirements for RWH systems.

As for that last bullet pertaining to the technical requirements: regulators often point to an existing code (or possibly multiple codes) written and maintained by third parties. For instance, the Province of Alberta has adopted The National Plumbing Code which is written, maintained, and issued by the National Research Council Canada.

Be careful, however, because many local jurisdictions adopt a code and then apply modifications, variations, and interpretations that take precedence over the base code itself. In addition, there may also be several different regulations that point to different codes pertaining to different aspects of a RWH system. For instance, there could be different regulations/codes related to plumbing, electrical, tank, water quality, safety, and health. If you are lucky, your jurisdiction will have published some additional guidelines or documentation to help you navigate the requirements for RWH systems.

Once you get your hands on the appropriate regulations, codes, guidelines, and any other publications for your jurisdiction, you'll discover that these documents often specify minimum requirements and attributes, but not much more. This is where standards can come in. A standard is a document, usually written and/or recognized by a technical society, that provides increased information and/or requirements for the design, materials selection, methods, etc.

In 2013, the American Rainwater Catchment Systems Association (ARCSA), the American Society of Plumbing Engineers (ASPE), and the American National Standards Institute (ANSI) jointly developed *ARCSA/ASPE/ANSI 63: Rainwater Catchment Systems* (also known as *Standard 63*). In mid 2018, the Canadian Standards Association (CSA) and the International Code Council (ICC) published CSA/ICC B805 Rainwater Harvesting systems. It's important to know that a standard is only legally binding if it has been enacted as such by your local legislation. Otherwise, the standard is purely advisory. It's sometimes worth looking at who was on a standard committee to understand any inherent bias that the standard may possess.

So, when getting started, go straight to the regulatory framework for your jurisdiction, and follow the rabbit-hole from there. Find out if rainwater capture is even legal, if there are restrictions on certain uses, and if there are requirements, regulations, and codes that must be satisfied. Make sure you understand any local variances to the code. Also worth noting is that even though you may run into a regulatory roadblock, there are often alternative compliance pathways — be sure to ask your regulator about this possibility.

In addition to rainwater-specific legal requirements, you may also need to consider general developmental approval or planning permission that may be required by your jurisdiction. For instance, installing a tank on your property might require a permit and/or inspection to ensure that the applicable codes and standards have been met and/or that the placement of your tank meets minimum property boundary distances.

Because this isn't always straightforward, a good starting place is to seek out your local rainwater harvesting advocacy group — who, hopefully, have already done some of this research for you. We've also included a listing of the most commonly referred-to codes and standards relating to the installation of RWH systems in North America in the Resources section of this book.

We reiterate that the important thing to know is that your local laws may supersede all of, or parts of, common rainwater harvesting standards or practices, and you can't use information from any book or document on the technical design of a RWH system without an understanding the larger regulatory context that you find yourself in. Also, standards and codes start from the baseline that you've already decided to build a system, and therefore they contain no useful information on establishing feasibility, optimizing performance, or the design process as a whole. That's one (of many) reasons you'll find this book particularly useful.

Chapter 2

Fundamentals

In this chapter, we present the preliminary considerations and some of the fundamentals you'll need to understand before jumping into calculating the system sizing and other requirements. This will help you determine what benefits you might expect depending on your system set-up and how to approach the design process as a whole.

Water Quality

There are many things that will degrade — and some things that will improve — the quality of the rain-harvested water that comes out of your tap.

Some things that may degrade your water quality are:

- Contamination by biological material, such as leaves and decay left on the roof and in gutters, as well as feces from birds and other small animals deposited on your catchment surface or directly into your tank.
- Pollutants from the atmosphere. This is particularly a concern if you live near an industrial area or in a rural area where agricultural sprays are commonly used.
- Compounds leached from RWH materials. Your roof, your gutters, your tank, and your piping (or the coatings in/on them) may leach contaminants into your water, with some materials leaching more than others, particularly when exposed to UV.
- Compounds leached from the materials of your indoor plumbing fixtures. Although perhaps not technically part of the RWH system itself, know that even your indoor plumbing (indoor copper or PEX piping, etc.) and your hot water tank may leach compounds into the water that exits your tap.

Regardless of these potential contamination sources and risks, a well-designed and sensibly maintained home-scale RWH system has been shown to act as a treatment train and deliver water of a quality suitable for many end uses, including drinking (Coombes, 2016; enHealth, 2012; Morrow, 2012; Evans, et al., 2009; Morrow, et al., 2007).

