Engineering in the Village

Peter N. Saeta

18 August 2010

Are you tired of having your work appreciated? Does it embarrass you when people celebrate your achievements by cheering, singing, and dancing? Do you find it annoying when people insist on pointing out the valuable aspects of your efforts when you feel it much more fitting to dwell on the failures? Yes? Well, then I don't recommend working on a water and solar power project at the Clay International Secondary School in Ngomano, Kenya.

Of course, I didn't realize the work would be quite so rewarding when I was tapped to replace Prof. Susan Martonosi, who had to stick around at HMC for a math REU program. The six-week trip was organized by the Harvey Mudd chapter of Engineers for a Sustainable World. I was added to the team after most of the legwork had been done, for which I owe Susan and Richard Haskell a great debt. Four engineering students and I arrived in Nairobi on 10 June 2010: Rob Best ('10), who had been to the school once before in January 2009; Isabel Bush ('12); Evann Gonzales ('12); and Ozzie Gooen ('12). Two weeks later, my wife, Linda, and boys Ethan (Stanford, '13) and Ryan (CHS, '13) joined the group and became an integral part of our efforts.

All of us were deeply affected by our time in Kenya. Our hosts at the school couldn't have been more gracious and welcoming, nor could they have been more appreciative of our efforts. I write this report in part to remember the ups and downs of the project, and in part to share the story, with deep gratitude, with those who made the trip possible.

Figure 1: *Benson Mutua, prime mover of the Clay International Secondary School in Ngomano, Kenya.*

1. Background

The Clay International Secondary School in Ngomano, Kenya, was founded six years ago by Benson Mutua, with financial support from HMC Trustee Andy Leebron-Clay and her husband, Jim. It serves the poor, rural community where Benson grew up—effectively as an orphan from age six—and where his grandmother still lives. The school provides quality education for local children who achieve satisfactory grades in primary school;

it follows the Kenyan national curriculum while declining funds from the government to maintain certain standards. Benson is eager to have the school develop a revenue stream to reduce dependence on monthly contributions from the Clays. By providing a steady supply of water for irrigation without using fossil fuels, our project would play an important role in that revenue stream. In addition, we planned to wire the classrooms for lighting, using spare power captured by the solar panels that also power the pump.

Currently the school draws water from a dry river bed nearly a kilometer away. Although usage varies with the season, during the winter while we were at the school the diesel-powered pump was run twice weekly to fill a large storage tank above the school, from which smaller tanks are gravity fed. These supply the water used at the school for cooking, cleaning, laundry, and agriculture. Four years previous, a borehole was drilled just below the teachers' residences and an India Mark II hand pump was installed at a depth of about 50 m. However, the water from this well was extremely salty and unsuitable for drinking, cooking, or agriculture. There had been little incentive, therefore, to pump the well out repeatedly to see if the salt concentration would drop, as expected by the drilling company. Our project aimed to install a solar-powered pump in the well, which would provide a straightforward way to flush the well and to determine whether the water will become widely useful. Because this is not guaranteed, however, we felt it important that extra power from the solar panels would be used to provide lighting for the student classrooms, to allow students to study more effectively on campus in the evening.

2. Choosing a Pump

As the spring semester wound down, we identified a solar-powered pump that would easily fit in the borehole, which we were told had a diameter of six inches. The Lorentz HR-04H helical rotor pump has a maximum pumping speed of 800 l/h and requires 72 V DC. Based on the estimated water consumption at the school of 75 m^3 every two weeks, or

(a) The riverbed (b) The tank

Figure 2: *The existing source of water: a pumping house on a dry river bed, which is used to fill the main tank above the school.*

5400 l/day, this pump could conceivably supply all the school's water if it could operate at full speed for 7–8 hours a day.

Helical rotor pumps operate under a fairly narrow range of temperatures, due to the tight tolerances between the rotor and stator. The standard model expects water temperature no higher than 22°C, which we thought might be too low for Ngomano. Greg Lyzenga confirmed that the water temperature in the well will be the annual mean surface temperature, which we estimated to be well in excess of 22°C. We therefore ordered a high-temperature model of the pump from a supplier in Texas, so that we could test it in Claremont, where we would have access to power supplies and other equipment that we thought might be difficult to find in Kenya.

