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Chapter

Cost-Effective, Sanitary Shallow Water Wells for Agriculture and Small Communities Using Mechanized Tube Well Installation

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Abstract

Multiple studies have adequately demonstrated the connection between sanitary water supply for developing communities and sustainable economic growth. Unfortunately, the cost of traditional drilled water wells prevents their more rapid installation across much of the developing world. Numerous communities and agricultural areas could benefit greatly from access to groundwater less than 10 meters deep. Researchers have developed a means to mechanize shallow tube well installation to provide sanitary water wells of modest capacity. A hydraulic ram for agricultural fence post driving has been attached to a small PUP utility vehicle and repurposed to drive small diameter well pipe. This chapter will outline the water access problem from a global perspective, describe the traditional means of construction for sanitary water wells in remote areas and their relative costs, and detail the recent advancements and potential cost savings provided by a simple mechanized means to install tube wells in shallow water table areas.

Keywords: irrigation, potable water, sanitary water, shallow wells, tube well installation

1. Introduction

Globally, 1.8 billion people (22.5%) use an unimproved source of drinking water with no protection against contamination from feces. Safe drinking water, combined with good hygiene and improved general sanitation, is generally known as WASH. Improved WASH conditions could potentially prevent around 842,000 deaths each year [1]. The WASH acronym specifically stands for: safe Water Access for drinking and household use that is free from chemical and biological pollutants, Sanitation including access to a toilet (latrine) that safely separates human excreta from the environmental, and Hygiene focusing on public health and prevention of the transmission of fecal-oral diseases [2]. This chapter will examine the state of the water component of WASH programing in the developing world. Traditional techniques to

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access groundwater will be reviewed, and recent work using mechanized tube well installation will introduce the Well-Driver PUP technology [3]. Implementation of this technology could provide meaningful progress toward addressing the sixth U.N. Sustainable Development Goal (SDG): "To ensure availability and sustainable management of water and sanitation for all", which incidentally will help drive progress across many other SDGs [1]. People must have equitable and affordable access to safe and sufficient water, that is palatable and in sufficient quantity for both drinking and domestic purposes [4]. On-going research proposes to increase access to subsurface water by improving the operational capabilities of the Well-Driver PUP (Purdue Utility Project) vehicle [5]. Implementation and dissemination of this novel vehicle technology could improve access to safe water for drinking and domestic purposes in developing countries and can play a key role in WASH programing.

1.1 Water quality access

In developing countries, access to safe water is critical to the quality of life and the potential for economic growth. Water-related diseases pose a major risk to individuals in developing countries, through the consumption and use of unsafe and poor quality water sources [4]. Often, water sources are prone to contamination, due to the movement of contaminates through surface transport processes. Water contamination due to surface runoff, leaching, and pollution from agro-chemicals into groundwater sources can lead to increased risks of humans contracting waterborne pathogens from drinking water. Poor waste management and the inappropriate disposal of human and animal excreta can result in higher levels of contamination in water resources. The presence of excreta in water used for human consumption, often leads to serious, but preventable, diseases, such as typhoid and cholera. Water that is high in fecal coliform bacteria, which is generally greater than 99% *Escherichia coli*, indicates a level of human and animal waste contamination in the water and the possible presence of other harmful pathogens [4].

Excess fertilizer use can lead to the leaching of dissolved nitrogen through the soil profile, resulting in additions of nitrate into groundwater resources. The consumption of drinking water containing nitrate higher than 2 mg/L for adults has also been shown to lead to adverse health effects, specifically higher risks of cancers [6]. For mammals, the adverse health pathway is nitrate within drinking water increasing the production of N-nitroso compounds, which are highly carcinogenic [7]. Infants ingesting drinking water containing a high nitrate content can have low oxygen levels in their blood, leading to a potentially fatal condition, known as "blue baby syndrome." Access to water that is safe and considered of good quality is essential to overall community health and healthy living conditions for people and domestic livestock around the world.

1.2 Water quantity access

In many locations around the world, people use unsafe water sources or lack sufficient access to water for both drinking and domestic purposes, creating very unhealthy circumstances for these individuals. This is because in developing countries, clean water access is not always possible. Water resource use is often constrained due to the terrain and hydrology of a specific location. Particularly in sub-Saharan Africa, women and children often walk great distances to obtain access to water for household use. In many regions, water is carried on top of one's head, while simultaneously leading and watering

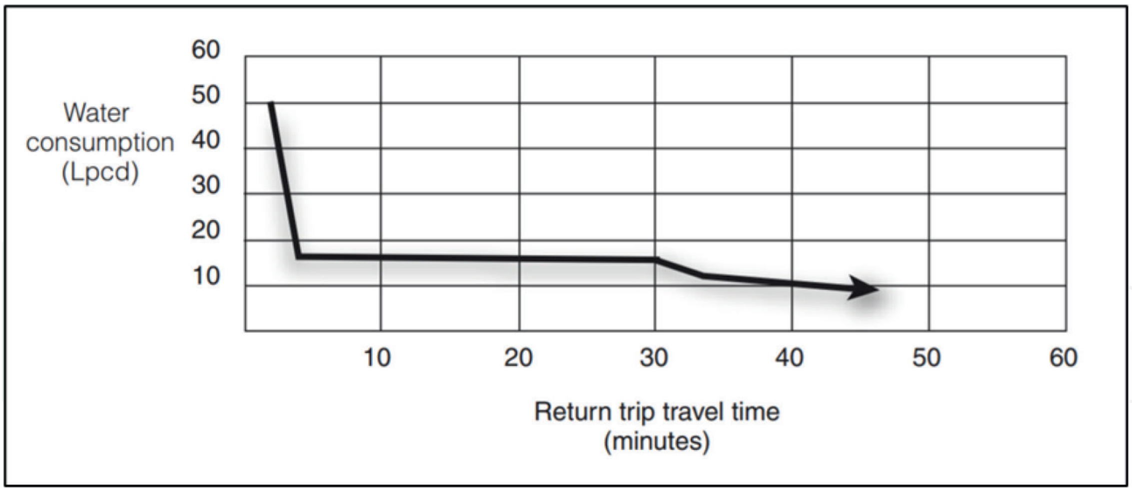

Figure 1.
The relationship between water collected, journey time, & domestic consumption [8].

livestock. According to the SPHERE humanitarian standards, for any water-based source, the distance from the household to the nearest waterpoint should not exceed 500 m, and the queue time for water sources should be no greater than 30 min [4]. In situations requiring longer travel times, individuals are far less likely to collect larger amounts of water, as seen in **Figure 1**.

These data indicate that families, especially those living farther away from a water source, will only collect the basic minimum amounts of water required for survival. Within a just society, all people would have an equitable and an affordable means of access to a sufficient supply of water that could be used for drinking, hygiene, and domestic purposes [4]. **Table 1** displays the SPHERE recommended minimum total water need for basic survival. The average water used for drinking, cooking, and personal hygiene in any household is 15 L per person per day, or for an average month of 30 days, 450 L. For a family of five, 2250 L or 2.25 ton of water would be required to meet the minimum demand for all domestic uses. Obviously, the amount of water required for an individual can vary, based-on the community and context, but human living needs require a minimum level of water of survival [4]. When this water is not located in the home and must be collected elsewhere, productive time for alternative activity is lost [9]. Women and children are disproportionately impacted by this cruel labor requirement. For women, it shortens the available time for them to be with their families, provide childcare, perform household activities, and engage in entrepreneurial enterprises. Water collection by both boys and girls, can take time away from their educations, and sometimes, it can even prevent them from attending school

Survival needs: water intake (drinking and food)	**2.5–3 liters per day**	**Depends on: the climate and individual physiology**
Basic hygiene practices	2–6 liters per day	Depends on: social and cultural norms
Basic cooking needs	3–6 liters per day	Depends on: food type, social as well as cultural norms
Total basic water needs	7.5–15 liters per day	

Table 1.
Simplified table of basic survival water needs [4].

altogether. The brutality of having to collect water and transport it on a daily basis robs both women and children of their most valuable resource [9].

1.3 Current methods of sourcing groundwater

There are three primary types of wells utilized to obtain groundwater resources for both drinking and domestic purposes. These methods include hand-dug wells, drilled wells, and driven tube wells. Hand-dug wells are constructed manually and require individuals to dig until below the water table [10]. These wells must be dug during a dry season in order to ensure that the water table is at the lowest possible level. In situations where the water table has receded below the depth of the well, the bottom of the well must be dug deeper to access the water table [11]. Hand-dug wells have a circular cross-section and should be lined with stone, brick, or tile to prevent the earthen sidewalls from collapsing inward. This type of well does not have a continuous casing and grouting, making it far more prone to contamination from surrounding surface sources [12].

The most common method for obtaining groundwater is by creating a drilled well. Unfortunately, this technique is always the most expensive of the methods considered, but you get what you pay for. This type of installation produces a dependable, long-term, sanitary well, and it is considered the "gold standard" of groundwater access. Through this means, groundwater is accessible to deeper levels than by other options. Throughout the world, the general preference for WASH programming is to install a deep-drilled well to access groundwater having a lower likelihood of containments. However, in developing countries, there are often not enough reputable companies with available drilling equipment to meet the demand for installed wells, at an affordable cost, in a timely manner. In Haiti for example, there are very few drilling companies. Even when an organization or individual has sufficient funds to install a deep well, the wait time for a drilling company to come and install a new well can be over 1 year [13].