What does it mean to be well designed and sensibly maintained? Answering that is, in part, the purpose of this book. But to summarize, and give you a sneak peek, as the designer and the owner of the RWH system, your job is to:

- Minimize the contamination sources and vectors through your upfront material and design choices (such as the layout of components and the inclusion of components like screens).
- Design for easy maintenance, including consideration of maintenance during layout and component choices.
- Support the inherent and naturally occurring treatment processes going on in your tank. This includes:
  - Design and operation that minimizes contamination inflows into your rain tank.
  - Design and operation that encourages sedimentation (and the resulting removal of heavy metals from the water column).
  - Design and operation that supports the actions of the functioning ecosystems within the tank (these ecosystems provide vital water-cleaning services).

- ❍ Design that ensures that the sedimentation layer is not disturbed when water is drawn from the tank.
- ❍ Routine maintenance on an ongoing basis.

If you do all of the above, and follow the good design and sensible maintenance practices outlined in this book, your harvested rainwater will be clear, will have little taste or smell, and will be of good quality, without the need for end-point ultraviolet (UV) disinfection, ozone disinfection, or chlorine sterilization.

Thinking About Demand

Demand is the first side of the equation when it comes to rainwater harvesting. Demand can be thought of as simply: *What am I planning on using this water for?* Examples of typical uses for rainwater include: domestic supply where high quality is required (drinking); domestic supply where mid- or lower-quality water is acceptable (toilet flushing, washing machines, lavatory faucets, etc.); and irrigation. Your local laws may, however, disallow certain uses for rainwater (such as drinking or showering), which will narrow your early design options.

More specifically, to determine demand for your intended uses, you'll need to determine:

- the volume of water needed
- the quality of water needed
- seasonality (the volumes required over time)

Domestic water use typically stays constant in a household over the course of a year, as long as the number of occupants stays relatively constant. For instance, a family can be expected to use approximately the same amount of household water (showering, cooking, toilet flushing) each month over the course of the year. An exception to this would be a vacation home or other seasonal dwelling.

Water volumes can also vary quite significantly based on the types of fixtures (i.e. high-efficiency vs standard). A common example of this is an ultra low-flush toilet vs a standard toilet.

Irrigation volumes will depend on the land size, aridity, and soil carbon levels, as well as plant species; these demands are usually seasonal. (And remember that healthy soil will require less water.)

When heading down the rainwater harvesting path, you'll quickly realize that the more water you need or want to supply (i.e. the larger your demand) usually means a larger system and more cost. So reducing your demand — or at least critically evaluating what your demand actually needs to be — is the very best way to minimize the cost of your RWH system.

How to calculate/estimate demand volumes is covered in detail in Chapter 3, but first let's consider some major factors affecting water usage volumes.

Potable Rainwater

Your private, home-scale RWH system may — or may not — be regulated by your local authorities. If it is regulated, your system will likely fall into one of two classifications: *potable* or *non-potable*.

Potable RWH systems have stringent regulatory requirements in terms of the materials used for the roof, gutters, piping, fittings, valves, tanks, etc. Sometimes this means that you must select, purchase, and use materials that come with a manufacturer's third-party-certified potable rating.

In addition, your regulator may require you to provide end-point disinfection or sterilization — regardless of the actual water quality your RWH system delivers. Regulatory requirements for filtration and disinfection are covered in more detail in Chapter 8.

Behavior and Feedback

In our modern-day lives and homes, most of the services we depend on (water, electricity, waste, natural gas, propane, heating oil, etc.) are provided by centralized systems. These systems satisfy our needs by generating power, pumping water, or treating waste in facilities far away from our homes. Although we may enjoy all this convenience, the ramifications of participation in centralized systems are mostly removed from view.

Feedback is the process in which the effect of an action is returned to the doer. We consider feedback to be a primary and fundamental principle that must be present in good design because it has drastic and positive implications on behavior.

For example, individuals living with solar photovoltaic systems reduce their power consumption; solar thermal users change showering and bathing patterns; greywater and septic system users drastically reduce the amount of toxic chemicals used in the home and discarded down the drain; and — you guessed it — rainwater system users drastically reduce the amount of water they consume, simply through changes in behavior.

We've found in practice that the actual volumes of domestic water used in households using rainwater in prosperous parts of the world is far less than the typical or average household volumes reported in engineering standards and technical design tables.

Don't forget that there are also circumstances that will increase domestic water usage *above* an anticipated average — circumstances that you have no control over as a designer. Examples include extra guests for an extended period, social gatherings, and hot-weather periods.

