VISUALIZATION OF CONSTRUCTION OF A GRAVITY-FED WATER SUPPLY AND TREATMENT SYSTEM IN DEVELOPING COUNTRIES

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1. INTRODUCTION

This paper will cover every aspect of the design and construction of a water supply system utilizing potential energy (gravity) for delivery. The typical layout of a gravity-fed water system (Figure 1.1) includes a water source, transmission main, reservoir and distribution system. Every component between the water source and the reservoir will be discussed in this paper, which focuses on everything related to the transmission main. This includes pipeline route survey, water resource planning, pipeline design and pipeline construction. Water treatment systems will only be introduced and discussed briefly. For more information on these vital components of a water supply system, refer to the sources at the end of this paper for further reading. All calculations and measurements were done using the metric system. A large majority of communities that would find this information useful use the metric system. If the system will be designed using english units, it is suggested that the conversions are made from english to metric in the survey, design done in metric and then converted back to english units because all of the tables used to design the system are in metric. Refer to appendix A for conversion factors from metric to english.

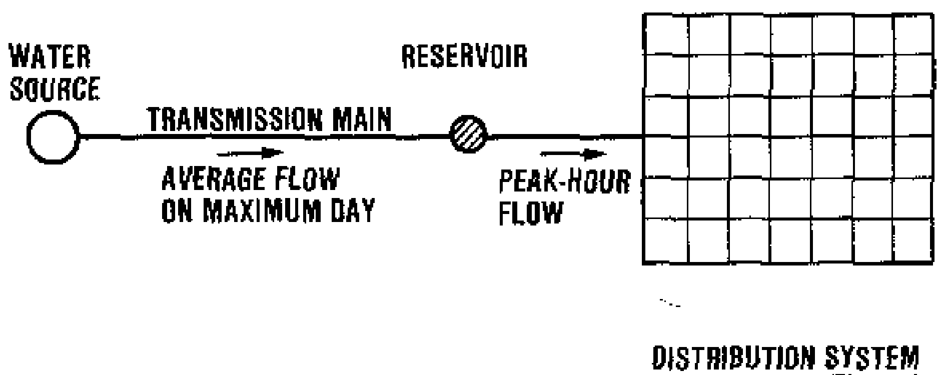

Figure 1.1 Typical Gravity-Fed Water System (IRC 1981)

2. PIPELINE ROUTE SURVEY

Surveying is needed for collecting data to help in the design of the transmission main, placement of the water storage tank and, if necessary, placement of the break-pressure boxes. The type of survey needed for planning the pipeline depends on the route topography. If the route topography is noticeably downhill with no ridges, cliffs or plains, then a survey could be performed with reasonable accuracy with a three-man crew using a clinometer, compass and tape. For more varied route topography, a topographic survey would need to be preformed. This requires more time and usually needs a theodolite instrument. Theodolites are expensive, bulky, require a skilled surveying crew to operate and typically not available in developing countries. These surveys could be performed using the simpler instruments described above but would take even more time and a larger crew to complete. For the purposes of this paper, I will focus on simple surveys using the simpler less accurate instruments. It will also be assumed that the landowners where the pipeline will be placed have given permission for the pipeline to cross their property.

2.1 Survey Instruments

Figure 2.1 Prismatic Compass

Distances are measured directly using tapes. They may be made of steel or synthetic materials 10, 20 or 30 meters long and marked in meters, tenths and hundredths of meters. They are usually wound into a case with a handle for re-winding. Another method for measuring distance, called pacing, uses a predetermined number of steps required to travel a specific distance. This pace differs from person to person and is usually accurate enough for small distances on flat terrain, but steep terrain makes it difficult to keep a stead pace, which can lead to inaccurate measurements. Pacing is thus reserved as a last resort when it is not possible to obtain a tape. Horizontal angles are measured using prismatic compasses. The prismatic compass (Figure 2.1) consists of a round glass-topped case containing the pivoted needle and card or ring, with a prism and sighting wire in a frame at opposite ends of a diameter of the case. The prism holder has a fine slit at the top and when the instrument is held at eye level with the prism towards the observer, a distant object can be sighted by lining it up with the slit and the sighting wire. At the same time the degree graduations on the ring or card can also be observed and recorded (Longland 1983). These angles, along with distance measurements, are necessary to paint the picture of what exists in the field. Drafters use these angles and distances to position measured objects, pipeline route points and measured vertical distances on a scaled map. This map will help the designers for the water systems to determine pipeline length, topography, terrain and physical obstacles such as rough soil or dense underbrush.

Figure 2.2 Abney Level

The clinometer is used to measure vertical angles from which vertical distances can be determined using trigonometry. The most commonly used clinometer is the Abney level. The Abney level (Figure 2.2) is basically a square tube with an eyepiece at the observer's end and horizontal cross hair at the objective end. Near the center of the tube is a 45-degree mirror, which reflects half of the line-of-sight upwards through an aperture in the tube. Mounted above the aperture is a bubble level with an index mark etched at its center. The bubble level is affixed to a moveable index are, which adjusts against scale graduations on a metallic arc (Jordan 1980). The Abney level is widely used over the theodolite because it is easier to use, faster, lighter, simpler to use and easy to adjust in the field. Though not as accurate as the theodolite, the Abney level is sufficiently accurate for pipeline route surveying.

The accuracy of the survey is directly related to the accuracy of the instruments used to take measurements in the field. Engineering and scientific practices state that no instrument is more accurate than one-half the smallest scale of division displayed (Jordan 1980). This means that the Abney level, which only has divisions every degree, is only accurate to one-half of a degree. The prismatic compass typically has divisions every degree as well. Tapes typically show divisions every 10 cm, making them accurate to 5 cm. The limits of the instruments should be taken into account during the design phase and design results presented with reasonable accuracy. This means that a design calculation that shows one section of the pipeline dropping 5.34 meters should be presented as 5.5 meters because the accuracy of the instruments is not accurate enough to merit the design measurement.

2.2 Performing Route Survey

Before any surveying is started the Abney level must be calibrated. This is very important as a poorly calibrated instrument can lead to erroneous field measurements, which leads to lost time. The instrument should be calibrated everyday before surveying and anytime it is dropped. For information on how to calibrate the instrument or to set the bubble, mirror or height of the bubble level, refer to Jordan's book "A Handbook of Gravity-Flow Water Systems" or the manufacturer's manual that should have come with the purchase of the Abney level.

A minimum two-man crew size is required for the route survey, one to measure vertical and horizontal angles, and another to hold the reference rod and help with distance measurements. The person in charge of taking and recording measurements from the prismatic compass and the Abney level is called the surveyor. The reference rod used has to be cut to match the eye-level of the surveyor. If an adequate rod is unavailable, an assistant should be selected that is close to the surveyor's height. Care should be taken when measuring to make sure the same assistant is used throughout the survey. The survey technique used is relatively simple. The surveyor's assistant places the reference rod on a point along the pipeline route. After measuring the distance from the surveyor to the assistant using the tape (Figure 2.3), the surveyor lines the top of the rod up on the Abney level crosshair and adjusts the scale until the bubble, crosshair and object are aligned in the sight. The rod can be hard to see through the level. Tying a brightly colored cloth to the top of the rod or having the assistant place their hand on top of the rod can help the surveyor target the rod. Due to the Abney level's inherent inaccuracy, 2-3 measurements should be made and the average recorded in the field book. An example of measuring vertical angles and the necessary calculations to find the vertical distance is shown in Figure 2.4. Refer to appendix B for a table on converting the degree readings from the Abney level to vertical distances. Both of these measurements are recorded in the field book along with the magnetic bearing taken with the prismatic compass and any sight conditions that could prove difficult during construction. The surveyor has to be mindful during the survey that a trench will have to be dug approximately 1-1.5 meters deep along this route and any difficult soil, terrain or vegetation will have to be noted in the field book. The proper route may not always be obvious. A path through thick vegetation may be preferable because of softer soil than the clear path where the soil is more difficult to trench. More workers may be needed to cut away vegetation that stands in the way of the survey. Anything obscuring the view of the surveyor to the next mark has to be cut or moved while the reading is taken. In areas where there are large forests, a sizeable crew will have to be assembled to slash their way through the vegetation that lies in the path of the route survey.

Figure 2.3 Measurements taken in the field in Honduras (John Simpson)

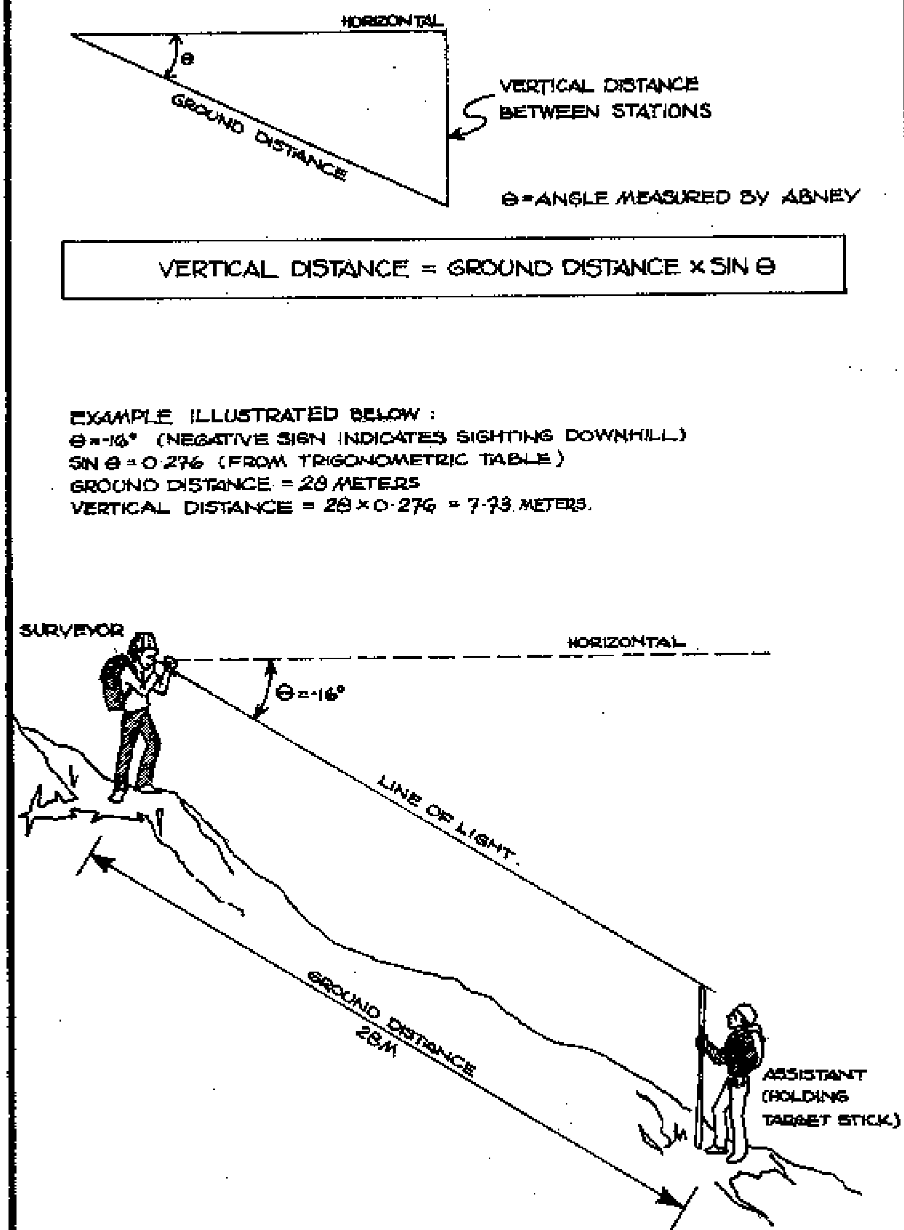

Figure 2.4 Trigonometric Surveying with an Abney Level (Jordan 1980)

It is recommended that a three-man crew perform the survey so that the surveyor can efficiently take backsight measurements to check the accuracy of vertical elevations. This is known as closing the survey. By adding another assistant to the survey crew, this extra person can occupy the previous spot the surveyor occupied. Using the same reference rod described before, the surveyor can take a forward reading, quickly turnaround and take a backward reading. It is not necessary to take a backward distance measurement. This is an efficient way of checking the accuracy of the survey. The difference between the forward survey readings and backward survey readings should agree to within 6% of the original surveyed elevation change (Jordan 1980). For example, if all the vertical elevations from the forward readings equaled 75 meters and backward readings equaled 78 meters for a difference of 3 meters, then the accuracy of the survey would be 3.8% (3/78 x 100 = 3.8%), which is within the 6% limit.