A driven tube well can be an acceptable alternative to traditional drilled wells under certain conditions [14]. Tube wells are constructed with a well point connected to galvanized steel pipe, which serves as the well casing. The well point is sharpened and driven through the soil, accessing groundwater through a fine mesh or perforation on its circumference near the point. This type of well is commonly driven by hand, with a tripod system set-up, and installation tends to be a very labor-intensive effort. Reducing the labor element in the tube well installation process could potentially make this type of well more feasible across a considerable range of developing territory [15, 16]. The Purdue Well-Driver PUP mechanizes the tube well installation process by using a hydraulic ram. This mitigates the intensive labor component generally accompanied with driven wells and dramatically reduces the installed cost of sanitary water sources, through the improved productivity of equipment and personnel involved. The remainder of this chapter describes the current status of groundwater access, the Well-Driver PUP technology, and the economic potential of the technology.

1.4 Individual access to groundwater from wells

The physical water access point is a critical element of all wells, but it is particularly vital to community wells or those with shared access. Modern well standards require that the designer do everything possible to prevent contamination on the surface from entering the well aquifer. This criterion alone discourages the investment of effort and resources into hand-dug wells, as it is far more difficult to maintain sanitary access conditions for these types of wells. For all wells in general, surface-to-aquifer contamination results from two sources: down-the-borehole backwash and beside-the-casing downward drainage. To seal the casing from the surface, all modern wells should have adequate concrete pads surrounding the casing as it rises above the surface of the ground. The pads need to be extra strong in community well situations to withstand the burden of heavy traffic near the well-head. The pads need to be properly sloped, so the drainage is carried away from the well-head and does not accumulate nearby. The concrete pads for pumps must be left to cure adequately before the pump head and water outlet assemblies are installed. Down-the-borehole contamination is best prevented by using a check valve, sometimes called a backflow preventer, in the pump assembly. The process that must be prevented is a syphon from an above-ground water storage tank back-down into the aquifer. Any contamination present in a storage tank could potentially be injected into an underground aquifer during a syphon event at a wellhead. A community water bucket dropped into a hand-dug well poses essentially the same risk of contamination. For a drilled or driven well, a hand pump or an electric pump in the casing is the recommended means to keep a water well access draw-point sanitary and safe for all patrons.

2. Review of groundwater access technologies

This section will contain a review of groundwater access options and the types of wells and drilling methods used throughout the world. Hand-dug wells and drilled wells will be explored. The components required to install a tube well are introduced, along with a discussion of previous tube well installations using the prototype Well-Driver PUP.

2.1 Groundwater accessed drinking water options

Water sources are often classified as "improved" or "unimproved." Improved sources are piped public water into homes, public standpipes, water wells or boreholes, protected (lined) dug or hand-dug wells, protected springs, bottled water, and rainwater collection [17]. Unimproved sources are unprotected wells or springs, sachet water, vendors, tanker-trucks, and surface waters [17]. International WASH efforts tend to push communities toward the installation of improved water sources. Common components within current WASH programming efforts include community involvement through the establishment of a community-led WASH committees, the construction of new water access points, the rehabilitation of pre-existing water sources, the installations of new wells or community boreholes, small town water systems, and pipe extensions [18].

In many cases, women, poor households, and marginalized groups disproportionately experience the negative impacts of inadequate WASH resources. This primarily occurs, because these groups are more than likely to have limited access to WASH services [19–22]. Marginalized groups often have less input, both at the household and at the community level, in decision-making processes and the governance of resources relating to WASH [23]. Studies show that income, education, household size, and region are all significant predictors of access to improved water and sanitation

[24, 25]. Therefore, many WASH programs and interventions utilize the methodology of empowering beneficiaries, which increases equitable access and the sustainability of water and sanitation infrastructure solutions [26–28].

2.2 Groundwater

Water that is below the water table in soil is generally called “groundwater” [29]. This is underground water that can be removed by wells. The groundwater zone acts as a natural reservoir or system filled with fresh water. “An aquifer is a saturated bed, formation, or group of formations which yields water in sufficient quantity to be used for economic purposes” [14, 29]. Water storing formations and groundwater reservoirs are synonymous for “aquifer”. There are two main types of aquifers: confined and unconfined [29]. An unconfined aquifer is where water enters from the soil surface and passes through the soil profile to enter the aquifer. A confined aquifer has an impermeable geological layer that prevents surface water from directly flowing into the aquifer. The installation of a well or borehole under these conditions includes drilling through the geological layer confining the aquifer, in order to move the water from the deep aquifer, up to some higher level. In this way, water wells are accessed for groundwater across the globe, for both drinking and domestic water uses. Properly accessed groundwater is sanitary, and it is generally sustainable.

2.3 Types of wells

In many countries, particularly those in sub-Saharan Africa, individuals obtain their drinking water from community wells, which include both protected wells and boreholes. These water access points are most commonly located outside of dwellings and are in the form of a public tap or standpipe. The terms “wells” and “boreholes” tend to be used interchangeably worldwide. A borehole is the generalized term for any narrow shaft drilled into the ground. It generally contains both a pipe casing and a well screen, to prevent the entry of soil into the water flow [30]. There are three primary methods of well construction: dug, drilled, and driven wells. Water wells can be installed either through manual methods or with powered tools [11].

2.3.1 Dug or hand-dug wells

Traditionally, dug wells are excavated by hand, using simple tools such as a pick and shovel, with a bucket on a rope to remove cuttings [11]. **Figure 2** portrays an example of a hand-dug well installation. Although some pieces of dug well construction may be mechanized to a certain degree, the process to construct this kind of well is very manual labor intensive. A dug well is excavated below the water table during the dry seasons, until the incoming water exceeds the digger’s bailing rate. These wells should be circular in cross-section and lined with stones, bricks, tile, or other material to prevent the well from collapsing inward. This type of well does not have a continuous casing and grouting, making it more prone to contamination from surrounding surface sources. Dug wells have larger diameters and expose larger areas of the aquifer to the excavation. Therefore, these wells are able to obtain water from less-permeable materials, such as very fine sand, silt, or clay [12].

Most wells of this type are shallow and not able to achieve the depths that a bored or driven well can. This type of well often goes dry during droughty seasons, because the water table drops below the well bottom. It is during this type of period that

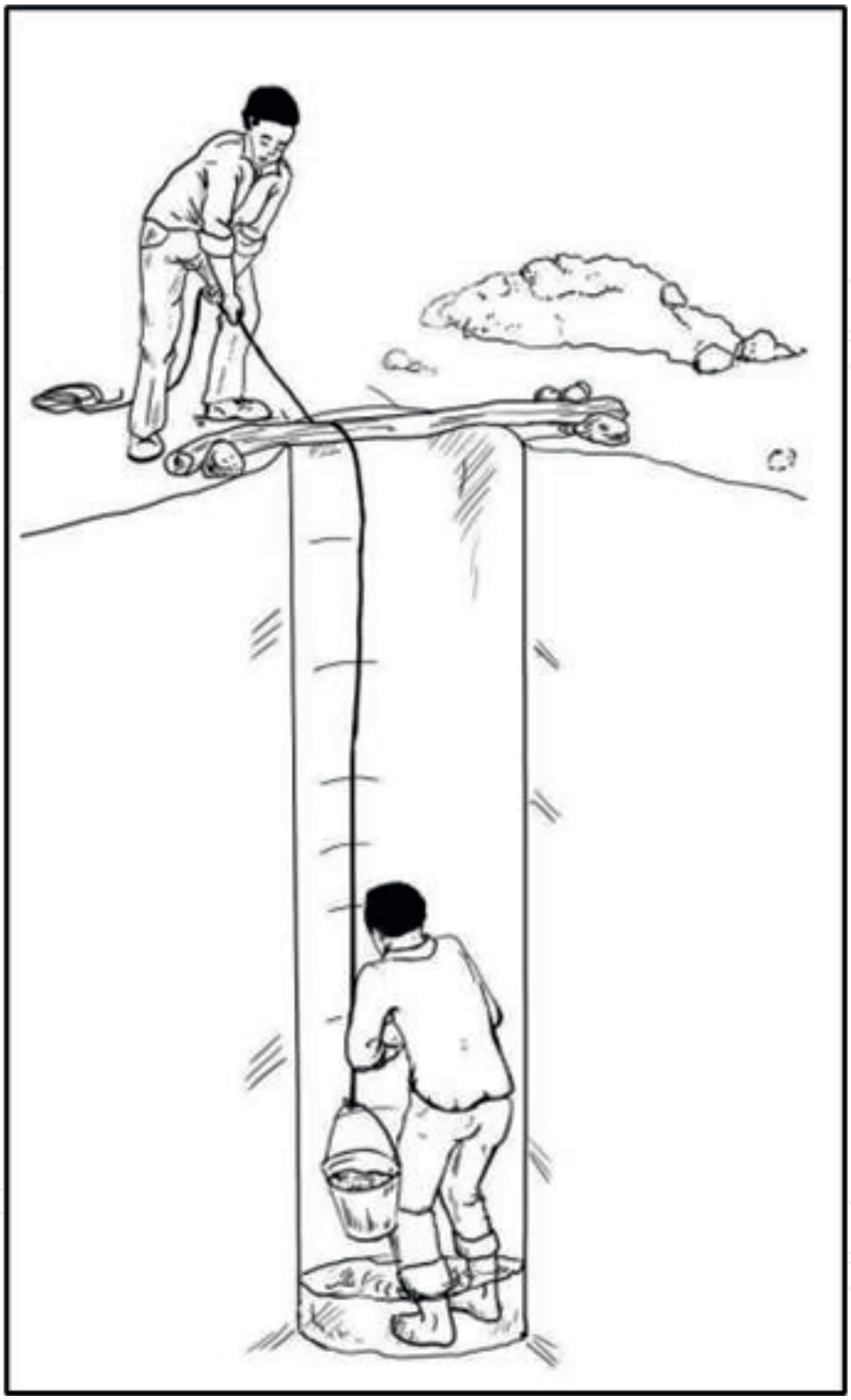

Figure 2.
Cross-section view of hand digging a water well [11].

maintenance on the well can be performed. However, working on dug wells is quite risky. Someone must be lowered into the well to work. Labor under these installations is potentially dangerous, due to the high potential for cave-ins and the lack of oxygen. Since it is difficult to dig very deep, hand-dug wells generally extend no further than 30 m in depth [11].