Figure 3: *Isabel working hard to measure the flow rate of the pump. Guys, what are you doing?!* [May 31]

We were planning on using either a high-current DC power supply or a string of several car batteries to test the pump. However, the students had contacted Kevin Holme at RCC Solar in Upland with a question about how we could supply 72 V to the pump and also send residual power to charge a 12-V battery when he offered to lend us three solar panels for a weekend so we could check out the pump in a more realistic arrangement. On 31 May 2010 we wired the panels in series and connected them to the pump controller, which had been wired to the pump. With the pump immersed in the spa of the Saeta swimming pool, we flipped on the pump controller and measured the maximum flow rate of the pump. It agreed nicely with the specifications in the manual, so we dried the pump off and packed it for the trip to Ngomano.

3. Arrival

We arrived in Nairobi on Thursday, 10 June 2010, and headed towards Ngomano the next day, after purchasing food, some tools and supplies at the Nakumatt, as well as solar panels, a charge controller, inverter, and solar battery at Chloride Exide in Nairobi. Chloride Exide is the largest manufacturer and distributor of solar power products in Kenya. We spent the night of the 11th in Wote, a town roughly 45 minutes from Ngomano. Wote has electricity (usually); the Acacia Resort where we stayed had a television showing the opening game of the World Cup. I thought this would be the first and last game I'd see, since there's no electricity at the school (as far as I knew). The next morning we bought a 4200-liter tank, some cement, rebar, and wood for forms to build a support platform for the tank before heading to Ngomano and the school.

We drew water samples from the well using the hand pump and measured the total dissolved solids using a small meter we brought, finding 4200 ppm. As a check, we tested the

Figure 4: *Raising the old pump. Note how the flange with the spigot appears to be impacting the rope that holds the chain hoist.* [June 13]

bottled water we used for drinking. It registered 120 ppm, as expected. So, the well water was still quite salty, although the concentration had dropped somewhat from earlier samplings. Rob Best confirmed that it didn't taste quite as bad as it had in January, 2009. According to a test conducted by Patrick Karanja of the Kenyan Ministry of Water and Irrigation on 24 January 2007, the total dissolved solids were 5995 mg/l. His report concluded with the comment "Highly mineralized water requiring demineralization before being put to domestic use."

4. Raising the Old Pump

The first challenge was to remove the existing pump. It was mounted on 1.25-in galvanized iron (GI) pipe, which was screwed into a flange bolted to the top of the well. Inside the pipe ran iron rods that were used to actuate the pump when the handle was raised and lowered.

To raise the old pump, Benson assembled a tripod using three strong segments of pipe lashed together near the top with a piece of the polypropylene rope that we bought at Lowe's.

We borrowed a chain hoist from a friend of Benson's and attached it to the tripod with some rope. After unbolting the flange and attaching the hoist to the chain connected to the rod, we succeeded in raising the rod, flange, and pipe off the top of the borehole enough to be able to grab the pipe in the jaws of a two-foot pipe wrench. With the pipe held by the wrench, the hoist was lowered to allow the chain to be wrapped twice around the top of the pipe and clipped to itself. The pipe was again raised roughly to the limit of the chain, held with the pipe wrench once more, lowered, rewrapped, and raised again. At one point, the hoist appeared blocked and we noticed that the top flange was bumping into the rope binding the hoist to the tripod. We lowered a bit, pushed the pipe/flange away from the hoist, and raised again until there was enough pipe beneath the first coupling (socket) to allow the first pipe segment to be removed.