Throughout the survey, wherever a measurement is made, well-marked stakes should be placed and marked with a number corresponding to the recorded values in the survey field book. These stakes will be used later during the construction staking to layout the pipeline after it has been properly designed. It is commonly understood that some of the stakes will be lost from various unavoidable causes. Therefore, it is important that each stake should have a distance and horizontal bearing to two permanent objects in the field. The objects can be buildings, fences, trees, rock outcroppings; anything that would not move before the design and layout of the pipeline takes place. In the approximate area where the water storage tank will be installed, the survey crew should place a stake for the proposed inlet and outlet of the tank and tie in everything within a 30-meter radius of the tank. This data will later be used to help orient the tank during construction staking.

2.2.1 Design Example

The survey data shown below in table 2.1 will be used to design the water system in the subsequent chapters and is an example of how survey data is organized in survey field notes. This data was collected using the same methods described in this chapter.

Table 2.1 Design Example Survey Field Note Data

Stake Number	Ground Length (m)	Vertical Angle (Degrees)	Vertical Distance (m)	Elevation (m)	Horizontal Distance (m)	Horizontal Angle (Degrees)	Comments
	0	---	---	1000	0	---	Start Survey @ Water Source Exit
1	50	11.5	10.0	990	49.0	119.5	
2	100	9.0	7.8	982	98.4	120	Rocky Soil
3	150	5.5	4.8	977	148.2	119	
4	200	8.0	7.0	970	197.7	117	
5	250	14.0	12.1	958	246.2	115	
6	300	3.5	3.1	955	296.1	125	
7	350	2.5	2.2	953	346.0	120	
8	400	3.5	3.1	950	395.9	160.5	Sharp turn in pipeline route
9	450	11.5	10.0	940	444.9	158	
10	500	17.5	15.0	925	492.6	154	
11	550	11.5	10.0	915	541.6	154	Thick vegetation
12	600	10.5	9.1	906	590.8	153	"
13	650	8.0	7.0	899	640.3	152.5	"
14	700	4.5	3.9	895	690.1	148	
15	750	3.5	3.1	892	740.1	146.5	
16	800	4.5	3.9	888	789.9	145	
17	848	2.5	2.1	886	837.9	146	End Survey @ Water Tank Entrance

2.3 Construction Surveying

Construction surveying is not as labor intensive as the route surveying because the vegetation has been cleared and stakes have been set along the proposed pipeline route. During the construction of the pipeline, the surveyor takes the design plans and previous survey field book and checks to make sure all of the stakes are still in place from the last survey. There are usually a few stakes that are missing and have to be placed again for the construction crew to follow. Resetting the missing stake is easy if the two permanent objects tied to the missing stake are still in the field. By measuring off the distances recorded in the field book from the respective objects, the point where the two meet is where the stake is placed. This process can be done 10-20 meters ahead of the construction crew. Also, setting stakes between the survey stakes every 5 meters apart along the pipeline route is necessary so the construction crew does not stray far from the design route. This can be done by drawing a tape from one survey stake to the next and setting a construction stake every 5 meters.

3. WATER RESOURCE PLANNING

There are many questions to answer before the designing the water system. Identifying a water source and determining the average quantity of water supplied. Checking the quality of the water and determining the necessary water treatment methods to employ. It is always better to avoid water sources with water quality issues even if those sources are farther away. The initial cost of more pipeline would be offset by the added operation and maintenance costs of water treatment systems. Water source supply, water treatment and water storage structures will not be discussed in this paper. Design period factors help the designer to correctly size the system. These values should be determined before the survey and pipeline layout to make sure the water source chosen can supply enough water for the community.

3.1 Types of Water Sources

3.1.1 Springs

This source of water is usually located in hilly terrain and is a result of the water table percolating to the surface. Depending on how high the water table is, springs can be very reliable. Springs located toward the top of the water table tend to dry out as the water table lowers during the dry season, while springs located lower on the water table only reduce their output. Care should be taken when selecting a spring to avoid developing one that will dry out during the dry season. Surveying the community nearest the spring about the history of the spring output could help in determining this.

3.1.2 Lakes, Ponds and Reservoirs

These sources of water tend to be man made. Choosing to dam a stream or river to produce a reservoir is expensive and technologically challenging. The driving motive for pursuing a reservoir is overall water supply and supply during the dry season. Natural lakes and ponds provide the same benefits but are not as abundant in most countries.

3.1.3 Rivers and Streams

These are the most likely sources of water for a community without a proper water supply system. The quantity of water tends to fluctuate greatly from year to year and is thus not as reliable as a spring. As explained before, this is why reservoirs are desired to provide a more stable supply of water. Because this is already a supply of water to most people, it should be relatively close to the community making installing a pipeline cheaper.

3.2 Quantity of Source Water

3.2.1 Springs

The easiest way to determine the quantity of water supplied by a spring is to determine the amount of time (in seconds) it takes to fill a bucket of a known volume (in liters) with water from the spring (Figure 3.1). Dividing the volume by the time will result in the quantity supplied in liters per second. For example, a 5-liter bucket is used to test the quantity of water flowing from a spring. It takes 5 seconds to fill the bucket. Dividing the volume by the time (5 liters/5 sec) results in 1 liter per second of flow. When measuring any water source for quantity, at least 3 measurements should be made and an average taken. If the measurements differ greatly from one another, then more than 3 measurements should be made.

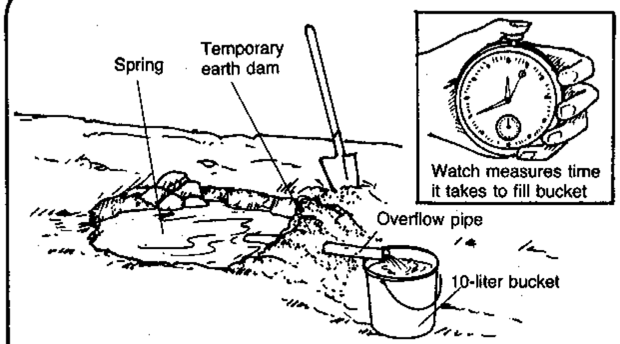

Figure 3.1 Spring Quantity Measurement (USAID 1982)

3.2.2 Lakes, Ponds and Reservoirs

The volume of a reservoir should already be known from designing the dam, so the quantity of water from a reservoir is already determined. Determining the volume of a lake or pond is no easy task. The approximate surface area and greatest depth have to be determined. Lakes will only be referred to in the rest of this section but the same methods can be applied to ponds as well. Measuring the depth is relatively easy depending on the size and depth of the lake. The local communities would know if the lake is shallow enough to walk across or if you would need a boat to traverse it. If it is shallow, the depth can be found by simply walking around the lake until the deepest portion is found. If is not shallow, a boat will have to be used and a score of well-chosen measurements made. The best way to measure the depth would be to tie a rock to the end of the tape used during the survey. Drop the rock over the side and let the tape go until there is no resistance felt. Then lift on the tape until resistance is felt again and record the value at water level. Take the reading and subtract the distance from the end of the tape to the bottom of the rock, this is the depth. Choosing where to make measurements should be based on local knowledge of the lake and geography. The average width and length of the lake for area calculations is difficult to obtain without trigonometric surveying. For more information on measuring inaccessible distances refer to Longland's book "Field Engineering" on page 35.

After determining the area and greatest depth, the volume can be determined. Multiplying the greatest depth by 0.4 will result in the average depth. Take this value and multiply it by the area to get the total volume. Because of evaporation and percolation into the groundwater, the useable volume is actually lower. Assuming 20% of the water is unusable, multiplying the total volume by 0.8 and 1000 liters to get the actual available water in the lake in liters.

3.2.3 Rivers and Streams

Determining the amount of water flowing in a river or stream is much a simple matter. Rivers will only be referred to in the rest of this section but the same methods can be applied to streams as well. First determine the cross sectional area of the river. Accomplish this by measuring the depth on the sides and in the middle and measuring the width of the river using the same techniques for the lake if the water is too deep or wide. Calculate the area using the equation in figure 3.3. After calculating the area, place a floating object in the river and record the time it takes to float a predetermined distance downstream. Use the equation provided in Figure 3.2 to calculate the quantity of water flowing in the river in liters per second.

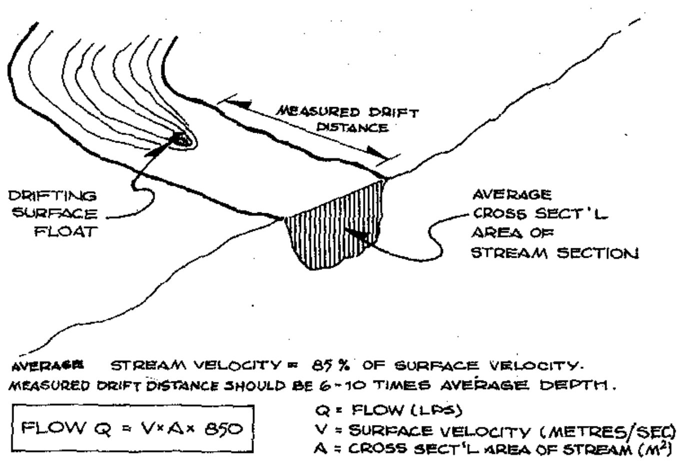

Figure 3.2 Stream Quantity Measurement (Jordan 1980)

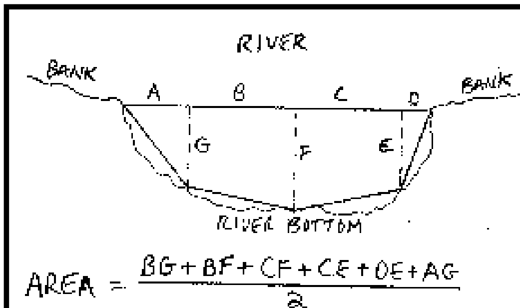

Figure 3.3 River Cross Sectional Area

3.3 Quality of Source Water

There are many requirements that drinking water be free of pathogenic (disease-causing) organisms, suspended particles (turbidity), minerals and salts, bad smells and tastes, compounds that can cause damage to the water system through corrosion or encrustation, and compounds that can have an adverse effect on long term human health (Adapted from IRC 1981, USAID 1982 & Jordan 1980). These demands are set by international health organizations, communities using the water and the states requesting the infrastructure. The level of acceptable pollution depends on the community and on economics or the cost of treating the water. There are basically three types of contaminated water in need of treatment. Water containing pathogenic organisms, suspended solids and minerals and/or salts. The methods of treatment used are disinfection, clarification or sedimentation, and conditioning respectively. These methods of water treatment will be introduced briefly later.

3.3.1 Springs

Springs are typically the cleanest source of water available next to groundwater because the water passing through the various soil textures in the water table act like a sand filter removing bacteria and viruses. There can be problems with mineral or salt content depending on what type of soil the water is filtering through. Most causes of pollution from these sources occur at the mouth of the spring from poor spring box construction or pipe connections to the spring box. Caution should be taken with springs that are flowing from limestone as these are poor filters and can become highly turbid during heavy rainstorms.

3.3.2 Lakes, Ponds and Reservoirs

Lake, Pond and Reservoir water quality is not as good as that of springs because the water is stationary and generally warmer promoting bacteria and algae growth. This can increase the turbidity of the water as well. These water sources are usually avoided unless they can be treated. Irrigation and livestock water are the better uses for this water then domestic consumption.

3.3.3 Rivers and Streams

Rivers and streams are the water sources most susceptible to water quality issues because of runoff from agricultural fields, use upstream by communities for disposing of trash and human excrement, and turbidity caused from periodic flooding following rainstorms. These waters also tend to have minerals collected from the river bottom that affect the taste of the water and can damage the water system. It is impossible to control the water quality over the entire watershed that is served by the river to prevent contamination. If this source is selected there is usually some form of treatment installed with the water system to protect against the seemingly inevitable water quality problems.

3.4 Design Period Factors

The design period itself is a template of how long the system is expected to serve the community before needing major repairs, upgrades or outright replacements. Selecting a time period depends on what the community wants. If this system is being installed to support the community until water from another location is delivered, the design period might be between 5-10 years. This is usually not the case. Design periods of 15-25 years are typically expected since most rural communities are expecting no outside source of water from the state and the state is looking for a more local and sustainable form of development.

3.4.1 Population Growth

The water system not only has to be designed for the current residents requesting it, but also for the future population it will inevitably serve during the design period and an increased water use per person in the future. This is the most difficult factor to account for since there are so many other factors and events that can take place to effect the growth of a population. The larger the design period is the more inaccurate the prediction. A general rule of thumb for population prediction is 50% growth over 10 years. This is a high-end estimate, but it is always safer to over design then under design. If the over designed system is economically unfeasible, a more accurate assessment of growth can be made but requires more time and a better assessment of the community's future.