To access more water in situations where the water table has dropped lower than the depth of the well, the bottom of the well must be excavated deeper to reach the new aquifer level. Water is typically lifted to the surface by attaching a bucket to a rope and drawing the water up by hand or crank. Unfortunately, obtaining water in this manner can also transmit bacteria into the groundwater source. Contamination of the water source is best prevented by sealing the walls, pouring a concrete apron around the base of the well, providing a raised parapet above the face around the well, using a lid over the top of the well, and utilizing a hand or electric pump to obtain water. Obviously, these features add additional costs to the well [11].

2.3.2 Drilled wells

A well drilling machine is normally referred to as a “drill rig” or just a “rig” [11]. Drilled wells are able to penetrate consolidated material and require the installation of casing and a screen to prevent the inflow of sediment and to keep the well from collapsing inward [12]. This type of well can be pushed to more than 300 m in depth. The surface area around the casing has a segmented or concrete pad that is constructed to prevent contamination by water draining from the surrounding surface downward around the outer portion of the casing. The pad is most often constructed from neat cement or bentonite clay [12]. Pads are typically left to cure for a period of time prior to well commissioning, during which a well casing cap remains on the newly drilled well to prevent contamination. After the pad has cured, the pump cap can be removed, and a pump head can be installed. Installing a pump head too soon, prior to pad curing, can lead to breakage of the concrete pad in use. Thus, it is vital to provide a proper cure time for the concrete when installing pump equipment and subjecting the pad to heavy operational loadings. Powered well drilling methods include the percussion cable tool, jetting, mud rotary, and air rotary techniques [11]. The most common powered installation methods used today are the percussion cable method and the mud and air rotary methods, but drilled wells can also be installed by hand [12, 31, 32].

2.3.3 Bored or hand augered wells

This method of drilling a well uses a small-diameter open-bottom bucket with angled teeth to manually cut into the soil. An example of this type of installation is shown in **Figure 3**. The bucket is attached to a t-shaped handle at the top through a series of steel rods, which can be rotated manually and pushed downward. As the bucket fills, the contents are lifted-out and emptied. Additional rods are added as the hole deepens. This method is sometimes used for soil sampling, in addition to shallow well construction. The diameter of the hole produced by this method is typically less than 8 cm, and the process is very depth limited, as the drilling rate and material removal are very slow. Once below the water table, it is generally problematic to go deeper, and it is difficult to prevent the hole from collapsing inward. As well, the soil profile and composition greatly affect the depth of a well that can be installed using this method. In loose silt or sand, it is possible to go up to 10 m in depth, but in more compacted soil, it would be quite difficult to reach this depth manually drilling [11]. Therefore, most drilled well installations have been adapted to utilize machinery instead of human power.

2.3.4 Percussion (cable method)

This well drilling method utilizes repeated lifts and drops of a chisel-edged bit to break-loose and pulverize material in the bottom of the hole. A small amount of water is

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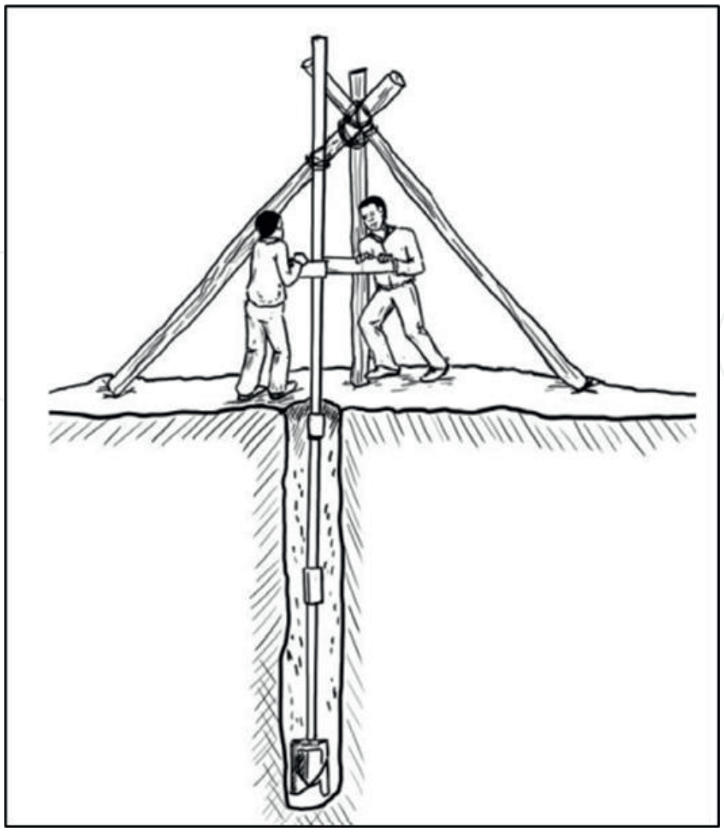

Figure 3.
Cross-section view of a hang augered water well installation [11].

added to the hole to form a slurry of the excavated material. The percussion bit is removed periodically, and a bailer lowered into the hole to remove the slurry mixture containing the excavated material. The excavated material is brought to the surface and discarded. Bailing is repeated until the hole has been thoroughly cleaned. Bailing and drilling are alternated in this fashion, until the desired depth is reached. If the hole is unstable, a casing can be lowered into the hole to prevent it from collapsing. The percussion drilling method is able to penetrate all types of materials, but in very hard stone, progress can be quite slow. The percussion technique is frequently associated with a large, truck-mounted attachments or motorized trailers, similar to that shown in **Figure 4** [31]. "The [percussion] machinery ranges from a basic skid-mounted powered winch with a tripod, to a complex set of pulleys and runs with a large mast" [11]. These larger cable tool rigs have hydraulic motors to raise and lower the mast and rotate the drums of the cable. Fewer cable tool rigs are being utilized in developed areas of the world today, because compared to hydraulic rotary drill rigs of similar size, percussion drill rigs work slower [11]. Additionally, when drilling in loose sediments, it is necessary to drive a steel pipe behind the drill bit to prevent the borehole from collapsing. The sections of this "drive casing" must be welded together going in and cut apart coming out, which requires that an arc welding and cutting torch set be available during the drilling process [11]. These additional processes are not required when using alternative well drilling technologies.

2.3.5 Jetting

This well drilling technique utilizes a high-pressure pump to force water down a drill pipe and out a small diameter nozzle, in order to make a "jet" of water that

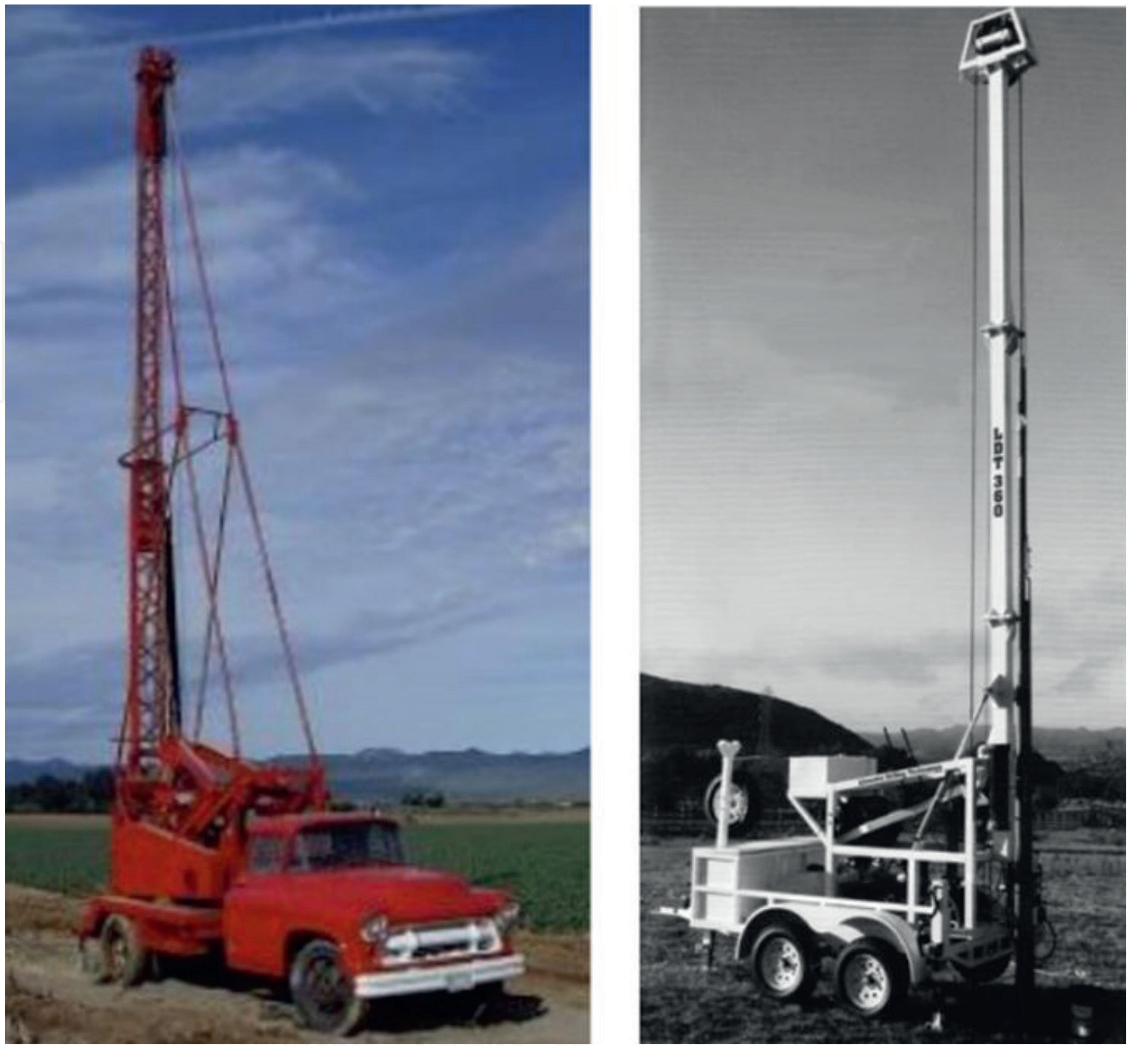

Figure 4.
Truck-mounted cable tool rig (left) and trailer-mounted tool rig (right) [31].

loosens the soil. The return flow of water outside the drill pipe carries the cuttings up to the surface and into a settling pit. A circulation pump returns the water back-down the pipe to continue bringing more cuttings to the surface. A tripod set-up is typically used and rotated by hand to ensure a straight borehole. In addition to the water piping components, this well drilling technique requires a high-pressure water pump and two people to set-up and operate the rig. **Figure 5** illustrates this method of well drilling. Unfortunately, this method is only suitable for fine-grained and soft sediment soils, and it requires a nearby water source to supply the jet system. This well drilling technique is not suitable for gravel or in hard soil profiles [11].