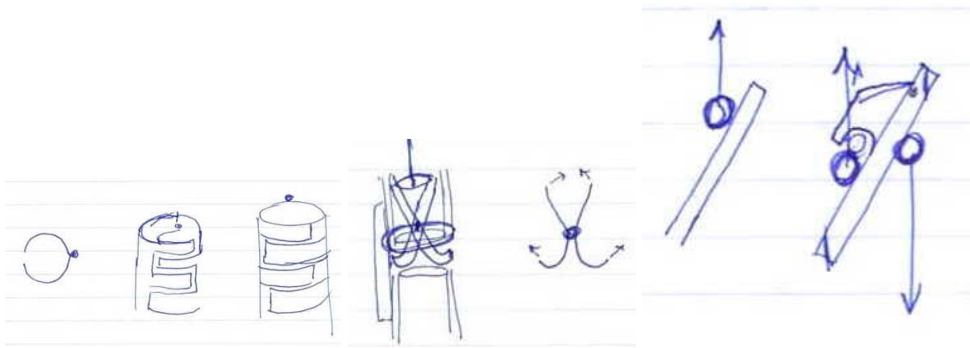
At this point, Benson realized that we needed a pipe vise to hold the pipe securely while unscrewing the top pipe segment with the pipe wrench, so he sent handyman Mbithi David to fetch it. The pipe was being held by the chain hoist; the pipe wrench was held loosely around the pipe at the top of the well. Soon after Mbithi left, Benson turned to Rob and asked, "Tell me, Rob, what's the stupidest thing you did in college?"

Before Rob could answer, the rope holding the chain hoist gave way, the chain holding the pipe loosened, and the pipe fell into the well, crashing into the pipe wrench on the way. The wrench upended and fell head first down the well. When the flange struck the top of the well, the top pipe sheared off at the base of its threads, and we heard the pump, pipe, and wrench rumble rapidly down the well.

Figure 5: *Just after gravity reared its unfortunate head.* [June 13]

The top of the rod, however, remained attached to the flange, allowing us to begin hoisting out the rod piece by 3-meter piece. At the bottom of the rods was a short stainless rod which must have been attached to the pump. The pump, however, was surely still at the bottom of the pipe, now at the bottom of the well. *Our first step was a truly giant step backward!*

I'm sure that this sort of thing happens all the time. In fact, Benson said that the company that installed the pump managed to drop it down the hole before attaching it to the pipe. It took them two weeks to fish it out. However, this happened when Benson was not at the school; so, he didn't observe how they did it. He called the company to ask if they could fish out the pump and pipe for us. They said it would cost a minimum of $1000 to come out, and



(a) Trying to capture the outside of a pipe (b) Or maybe the inside (c) The Harpoon of Death

Figure 6: *Ideas for a "hook" to catch the pipe. Pulling up on the left side of the Harpoon will cause the hook to rotate clockwise, wedging itself inside the coupling between pipes.* [June 15]

that it would take quite awhile, as the crew was off working in Uganda. We decided to tackle the job ourselves. After all, we had to learn all about engineering in the village!

4.1 Fishing, Part I

Having hoisted about 50 meters of rod out of the well, and knowing that the borehole is 102-m deep, we figured that the top of the pipe should be about 50 m down. Although we could lower the new pump to rest just above the top of the pipe, this positioning would limit the amount of water we could pump each day. It would be better to remove the old pump and pipe first, then lower the new Lorentz pump. The flange at the top of the well has an inside diameter of 6 inches, but the casing quickly narrows down to about 4.75 inches, which it appears to maintain to the bottom. Pipe is sized according to the inside diameter; the thick-walled GI pipe has an outside diameter of about 1.6 in and the couplings have an outside diameter closer to 1.75 in. We thus needed to fish for the comparatively small top of the pipe, which was no doubt leaning against the well casing.

We considered many possible designs (see Fig. 6), but settled on a kind of hook that would be lowered on a chain inside the top of the pipe past the first coupling. On pulling up on the chain, the hook would settle inside the coupling and push against the bottom of the top segment of pipe, allowing us to raise the pipe and pump with the chain hoist. Besides coming up with a workable design to take to a blacksmith in Wote, we also needed to figure out how to ensure that the hook would find the opening of the pipe. Both tasks posed significant challenges.