Population tends to be determined by:

1. Future economic developments in the community
2. The character and location of the community in relation to other population centers
3. The presence or possible introduction of small industries into and around the community (the installation of the water system itself will cause population growth) (Peace Corps R-29 1969)

3.4.2 Community Water Use

Each community differs slightly on the daily amount of water consumed. To reduce demand on the system it has to be known that people for drinking, bathing and cooking or any other personal use related to health and hygiene, can only use the water. The water must not be used by large livestock herds or for the farm field. This will produce unusually large demand on the system and it will consequently fail. It is also assumed that this system is only for residential use and no industries or retail shops will have access unless their business is part of their home. There are many estimates on what each person uses per day in water and the best choice is to perform a survey in the community on how much water is used per day knowing it will increase once the system is installed. If the survey cannot be performed a good rule of thumb is between 40-60 liters per person per day. This accounts for all personal needs described above and also a small amount for domestic animal needs.

3.4.3 Average Daily Water Demand

The average daily water demand is the amount of water needed in liters per second to supply every member of the community with the necessary daily amount of water over the design period. This takes into account the population growth and increase in water use over the design period. The value is also used to determine the necessary pipe size to supply water at that flow rate. Take the existing population and multiply it by the population growth factor (whatever that may be). Then, multiply this value by the community water use factor. Divide this number by 86400 seconds to get the average daily water demand in liters per second.

3.4.4 Peak Water Demand

The water demand determined above is an average of the daily needs of a community and do not take into account cultural or religious events, harvests or climatic changes that require more water than usual for the time periods when these events occur. This is called a peak water demand factor and usually requires 10–30% more water than the daily average. The other peaking factor is an hourly one that occurs during an average day, which is more severe. This demand is what the water storage tank is typically designed to handle. This peak water demand usually occurs during the morning, when everyone is waking and getting ready for the day, and in the late afternoon, when everyone is preparing supper and returning from work. This factor requires 50-100% more water than the daily average and since the water storage tank is designed to handle it, the main pipeline does not have to be designed using the peak water demand (Figure 1). Since the distribution system is continually expanded as the community grows during the design period, it is better to be safe and design the system with both peaking factors (IRC 1981).

3.4.5 Design Example

This example is adapted from the design and construction of a gravity-fed water supply system Returned Peace Corps Volunteer Matt Niskanen supervised in the Dominican Republic (Niskanen 2003). The community has a population of 430 people and wants a system with a design life of 20 years. The daily water consumption is determined to be 50 liters per person per day. Population growth is calculated to be 100% at the end of the design life of 20 years (50% every 10 years).

1. 430 people x 100% = *860 people*
2. 50 liters per person per day x 860 people = *43000 liters per day*
3. 43000 liters per day / 86400 seconds per day = *0.50 liters per second (Average)*
4. Assuming maximum peak demand factors :

   0.50 liters per second x 1.3 x 2 = **1.3 liters per second** (Peak Water Demand)

This example will be continued throughout the paper to help in understanding the design process.

4. WATER TREATMENT SYSTEMS

Water treatment systems are necessary to render contaminated or unaesthetic water fit for domestic use. The problems with water treatment technology are that they need regular supervision and maintenance. If they fail from lack of care, then the community will probably keep using the water even though it is poor in quality. This defeats the purpose of constructing the system to begin with. Therefore, the most important design considerations for water treatment systems in small communities are low cost, minimal use of mechanical equipment, avoiding the use of chemicals when possible, and ease to operation and maintenance. If most of these conditions cannot be met, then choosing another source of water would probably be more feasible, even if it were farther away. There are three general types of water treatment processes. Disinfection treats water contaminated by disease-causing and pathogenic organisms. These organisms are the primary reason proper treatment systems exist to remove them from the water. Clarification treats turbid water removing suspended solids by means of filtering or settling. Conditioning treats water with high concentrations of minerals, salts and/or metals that give water bad taste, poor color or odor. In some cases the metals present are harmful to human health if continuously consumed but mostly this form of treatment is of secondary importance. Conditioning the water can increase the aesthetic value of the water and convince more people to drink it rather than choose a water source that is more aesthetically pleasing but contaminated with undetectable disease-causing organisms. The different technologies used to treat water and obtain the water quality standards discussed earlier are outlined below.

4.1 Household Level

There are four types of treatment methods that can be used to treat water at the household level. These are storage, filtration, boiling, and chemical disinfection. None of these methods condition the water to any great degree to remove minerals or bad tastes and odors. Community level systems will have to be used if the water requires any conditioning.

4.1.1 Storage

Storage is the simplest process of them all. By storing water in a 10-30 liter container for two days, most harmful organisms will die off or be greatly reduced in number and some turbidity will be reduced from allowing suspended solids to settle. These containers must be covered to prevent evaporation and algae growth from occurring and insects and dust from getting in the water.

4.1.2 Filtration

Filtration is the most effective water treatment process at the household level for lowering the turbidity in water but is relatively ineffective at removing bacteria and finer particles from the water. Sand filters consisting of a barrel filled with a layer of gravel, sand and then gravel again, are relatively inexpensive and easy to construct (Figure 4.1). The water passes through the sand medium and traps suspended solids that contribute to high turbidity. The effluent from these filters is usually clear. The sand medium should be changed every two to three weeks to remove solids and prevent biological growth. The removed sand can be washed, dried and reused.

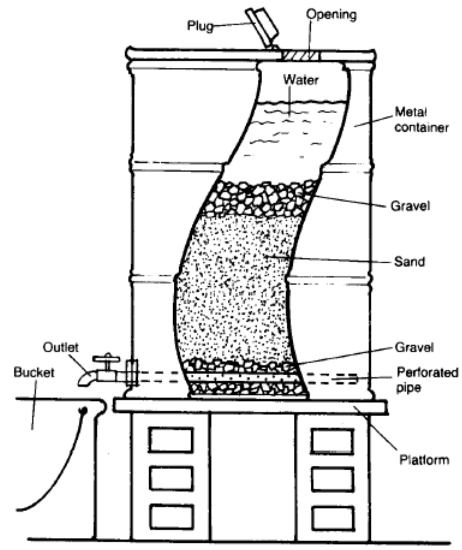

Figure 4.1 Household Sand Filter (USAID 1982)

4.1.3 Boiling

Boiling water is the most effective way of disinfecting. Within 3 minutes of boiling, the water should be completely disinfected. The cost of fuel to boil the water could lead to increased dependence on energy sources such as wood, which could lead to increased rates of deforestation. Unless renewable or alternative forms of energy are made available, this treatment method is not sustainable. Though in emergencies this method is ideal.

4.1.4 Chemical Disinfection

Chemical disinfection is usually completed with doses of iodine, bromine or chlorine added to the contaminated water by hand. The difference between this and community level chemical disinfection is that at the household level it has to be applied manually while the latter is applied automatically. This method can kill most disease causing organisms but not all pathogens and organisms attached to particles. Turbid water must be filtered first before disinfection to increase the effectiveness of the chemicals. Chlorine is the most widely used chemical for disinfection because of its lower cost and relative availability. The source of chlorine varies considerably with liquid laundry bleach being the easiest form to apply on the household level. The disadvantage of chlorine on the household level is if not enough is added, disinfection will not take place on any level and if too much is added, the water will have such a bad taste and odor that no one will want to drink it.

Table 4.1 Household Level Water Treatment Methods

Method	Type of Treatment	Construction Cost	O & M Cost	Reliability	Construction Skill Required	O & M Skill Required
Storage	Clarification of mild turbidity and killing of some disease-causing organisms	Low	Low	Small Volume of water only; used with filter and/or disinfection	Low	Low
Filtration	Clarification of turbid water; removes some pathogens	Low	Low	Up to 2700 liters/day; used with disinfection	Low	Low
Boiling	Complete Disinfection	Low	High	Small Volume	Low	Low
Chemical Disinfection	Disinfection of clear water; kills most pathogens	Low	High	Difficult to determine; taste test only	Low	Medium

Source: USAID 1982

4.2 Community Level

There are four types of treatment methods that can be used to treat water at the community level. These are sedimentation, aeration, slow sand filtration and chemical disinfection. Most of these are used in series to treat water of varying quality. Disinfection always follows methods that clean turbid water, for example. There are other more advanced methods that required highly skilled staff to build and operate them but since they are not economically feasible for almost all small rural communities, they will not be discussed.

4.2.1 Sedimentation

Sedimentation tanks allow suspended solids in highly turbid water to settle out by holding the water for a specified amount of time or making the tank long enough for the particles to settle out while the water is moving. The water that reaches the outlet is clarifies water usually low in turbidity. The settled particles form a sludge layer on the bottom of the tank, which is sloped to direct settled particles toward the drain where during regular cleaning, the tank is flushed from this drain located at the lowest point in the tank (Figure 4.2). If filtration is not available following sedimentation, the tank should have a roof to prevent algae growth or recontamination from insects.

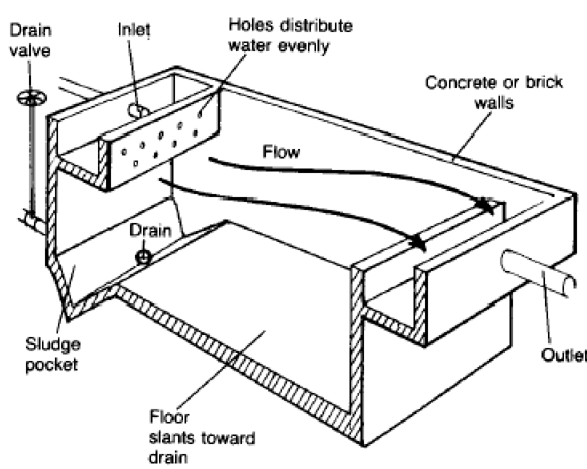

Figure 4.2 Sedimentation Tank (USAID 1982)

4.2.2 Aeration

Aerators are the only cheap treatment method that can condition water to make it taste and smell more appealing without using chemicals. The aerator exposes the water surface to the air by creating a turbulent flow. The water then increases in dissolved oxygen and changes iron and manganese, two common metals related to taste, into solid particles that then settle out of the water in subsequent treatment methods. This process also removes hydrogen sulfide, methane and other volatile organic compounds that are related to bad taste and odor (IRC 1981). One side effect is the reduction in carbon dioxide, which can change the hardness of the water increasing the effect of calcification or encrustation on the inside of the pipeline. The cascade aerator is composed of 4-6 steps that water flows over and drops onto until it reaches the basin at the bottom creating a turbulent effect that increases the dissolved oxygen in the water (Figure 4.3). As the water flows over one step, it hits the small pool of water collecting on the step, disturbing the water surface and forcing air to flow through the water. This method is similar to a waterfall or river rapids.

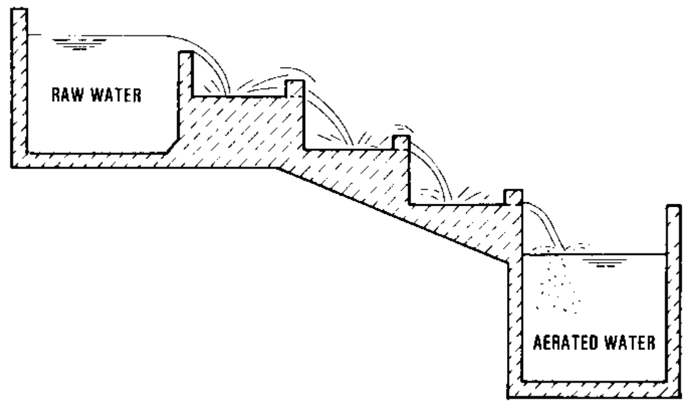

Figure 4.3 Cascade Aerator (IRC 1981)

4.2.3 Slow Sand Filtration

Slow sand filters remove suspended solids from turbid water and also remove most of the disease-causing organisms and pathogens from the water. If the raw water being treated is highly turbid, it is suggested to install a sedimentation tank before the slow sand filter because the filter will clog with suspended particles relatively fast. These filters have the same layering technique as in the household sand filters, except for the layer of gravel on top of the sand. The tanks are filled only half full with sand and a small layer of gravel at the bottom. The rest of the tank is filled with water. To keep the sand from being eroded by water coming from the inlet, a rock or other flat surface is placed close to the inlet in the sand to disperse the energy from the water. The sand also needs to be exposed to allow for a biofilm to form. This biofilm is a very thin slime layer that forms on the surface of the sand and feeds off of the organic material in the water as it passes through the sand. Pathogens and other disease-causing organisms either get trapped in the biofilm and die or are consumed by the microbes living in the biofilm. The slow sand filter should never be operated with a water level below the biofilm because it will not survive and pathogenic organisms could get through the system. This biofilm does not occur in nor can it occur in the household filters because the water is not continuously flowing through the filter. The stagnant water breeds more pathogenic organisms and if the biofilm does not receive a constant flow of nutrients through it, it will die off. The same maintenance requirements that apply to the household filters also apply to the slow sand filter.