2.3.6 Mud rotary

A mud rotary drilling rig includes a "jet", in combination with a larger diameter cutting bit, pre-cut and threaded lengths of steel drill pipe, a motor to turn and lift the drill pipe, and a sturdy mast to grip and support the pipe. **Figure 6** illustrates an example of this process. A mixture of bentonite clay or other materials is used in combination with water to improve the ability to lift the cuttings out of the borehole.

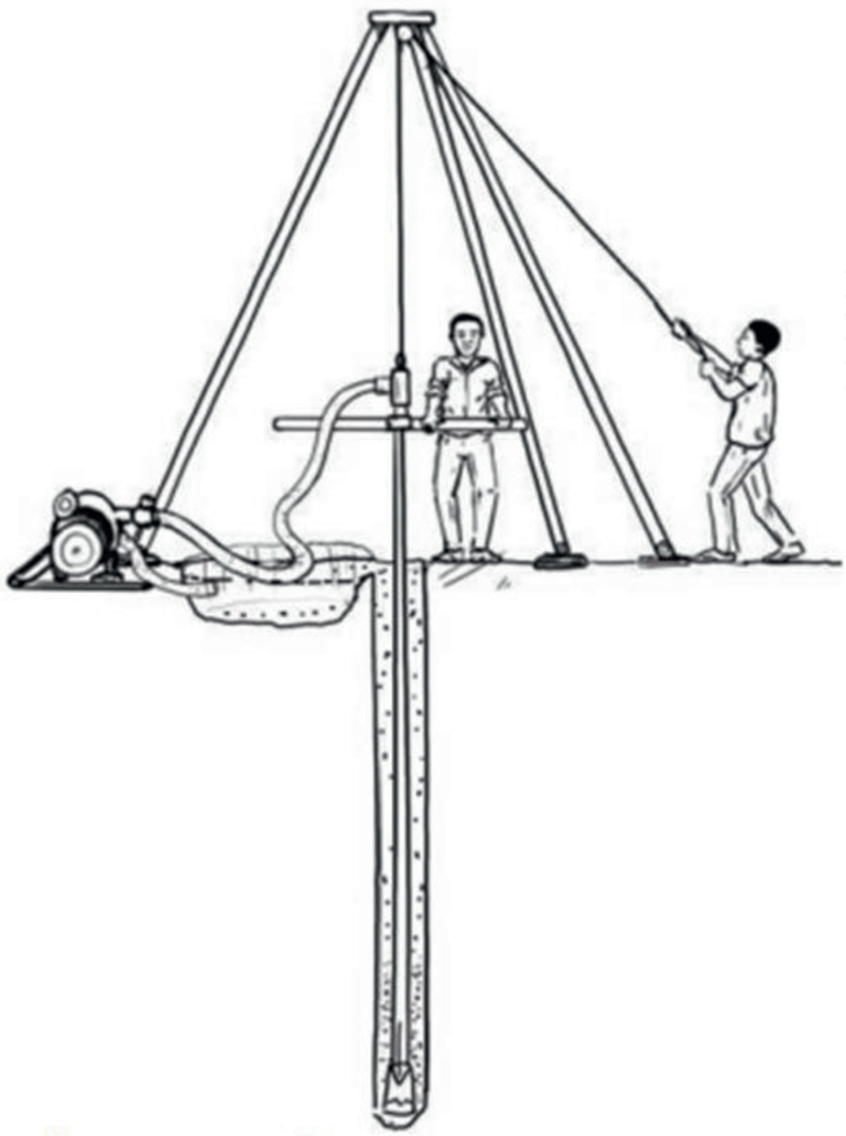

Figure 5.
Cross-section view of jetting a drilled water well [11].

This mixture is called "drilling mud" or just "mud". There are many different kinds of rotary drilling rigs, but they can be summarized into two basic set-ups: a table drive unit or a top-head drive unit. A table drive drilling rig rotates the pipe using a pipe grip and spinning mechanism near the base of the rig. A top-head drive turns the drilled pipe by way of a motor attached to the upper end of the pipe. In both set-ups, the drill pipe is also attached to a lifting mechanism that lowers and raises the pipe along the mast. A swivel on top of the pipe is present in both set-ups, allowing the drilling mud to be pumped down the drill pipe, while it is rotating.

Mud rotary well drilling is much faster than using the cable drilling technique, and mud rotary machines are capable of drilling a borehole of up to 60 cm or more in diameter. They can achieve depths of up to 60 m. In comparison with the cable drilling technique though, mud rotary rigs are more energy intensive, and they require more fuel per hour to power them. Additional components on this machine beyond a cable drilling rig include a motor to rotate the pipe column, the pipe winch, and the mud pump [11].

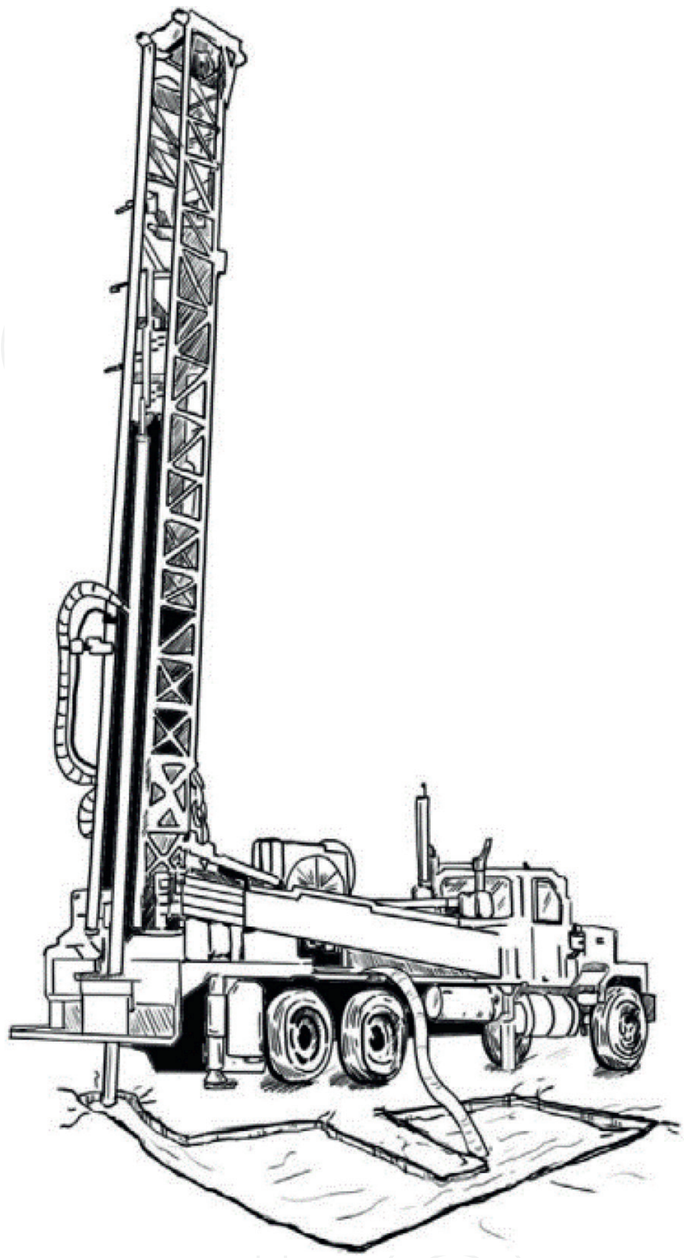

Figure 6.
An onsite isometric view of a mud rotary drilling rig in an operational configuration [11].

2.3.7 Air rotary

The primary difference between the air rotary drilling method and the mud rotary drilling method is that the air technique utilizes compressed air to remove the cuttings, rather than drilling mud. A type of "foam" can be added to the air stream in order to improve its effectiveness at the cuttings removal and provide additional stability to the borehole. The mechanical elements of the pipe mechanisms on the mud rotary and air rotary machines are the same. Both styles of machine can come with either a table drive unit or a top-head drive unit. Both require a pipe winch. The air rotary rig utilizes the same type of drill bits as that of a mud rig, but it also makes use of a "down-the-hole" hammer drill action. The bit used in air rotary rig operations directs a jet of compressed air to break-up rock and drill extremely fast. This type of drilling technique can be set-up very quickly, since no mud or cutting mix is utilized,

Figure 7.
An air rotary drilling rig in transport configuration [31].

only compressed air. This method is able to drill much faster than other rigs of comparable size, and it creates less of a mess at the bore site. However, the air compressors utilized by air rotary rigs are generally very large, which adds additional capital cost, potential maintenance needs, and further increased fuel use [11]. An example of a typical air rotary drilling rig is shown in **Figure 7**.