We ended up with a design for the hook akin to two interlocking tongue depressors made of strong metal. The chain would be mounted to one of the pieces, whose top end would be filed to conform to the inside of the coupling and have a sharp edge to bite into the bottom end of the pipe. The companion piece would also have a sharpened upper edge, to help bear the load. Of course, settling on a design is one thing; having it fabricated is something else,

Figure 7: *The Harpoon of Death, up close. A link of chain slips around the hook at the right, and the edge at the extreme lower right is sharpened to grab the bottom of a pipe segment inside a coupling.* [June 17]

as we were about to find out. Benson took us and our designs to Wote, where we stopped at a blacksmith's shop. I'm not really sure that this guy understood our design, but in any case, he insisted on "improving" it. We left him working on it do some shopping and to find another blacksmith.

This guy did what Benson directed (in Kiswahili), and we watched and guided every step of the way. His version is shown in Fig. 7 and cost us a whopping KSH 300 (about $4), not counting the filing and shaping that we did after we returned to the school. We christened the better one, shown in Fig. 7, the Harpoon of Death (for reasons that escape me). We looped back to the first blacksmith, who wanted to charge us way more for his less satisfactory

Figure 8: *Demonstration that the Harpoon of Death works.* [June 17]

Harpoon, but Benson gave him the same KSH 300 fee and we left. Rob and others sawed, filed, and shaped the two Harpoons to get them ready to go. We needed to bend a stiff wire on the Harpoon, but this wasn't working with the wrenches we had. Benson tried using the cheap Chinese pipe vise, but the loud crunching sound it made signaled that the upper jaws of the vise had cracked. Fortunately, they were still usable to grab pipe. Meanwhile, we tested the better one on a segment of pipe having a coupling at one end with a modest tug-of-war match; it seemed to hook readily and hold strongly.

4.2 The Skirt of Salvation

How to thread the Harpoon into the pipe? By lowering a rope tied to a 2-liter Coke bottle filled with sand, we readily confirmed that water level was about 23 m down and the top of the pipe was 27 m below that, but we had no idea where along the circumference of the casing the pipe rested. We thought it would be tedious and unproductive to lower at random in hopes of getting the Harpoon to slide into the pipe. So, we set about designing a "skirt" to guide the Harpoon into the pipe.

Figure 9: *The "Skirt of Salvation," just before it was lowered into the well to settle onto the top of the pipe and guide the Harpoon of Death into the pipe.* [June 17]

The ultimate design consisted of a top portion made from the neck of a 20-liter water bottle, which would mate happily with the top of the pipe. The lower portion of the "Skirt of Salvation" (Fig. 9) would be a gently tapered conical piece that would rotate the Skirt as it encountered the top of the pipe, thereby aligning the bottle neck with the pipe. Ozzie and Isabel worked hard to translate this concept into a working device, using the modest materials available: plastic from the water bottle, nylon cable ties, and wire mesh we bought in Wote. The Skirt was attached to a rope so we could lower it along with the Harpoon, but leave the Skirt in place while we were fishing with the Harpoon.

All necessary parts were assembled on the morning of June 17th. We lowered the Harpoon and Skirt together, having marked on both the rope and the chain the depth to the top of the pipe. Once the Skirt was at the appropriate depth and the rope had gone a bit slack, we continued lowering the Harpoon on the chain for another four meters or so. However, on attempting to raise the Harpoon and have it catch inside the pipe, we felt no sudden increase in weight. So, we decided to pull it up to see what shape the Harpoon and Skirt were in. When the chain came up, we saw that the Harpoon had fallen off and when we raised the Skirt, we were met with only a small piece of the top. So, we had managed to lodge the Skirt in the well at some point above the pipe and to lose the Harpoon of Death. *We had taken a second giant step backward.*

We lowered large and small sand-filled Coke bottles, which showed that the Skirt was about 7 m below water level. Further attempts to fish for the top of the pipe now had to contend with a significant obstruction in the well some 20 m above the top of the pipe.