4.2.4 Chemical Disinfection

The same chemicals with the same doses and requirements in household disinfection also apply here. The difference is that community systems disinfect automatically and usually with more accuracy. They require far more maintenance since the level of chlorine has to be kept up. There are two types of chlorine dispensers: diffusers and drip-feeders. Diffusers are simply pots with a few holes drilled in them and chlorine tablets or bleach mixed in them. These pots are then placed in non-flowing water supplies, like storage tanks, and the chlorine mixture slowly diffuses from the holes to disinfect the water (Figure 4.4). This method requires refilling the pot every two to three days. The drip-feeders feed a constant flow of chlorine to a reservoir of slowly flowing water. A steel drum with a volume of 200 liters is filled with chlorine solution and a bowl with a flexible tube coming from the bottom to the outside of the tank is floating inside the drum. This bowl also has a small glass tube extending from the bottom into the solution. Solution slowly flows from the glass tube into the bowl, out the flexible tube and into the water being treated. Lowering or raising the glass tube in the bowl can regulate the amount of solution getting to the flexible tubing. This method requires keeping the chlorine solution full in the drum and repairing the drip-feeder whenever there are problems.

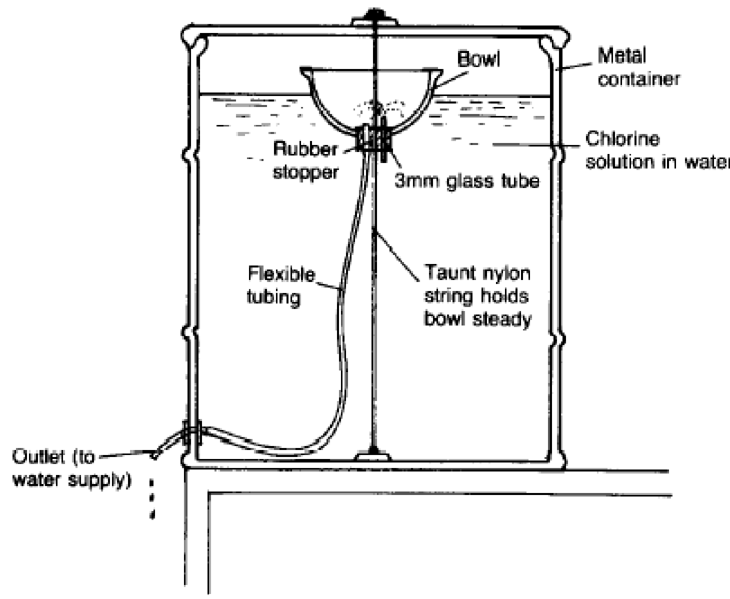

Figure 4.4 Drip-Feeder Disinfection (USAID 1982)

Table 4.2 Community Level Water Treatment Methods

Method	Type of Treatment	Construction Cost	O & M Cost	Reliability	Construction Skill Required	O & M Skill Required
Sedimentation	Clarification of very turbid water	Medium	Low	Use with filtration and disinfection	Low	High
Aeration	Conditioning of water to remove minerals, salts bad taste and odor	Medium	Low	Use with filtration and disinfection	Low	Low
Slow Sand Filter	Clarification and Disinfection	High	Low	Kills most pathogens with proper maintenance	High	Medium
Chemical Disinfection	Disinfection of clear water; kills most pathogens	Low	High	Frequent chlorine checks are necessary	Medium	High

Source: USAID 1982 & IRC 1981

5. PIPELINE DESIGN

The pipeline design usually involves using the survey data and design period factors to determine the size of the pipe and storage tank necessary to supply the community. The pipe material selected for the pipeline is PVC because it is relatively cheap, easily available in most parts of the world and is very easy to repair. Schedule 40 PVC pipe will be the assumed quality of pipe available. Galvanized Iron (GI) pipe is also mentioned during the design phase and is installed in areas where little or no cover for the pipe can be provided, mostly at the beginning and end of the pipeline as well as across well-traveled roads. The following sections will discuss the method used to design the pipeline.

5.1 Hydraulics Background

Before any designing can begin, the basic concepts of hydraulics have to be understood. There are many references on hydraulics that will give a more in depth description of the principles, but this paper will only focus on the basic concepts necessary to design water systems. Water systems need energy to move water uphill or downhill. Pumps are used to supply energy for uphill movement while the potential energy stored in water in the form of gravity is used to move water downhill. The requirement for gravity systems is that the source be higher in elevation than the delivery point. There are other requirements that have to be factored into the design for the system to work and these are explained in the following section.

5.1.1 Fluid Mechanics

There are two states of fluids, those in motion (dynamic) and not in motion (static). Fluid statics are related to the total energy available in the system for the movement of water. This is called the static head and is also another way of looking at the unit pressure in the pipe at a specific point. As the pipeline lowers in elevation, the pressure and energy increase as the water in the pipe drops farther below the water surface. If the energy in this process were completely conserved, there would be no need to design water systems since the water would always reach its destination as long as the exit was lower in elevation than the water surface.

Fluid dynamics exists because energy is always lost as water is flowing through the pipes, valves, pipe entrance and fittings. This energy loss is called friction. Friction is directly related to pipe sizes, fittings and material. The purpose of design is to find the right combination of pipe material, fittings and size to leave enough energy for the water to reach its destination. This is done using the hydraulic grade line (HGL). This line displays how much energy is left in the pipe as water moves from the water source to the water storage tank (Figure 5.1). The distance from the HGL to the pipe below is called residual head and refers to the amount of head present while water is flowing. The distance from the HGL to the static head line is called the head loss and refers to the energy lost due to friction. The slope of the HGL is directly related to the friction loss coefficient. If the HGL ends below the pipe exit, water will never flow without a pump because the pipe exit is in the zone of head loss and not residual head meaning that energy is required to move the HGL line above the pipe exit and get water flowing. The HGL also cannot drop below the pipeline in transit to the water tank because the water is siphoned rather than pushed through the pipe. This can suck air in the pipe, from leaky joints or collect air present in the water, and cause an air jam that will stop system flow. A pump would be needed to remove the air and restore the siphon to get water flowing again. This would be unnecessarily costly maintenance for the community, so it should be avoided.

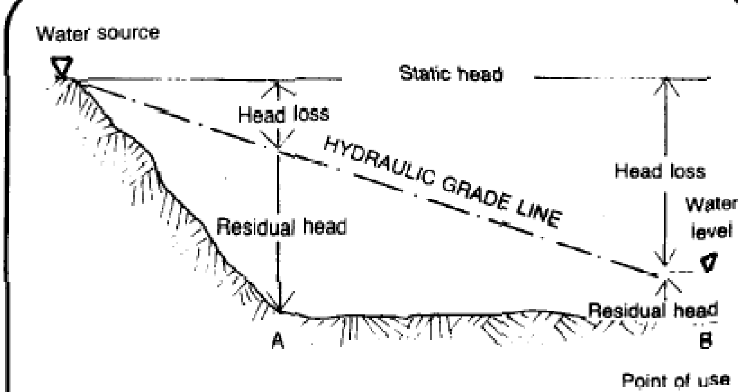

Figure 5.1 System Hydraulic Energy (USAID 1982)

5.2 Pipeline Profile

The profile displays the vertical survey data along the pipeline route in graphical form and is used to determine the pipeline length, maximum static head and vertical difference between the water source outlet and proposed water tank inlet. The horizontal distance is displayed on the horizontal axis and the vertical distance on the vertical axis. The line produced from plotting the survey data is the pipeline profile. The length along this line should be equal to the ground distance. If access to Excel is available, creating the profile should not take much time. If no access is available, the profile can be produced using graph paper, metric engineering scale and pencil.

5.2.1 Design Example

Using the survey data from table 1 the pipeline profile can be drawn (Figure 5.2). The water source surface is located 1 meter above the pipeline at an elevation of 1001 meters and the storage tank water surface is located 4 meters above the pipeline at an elevation of 890 meters.

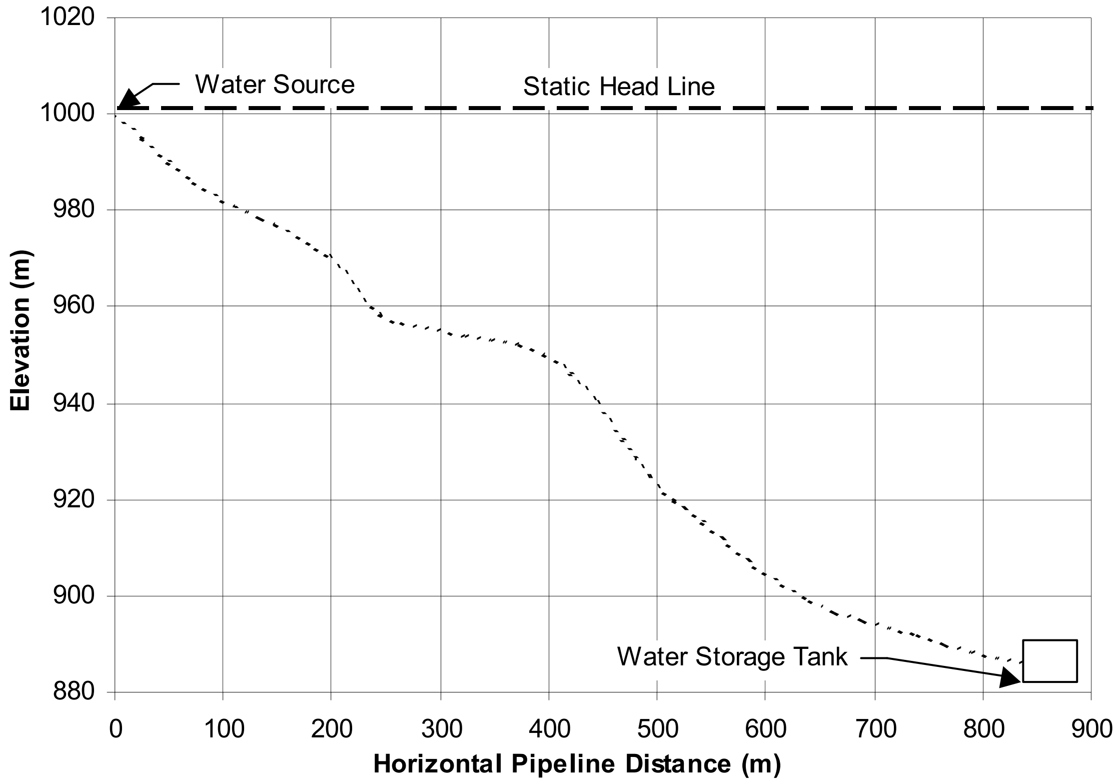

Figure 5.2 Pipeline Profile of Design Example

5.3 Maximum Pipeline Pressure

Looking at the pipeline profile and identifying the point in the pipeline that is farthest from the surface of the water source is the highest static head, which is also the maximum pressure. The static head line is a horizontal line drawn from the water source surface across the graph. This value should be less than the maximum pressure limit for the PVC pipe diameter that was selected or else a break-pressure tank needs to be installed. For simple calculations, the maximum pipe pressures were tabulated in static head in meters (Table 5.1).

Table 5.1 Maximum Allowable Static Head in PVC Pipe (in Meters)

	Pipe Diameter, mm					
Pipe Material	25	32	40	50	80	100
PVC (Sch 40) *	253	208	186	157	146	124
PVC (Sch 80) *	354	292	264	22.5	208	180
PVC (Sch 40) **	127	104	93	79	73	62
PVC (Sch 80) **	177	146	132	112	104	90

* For water at 73.4°F with solvent cemented joints. 20% Factor of Safety
** For connecting pipe by force (Assumed 50% reduction in strength). 20% Factor of Safety

Source: Harvel Plastics Inc. (PVC)

5.3.1 Break-Pressure Tank

These tanks are designed to relieve the pressure in the main pipeline to prevent pipe failure. Relieving the pressure sets the static head back to zero making the water surface in the break-pressure tank the new static level. In systems with elevation differences greater than 150m, multiple break-pressure tanks may need to be installed to keep the pressure low enough for the PVC pipe material to handle it. The surface water level in break-pressure tanks tends to be 1 meter above the pipeline profile. The break-pressure tanks are made from masonry or reinforced concrete, have small internal volumes and the inlet pipe is set higher than the outlet pipe.

5.4 Determining Pipe Size

The pipeline length and static head from the water source to the water storage tank are used to determine the boundaries of the design. Other restrictions include the residual head never dropping below 5 meters anywhere in the pipeline. This is to avoid creating siphon sections in the pipeline as previously described. Also, the exit has to have at least 5 meters of residual head above the proposed water surface in the water storage tank. This restriction exists to protect the system from design or construction errors and as a precaution for errors inherent in the survey itself.