Reducing Demand Through Design

Our landscapes and our homes can also be set up to use less water right from the onset. The reality is that our conventional household fixtures are huge water-guzzlers.

Landscape and irrigation volume requirements are substantially reduced by employing the strategies discussed in Chapter 1 for full-property water security. To reduce the water used in the home, you can change to or select low-water-use fixtures. The amount of water used by a low-flush toilet can be one-third that of a standard toilet. The same goes for regular washing machines vs high-efficiency ones. These types of water efficiencies are significant when calculating expected usage volumes.

Off-grid rainwater-supply scenarios should absolutely employ numerous conservation strategies, including using low-volume fixtures throughout the home and perhaps even a composting toilet. In addition, water that is still relatively clean after its original use (such as after hand washing), should be directed to a secondary use (such as irrigation).

The term *greywater* is used to describe water that is redirected from lavatory faucets, showers, bathtubs, and washing machines to the landscape for irrigation. A greywater strategy can substantially reduce the demand loads for a RWH system. One of the most innovative thinkers we have run across in the area of water conservation and reuse is Michael Reynolds, pioneer of the Earthship concept (see Resources for more information). Reynolds has thought very deeply about how to harvest, capture, and use water multiple times in a building to get the most out of every drop. His systems combine rainwater harvesting, greywater collection and processing, blackwater utilization, and food production. Mapping the flow of water in an Earthship is a fascinating exercise that will open your eyes to conservation and reuse in water design. See also Figure 1.1 in Chapter 1, where many of these same ideas are applied to the design of a resilient and sustainable home and landscape.

Despite what has been shown to be possible, there are many places and municipalities that do not permit water reuse. Some only permit certain types of water reuse, or have requirements for treatment (chlorination, for instance) prior to reuse. Readers are advised to always inquire about and follow location-specific laws and regulations pertaining to greywater and water reuse.

See the Resources section for more information on using and designing greywater systems for your home.

Thinking About Supply

In order to estimate the amount of rain that you expect to collect, you'll first need to get your hands on an appropriate rainfall dataset for your location. A rainfall dataset is the set of numbers that describes your average rainfall volumes and associated patterns, expressed over the course of one calendar year.

Note that the rainfall on the first day of spring last year may look very different from the rainfall on the first day of spring the year before. To account for this annual variability but still represent an accurate overall pattern, multiple years of past rainfall data are usually averaged to create an average, calendar-year rainfall dataset. The number of years used to calculate this average is called the *duration.*

Also, whereas in real life we experience rainfall instantaneously (as it is happening), on paper we express rainfall as a depth over some set amount of time. For instance, you'll see rainfall defined as mm per second, mm per minute, mm per hour, mm per day, or mm per month (or inches, of course). The size of the time interval (second, hour, month, etc.) is the *time step.*

Here are some examples of possible time steps and durations and the subsequent number of data points in the final calendar-year rainfall dataset.

- Monthly time step based on 1-year duration (12 data points: Jan–Dec)
- Monthly time step based on 30-year duration (12 data points: Jan–Dec)
- Daily time step based on 15-year duration (365 data points: Jan 1–Dec 31)
- Hourly time step based on 15-year duration (8,760 data points: Jan 1 01:00–Dec 31 24:00)
- Five-minute time step based on 30-year duration (105,120 data points: Jan 1 00:05–Dec 31 24:00)

It's intuitive that the last dataset in the list above would provide far more accurate supply estimations than the first one. In fact, research into the simulation of RWH systems has shown that performance modeling is critically dependent on both the time step chosen and the duration (Lucas, et al., 2006). However, there's a pragmatic trade-off, particularly for the average home-scale RWH system designer. When seeking out rainfall data and performing calculations, selecting too small of a time step will result in data management and computational problems. Although a five-minute time step may provide high accuracy, it would require 288 data points per day, or over one hundred thousand subsequent computations to model a full year of supply and demand. Also, data over small time steps is much harder to get your hands on. On the other hand, selecting too large of a time step results in an unwanted averaging effect. The low granularity of the data increases the possibility for erroneous results and inadequate design.

Despite the inherent gross simplifications, we usually recommend that you seek out rainfall averages in mm/month (in/month) over the course of 30 years, in part because this historical dataset is often made readily available by most governments. We'll show you where to find this dataset, and discuss limitations of using this level of data granularity in Chapter 3.