4.3 The Rocket of Reclamation

Meanwhile, we worked on a new design for a "hook" to grab the pipe. Inspired by a suggestion from Benson that we aim to slide around the outside of the pipe and grab a coupling, rather than the end of a pipe inside a coupling, we designed the "Rocket of Reclamation." No more Mickey Mousing around; this time we needed a robust device that (a) wouldn't be deposited in the well, and (b) would pull up the pipe. It would have a loop at the top to which we could attach a chain to provide a backup means of securing the Rocket against falling into the well. Unfortunately, Benson's younger brother, Edward, died on June 18th. He had been ill with Guillain-Barré syndrome for over a year, but had been released from the hospital only the week before. Since we were "confined to base," we spent a couple of days refining our design for the Rocket.

Paul returned to handle driving duties, and took us to Wote where we met Mbithi. He

Figure 10: *The Rocket of Reclamation, which was initially welded in Wote on 21 June 2010. The curved structure at the right is the "scythe" designed to sweep the pipe away from the wall and into the Rocket's funnel.*

took us to a third Wote blacksmith, a longtime friend of his, on June 21st. This blacksmith was a master craftsman whose weapons of choice were a Makita grinder and an arc welding setup. He worked quite efficiently, except when the power went off several times, but the work took all afternoon and cost KSH 2500 (about $31). It was worth every shilling!

The Rocket (Fig. 10) was a much more substantial piece of machinery than the Harpoon of Death and the Skirt of Salvation; it reflected a decision that we were not going to mess around with flimsy, half-baked solutions that would get stuck in the well. However, we were concerned that the Skirt might interfere with the Rocket and prevent it from sliding over the top of the pipe. What to do about that?

4.4 Fishing, Part II

Before lowering the Rocket, we decided that we had better dispense with the Skirt, which had now morphed into the "Apron of Annoyance," at least in name. Ozzie crafted some hooks from available material and attempted to fish it out. Despite considerable patience, he did not manage to hook the Skirt. Frustrated that his hooks wouldn't catch, he decided to lower a flashlight and a digital camera in video mode to take a look at the configuration of the Skirt. He placed these items in a plastic bottle and lowered it several times, but no usable pictures emerged. At least the camera didn't drown and didn't join the other junk we had dumped into the well!

On June 22 we decided, instead, to use the rods to push the Apron of Annoyance down past the top of the pipe. Although the jaws of the pipe vise had broken, it still worked reasonably well. Rob and I lowered about 15 segments of rod by hand, using the vise to hold as we attached each subsequent rod. Then we switched to the hoist to lower the final four rods, which should have pushed the Apron well below the top of the pipe. Then the rod slipped. Isabel and Rob both grabbed for the rod, dragging Isabel's hand onto the vise and dislodging the broken pieces of the jaw, which tumbled into the well.

Luckily, Isabel's hand wasn't cut too badly and the chain managed to grab the top of the rod, which flares out a bit. However, it was holding by friction alone, because the fall had jarred the hoist's chain out of its hook. I scrambled to find something to serve as a makeshift jaw for the vise, landing on a piece of pipe lying around near the well. When lined up carefully, it seemed to hold the rod firmly, which allowed us to wrap the chain properly around and carefully raise and remove

Figure 11: *An assortment of hooks used to try to catch the "Apron of Annoyance."* [3 July 2010]

the rods. However, when we used the Coke bottle to confirm that we had indeed pushed the Apron out of the way, we encountered an obstacle in the same place (7 m below the surface of the water) as we had before!

Having managed to injure Isabel's hand and to deposit a few more bits of junk into the well, we decided to cut our losses. We were leaving on the 24th for Nairobi, three days at Maasai Mara, and three more in Kisii at an orphanage before returning to Ngomano via Nairobi. We had sent Linda and the boys a hardware shopping list:

- locking pliers (large)
- Channelok pliers (large)
- at least 100 yards of fishing line
- some S hooks and eye bolts with washers and nuts, each capable of supporting about 500 pounds.

We figured that it would be easier to fish for the Skirt using light-weight fishing line, rather than the rope we were using, which was heavy enough to make it difficult to tell whether you had managed to hook something. We also asked them to bring some drill bits from our garage, and planned to shop for whatever additional tools and supplies we might need when we returned to Nairobi.