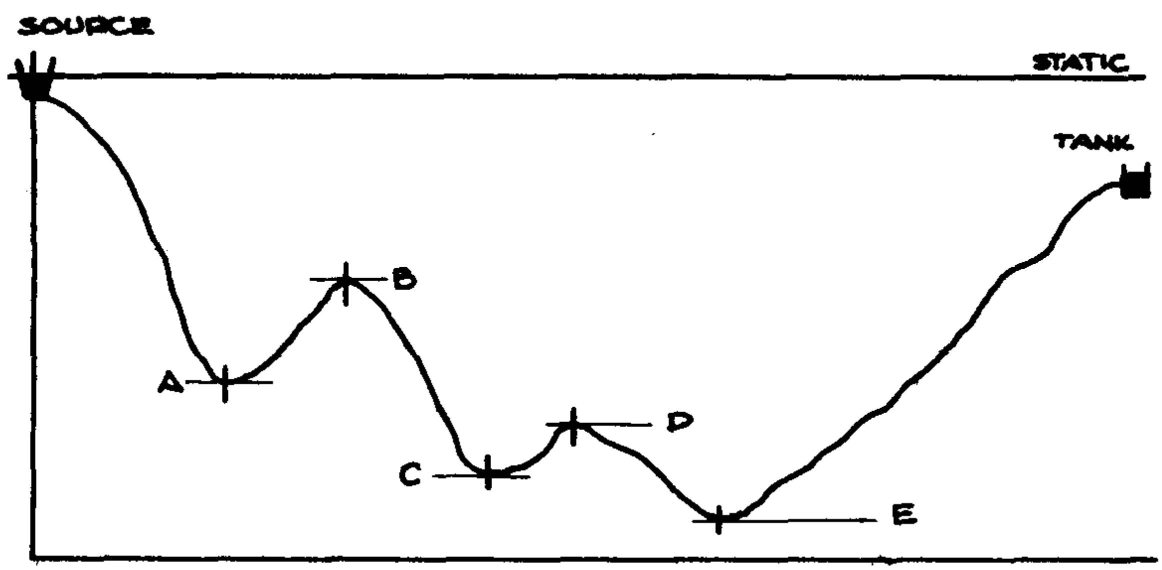

Figure 5.3 Air Relief and Drain Valve Locations (Jordan 1980)

Air release valves (Figure 5.4) should be installed at pipeline high spots (B and D) to remove air that may accumulate and drain valves (Figure 5.5) should be installed at pipeline low spots (A, C and E) to periodically flush out the sediments that will collect (Figure 5.3). UNICEF provides sturdy air relief valves that operate automatically and only require periodic checking. There are manual air relief valves available if the UNICEF ones are unavailable that have the same configuration as drain valves. The drain valves still have to be maintained manually. Both of these valves use a tee to branch off of the pipeline. Therefore, for every air release and drain valve there is a branch tee when totaling friction losses from pipe fittings. The valves themselves do not figure into the friction loss equation because they are closed and only used for maintenance.

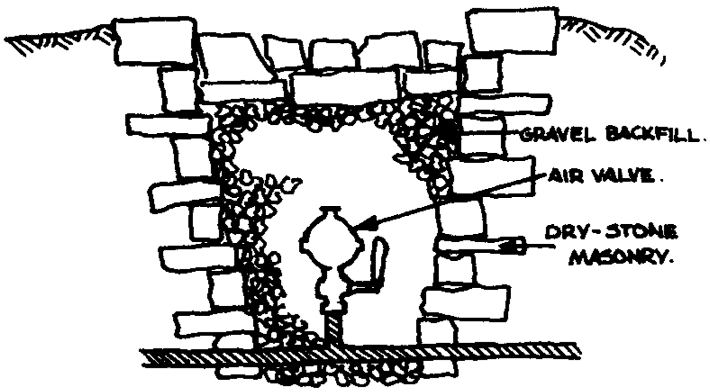

Figure 5.4 Air Relief Valve (Jordan 1980)

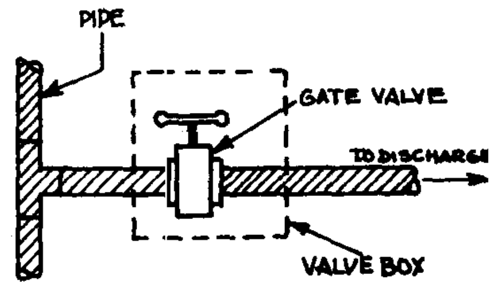

Figure 5.5 Drain Valve (Jordan 1980)

Here are the steps to follow while designing the water system.

1. Calculate the maximum pipe pressure and determine if a break-pressure tank is needed. If a break-pressure tank is needed, draw a line from the water source surface to a point 5 meters above the storage tank water surface and locate a point in the profile that is closest to or farthest above the line drawn. This is where the pipeline profile should be placed. After drawing the break-pressure tank on the pipeline profile, the static head line is reset to the water surface level in the break-pressure tank.
2. If the line drawn in step 1 never gets closer than 5 meters above the profile, go to step 3. This line will be used as a minimum HGL line. If it does, identify the point along the profile that is the farthest above this line and place a point directly 5 meters over it. Draw a new line from the source water surface through this point and extend it until it reaches the water storage tank. If the residual head from this line to the storage tank water surface is greater than 50 meters, two different sized pipes will need to be used. If not, go to step 3. Draw a line through this new point to the storage tank and repeat this step again until the line is never closer than 5 meters to above the profile. Remember that break-pressure tanks reset the static head line and that the minimum HGL has to start from this new line at the exit end.
3. Determine the slope(s) of the minimum HGL line(s) drawn in step 2. Use the head loss and the ground distance from the pipeline profile to calculate the slope using the following equation. The slope for all of the minimum HGL lines should be calculated.

$$\text{Slope} = \left(\text{Headloss}/\text{Distance}\right) x100$$

4. Using the friction loss tables in appendix C, the approximate pipe size can be determined by choosing a pipe with a friction loss value less than the minimum HGL value.
5. Determine the number of pipe fittings present in the system and calculate the total equivalent length from fittings using Table 5.2. There should be two gate valves, one at the source pipe exit and one at the storage pipe entrance. If there are break-pressure tanks, there are two gate valves and a pipe entrance for each tank. If the pipeline is longer than 1000 meters, there should be a gate valve at least every 1000 meters for ease of maintenance and repair. Any reduction in pipe size needs to be accounted for as well. Count the number of air release and drain valves and include them as branch tees. Any major turns in the pipeline that use 45° or 90° elbows have to be included. The pipe entrance from the water source is included as well and needs to be checked to see if there is a screen on it or not. Also include the union coupling used to join the PVC pipe with the GI pipe if the source pipe exit is above ground.

Table 5.2 Equivalent Lengths of Pipe Fittings in meters (Adopted from Hauser 1991)

	Pipe Diameter, mm					
Pipe Fittings	25	32	40	50	80	100
Gate Valve - Open	0.2	0.2	0.3	0.4	0.6	0.7
90 Elbow	0.8	1.1	1.3	1.7	2.7	3.4
45 Elbow	0.4	0.5	0.6	0.8	1.2	1.5
Branch Tee (Straight)	0.8	1.1	1.3	1.7	2.7	3.4
Branch Tee (Side)	1.7	2.1	2.7	3.4	5.4	6.7
Union Coupling	0.2	0.2	0.3	0.4	0.6	0.7
Free Entrance	0.8	1.0	1.2	1.5	2.4	3.1
Screened Entrance*	3.8	4.9	6.1	7.6	12.2	15.3
Pipe Reducer to**	0.2	0.2	0.3	0.4	0.6	0.7

*Assumed to be 5x Free Entrance value (Jordan 1980)
**The equivalent length of reducing the pipe size to this diameter from the next largest diameter.

6. Add the equivalent length to the total length of the pipe from the pipeline profile. If there are more than two pipe sizes, add the equivalent lengths from each pipe size to their respective lengths from the pipeline profile.
7. Use the total length and flow rate to find the actual friction loss, using appendix B. Check again that this value is smaller than the minimum HGL value. If it is, then the pipe sizes have been determined. If not, choose the next largest pipe size and repeat steps 5 and 6.

5.4.1 Velocity Limits

There is one last check to make before the pipe diameter is selected. The water velocity through the pipe has to be between 0.7 meters per second (m/s) and 3 m/s. If the velocity is lower than 0.7 m/s any suspended solids in the water will settle out and collect in the pipe. This can increase the head and lead to clogging in the pipe. Drain valves can control this accumulation but any lapse in maintenance will lead to problems. If the system cannot be designed without avoiding a lower velocity, more frequent line flushing will have to take place or a sedimentation tank installed at the beginning of the pipeline. If the tank is installed, the pipeline will still have to be flushed using the drain valves just not as frequently. If the velocity is greater than 3 m/s the interior of the pipe can be seriously eroded leading to a reduction in the systems design period. A larger pipe size must be selected to reduce the velocity. The flow rate limits for each pipe size have been calculated and tabulated in Table 5.3.

Table 5.3 Pipeline Flow Rate Design Limits (L/s)

Limits	Pipe Diameter, mm					
	25	32	40	50	80	100
Minimum	0.35	0.60	0.90	1.4	3.5	6.0
Maximum	1.4	2.0	3.5	5.0	n/a	n/a

5.4.2 Design Example

Using the peak water demand of 1.3 liters per second previously calculated, the pipeline length of 848 meters and vertical difference of 111 meters determined from the pipeline profile (Figure 11), the pipe diameters can be calculated.

1. Assume forcing the joints together because no PVC cement is available to connect them. The maximum static head of 111 meters is greater than all the pipe sizes, except 25 mm diameter pipe (Table 3). Drawing the line from the source water surface to a point 5 meters above the storage tank water surface reveals a location in the profile for the break-pressure tank placement that is located, from the survey field notes, directly on stake #8 (Figure 5.6). The static head line is redrawn accordingly at an elevation of 951 meters.

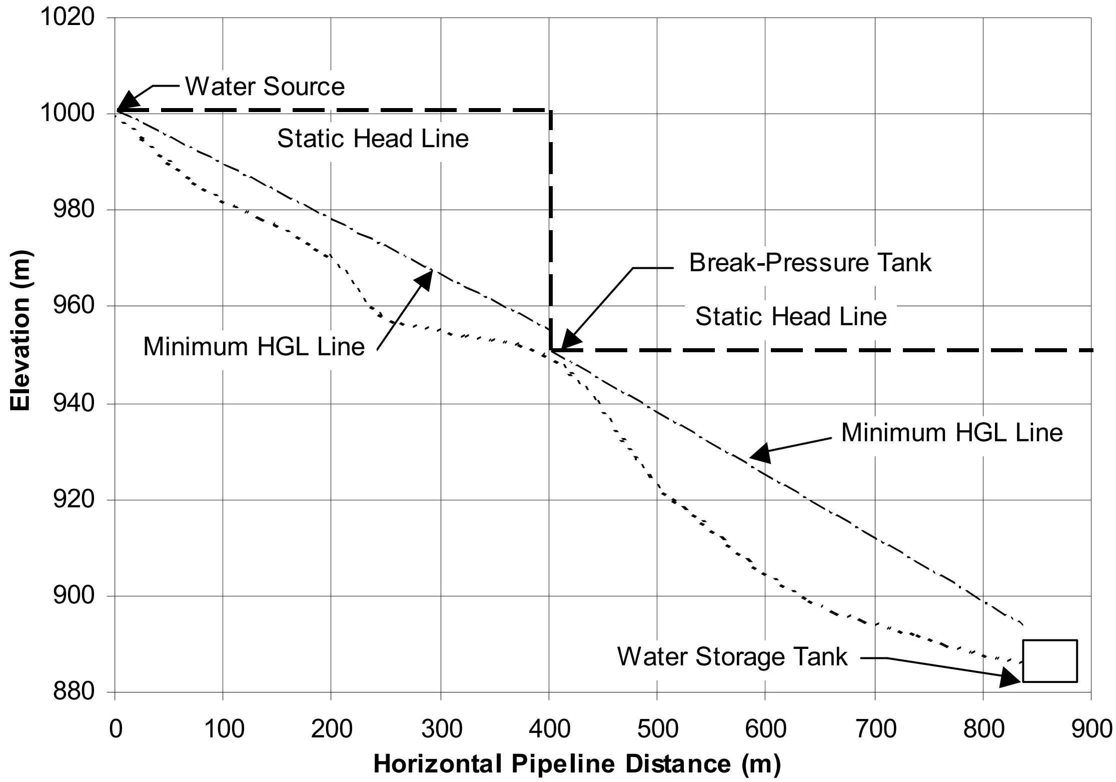

Figure 5.6 Break-Pressure Tank Placement for Design Example

2. First line was too low. Choose spot where break-pressure tank was to raise pipe 5 meters. Extended this new line to the storage tank where the residual head was 8.5 meters.
3. HGL line: Slope = (1001-955)/400 x 100 = *11.5 m/100m*
4. *40 mm diameter pipe = 3.8 m/100m*. Check the residual head with this pipe.
   11.5 – 3.8 = 7.7 x 8.48 = 65.3 + 8.5 = *73.8 meters of residual head* TOO HIGH! Repeat step 2.
5. There will need to be two different sized pipes for this water system. The larger of the two will be placed first. See figure 12 for the two minimum HGL lines.
6. First HGL line: Slope = (1001 – 955)/400 x 100 = *11.5 m/100m*
   Second HGL line: Slope = (951 – 895)/448 x 100 = *12.5 m/100m*
7. First pipe: *40 mm diameter pipe = 3.8 m/100m*
   Second pipe: *32 mm diameter pipe = 11.9 m/100m*
8. First pipe: Screened entrance (6.1), 2 gate valves (0.6) and 4 - 90° elbows (5.2), 2 at the water source and 2 at the break-pressure tank, for total of 11.9 meters.
   Second pipe: Free entrance (1.0), 2 gate valves (0.4), 45° elbow (0.5) and 4 – 90° elbows (4.4), 2 at the break-pressure tank and 2 at the water storage tank, for total of 10.3 meters.
9. First pipe: 11.9 + 400 = *411.9 meters*
   Second pipe: 10.3 + 448 = *458.3 meters*

10. First pipe: 411.9 x 3.8/100 = *15.7 meters of head loss*

    Second pipe: 458.3 x 11.9/100 = *54.5 meters of head loss*

11. First pipe: (1001 – 955) – 15.7 = *30.3 meters residual head* **40 mm diameter pipe** OK!

    Second pipe: (951 – 895) - 54.5 = *1.5 meters residual head* **32 mm diameter pipe** OK!