Rainfall Pattern, Catchment, and Storage

There's four important concepts to understand when it comes to supply: *rainfall pattern,* *catchment, storage* and perhaps most importantly, the *interplay* between rainfall pattern, catchment, and storage.

Rainfall Pattern

Your rainfall pattern is described by both your total average annual rainfall, mm/yr (gal/yr) and the percentage distribution of rain on a calendar-year basis. It is entirely dependent on where you live and is something that you have no control over. To give you a better understanding of how rainfall patterns differ from location to location, Figure 2.1 shows the monthly rain distribution for four different cities. The total average annual rainfall for each city is stated in the legend beside the city name.

You may live somewhere that receives a fairly steady amount of rain every month of the year, and total amount of rainfall is moderate to high (like Worchester, Massachusetts). Or perhaps your climate provides a moderate-to-high amount of rain that is unevenly distributed and most of it comes in the winter months (like Vancouver, British Columbia). If you live somewhere like Flagstaff, Arizona, you receive only a small amount of rain on an annual basis, and it tends to come in early winter and late summer. From a design perspective, places like Amman, Jordan, have the most challenging rainfall patterns, as they receive virtually no rain for half of the year, and then they have several very large rain events during the other half of the year.

Catchment Area

The catchment area is the total area from which you can harvest your rainwater. In home-scale rainwater design, your catchment area is basically the footprint of your roof, as it's impractical to attempt to harvest rain from other surfaces such as your driveway (although something like this might be done in a commercial system). Note also that harvesting water from surfaces other than your roof is likely to result in a

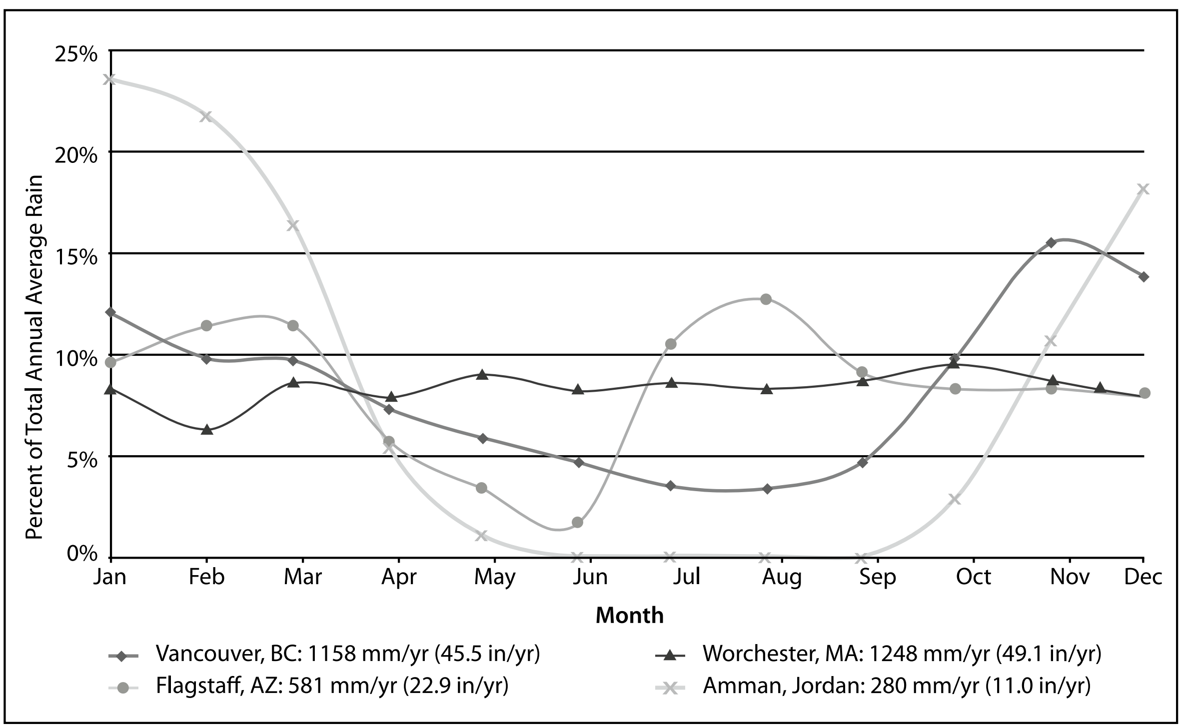

Fig. 2.1: *Percentage of total annual rainfall on a month-by-month basis for four cities. The total annual rainfall for each city is shown in the legend.*

dramatic reduction in water quality. When we say: *Increase the size of your catchment,* what you need to do is assess if you can increase the footprint of your roof by changing the shape of your building, or by adding other roofs, such as a shed, a garage, or perhaps even a neighbor's roof to your system (if it's practical to do so).