2.3.8 Driven wells (tube wells)

Driven wells require the following four primary components: a well point, well point couplings, lengths of galvanized steel pipe, and a well point drive cap [10]. Each of these components is displayed in **Figures 8-11**. Galvanized pipe is required for long-term water system integrity and is commonly available [33]. Driven wells or shallow tube wells are constructed by driving a small diameter pipe into a shallow water-bearing soil profile composed of primarily sand or gravel [12, 32]. Unlike the other well construction techniques mentioned previously, material is not removed, but rather, it is forced aside during the driving process [31]. A screened well point is attached to the bottom of the casing before driving [12]. Couplings are used to connect each section of piping as needed. The drive cap is screwed onto the upper end of the section of pipe that will be driven, so as to protect the pipe threads during driving. "The drive and couplings, in addition to being heavier than standard pipe, are designed so that the pipe ends butt together inside the coupling, resulting in most of the driving force being transmitted by the ends of the pipe rather than by the threads" [31]. Driving is done by alternately raising and dropping a weight, which is used as the driving ram. A drive point and manual installation are shown in **Figure 12**. In place of only using a hammer to drive, guides can be employed to

Figure 8.
A well point for a 2" pipe driven tube well installation [10].

Figure 9.
A drive coupling for a 2" driven tube well stack [5].

Figure 10.
A typical unthreaded piece of potable water safe galvanized 2" steel pipe [33].

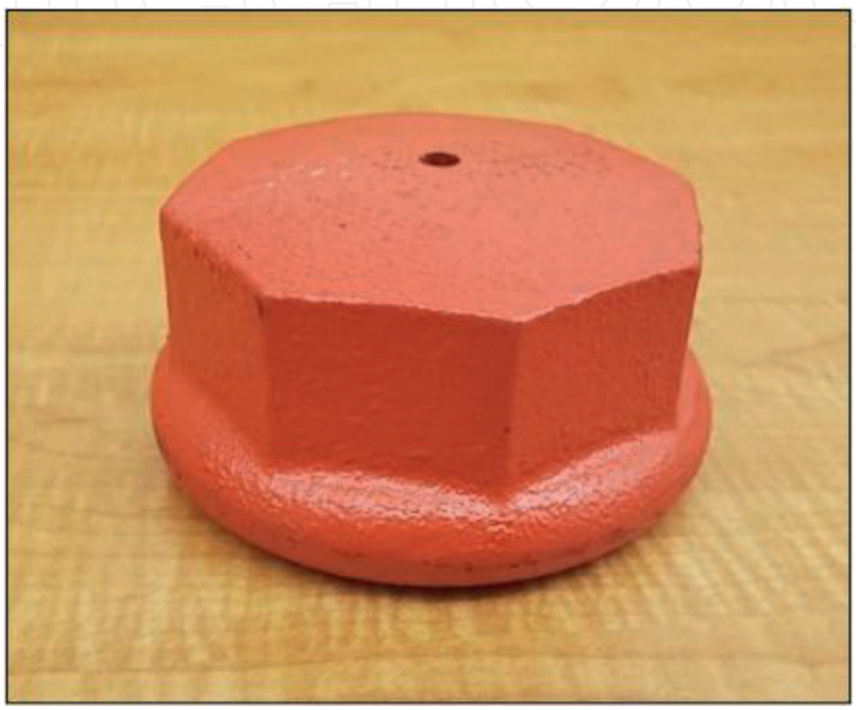

Figure 11.
A tube well installation drive cap [5].

direct the pipe during driving. This can be done either by having a guide on the outside of the pipe or the inside of the pipe as shown in **Figures 13** and **14**, respectively [31]. Prior to the Well Driver PUP, driven wells were typically installed manually or using a derrick constructed in place for the specific purpose [10].

The achievable depth to which a tube well can be driven depends on the build-up of friction between the well pipe, the material penetrated, and the transmission of the force of the driver down the length of pipe [31]. It is possible to achieve maximum depths of 25–30 m, but hard formations cannot be penetrated [31]. Tube wells are most easily installed in locations where the soil profile is mostly loose sand, and the water table is high. Locations close to a river, lake, or stream are especially good [11]. Driven wells are simple and economical to construct. Driven wells are generally not sealed at the surface using grouting material [12], and therefore, they may normally lack an adequate sanitary seal [31]. For these reasons, this type of well is more prone to contamination. However, the proper finish with an apron and riser pipe can prevent most common contamination issues [10]. Manually-driven wells are not generally able to penetrate more than 5 m below the surface [12], but this level has already been surpassed by the mechanized Well Driver PUP technology [3].

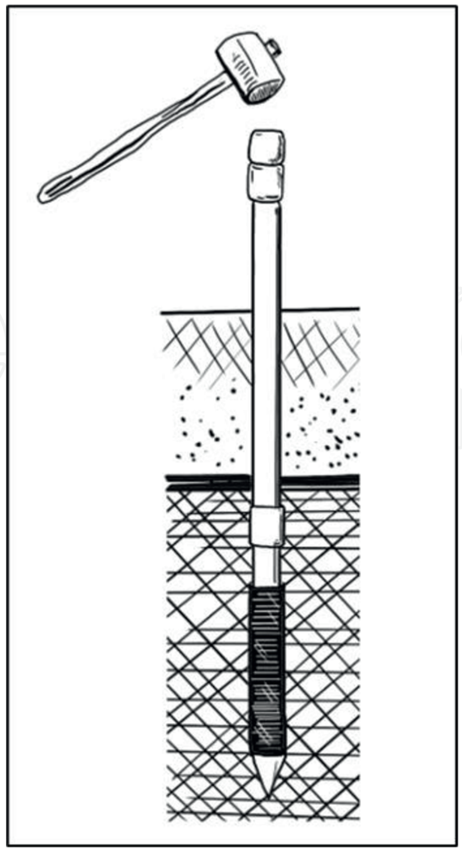

Figure 12.
A cross-section view of a manual installation of a drive tube well installation [11].

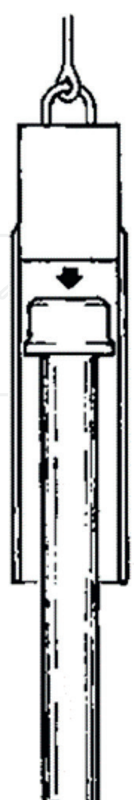

Figure 13.
Cross-section view of a device for well driving by a guiding sleeve outside of the well pipe [31].

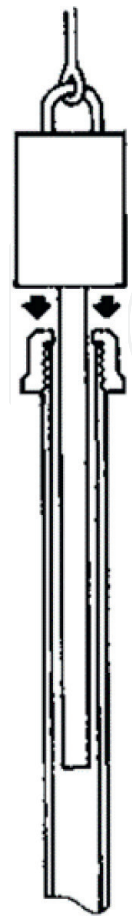

Figure 14.
Cross-section view of device for well driving by a guiding line-up probe inside of the well pipe [31].

3. Well-driver PUP

The PUP vehicle is a development of the Agricultural and Biological Engineering department at Purdue University under the direction of Dr. John Lumkes. This device is a versatile, useful, and inexpensive tool for the developing world. Researchers at Purdue have modified the basic device to install tube wells [10]. This section will introduce the PUP vehicle, the hydraulic ram attachment, the potential for impact worldwide, the components need to drive a tube well, and the results from preliminary work. A review of healthy water quality will be provided, along with an estimated cost structure for these types of installations.

3.1 Purdue utility platform (PUP) with well-driver attachment

A hydraulic post driver mated to a Purdue Utility Platform (PUP) vehicle has been designed to mechanize the process of installing driven water wells. This machine has been designated the Well-Driver PUP [10]. A PUP is a three wheeled, low-cost utility vehicle designed at Purdue University for use in developing countries [3, 34]. These vehicles are typically built in-country with minimal tooling and using only locally-sourced materials. The experience base for this vehicle is predominately in sub-Saharan African countries, mainly being Guinea, Cameroon, Nigeria, Uganda, and Kenya [34, 35]. **Figure 15** shows multiple examples of Purdue student-built PUP vehicles. These vehicles have been used previously for light commercial transportation

Figure 15.
PUP vehicles produced under the direction of Dr. John Lumkes of the Purdue University Agricultural and Biological Engineering Department [10].

purposes, including use as a small pickup truck, taxi, fire truck, or for miscellaneous hauling in areas where normal vehicles are not appropriate, due to the severe terrain and lack of road accessibility. These vehicles have even been used as ambulances to get individuals in need of medical services from extremely rural areas to hospitals and clinics. They have been used for transporting goods to and from market, as school bus alternatives, garbage collection vehicles, and light utility tractors. Tillage attachments, seeders, harvest heads, water pumps, generators, threshers, and maize grinders powered by the PUP have been designed and tested [3, 15, 16, 34, 36]. These implements have helped improve small-holder farmer access to markets, and they have improved the livelihoods for many of those in sub-Saharan Africa. The Well-Driver PUP is a further example of alternative use for this versatile vehicle, and it is displayed in **Figure 16**. The Well-Driver PUP could potentially reduce dependency on manual labor for driven well installation in developing countries, improve productivity, and keep laborers safer [3, 10, 15].

In locations where the number of drilling rigs are reduced, and labor is scarce, the Well-Driver PUP vehicle could be used as an instrument of economic development, providing micro-business development opportunities focused on well installation. Installing low-cost driven wells would improve the availability, quality, and accessibility of water in locations lacking sufficient water supplies. In order to be successful, the Well-Driver PUP operation and components must remain low-cost, easy to maintain, and based on locally accessible materials as much as possible. Although the efficacy of the effort might be diminished, it is intended that operation of this vehicle should not require formal training in well drilling or geology. In locations of appropriate water table depth, this vehicle could decrease both the wait time to install and the final cost of installed sanitary water wells [10].