    Replacing the gate valve before the 40 mm pipe enters the tank with a globe valve and leaving it ¾ of the way open can reduce the residual head entering the break–pressure tank.

12. Check the velocity limits.

    First pipe (40 mm): 0.90 < 1.3 < 3.5 OK!

    Second pipe (32 mm): 0.60 < 1.3 < 2.0 OK!

13. The final pipeline profile is shown in Figure 5.7.

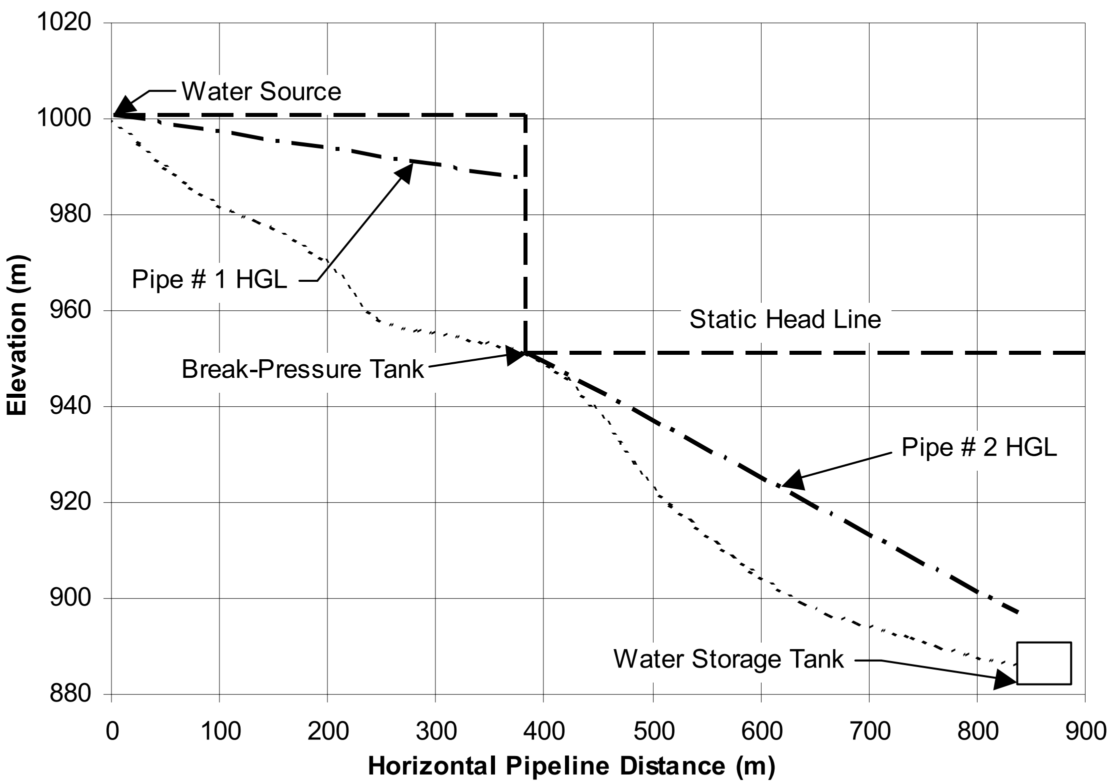

Figure 5.7 Finished Pipeline Design for Design Example

6. PIPELINE CONSTRUCTION

The construction of the pipeline is the most important stage. Up to this point, there have only been small groups of people directly involved in the project and the amount of resources used was small. Now everything that has been conceptually developed and designed has to be placed in the field.

6.1 Organizing Material and Labor

There are two different types of labor, skilled and unskilled. The unskilled labor mostly comes from the community receiving the water supply system and is usually voluntary. Skilled labor cost more but they work everyday. Because of that and their training they work much faster due to familiarity with the job site. Community labor changes everyday as each person in the community is assigned to work a little on the project. No familiarity with the job can be created when the laborers change everyday. The work can be interrupted by market days, weddings, funerals, and so on (Davis & Garvey 1993). Timing is important for construction with a voluntary workforce because it must fit into the community's seasonal pattern of activities. This includes festivals, harvests, religious events, and so on. Voluntary labor should not be viewed as free. People's time has value since they could be using that time on tending farm fields, preparing food, etc. The supervisor should make sure that the people who have volunteered did so of their own accord. There are many accounts of community leaders volunteering and not consoling the community or men volunteering their women for the work. Such volunteers will not be enthusiastic about the job and quality of the will suffer. Ultimately the construction supervisor serves as a technical liaison and project "cheerleader" or overseer trying to keep the workforce motivated about the project. At the beginning of the project, community members are the most enthusiastic and involved. It is at this time that the most difficult parts of the project should be tackled.

Materials and tools should be ordered and on site as soon as the design is complete and before the construction begins. A general list of tools necessary for construction is provided in Table 6.1. Any shortage in materials or tools when the labor is ready to begin can lead to an enormous motivation crusher. Once the project gets moving in the construction phase, every effort should be made to keep it moving. Any shortages should be resolved quickly. Availability of materials and tools within the project site area usually pose the greatest problems. PVC pipe is typically available in 6 meter lengths making them easier to work with. Each worker is usually responsible for delivering and installing one length of pipe on the site during a workday.

Table 6.1 General List of Tools Necessary for Pipeline Construction*

Excavation	GI Pipework
Crowbar	Hacksaw Frame & Blades
Round-edged Shovels	Flat File
Tape Measure	Wire Brush
String or Rope	Pipe Wrenches
Picks and Handles	Pipe Threader & Die
Sledge Hammers	Pipe Vise
Tamping Rods	Oil
Screening Sifter	

Masonry/Concrete Work
Sledge Hammers
Flat-Edged Shovels
Mason Trowels
Screening Sifter
Steel Buckets

*Adapted from Jordan 1980

6.2 Installing Pipeline

This is the most labor intensive and important part of the pipeline construction. There are six steps to installing pipe and they should be followed in this order. They are excavating trenches, bedding trenches, pipe joining, thrust blocking, backfilling trenches and disinfecting pipeline and they are all explained in the following sections. Securing the construction site during construction and when no one is on site is also discussed.

6.2.1 Excavating Trenches

Excavation should begin at the water source and continue on until reaching the water storage tank if break-pressure tanks are to be installed in the system. This will give the crew constructing the tanks enough time to finish building them in time to connect to the pipeline. If no break-pressure tanks need to be installed, excavation can begin really anywhere along the pipeline. Before beginning, the surveyor should identify all of the stakes from the route survey that are missing and reset them using the field survey notes. After resetting the missing stakes, connect the first two stakes along the pipeline route with some rope or string to give the excavation crew a line to follow while digging. This process should be repeated after each survey stake is reached during excavation. If there are any difficulties encountered like rocks or clayey soil where it would be easier to excavate the pipeline around them, the surveyor must resurvey the proposed route and the designer has to check the design to see if the changes will affect the system. Excavation should not move faster than the pipe can be set in the trench and backfilled. This is to avoid having too much trench exposed to the risk of filling in during bad weather and having to excavate the same trench again. This can severely lower moral in the work crew if they are volunteering labor. The trench should never have more than 8 meters of exposed length. This should allow for enough room to join the next 6 meter pipe length and backfill the trench while the excavation crew keeps working.

The trench should ideally be 1 meter deep to avoid the pipe from being damaged by livestock or people walking over it. This also protects the pipe from exposure due to erosion and protects it from extreme temperatures. This is the hardest thing to regulate with a voluntary work crew. Taking the time before excavation begins to explain that the system design life could be severely reduced if the pipe isn't set deep enough usually alleviates these problems. If the trench bottom is composed of rock at 1 meter then 20 cm of the trench bottom will have to be removed and replaced with soil free of rocks. This is important because rocks resting against the pipe can puncture the wall after the trench is backfilled. There is no necessary minimum width for the trench but 45 cm is usually enough room to work preparing the bottom for the pipe and joining the pipe. If the soil is such that 1 meter depth cannot be reached without the trench walls caving in, the trench top should be excavated out at the sides to widen the trench.

Figure 6.1 Pipeline Excavation in Kenya (IRC 1981)

Figure 6.2 Pipeline Excavation in the Dominican Republic (Niskanen 2003)

6.2.2 Bedding Trenches

After the trenches have been excavated, the bottom needs to be prepared for the pipe. Any rocks or rocky soil have to be removed. When setting the pipe, make sure that the it is supported all along its length, including near the joints, by the trench bottom (Figure 6.3). Making a small depression in the trench bottom using selected soil that has passed through the screening sifter and had all the rocks and material of a certain size removed can do this.

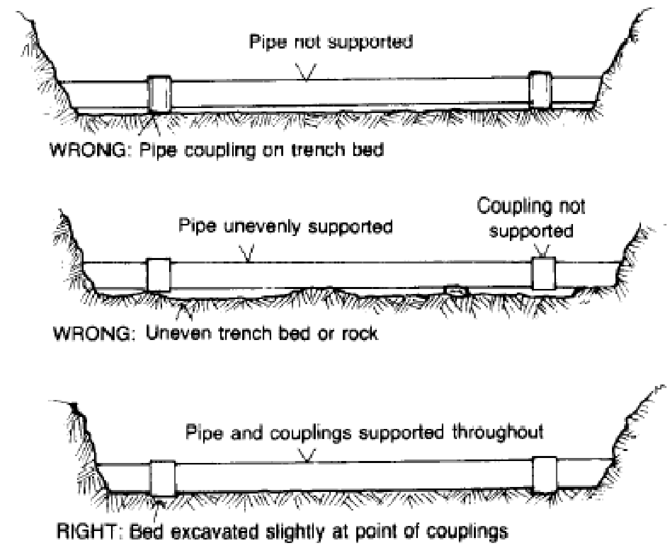

Figure 6.3 Pipeline Bedding Examples (USAID 1982)

6.2.3 Pipe Joining

There are only two ways to join PVC pipe: by forcing them together or by cementing them together using PVC cement. Care should be taken when joining to keep soil from getting in the pipe as it will result in a longer time to flush the system at the end. When applying the cement the pipe surface should be clean. Any sand or soil that mixes with the cement during joining could contribute to joint failure in the future.

6.2.4 Thrust Blocking

These concrete blocks should be installed at every sharp turn in the pipeline. The placement of the blocks on the pipe to resist the forces is shown in Figure 6.4. They are always placed between the pipe and the trench wall. The size of the thrust block is determined by the pipe size, type of fitting, water pressure and soil stability. Design information should be collected from the pipe material manufacturer for more accurate design parameters (USAID 1982). In rural areas, it is sufficient to pour concrete between the trench wall and the pipe so long as it provides full support to the pipe and extends to undisturbed soil.