Storage

The primary role of your storage is to smooth out supply and demand. Think of it this way: on a second-by-second basis, you'll potentially have rain coming in (supply) and rainwater going out (demand). Sometimes you may have a positive net supply (more supply than demand) and other times a negative net supply (less supply than demand). Your storage is used to carry-over the net surplus or make up the difference in the event of a water deficit.

The tank is typically one of the most expensive elements in a system, especially in larger RWH systems — even more so in cold climates because tanks must often be buried below the frost line for freeze protection. Therefore, when selecting a tank, you'll almost always want the smallest storage volume that will meet your demands over the course of a year.

Rainfall Pattern, Catchment, and Storage Interplay

If the owners of a home in each of the four cities presented in Figure 2.1 were designing RWH systems to supply approximately equivalent domestic demands, here is how their systems would compare:

- Worchester, MA: Smallest storage.
- Vancouver, BC: For the same catchment area as the Worchester home, moderately larger storage.
- Flagstaff, AZ: For the same catchment as the Worchester home, significantly larger storage.
- Amman, Jordan: Would require at least double the catchment area and an enormous storage capacity compared to all of the others.

Space and Cost

Your ability to increase supply by increasing catchment, or your ability to "smooth" out your rainfall pattern by increasing storage might be space-constrained from the onset. For example, if you are adding RWH to an existing urban home on a small lot, your roof size is fixed, and you may be limited by the size of tank that can actually fit onto your property.

Alternatively, if you are planning a new home, you'll likely want to use your RWH system design to inform your building shape and the resultant roof footprint; this initial stage is the easiest time to add an additional secondary roof to your system to meet your demands.

If you are planning on year-round rainwater harvesting where frost protection is required, you'll definitely need to think about where you are going to put your tank. You'll need to protect your tank from freezing by burying it, integrating it into a basement, or by some other means. Regardless, it requires substantial upfront space-planning.

We often don't appreciate just how much water we and our conventional homes consume. When we attempt to meet our water demands on a rainwater budget, we sometimes discover that the required catchment area would be absurd and/or the size of tank required would be completely unfeasible from a space perspective, or from a cost perspective, or both.

Managing Your Risk

Using Averages in Design

When it comes to predicting future rainfall, we've already suggested that you seek out monthly rainfall averages in mm/month (in/month) over the course of 30 years, and use those numbers as the starting point for your design calculations.

But before proceeding blindly with averages, it's well worth looking a little closer at your dataset to get a sense for the amount of actual variation or spread that might be considered normal for your particular climate.

Table 2.1 shows the monthly rainfall averages in mm (inches) for Calgary, Alberta, for the month of May for the ten-year period 1990–2000. If you were using this ten-year duration for your dataset, you'd use 50 mm (2 in) as your average rainfall volume for the month of May in your preliminary design calculations.

Note however that, within this ten-year dataset, there were four years when the rainfall was less than 30% of the monthly average, and two years where the rainfall was half. That's quite a substantial deviation, especially given that this is a relatively small dataset. A larger dataset would likely show more spread and a larger variation from the mean. Depending on how robust you want/need your RWH system to be, the year-to-year variation might be a major consideration in your design. We'll discuss how your design can compensate for this rainfall variability in Chapter 3.

Therefore, we highly recommend that, in addition to looking at the average multi-year precipitation number, you always dig a little deeper into the data to get a sense of what size of variation is historically normal. It might not be unreasonable at all to even look at the daily rainfall data, especially if you have access to that data.

Extreme Rainfall

Water forces are powerful, and mishandled surge volumes can compromise tank and building foundations, or cause serious erosion on your site. No matter which RWH design scenario you employ (supplemental, primary, or off-grid),

Table 2.1

Year	Average Precipitation in May, mm [in]
1990	91 [3.6]
1991	21 [0.8]
1992	34 [1.3]
1993	62 [2.4]
1994	62 [2.4]
1995	60 [2.4]
1996	26 [1.0]
1997	32 [1.3]
1998	86 [3.4]
1999	47 [1.9]
2000	29 [1.1]
Average	50 [2.0]

Table 2.1: *Monthly rainfall average in mm [inches] for Calgary, Alberta for the month of May, 1990–2000.*

you want to ensure that you design your gutters, conveyance, and tank overflow appropriately to minimize the potential of damage to infrastructure and landscape.