Before heading to the airport, we picked up some 100-pound-test fishing line and an assortment of fishing hooks in Nairobi. That evening we had a glorious dinner at the Carnivore, then headed with Paul to Maasai Mara. After three glorious nights at Mara West, followed by two nights in Kisii visiting the orphanage, we decided to stop for two nights in Nakuru, where we could show for more hardware. I was determined to supplement our assortment of tools and building materials to give us the best possible chance to fish out the Skirt and then the pipe. Besides more wire to stretch across the field to the staff office, we bought:

- two pipe wrenches, one 24-inches long, the other a bit smaller
- a replacement pipe vise, nearly identical to the broken one
- a larger pipe vise
- five hard hats
- a roll of stiff metal wire
- a corded electric drill (over the students' mild objections)
- two large C-clamps
- an assortment of bolts, nuts, and washers
- a rat-tail file and a rounded-edge file.

We were now armed for a serious struggle to fish out the old pump.

4.5 Fishing, Part III

We returned to the school after dark on July 2nd, and set to work fishing the next morning. After I gave a quick lesson on tying fishing hooks, we prepared a curious combination of the hooks using some of the stiff wire from Nakuru to fish for the wire mesh portion of the Apron (Fig. 11). These weren't particularly successful. It seemed that any part of the Skirt that caught the hook wouldn't hold. Most everyone took turns fishing throughout the day, and Ozzie fished into the night. Only a small piece of mesh came up, which Ozzie eventually realized was a piece he had previously lowered in an attempt to make an impression of the top of the pipe.

Rob had the first real success on the morning on July 4th when he pulled a bent stick from the well (Fig. 12). *Who ordered that?!* Evidently, someone happened by the well while we were gone and opted to run yet another test of well gravity. When the store-bought fishing hooks didn't seem to work, Ozzie used some of the stiff wire to craft his own hook. Around noon on July 4th, after a tense 20 minutes with fingers crossed that it wouldn't fall off the hook, Isabel, Ozzie, and Rob managed to fish the Apron of Annoyance out of the well, along with the mangled pieces of pipe vise that had fallen on top. Meanwhile, the cement of the tank support structure had cured sufficiently that we could mount the solar panels above the tank. Finally, it seemed that we were making forward progress. We had a wonderful Independence Day celebration!

(a) Rob first removed a bent stick from the well. (b) The triumphant trio.

Figure 12: *Eureka! The Apron of Annoyance was removed.* [4 July 2010]

4.6 Fishing, Part IV

Flush with the success of fishing out the Apron, it dawned on us that we may be facing considerable difficulty with the pipe wrench becoming wedged between the pipe and joints in the casing. Furthermore, if the wrench were near the top of the pipe, it might prevent the "scythe" of the Rocket from pulling the top end of the pipe away from the wall enough for the Rocket's funnel to surround it. Using wire mesh and zip ties, Ozzie constructed a model showing how tightly the wrench would fit against the pipe. All signs pointed to our need to fish out the pipe wrench before essaying the Rocket. We also determined that the thread on the bolt we had had welded to the Rocket was incompatible with the rods, so we needed to have it replaced by a compatible bolt or segment of rod.

Our progress was interrupted by the afternoon's football matches in Kathonzweni, but the matches seemed to be operating on African time, so we visited our favorite blacksmith in Wote to have the Rocket modified and for him to fashion a hook we could use to fish out the pipe wrench. We brought along a model of the pipe and casing Ozzie had made from the left-

(a) The first wrench hook. [July 7]

(b) Failsafe chain.