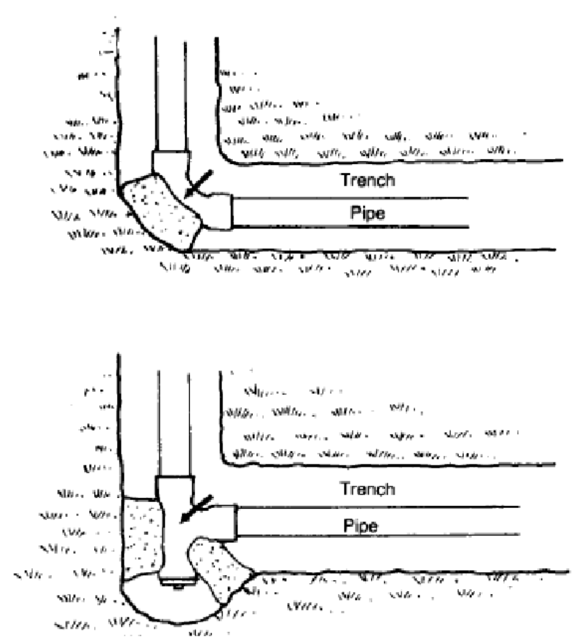

Figure 6.4 Thrust Block Locations (USAID 1982)

6.2.5 Backfilling Trenches

Figure 6.5 Screening Sifter (Dr. Tom Van Dam 2002)

Proper backfilling is essential in protecting the pipe, preventing erosion and preventing too much settling in the trench (USAID 1982). The trench should be backfilled as soon as the pipe has been laid to reduce the risk of curious people and animals from falling in and/or damaging the pipe. At least 30 cm of the pipe being buried should be left exposed to allow room for the next pipe to be joined. The soil that will be used to cover the pipe 30 cm deep should be free of rocks and organic material. This soil can be passed through a screening sifter to remove any rocks from it (Figure 6.5). Sand or sandy loam would be the ideal backfilling material for this part of the trench if it is available. Once the selected soil is available, backfilling can begin. The soil is placed and tamped to compact it on either side of the pipe in 10 cm layers until the pipe is covered by approximately 30 cm of compacted soil (Figure 6.7). After this, the soil previously excavated from the trench can be thrown into the trench, even if rocks are present. Only after there is about 30 cm of extra soil piled in a mound on top of the trench is backfilling complete. If the pipeline is crossing a road or pathway the backfill cannot just be thrown in without compacting. After the initial 30 cm of cover provided is provided for the pipe, the excavation soil has to be compacted in layers of 30 cm each until the surface is reached (Figure 6.6). Finally, a mound of 30 cm tall is placed and compacted.

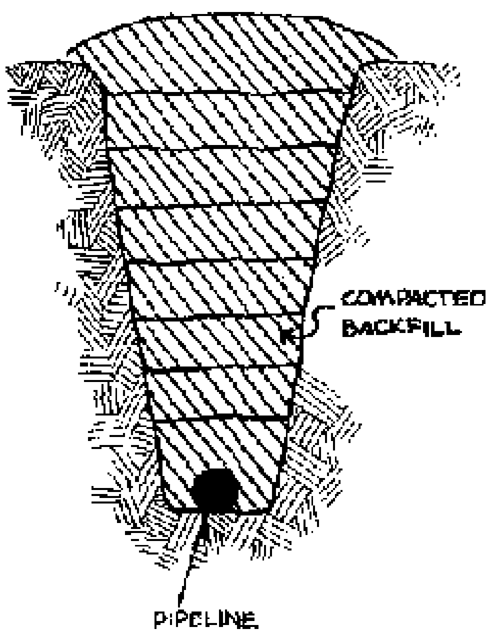

Figure 6.6 Road Backfilling (Jordan 1980)

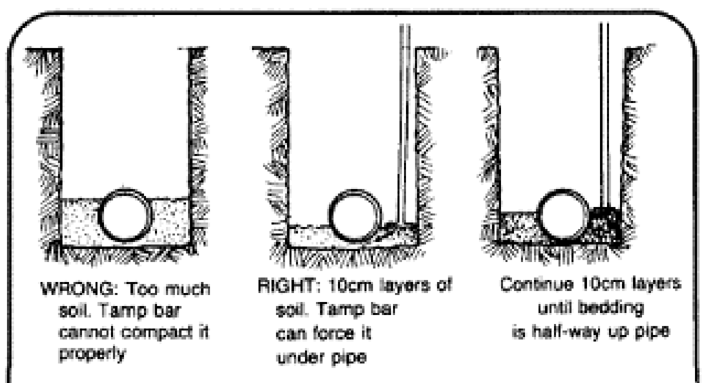

Figure 6.7 Backfilling around Pipe (USAID 1982)

6.2.6 Important Site Considerations

When leaving the construction site for the day, everything should be properly secured and precautions taken to prevent damage to the pipeline. Children and their curiosity will always pose a problem. Though not deliberate, their curiosity can to much damage and repetition of work. Adults, especially ones from other communities, are also a curious. Sections of pipe and fittings could disappear overnight from individuals "visiting" the site. A more common problem is that of heavy livestock stepping on pipe and damaging it. Also (more serious to community members) open trenches pose a risk to these animals who, in the night, fall into them breaking their limbs maiming them or worse breaking their necks killing them. Common approaches to preventing these problems from occurring include covering the end of the exposed pipe in the trench where work has ended for the day with thorny bushes and carefully placed large rocks. The end of the pipe should also be plugged to prevent critters from making a home. Do not install the attractive control valves unless the valve boxes can be installed the same day. Removing the valve handle will also prevent tampering (Jordan 1980). These are all suggestions and differ depending on the local culture and economy within the site area.

6.3 Break-Pressure Tank Construction

The break-pressure tank has to be constructed before the excavation of the pipeline reaches it. Excavation can be started while the tank is being constructed so long as the tank is complete when the excavating crew reaches it. The tank needs to be constructed by skilled labor since it has to be made out of concrete or masonry. For more information on concrete and masonry construction, refer to Chapter 19 in Jordan's Book "A Handbook of Gravity-Flow Water Systems". The tanks do not need to be designed to retain a certain volume of water. They just need to be able to discharge the same flow rate that is entering the tank. The typical dimensions for masonry tanks are 20 cm thick walls, 40 cm inner width and length (80 cm length if using a float valve), and 50 cm depth with a 10 cm thick concrete base (Jordan 1980). Besides what is shown in Figure 6.8, the inlet pipe should be installed outside of the masonry wall. If there were any damage to this pipe, the tank wall would have to be taken apart to repair it. If there are no overflows installed at the water source or water storage tank, then an overflow pipe should be installed in the break-pressure tank and proper drainage provided for the run-off. Flow into the tank can be regulated with a float valve. The float valve is installed in the inlet and operates much like the plunger

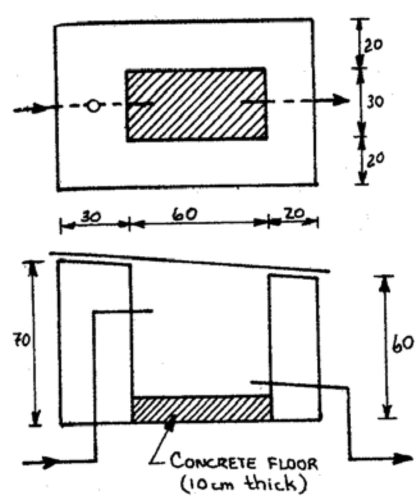

Figure 6.8 Break-Pressure Tank Design (Jordan 1980)

in a standard American toilet. As the water rises in the tank, it pushes the float higher and slowly closes the intake valve. Stopping the intake can have serious consequences for the next structure upstream from the tank if it does not have an overflow pipe installed. Excavation for the tank should be 30 cm into firm soil, and the floor of the excavation leveled, compacted and filled with 10 cm layer of gravel. The tank wall should be a minimum of 20 cm above the ground and the soil should be sloping away from it. Drainage should also be placed around the tank to prevent any run-off from contaminating the water (Jordan 1980). Choosing to enclose the top of the tank depends on the community. The float valves and other structures can easily be taken by strangers or even accidentally damaged by curious children as explained earlier. It is suggested that a metal lid be attached to the top and locked (Figure 6.9).

Figure 6.9 Finished Break-Pressure Tank in Dominican Republic (Niskanen 2003)

Figure 6.10 Break-Pressure Tank Under Construction in the Dominican Republic (Niskanen 2003)

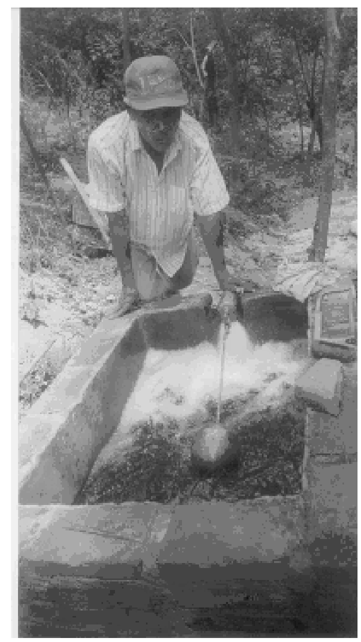

Figure 6.11 Break-Pressure Tank with Float Valve in Honduras (Simpson 2002)

6.4 Valve Box Installation

All control and drain valves in the pipeline need to be accessed for periodic maintenance. Valve boxes provide a means of access. The easiest and cheapest box to install is not even a box. Cutting a small section of GI pipe and placing it over the control or drain valve before backfilling keeps the valve from being covered (Figure 30). The proper sized pipe to use depending on the valve diameter can be determined from table 8. Placing a GI cap over the valve "box" will keep out rain, soil, small animals and curious neighbors without the proper tools.

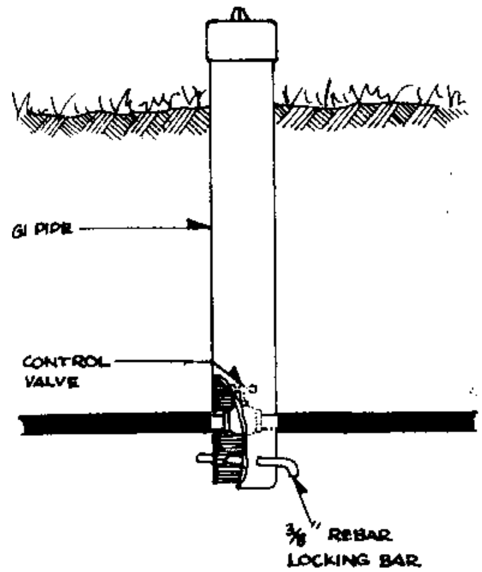

Figure 6.12 GI Pipe Valve Box (Jordan 1980)

Table 6.2 GI Pipe Valve Box Size Determination

Valve Size (mm)	GI Pipe Size (mm)
25	80
32	80
40	80
50	100
80	150
100	200

6.5 Marking the Pipeline Route

After all of the construction has been finished, permanent markers have to be set along the pipeline to help identify it for future maintenance and repair. A short piece of rebar driven into the ground serves as a good marker. To protect the rebar markers, follow the same methods and using the same materials used to install the valve boxes; set a short piece of GI pipe around the marker and cap it. These markers should be placed at important points in the pipeline, offset exactly 150 meters and marked with an arrow indicating what side the pipeline is on. Sharp changes in direction and pipe size reductions all need markers to identify them. Also place the markers at least every 200 meters along the pipeline in open areas and every 50 meters in jungle or overgrown areas. After all the markers have been placed, a surveyor needs to create a map of where all the markers are located as well as all air release, drain and control valve located. A copy should be kept with the community and with the agency that supervised the construction.

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i. Designing a System of Gravity Flow
ii. Methods of Water Treatment
iii. Selecting Pipe Materials
iv. Installing Pipes
v. Selecting a Source of Surface Water

APPENDIX A
ENGLISH/METRIC CONVERSION FACTORS

Conversion Factors

English to Metric	Metric to English
1 in = 2.54 cm	1 cm = 0.39 in
1 ft = 30.48 cm	1 m = 39 in = 3.28 ft
1 yd = 91.44 cm	1 km = 3280 ft = 0.62 miles
1 mile = 1609 m = 1.6 km	1 gm = 0.035 oz
1 oz = 28.4 gm	1 kg = 35 oz = 2.2 lbs
1 lb = 450 gm = 0.45 kg	1 liter = 1.1 qt = 0.035 ft^3
1 qt = 0.91 liters	1 m^3 = 35.31 ft^3
1 gal = 3.63 liters	
1 in^3 = 16.39 cm^3	
1 ft^3 = 28.3 liters	

English	Metric
in = inch	mm = millimeter
ft = foot	cm = centimeter
yd = yard	m = meter
oz = ounce	km = kilometer
lb = pound	gm = gram
qt = quart	kg = kilogram
gal = gallon	
	1 km = 1000 m
1 yd = 3 ft	1 m = 100 cm
1 ft = 12 in	1 cm = 10 mm
1 lb = 16 oz	1 kg = 1000 gm
1 gal = 4 qt	1 m^3 = 1000 liters
1 ft^3 = 7.48 gal = 1728 in^3	1 liter = 1000 cm^3
1 mile = 5280 ft	

APPENDIX B
VERTICAL & HORIZONTAL DISTANCE TABLES

Vertical Distance Determination Table using Abney Level

Vertical Angle (Degrees)