Gutters, conveyance piping, pre-filtration, and tank overflows are sized based on the maximum rainfall intensity that you might reasonably expect. These topics are covered in Chapter 5.

If you are sending your tank overflows to the landscape, such as rain gardens or swales, you'll also want to consider the likely available retention capacity in your tank prior to a significant rain event combined with the estimated infiltration capacity of your soils. However, designing for landscape infiltration is outside of the scope of this book. See the Resources section for more information.

Drought

We've found that historical drought data is much harder to get your hands on than rainfall data. Drought is often not even included as a consideration in many RWH design resources. We assume that's because it's not as technically relevant from a system-sizing perspective (i.e.

too little rain won't wreck your infrastructure or cause foundation failure).

However, a failure to supply the water you actually need can be critical, depending on your context and scenario. For example, for primary systems with backup and/or where your rainwater is simply a supplemental system, you may not need to worry too much about the drought scenario. However, if you are designing for a remote off-grid acreage on an island with no groundwater, you'll want to thoroughly consider how to most reasonably (and cost effectively) manage your risk in the event of a long-term supply shortage.

Minimum Rain Limit

Stack all of the above on top of the general concern that the climate is shifting and precipitation patterns are changing, and you can see that simply using averages to design your system might be a bad idea.

On the other hand, there's another pragmatic trade-off between how much you want your design to handle the worst-case drought condition and how much you are willing to pay for it. For example, it might be tempting to state: *I want my system to meet all of my demand needs even if there is a 100-year drought.* The reality, though, is that achieving this goal is likely to be cost prohibitive and may not even be technically possible.

So, as part of the design process, you will have to make a decision about what reduction in rainfall is reasonable for you to design your system to handle. We call this the *minimum rain limit.* And although you might not have any idea what is reasonable to expect at this point, it will be helpful later down the road if you take some upfront time to consider the following:

- Look at the rainfall variation in your dataset. How big is the spread between the average and the low? How often does a low rainfall condition occur? How long did low rainfall conditions last in the past?
- Talk to longtime locals. Farmers and gardeners can be great resources and may even confirm qualitatively and perhaps quantitatively the severity and the lengths of any droughts that have occurred in the past.

Establishing a Minimum Operating Goal

A *minimum operating goal* is a statement about how you want your storage to perform at your minimum rain limit.

Unfortunately, there's not a prescriptive formula for what you should state here. Your context, your goals, and your values, combined with an understanding of historical variations in rainfall data for your climate will ultimately inform your minimum operating goal.

You should ask yourself: What is the consequence of not meeting my demand needs? Is the cost of importing water substantial? Other questions to consider are the other backup supply options available and the costs to drill a well or tie into municipal water.

You'll want to evaluate these things, and at least have an idea of cost and availability of water-supply alternatives before you set a minimum operating goal for your RWH system.

Also important is that you state your minimum operating goal in terms of the storage performance you expect from your system at your minimum rain limit.

Here are some examples of well-stated minimum operating goals:

- I'd like to store enough water to be able to irrigate for two months even if there is no rainfall in that period.
- I want three months of supply available and stored in the tank in the 20-year drought scenario.

- I want to continue to meet my demands even if rainfall is 50% of normal for two years.
- I only want to switch to my backup system if there is a three-month drought.
- I want my system to meet 40% of my demand needs in the 50-year drought scenario.

There's also another perfectly acceptable minimum operating goal: *I want my system to meet my demand needs as long as rainfall is close to the average expected amounts.* What you are really saying is that you are not too concerned about the low rainfall occurrence, likely because your demand needs are supplemental (or non-critical), because you have an existing backup system, or because you are willing to change or adjust demands during different rainfall conditions.

To give you a glimpse of how this all ties together, the minimum rain limit and the minimum operating goal help us to better optimize the design that starts out based on average rainfall conditions. And often — but not always — you'll discover that in order to meet your minimum operating goal, you have to tweak your design.

The good news is that because the design process is iterative (you repeat the calculations using different parameters), you can always start with some ideal resiliency, and then, if the system you come up with is cost prohibitive, you can lower your expectations until you find a design that works within your budget.