3.2 Potential locations of utility for the well-driver PUP in the developing world

Global estimates indicate that 68% of the Earth's freshwater resources are locked-up in ice and glaciers, and 30% are found within the ground [38]. Groundwater is the portion of the total precipitation that soaks into the earth's crust and percolates downward into the porous spaces within the soil and rock, where it remains, or

Figure 16.
Well-Driver PUP vehicle in operational configuration with the hydraulic driving ram erected [37].

potentially, from where it finds its way out to the surface [3, 10]. Groundwater serves as the world's largest source of fresh water, and it plays a critical role in meeting the household needs of people around the world [39]. Groundwater is the primary source of the world's drinking water, and it supplies water for agricultural and industrial activities worldwide [40].

Through testing, Horn demonstrated that the Well-Driver PUP could achieve depths of up to 7.0 m [3, 10]. Although not yet demonstrated through formal experimentation, Horn analytically determined that the vehicle should be capable of driving to depths of up to 15 m without significant changes to the apparatus [10]. The depth to the water table varies throughout the world, but significant areas of the world have water within 15 m. On-going work is aimed at increasing the proven maximum achievable depth for water wells with this equipment [5].

Prior to the work of Horn [10], the design of the Well-Driver PUP was a project of several senior capstone teams in the Agricultural & Biological Engineering Department of Purdue University. The first capstone team mounted the post driver onto the PUP frame using a static three-point hitch lower arms [41]. This design pivots on the rear balls of the lower link arms, thereby allowing the driving ram to be rotated by a hydraulic cylinder serving as the upper link arm. This allows the post-driver vehicle to have a more distributed weight during transport operations [42]. This has the effect of moving the mechanical driver from a vertical operational orientation to an inclined transport position.

A second capstone team refined the Well-Driver PUP with additional safety shielding around the hydraulic pump, fixed hydraulic leaks, and made various additional vehicle improvements [43]. A support cradle was added to allow the post driver to stabilize and minimize bouncing during travel. A transmission lockout was also added to force the vehicle's transmission to remain in neutral, while operational at high engine speeds. This prevented the vehicle, if bumped by accident during operation, from jumping into gear [43]. Various additional improvements were made to the vehicle by Horn [10] before any initial driving efforts could be carried-out. Modifications included rebuilding the engine, improving the efficiency of the hydraulic system, and fabricating outriggers to address the stability and weight distribution issues of the vehicle during well driving operation. **Figure 17** portrays the Well-Driver PUP in the transport position. One of the four outriggers designed by Horn [10] is clearly visible on the right rear of the PUP vehicle. The driver support members are also highlighted in the photograph. A third capstone team added well pipe support grips [44], and a fourth team worked on vehicle repairs and supplemental ram weight [45].

3.3 Well components required for tube well driving

The driving action performed manually when installing hand-driven tube wells, has been mechanized hydraulically by the Well-Driver PUP. The components required to install a tube well stack utilizing the Well-Driver PUP are similar to that of a standard hand-driven well. These components include: the well point, the drive couplings, galvanized steel piping, and a well point drive cap. These parts were utilized by Horn [10] during his experimentation and have previously been shown in **Figures 8-11**. In addition to these components, Horn fabricated a specialized tube well installation drive sleeve appropriate for driving 2″ diameter pipe [10].

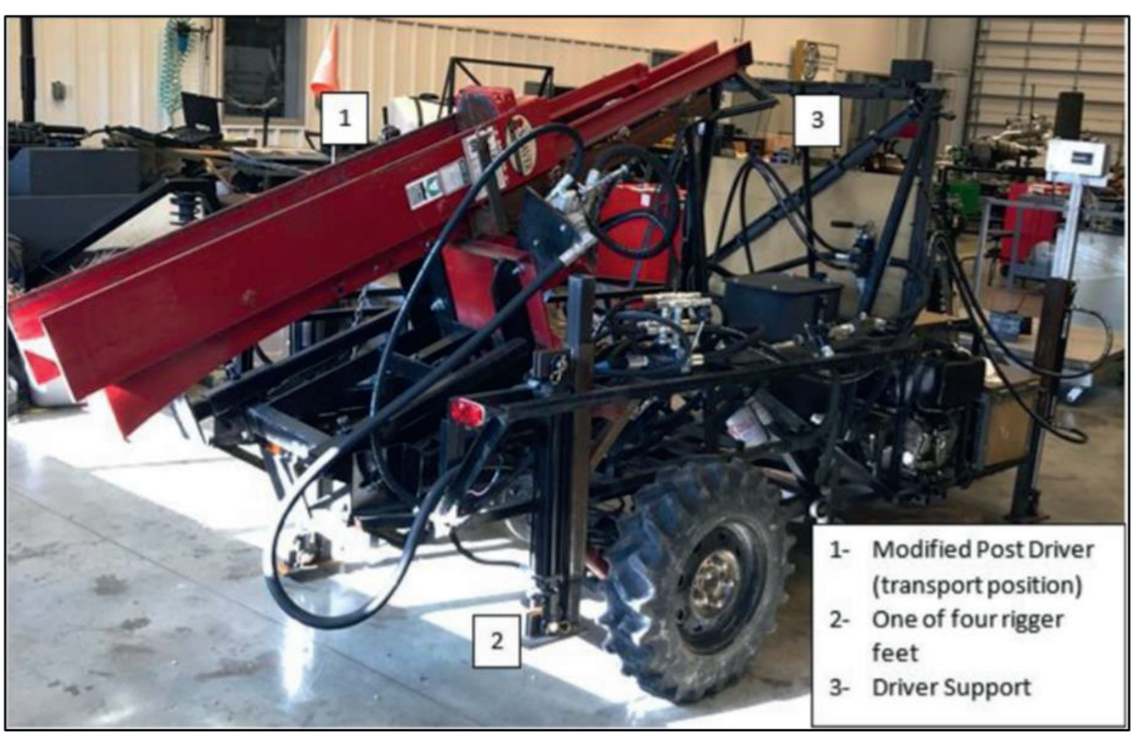

Figure 17.
Well-Driver PUP vehicle in transport configuration with the hydraulic driving ram collapsed into holding cradle [44].

Figure 18.
A comparison of the Horn 2" tube well installation drive sleeve (left) and the Shaver (Graettinger, Iowa) steel fence post driving sleeve [10].

The Horn-manufactured well sleeve is shown on the left in **Figure 18**. The driving sleeve shown on the right in **Figure 18** is used for fence posts and was created by Shaver Manufacturing (Graettinger, Iowa) [10]. "The [well pipe] drive sleeve was constructed of 4–1/2″ × 3/16″ wall-drawn over-mandrel (DOM) steel tube, ½″ steel rod, and ½″ A36 steel plate" [10]. The DOM tubing was specifically chosen, because the internal weld bead is ground flush, as opposed to a raised weld bead, which would have posed alignment problems and caused unnecessary damage to the well point drive cap. The fabricated well point drive sleeve cleared with an approximated 0.6 cm gap around the diameter of a well point drive cap for a 2″ diameter pipe. Rub rails made from ½" steel rods were used for the inner steel channel and to position the center of the steel tube sleeve inline with the center of the driver strike plate. A ½″ steel plate was welded to the top of the drive sleeve to act as a "cap", serve as a wear plate, and to hold the sleeve in the proper position for striking [10]. The drive sleeve used by Horn [10] was designed for installing wells with a 2″ diameter pipe and is shown in position within the driving ram in **Figure 19**. The installation of a well with a different pipe diameter would require the fabrication of a new drive sleeve with similar features that matches the new desired well pipe diameter.

3.4 Key experience gaps to be addressed in well-driver well installations

Horn [10] hit water at some point during the driving process for the five test well installations that were completed. The results are shown in **Table 2**. These wells were

Figure 19.
Horn 2" tube well installation drive sleeve positioned in hydraulic ram channel [10].

Well #	Well Depth (m)	Static Water Column in Well (m)	Confining Layers (m)	Water Supply
1	4.0	0.9	N/A	N/A
2	3.0	0.3	N/A	Intermittent
3	7.0	6.1	N/A	Continuous
4	5.2	N/A	2.7–3.4, 4.6–5.2	N/A
5	7.0	N/A	N/A	N/A

Table 2.
Summary of the Purdue Well-Driver PUP experience at tube well driving in Montgomery County, Indiana [3, 10].

all installed within Montgomery County, Indiana. The recovered water from the submersible pump varied from providing continuous flow, intermittent flow, or no flow [10]. Based on water supply ratings from these test installations, wells #1, #2, #4, and #5 were all deemed “dry” or “intermittent” wells. Well #3 provided a continuous water supply, and therefore, it was developed into a quality water well for testing purposes. This well had a depth of 7.0 m and a static water column of 6.1 m within the well [10].

The well pump utilized was a Waterra WSP-12 V-3B (Mississauga, Ontario) [46], which moved water at approximately 11.0 Lpm. Well #3 was completed, or finished, in accordance with the American Groundwater Trust procedure through the addition of a concrete pad, well surging, and disinfection [47]. The surging process removes the fine particles accumulated at the bottom of the well tube near the pump inlet, and it prevents these from being transferred into the drinking water drawn from the well [29, 48]. Surging also helps pack layers of fine particles around the well water inlet screen, which can then act as a "pre-filter" for large particles. The installation of a driven well of any other size than the 2″ diameter by the Well-Driver PUP would have required the purchase or fabrication of a wellpoint, drive cap, couplings, and galvanized steel piping, to match the diameter of the pipe desired. A larger pump would also have been required to surge and condition the larger diameter well for finishing.