Figure 13: *(a) Benson examines score marks on the first hook we used to try to fish out the pipe wrench. (b) To prevent the Rocket from falling if the rods should slip, Ethan buried a pipe to serve as a capstan (upper right). The chain wraps twice around the capstan, allowing the seated crew member to support many hundreds of pounds quite easily.*

over wire mesh and some cable ties, to help illustrate the challenge. The blacksmith quickly made a sturdy hook by bending a piece of rod, which we subsequently filed to make it as attractive as possible to the wrench (see Fig. 13). It did indeed seem to hook things, although deeper than we expected the wrench to be. Tests with Ozzie's model suggested that there would be three different ways for the key to hook the wrench, assuming the wrench were intact and had the maximum width of about 4.25 in. However, nothing would guarantee that the wrench would remain hooked once it was dislodged from its initial resting position.

This hook did appear to catch on the wrench, and it required considerable force to budge it once hooked, so much so that the end bent a bit (Fig. 13). We thought we were dislodging the wrench and raising it perhaps 3 meters or so, but it would then become stuck and fall down again when we jiggled the line. We decided to have a second hook made with a lip to keep the wrench from falling off once it was hooked. We also decided to add a release mechanism to the Rocket, in case the pipe should become stuck.

By design, the second hook would only catch the wrench from the side opposite the pipe. In fact, it was quite good at this—so good, that it got stuck and we couldn't pull it out. It confirmed, however, that the wrench was far below the top of the pipe. So, we decided to send down the Rocket—after spending the 9th in Kathonzweni celebrating the triumphant test results of the first graduating class of the Clay International Secondary School, which swept essentially all categories for secondary schools in the district.

4.7 Cue the Rocket

For redundancy, we attached a strong chain to the rocket and wound the chain around a two-inch pipe that Ethan had buried in the dirt, as shown in Fig. 13. He'd seen this done once in an episode of *Man vs. Wild*. Ryan paid out the chain slowly to limit the slack that would be taken up should the hoist slip on the rod. Because the Rocket needed to be rotated once the scythe was lowered below the top of the pipe, we needed to use the rods to lower it. This was accomplished using the new (small) pipe vise, along with the hoist. We slowed to a crawl when the scythe was due to hit the top of the pipe, and indeed encountered that obstacle right on cue. Rotating the rocket a few times, we were able to continue lowering until the funnel encountered the top of the pipe. Once again, rotating about half a turn allowed us to continue lowering. The scythe had swept the pipe into the Rocket's funnel just as we designed it to. We lowered another 4 meters or so to be sure that the Rocket's pawl slipped over the first coupling, and then anxiously raised the hoist. Within a meter or so, the load on the hoist increased markedly. *The Rocket had caught the fish on the first try!*

As we hauled up the pipe using the chain hoist to raise the rod (while simultaneously gathering in the chain), the rocket would become stuck from time to time, which we attributed to the wrench. We tried lowering the hoist a bit, rotating the rod, rattling the rod back and forth at the top of the well, and then hoisting some more. Ultimately, brute force was the most effective approach and managed to unstick the pipe every time.

With only four rods left before the Rocket was to emerge from the well, one of these episodes of twisting managed to unscrew the Rocket from the rod. Were it not for the Ryan and the chain, the Rocket and pipes would have fallen. We quickly removed the four rods and started hauling up the Rocket, now using a loop in the chain to attach it to the hoist. When the top of the pipe was within two rods of emerging, the pipe became more firmly lodged than ever before. In fact, when we lowered the hoist, the chain simply went slack. Evidently, the wrench was now so firmly lodged between the pipe and the casing that it was supporting the entire pipe. We couldn't rotate the rod, since all the segments were now all out of the well and there was essentially no chance of screwing it back on blind. So, we attached a large washer to the end of a rod, lowered it, and tried to bang into the top of the pipe when only a little slack was left in the chain. This freed the pipe and allowed us to lower again, in hopes that a second hoisting would get us past the blockage. Thankfully, it did.

Figure 14: *The Rocket emerges from the well, pipe firmly in tow.* [July 10]

Finally, the top of the pipe emerged from the well, followed quickly by the Rocket and then the second pipe. We grabbed the pipe with the large pipe vise, raised the Rocket above the coupling, and removed the top pipe. By the end of the day we had removed perhaps a third of the pipes and had become quite firmly stuck. After a particularly large tug on the hoist, we heard sand or gravel tumbling into the well. We had punctured the casing. Time for a break! Isn't there a nice World Cup game we can watch??