Ground Distance (m)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	0.0	0.0	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.2	0.2	0.2	0.3
2	0.0	0.1	0.1	0.1	0.2	0.2	0.2	0.3	0.3	0.3	0.4	0.4	0.4	0.5	0.5
3	0.1	0.1	0.2	0.2	0.3	0.3	0.4	0.4	0.5	0.5	0.6	0.6	0.7	0.7	0.8
4	0.1	0.1	0.2	0.3	0.3	0.4	0.5	0.6	0.6	0.7	0.8	0.8	0.9	1.0	1.0
5	0.1	0.2	0.3	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0	1.0	1.1	1.2	1.3
10	0.2	0.3	0.5	0.7	0.9	1.0	1.2	1.4	1.6	1.7	1.9	2.1	2.2	2.4	2.6
15	0.3	0.5	0.8	1.0	1.3	1.6	1.8	2.1	2.3	2.6	2.9	3.1	3.4	3.6	3.9
20	0.3	0.7	1.0	1.4	1.7	2.1	2.4	2.8	3.1	3.5	3.8	4.2	4.5	4.8	5.2
25	0.4	0.9	1.3	1.7	2.2	2.6	3.0	3.5	3.9	4.3	4.8	5.2	5.6	6.0	6.5
30	0.5	1.0	1.6	2.1	2.6	3.1	3.7	4.2	4.7	5.2	5.7	6.2	6.7	7.3	7.8
35	0.6	1.2	1.8	2.4	3.0	3.7	4.3	4.9	5.5	6.1	6.7	7.3	7.9	8.5	9.1
40	0.7	1.4	2.1	2.8	3.5	4.2	4.9	5.6	6.3	6.9	7.6	8.3	9.0	9.7	10.4
45	0.8	1.6	2.4	3.1	3.9	4.7	5.5	6.3	7.0	7.8	8.6	9.4	10.1	10.9	11.6
50	0.9	1.7	2.6	3.5	4.4	5.2	6.1	7.0	7.8	8.7	9.5	10.4	11.2	12.1	12.9

Vertical Angle (Degrees)

Ground Distance (m)	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
1	0.3	0.3	0.3	0.3	0.3	0.4	0.4	0.4	0.4	0.4	0.4	0.5	0.5	0.5	0.5
2	0.6	0.6	0.6	0.7	0.7	0.7	0.7	0.8	0.8	0.8	0.9	0.9	0.9	1.0	1.0
3	0.8	0.9	0.9	1.0	1.0	1.1	1.1	1.2	1.2	1.3	1.3	1.4	1.4	1.5	1.5
4	1.1	1.2	1.2	1.3	1.4	1.4	1.5	1.6	1.6	1.7	1.8	1.8	1.9	1.9	2.0
5	1.4	1.5	1.5	1.6	1.7	1.8	1.9	2.0	2.0	2.1	2.2	2.3	2.3	2.4	2.5
10	2.8	2.9	3.1	3.3	3.4	3.6	3.7	3.9	4.1	4.2	4.4	4.5	4.7	4.8	5.0
15	4.1	4.4	4.6	4.9	5.1	5.4	5.6	5.9	6.1	6.3	6.6	6.8	7.0	7.3	7.5
20	5.5	5.8	6.2	6.5	6.8	7.2	7.5	7.8	8.1	8.5	8.8	9.1	9.4	9.7	10.0
25	6.9	7.3	7.7	8.1	8.5	9.0	9.4	9.8	10.2	10.6	11.0	11.3	11.7	12.1	12.5
30	8.3	8.8	9.3	9.8	10.3	10.7	11.2	11.7	12.2	12.7	13.1	13.6	14.1	14.5	15.0
35	9.6	10.2	10.8	11.4	12.0	12.5	13.1	13.7	14.2	14.8	15.3	15.9	16.4	17.0	17.5
40	11.0	11.7	12.4	13.0	13.7	14.3	15.0	15.6	16.3	16.9	17.5	18.2	18.8	19.4	20.0
45	12.4	13.2	13.9	14.6	15.4	16.1	16.9	17.6	18.3	19.0	19.7	20.4	21.1	21.8	22.5
50	13.8	14.6	15.4	16.3	17.1	17.9	18.7	19.5	20.3	21.1	21.9	22.7	23.5	24.2	25.0

Note: May interpolate between values and sum distances for results
Example: Vertical angle 2.5, Distance 53 meters. 50+3 @ 2 Degrees = 1.7 + 0.1 = 1.8 and 50+3 @ 3 Degrees = 2.6 + 0.2 = 2.8 Interpolate the two to get (1.8 + 2.8)/2 = *2.3 meters*

Horizontal Distance Determination Table using Abney Level

Vertical Angle (Degrees)

Ground Distance (m)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
2	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	1.9	1.9	1.9
3	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	2.9	2.9	2.9	2.9	2.9
4	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	3.9	3.9	3.9	3.9	3.9	3.9
5	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	4.9	4.9	4.9	4.9	4.9	4.9	4.8
10	10.0	10.0	10.0	10.0	10.0	9.9	9.9	9.9	9.9	9.8	9.8	9.8	9.7	9.7	9.7
15	15.0	15.0	15.0	15.0	14.9	14.9	14.9	14.9	14.8	14.8	14.7	14.7	14.6	14.6	14.5
20	20.0	20.0	20.0	20.0	19.9	19.9	19.9	19.8	19.8	19.7	19.6	19.6	19.5	19.4	19.3
25	25.0	25.0	25.0	24.9	24.9	24.9	24.8	24.8	24.7	24.6	24.5	24.5	24.4	24.3	24.1
30	30.0	30.0	30.0	29.9	29.9	29.8	29.8	29.7	29.6	29.5	29.4	29.3	29.2	29.1	29.0
35	35.0	35.0	35.0	34.9	34.9	34.8	34.7	34.7	34.6	34.5	34.4	34.2	34.1	34.0	33.8
40	40.0	40.0	39.9	39.9	39.8	39.8	39.7	39.6	39.5	39.4	39.3	39.1	39.0	38.8	38.6
45	45.0	45.0	44.9	44.9	44.8	44.8	44.7	44.6	44.4	44.3	44.2	44.0	43.8	43.7	43.5
50	50.0	50.0	49.9	49.9	49.8	49.7	49.6	49.5	49.4	49.2	49.1	48.9	48.7	48.5	48.3

Vertical Angle (Degrees)

Ground Distance (m)	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
1	1.0	1.0	1.0	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
2	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.8	1.8	1.8	1.8	1.8	1.8	1.7	1.7
3	2.9	2.9	2.9	2.8	2.8	2.8	2.8	2.8	2.7	2.7	2.7	2.7	2.6	2.6	2.6
4	3.8	3.8	3.8	3.8	3.8	3.7	3.7	3.7	3.7	3.6	3.6	3.6	3.5	3.5	3.5
5	4.8	4.8	4.8	4.7	4.7	4.7	4.6	4.6	4.6	4.5	4.5	4.5	4.4	4.4	4.3
10	9.6	9.6	9.5	9.5	9.4	9.3	9.3	9.2	9.1	9.1	9.0	8.9	8.8	8.7	8.7
15	14.4	14.3	14.3	14.2	14.1	14.0	13.9	13.8	13.7	13.6	13.5	13.4	13.2	13.1	13.0
20	19.2	19.1	19.0	18.9	18.8	18.7	18.5	18.4	18.3	18.1	18.0	17.8	17.7	17.5	17.3
25	24.0	23.9	23.8	23.6	23.5	23.3	23.2	23.0	22.8	22.7	22.5	22.3	22.1	21.9	21.7
30	28.8	28.7	28.5	28.4	28.2	28.0	27.8	27.6	27.4	27.2	27.0	26.7	26.5	26.2	26.0
35	33.6	33.5	33.3	33.1	32.9	32.7	32.5	32.2	32.0	31.7	31.5	31.2	30.9	30.6	30.3
40	38.5	38.3	38.0	37.8	37.6	37.3	37.1	36.8	36.5	36.3	36.0	35.6	35.3	35.0	34.6
45	43.3	43.0	42.8	42.5	42.3	42.0	41.7	41.4	41.1	40.8	40.4	40.1	39.7	39.4	39.0
50	48.1	47.8	47.6	47.3	47.0	46.7	46.4	46.0	45.7	45.3	44.9	44.6	44.1	43.7	43.3

Note: May interpolate between values and sum distances for results
Example: Vertical angle 9.5, Distance 75 meters. 50+25 @ 9 Degrees = 49.4 + 24.7 = 74.1 and 50+25 @ 10 Degrees = 49.2 + 24.6 = 73.8 Interpolate the two to get (74.1 + 73.8)/2 = *74.0 meters*

APPENDIX C
FRICTION HEAD LOSS TABLES

Friction Head Loss Table in m/100m for PVC Pipe

Flow (Liters/Sec)	Pipe Diameter, mm					
	25	32	40	50	80	100
0.05	0.11					
0.10	0.35	0.11				
0.15	0.72	0.22				
0.20	1.22	0.36	0.12			
0.25	1.84	0.54	0.18			
0.30	2.58	0.75	0.25			
0.35	3.45	1.00	0.33	0.11		
0.40	4.43	1.28	0.42	0.14		
0.45	5.54	1.59	0.52	0.17		
0.50	6.76	1.93	0.63	0.21		
0.55	8.11	2.31	0.76	0.25		
0.60	9.58	2.72	0.89	0.29		
0.65	11.2	3.17	1.03	0.34		
0.70	12.9	3.64	1.18	0.39		
0.75	14.7	4.15	1.34	0.44		
0.80	16.7	4.70	1.52	0.50		
0.85	18.7	5.27	1.70	0.56		
0.90	20.9	5.88	1.89	0.62		
0.95	23.2	6.52	2.10	0.68		
1.0	25.7	7.19	2.31	0.75		
1.1	30.9	8.64	2.77	0.90		
1.2	36.6	10.2	3.26	1.06	0.10	
1.3	42.8	11.9	3.80	1.23	0.12	
1.4	49.5	13.8	4.38	1.41	0.14	
1.5		15.7	4.99	1.61	0.15	
1.6		17.8	5.65	1.82	0.17	
1.7		20.0	6.35	2.04	0.19	
1.8		22.4	7.09	2.27	0.22	
1.9		24.9	7.87	2.52	0.24	
2.0		27.5	8.69	2.78	0.26	0.09
2.5			13.4	4.25	0.40	0.13
3.0			19.1	6.04	0.56	0.18
3.5			25.8	8.14	0.74	0.24
4.0				10.6	0.96	0.31
4.5				13.3	1.20	0.39
5.0				16.3	1.47	0.48
6.0					2.08	0.67
7.0					2.79	0.90
8.0					3.62	1.16
9.0					4.54	1.45
10.0					5.58	1.78

Note: Based on Haaland's equation and an equivalent sand roughness (k_s) of 0.1 mm for smooth pipes. This value takes into account joints, wear and encrustation with solids.

Friction Head Loss Table in m/100m for GI Pipe

Flow (Liters/Sec)	Pipe Diameter, mm					
	25	32	40	50	80	100
0.05	0.11					
0.10	0.38	0.11				
0.15	0.81	0.23				
0.20	1.38	0.40	0.13			
0.25	2.11	0.60	0.20			
0.30	2.98	0.84	0.27			
0.35	4.00	1.13	0.36	0.12		
0.40	5.17	1.45	0.47	0.15		
0.45	6.50	1.81	0.58	0.19		
0.50	7.97	2.22	0.71	0.23		
0.55	9.59	2.66	0.85	0.27		
0.60	11.4	3.15	1.00	0.32		
0.65	13.3	3.67	1.16	0.37		
0.70	15.3	4.24	1.34	0.43		
0.75	17.6	4.84	1.53	0.49		
0.80	19.9	5.49	1.73	0.55		
0.85	22.4	6.17	1.94	0.62		
0.90	25.1	6.90	2.17	0.69		
0.95	27.9	7.66	2.41	0.77		
1.0	30.9	8.47	2.66	0.85		
1.1	37.3	10.2	3.20	1.01		
1.2	44.2	12.1	3.78	1.20	0.11	
1.3	51.8	14.1	4.42	1.40	0.13	
1.4	60.0	16.4	5.10	1.61	0.15	
1.5		18.7	5.84	1.84	0.17	
1.6		21.3	6.62	2.08	0.19	
1.7		24.0	7.45	2.34	0.21	
1.8		26.8	8.34	2.61	0.24	
1.9		29.8	9.27	2.90	0.26	
2.0		33.0	10.2	3.21	0.29	0.09
2.5			15.9	4.95	0.44	0.14
3.0			22.7	7.08	0.62	0.20
3.5			30.8	9.58	0.84	0.27
4.0				12.5	1.09	0.35
4.5				15.7	1.36	0.43
5.0				19.3	1.67	0.53
6.0					2.39	0.76
7.0					3.23	1.02
8.0					4.19	1.32
9.0					5.28	1.66
10.0					6.50	2.04

Note: Based on Haaland's equation and an equivalent sand roughness (k_s) of 0.2 mm for GI pipes. This value takes into account joints, wear and encrustation with solids.