3.5 Water quality results

Water quality samples were collected and submitted to the Montgomery County Health Department for analysis. The water quality parameters evaluated were Total Coliform and *E. Coli* count. Fecal Coliform count was not checked. These tests were done on a present/absent (P/A) basis. Installation of any new well in Indiana requires that upon receiving a continuous flow rating, a water quality sample be collected and sent to the perspective County Health Department for analysis. This was carried-out by Horn [10] in accordance with state regulations [29, 48]. The water quality test for Well #3 was reported to be absent for Total Coliform and *E. Coli* count, and therefore, satisfactory. Since the Montgomery County Health Department deemed the sample satisfactory, the water sample is considered "at the time of examination bacteriologically safe based-on U.S. EPA standards" [3, 10, 29, 48].

3.6 Potential impact

A high-resolution global-scale groundwater model was developed by de Graaf et al. [39]. A high-resolution global-scale groundwater model was created, highlighting the current water table depth on a global scale through computer model simulations. Most global-scale hydrological models (GHMs) do not include groundwater flow as a component of the model, due to the lack of consistent geohydrologic data available on a global scale. This model, run at 6° of resolution, utilized MODFLOW (U.S. Geological Survey, Washington, DC) to construct an equilibrium water table at its natural state. The aquifer schematization and properties used were based on the globally available data sets of lithology and transmissivities, combined with the thickness of an upper, unconfined aquifer. The model was initialized using outputs from the land-surface PCRaster Global Water Balance (PCR-GLOBWB) model (Utrecht University, Utrecht, Netherlands), which included net recharge and surface water levels. A sensitivity analysis of the various parameter settings was performed, and it showed that the greatest variation in saturated conductivity had the largest impact on estimates of the groundwater levels. The model validation with observed groundwater levels demonstrated that the predicted levels are reasonably well simulated for many regions of the world, particularly for sediment basins (R^2 = 0.95). These simulated regional-scale groundwater patterns help to provide insight into the availability of groundwater globally [39].

Figure 20 provides the expected water table depth below the land surface throughout the world based on the de Graaf et al. simulation [39]. Worldwide, there are many locations where the water table depth is projected to be within the 10–20 m

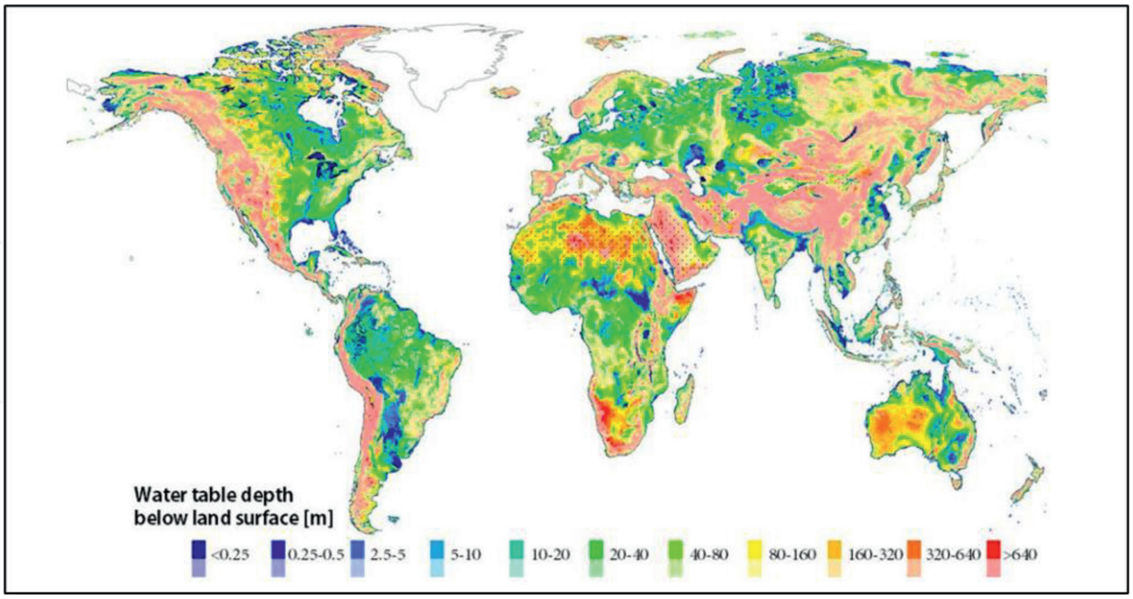

Figure 20.
Output for the estimated water table depth below land surface [m] from geological model [39].

range according to this model. Many of these locations are in sub-Saharan Africa, South America, northern India, Asia, and parts of the Asia Pacific Islands. These predictions simply identify potential locations where the Well-Driver PUP might be utilized, if sufficient depth can be demonstrated on a repeatable basis.

According to the United Nations, approximately 14.5% of the World's population is located within sub-Saharan Africa [1]. The Earth is projected to hold 9.8 billion people in 2050 and 11.2 billion people by 2100 [49]. The population of sub-Saharan Africa alone, is predicted to nearly double by 2050 [1]. Of the ten largest countries worldwide, Nigeria, which is located in sub-Saharan Africa, is growing the most rapidly [49]. It is projected to surpass the United States in population and become the third largest country in the world shortly before 2050 [49]. Clearly, when considering locations where the Well-Driver PUP could impact the largest number of people, consideration should be given to locations within sub-Saharan Africa.

The International Groundwater Resources Assessment Centre (IGRAC) and the UNESCO International Hydrological Programme have mapped-out the transboundary aquifers within Africa [50]. IGRAC, in collaboration with the British Geological Survey and the University College London, has developed maps to quantify the groundwater resources within Africa based upon local well data and known geological conditions. Their results for aquifer depth are highlighted in **Figure 21** and provide a high-resolution look at the depth to water table in Africa. When specifically looking at sub-Saharan Africa, the approximate depth to the groundwater is predominately less than 25 m, followed by areas in the 25–50 m range. These data demonstrate the vast number of locations within sub-Saharan Africa, where the Well-Driver PUP could possibly access groundwater. Once fully developed, this technology has great potential to have a substantial positive impact for the people in those regions of the World with little to no water access.

3.7 Potential people served per well estimates

The economic analysis of a water well installation depends upon the number of people that the well can serve, the depth of the water being pumped, the daily per capita water required, the duty cycle of the water pump, and the ability of the

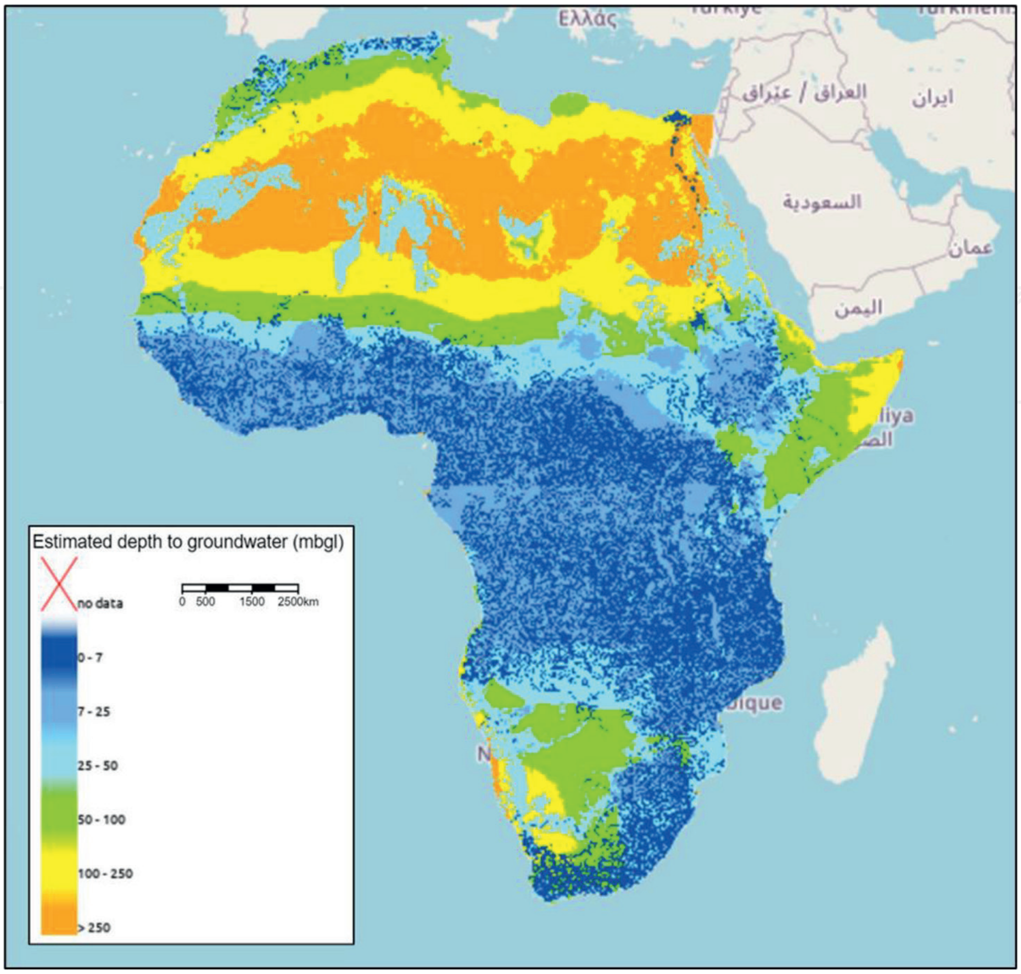

Figure 21.
Estimated depth to groundwater (mbgl) and transboundary aquifer of Africa based upon geologic and well drilling data [50].

water bearing formation to be sustained during pumping [10]. Additionally, the water table drawdown may affect the pumping flow rate over time. The successful water well installed by Horn [10] had a depth of 7 m and a pumping rate of approximately 11 L/m. If a continuous duty cycle on this well was run for 8 h per day, a total of 5400 L of water could be pumped [10]. According to the Sphere Humanitarian standards for Developing Countries [4] and WHO [8], the minimum water requirement is 15 L per person per day. Therefore, with a handpump, the maximum number of people using the Horn #3 well on a per day basis should not exceed 500, and a minimum flow rate of 16.6 L/m would be needed [4]. This guideline assumes that the water point is accessible for approximately 8 hours of the day [4]. Using these developed metrics, Horn's initial successful test well [10], could therefore supply water for between 270 and 360 people, if installed in a community setting.