Adaptive Strategies

Research has shown that users of RWH systems incorporate the monitoring and awareness of short-to-medium-term weather forecasts into the management and operation of their RWH systems. Therefore, before adding a ton of capacity (and potential cost) to your RWH system to meet your minimum operating goal, it's well worth discussing what we call *adaptive strategies.*

Adaptive strategies are real-time behaviors or backups that can be put in place in the event of a rainwater-supply disruption. Regardless of your RWH supply scenario (supplemental, primary, off-grid), your typical adaptive strategies for managing lack of rainfall or drought would be to:

- Employ water conservation: Reduce shower duration and frequency (changing from a six-minute shower to a three-minute shower is a massive savings in water use); reduce or eliminate irrigation; wash your laundry at a laundromat; wash dishes by hand; shower at the gym or at work, etc.
- Import or purchase water. This could be on a small scale (such as a bottled water supply) or on a large scale (such as bringing in trucked water).
- Switch to a backup system. Of course, this option would only be available if you included a backup system in your design.

For some for households (including many of our clients), suggesting that they shower less in the event of low rainfall is not always a warmly greeted design proposition. However, adjusting actual water usage is absolutely an acceptable risk strategy for a seasonal off-grid cabin or perhaps acreage owners looking to build a DIY system on the smallest possible budget.

The ease or cost of importing water will be entirely context dependent and is a definite factor for how much you decide to rely on adaptive strategies. If you are near a town or major center, hiring someone to deliver water several times a year might be very reasonable and cost effective. If the cost of bringing in water is prohibitive however, you'll certainly be looking to rely more heavily on designing a RWH system that meets your minimum operating goal.

If you are adding a garden irrigation RWH system to an existing home with municipal water supply, you may not be overly concerned about the risk of having no water in your rain tank because you will be able to simply switch to the other system already in place.

The main idea here is that if you are willing/able to rely more heavily on behavior-based strategies, you can likely find a suitable design with a smaller roof area and/or tank as well as reduce the size or even the necessity of a backup system. This could mean a lower upfront capital cost for your water-supply system.

To provide maximum optionality, scalability, and adaptability of your system in the future — no matter what your minimum operating goal is — you'll absolutely want to consider including level monitoring and spare connections on your tank. Monitoring is key to providing feedback and is therefore an important upfront design element. Spare connections should allow for the flexibility to add more storage (more tanks) or potentially tie-in more catchment (more roof) down the road.

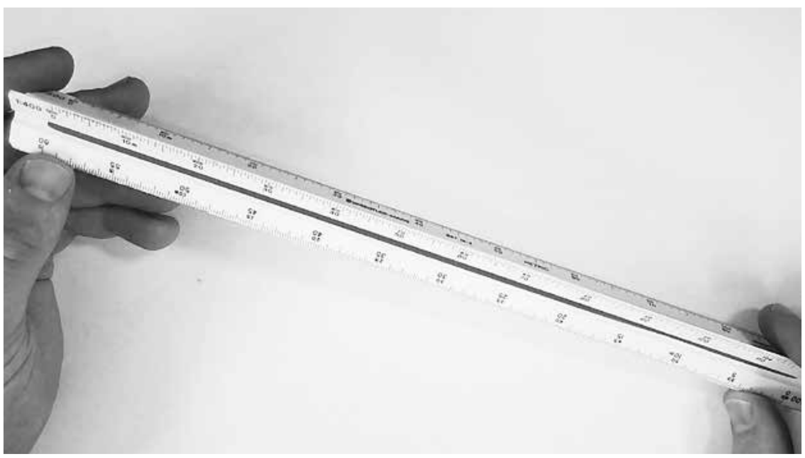

Fig. 2.2: *Architect's scale ruler.* Credit: Verge Permaculture

Fig. 2.3: *Hand-held sight level.* Credit: Verge Permaculture

Design Tools and Materials

There are a few basic tools that you'll want to get before getting started.

Pencil, Graph Paper, Clipboard, and Scale Ruler

You'll want a pencil and eraser as well as a pad of ledger-sized graph paper (279 × 432 mm [11 × 17″]) and a clipboard of the same size (letter-sized paper never seems to be large enough for a drawing and notes).

You can easily build a clipboard large enough for the ledger paper by using a ¼″ 11 × 17 medium-density fiberboard (MDF) with a binder clip. It is inexpensive — and indispensable when doing field assessments, scale drawings, site plans, and elevation plans.

Architect's Scale Ruler

An architect's scale ruler is another indispensable tool. It is basically a specialized ruler that makes drawing something to scale, or measuring something on a site plan an absolute cinch. Look for a metric scale ruler if you plan on doing your measurements in metric.