3.8 Well cost per depth & value proposition estimates

Horn [10] conducted a cost analysis per well depth ranging from 1 to 35 m, using the U.S. market prices of the driven well components in 2019. This was updated to reflect current prices of those components in 2022, and the results are shown in **Table 3**. The percent difference between the pricing periods was calculated to determine how much change in the costs have occurred during the intervening years. Even with the recent spike in steel

Materials for Well	Price in 2019 (USD)	Price in 2022 (USD)	Percent Difference	Per	Source	Length (m)
2″×10′ Galvanized Steel Pipe	37.12	56.96	35%	each	HD	3
2″×36″ Well Point	60.66	66.89	9%	each	HD	1
2″ Pipe Coupling	12.86	11.63	−11%	each	HD	0
2″ Well Point Drive Cap	17.29	15.99	−8%	each	HD	N/A
2″×5′ Galvanized Steel Pipe Section (plus cut/threading cost)	20	20a	0%	each	HD (approximate)	1.5
Submersible Water Pump	Not Reported	224.10	0%	each	Waterra	N/A
1–80 lb. Bag of Concrete	Not Reported	5.87	0%	each	HD	N/A

Table 3.
Driven tube well material costs for various required installation components [10].

Well Depth (m)	Actual Length (m)	Well-Driver Cost in U.S. (USD)	Cost in Ghana (USD)
1.5	2.4	512	565
3.0	4.0	530	687
4.6	5.5	549	809
6.1	7.0	567	931
7.6	8.5	585	1053
9.1	10.1	604	1175
10.7	11.6	622	1297
12.2	13.1	640	1419
13.7	14.6	659	1541
15.2	16.2	677	1663
16.8	17.7	695	1785
18.3	19.2	714	1907
19.8	20.7	732	2028
21.3	22.3	750	2150
22.9	23.8	769	2272

Table 4.
An updated driven tube well cost per depth projection for 2022 based upon US costs and a comparison against prices in Ghana [10].

prices, the net changes have been relatively small. **Table 4** provides an updated well cost per depth using the current prices in 2022, modeled after Horn's initial calculations. This table also compares tube well costs for installations in Ghana at the same equivalent depth. One meter is the length of the 2″ well point, and it was therefore selected as the minimum depth [10]. Economic assumptions included in the analysis were that the well casing extended 1 m below the ground surface and that any section of pipe used which was less than 1.5 m was considered to have the full cost of a 1.5 m section [10]. A maximum depth of 15 m was chosen, as recommended by the book *Groundwater and Wells* [14]. The text states that well points driven by hammers massing 113 to 454 kg (1.1–4.5 kN) should be able to reach depths of 15 m or more under favorable situations [14]. The effective weight of the spring powered driving ram, per the Shaver HD-8 Operator's Manual, is 1.6 kN, which indicates that a 15 m deep well should be within an acceptable potential cutoff range for the driver without any modifications [10, 51]. This cost per depth table is carried-out to below 15 m, in the event that such depths can be reached through further development.

If additional modifications can be made to allow the driver to attain still deeper depths, then **Table 4** could easily be expanded. The average cost of a drilled well in the United States without a well casing is reported to have a range of US$49–98/m, or potentially up to US$164/m in tough soil conditions [52]. By averaging the cost per depth from **Table 4**, a driven well within the capabilities of the driver would average about US$68.05/m in physical material costs, excluding the Well-Driver Pup vehicle cost and fuel costs.

Based upon these calculations, it is possible that a driven well could be cheaper per m, even in a U.S. context, than previously reported by Horn [10]. A tube well, driven by a Well-Driver PUP, could certainly be a cost-effective alternative to a drilled well in a developing country. The current average cost per depth in Ghana is US$80/m for a tube well, and US$109/m for a drilled well [53, 54]. These values were first cited by Namara et al. [53] in 2011, and in this work, they have been updated to account for the depreciation of the Ghana Cedi between 2011 to 2022. The price increases for steel have nearly doubled its total cost since Horn study [10] in 2019, clearly necessitating a reevaluation of the cost structure for tube well installation. The calculations in **Table 4** account for pump, concrete, and labor costs. According to the U.S. Bureau of Labor Statistics (2022) [55], the average hourly wage for labor within the Water, Sewage, and Other Systems industry is $34.86 per hour [55]. In Ghana, the hourly rate is $2.76 USD per hour [56]. It is assumed that 6 hours of labor would be required for a well installation. Fuel costs are excluded from these calculations, due to variation of fuel pricing in both the U.S. and Ghana. This indicates that using the Well-Driver PUP to install a driven well in Ghana would be on average a potential savings of 49% compared to the current process. There are numerous locations throughout the world, and more specifically in sub-Saharan Africa, where the depth to groundwater is within the Well-Driver PUP's potential depth of 15 m [39, 50]. However, this proposition requires further testing to prove that that this depth can be repeatably achieved, since the Horn 2019 study [10] only demonstrated an experimental depth of 7 m. Furthermore, increasing the achievable driving depth capabilities of the vehicle through design improvements would increase the number of locations across the globe where the vehicle could provide improved access to groundwater.

Over the last 8 years, the primary author has had significant professional experience working in Ghana on various international development projects related to agriculture and water, sanitation, and hygiene (WASH) programming and continues to have access to a variety of networks within the country that are expressing interest in the use of the Well-Driver PUP, once it becomes proven and commercially viable. Therefore, consideration was initially given to the appropriateness of the Well-Driver PUP, if tested and eventually available within Ghana. Located in sub-Saharan Africa, Ghana has a long history of accessing shallow groundwater for the purpose of agricultural irrigation [57]. This experience has predominately been in the Keta Strip, within the Volta Region. Groundwater has been accessed through various power sources to lift water, including human feet/hand-operated equipment, such as rope and buckets. Access to many traditional shallow groundwater sources was extremely labor-inefficient, often being via hand-dug wells. Newer systems exist, but they are often out of reach for an individual farmer or household, due to the capital costs of acquisition. Currently, there are a total of 34,263 wells recorded within the Keta District. However, these are predominantly used for irrigation purposes. The small depth range of current tube wells within this area is between 6 to 9 m, and water is lifted primarily through small electrically powered pumps, located near the tube well. There is increasing potential within this area, due to the shallow alluvial depths of the aquifers being less than 20 m below the surface throughout the dry season [57].

Ghana's precipitation, surface water, and largely untapped groundwater resources are wholly sufficient to meet most of their projected water needs [58]. Ghana's groundwater resources are predominantly untapped with ample room for scale-up, particularly for agricultural purposes [59]. Ghana's groundwater aquifers range from between 10 to 60 m in depth, with well yields rarely exceeding 6 m^3/h. However, these wells yields can be much higher and the depths can be much deeper in areas where limestone is present within the soil profile [60]. As highlighted by de Graaf, et al. [39] and IGRAC [50], portions of Ghana's groundwater are accessible within 15 m of the surface. In areas where the water table is within Horn's previously demonstrated depth, such as portions of the Keta Strip, the potential to benefit individuals already exists at 7 m. However, if depths of up to 15 m can be achieved, a far greater number of locations could also benefit from this well installation process. As per **Table 4**, a 49% cost savings to install shallow tube wells in Ghana by using the Well-Driver PUP technology is extremely promising.

4. Conclusions

In developing countries, water is not always palatable and available in sufficient quantities. In many locations around the world, people lack sufficient access to water for both drinking and domestic purposes, and they use unsafe water sources. Water-related diseases pose a major risk to individuals through the consumption and unsafe use of poor water quality sources [4]. This is particularly true in sub-Saharan Africa. People must have equitable and affordable access to safe and sufficient water that is potable and in sufficient quantity for both drinking and domestic purposes. Stored underground water that can be removed by wells is the most likely means to supply this need. In many countries around the globe, individuals obtain their drinking water from community wells, so this kind of water access is commonly used for drinking and domestic purposes.

Worldwide, there are many locations where the water table depth is less than 15 m, specifically in the 10–20 m range. Many of these locations are within sub-Saharan Africa. Ghana is one of the many countries located within sub-Saharan Africa where the Well-Driver PUP could have a positive impact on the quality of life for those living there. Horn [10] installed a series of test wells, with the deepest being that of 7.0 m. This well received a continuous water rating and was formally completed [10]. The well water quality results analyzed received a satisfactory rating from the Montgomery County health authorities [3, 10, 29, 48]. Horn's initial test well could potentially supply water for between 270 and 360 people, if installed in a similar community setting.

This chapter reviewed the three primary types of wells utilized to obtain groundwater resources: dug, drilled, and driven wells [11]. Water wells of these three types can be installed through either manual or powered methods [11]. The Well-Driver PUP is a low-volume manufactured utility vehicle with a hydraulic post driver mated to it, to mechanize tube well installation. The components required to install a driven tube well stack utilizing the Well-Driver PUP include: the well point, the drive couplings, galvanized steel piping, a well point drive cap, and drive sleeve. The implementation and dissemination of the Well-Driver PUP technology has the potential to improve water access of safe water in developing countries for both drinking and domestic purposes.

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Conflict of interest

The authors declare no conflict of interest.

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