Measuring Tape

Get yourself a 30 m (100 ft) and an 8 m (25 ft) tape measure. You'll very likely use both.

Hand-Held Sight Level

We all know that water flows downhill. However, when you are onsite, it can be surprisingly difficult to estimate elevations and/or distances and evaluate placement to meet minimum slope requirements, particularly for conveyance piping. This is where a hand-held sight level, combined with a measuring tape, are great tools.

We prefer non-magnified versions, and they typically they cost $30–$60.

Computer-Aided Design Program

In all honesty, all of your planning can be done on paper with a scale ruler and a pencil with an eraser. We still do a lot of designs this way.

However, there are considerable advantages to using computer-assisted design (CAD) software. Once you become familiar with the software you can save quite a bit of time because adjustments and changes to the design are quick and easy and don't require you to erase and redraw lines.

There are two types of drawings that will are most beneficial to you when planning a RWH system: a site plan (view from space), and an elevation plan (view from one side). A piping and instrumentation diagram (P&ID) is a third type of drawing that is sometimes useful as well.

There are many CAD and drawing software programs out there; some are free (like SketchUp), and some are very expensive (like AutoCad). When we want to use CAD, we use Smartdraw, as it is relatively inexpensive and does most everything we need.

Using a Spreadsheet vs a Calculator

Although everything presented in this book could be done by hand with a calculator, it's incredibly impractical to do so given the iterative nature of RWH system design. As such, spreadsheet programs like Microsoft Excel, Mac Numbers, Google Sheets (free), or OpenOffice Calc (free) are huge time-savers.

Only a very basic understanding of spreadsheets is required to successfully build your own calculation tool. As such, we will assume that nearly all readers will choose to use a spreadsheet program to perform their feasibility calculations. To make it super easy for you to follow along, each step is presented as a spreadsheet template. Basically, we'll show you exactly how to build your own spreadsheet table and which equations to put in which cells. We will also present all equations in the spreadsheet "language" of formulas, functions, cell references, and operators.

Regardless of your comfort with spreadsheet software, if you follow the templates you'll end up with a powerful calculation tool that will save you an incredible amount of time when testing iterations and design scenario permutations.

Don't want to build your own tool? No problem. Head to www.essentialrwh.com if you'd like to hit the ground running by purchasing our spreadsheet-based *Essential Rainwater Harvesting Tool.*

We can't really imagine doing these calculations without a spreadsheet, but it is doable. If you prefer to do the math by hand, you'll absolutely be able to follow along with the instructions and formulas provided. In that case, a simple calculator is all that you'll need.

A Spreadsheet Cheatsheet

Need a refresher on how to use a spreadsheet? Almost everything you need to know to build your own RWH calculation tool is summarized below:

Formulas: Formulas always start with an equal sign (=), and they contain any or all of the following: functions, cell references, and operators.

Functions: Functions are predefined mathematical operations. We'll use:

- SUM: adds the values in cells.
- IF: allows you to make logical comparisons.

Cell References: This is the identification of a particular cell. In the templates presented in this book, we use the same convention as in all spreadsheet programs. Columns are labeled with a letter (A, B, C, D...) and rows with numbers (1,2,3,4...). Cells are referenced by their column letter and row number. For instance, cell C2 is the cell represented by column C, row 2.

We may also reference a range of cells using the : (colon) symbol. Cell C2:C5 means cells C2, C3, C4, and C5. Alternatively A28:C28 means cells A28, B28, and C28.

Also, when you are building equations in a spreadsheet you'll save yourself a ton of time if you are familiar with how to use relative cell references and absolute references (using the $ sign).

Operators: The operators used in spreadsheets (and, consequently, those used in the templates here) are: +,-,*,/, >,<, and ^. Note that the * (asterisk) operator is a multiplier, the / (slash) operator is used for division. The < (less-than sign) and the > (greater-than sign) are used for comparisons, often within IF functions. The ^ symbol is used to denote an exponential operator. For instance 10^3 is 10*10*10.

Tabs: Tabs are simply separate "worksheets" within the application; they help to keep information and calculations organized. You can think of each of your tabs as pieces of paper within a stack.

If you have very little experience using spreadsheets, or if you are unfamiliar with how cell references work (using the $ sign), simply search for a basic online tutorial for the program of your choice (typically Microsoft Excel, Mac Numbers, Google Sheets, or OpenOffice Calc), and you'll be able to get started in no time.

	A	B	C	D	E	F
1						
2						
3						
4						
5						