The next morning we repeated the maneuvers that had failed to unstick the pipe the night before, but this time the pipe continued to rise. By mid-morning, the last pipe emerged, followed by the India Mark II pump with the wrench sitting atop it. Benson had been so sure that the wrench broke before tumbling into the well that he had promised us a goat if we

Figure 15: *The pump is out!* [July 11]

pulled it out in one piece. As the pump was removed, the upper jaw of the wrench tumbled into the well to find a comfortable resting place 102 meters down. Even so, our goat had been grazing peacefully all morning a scant forty meters from the well, occasionally cheering us on with his chatter…until his throat was slit. We enjoyed three days of tasty goat-inflected meals.

5. Lowering the New Pump

The students had previously tested the pump in my swimming pool in Claremont, but before lowering it down the well, we thought it prudent to test it above ground. Rob had sealed up the connections of the pump to the two three-conductor wires using the supplied crimp connectors, shrink tubing, and silicone sealant. To test the pump we just needed to use wire nuts to connect the wires from the power house that had been laid in the trench along with the pipe to those destined to be strapped to the pipe as the pump would be lowered. We put it in a bucket of water and turned on the pump controller to find it jerking very hesitantly and then stopping. There should have been plenty of sunlight to drive the pump, so something was clearly wrong. Is *nothing* easy?

We removed the motor from the pump, which meant pulling the helical rotor from the stator. Firing up the motor with the rotor free sent it spinning quite happily and normally. Given its lack of movement and warm weather for the previous month, the rotor had just begun to stick to the stator. We reassembled the pump, using Loctite to make sure the nuts wouldn't come unstuck, attached the first pipe, clamped the water level sensor to the pipe just above the pump, and began lowering the pump.

We were able to lower the pump most of the way, but a few of the twenty-three 3-m pipes needed to be rethreaded to allow us to place the pump at about 70 meters below the top of the well. Mbithi brought a die to cut fresh threads the next morning, and we were then able to finish lowering the new pump. We quickly connected the wires and threw the switch on the pump controller, which lit up and claimed that the pump was spinning at top speed. No water came out, however! A quick calculation showed that at the maximum pumping rate, it should take half an hour to fill the pipe. Sure enough, within a minute or two of the estimate the first water emerged from the pipe. The team went wild! Water at long last...and just in time. We had only five days left in Ngomano.

Figure 16: *Ethan celebrates the arrival of water from the well.* [July 13]

6. Electrical Systems

I now backtrack a bit to pick up the story of the powerhouse and electrification projects. Benson decided early on that the 4200-liter tank for the well water should sit beside the existing 5000-liter tank just above the teachers' residences and guest houses. By adding vertical pipes at the corners, we would be able to mount the solar panels above the new tank, while the powerhouse would be bricked in beneath it. Although we pitched in with mixing a batch of cement—only to discover that we lacked the muscles to manage it!—our role in the construction was largely to observe, kibitz, and occasionally to splash some water on the curing concrete. I especially wanted the students and my kids to see how Mbithi managed the

(a) Laying brick for the walls. [July 6]

(b) The finished powerhouse, with tank and solar panels on top. We're finishing the water line into the tank from the pump. [July 13]

Figure 17: *The powerhouse under our new water tank.*

various stages of the construction, as I suspected they'd never seen most of the techniques, including bricklaying, before (Fig. 17).

6.1 The Powerhouse

Once the walls were finished, Isabel, Ozzie, and Evann started installing the electronic equipment. As shown in Fig. 18, the positive lead from the solar panels passes through a switch before entering a junction box from which connections are made to both the pump controller (on the left) and the charge controller (on the right). These two controllers cooperate nicely: the pump controller has priority, and the charge controller takes whatever power is left over to charge the battery. It also handles the voltage step-down from the > 72 V coming from the panels to the roughly 12-V required to charge the battery, making constant adjustments to charge the battery nicely.

The 12-V output of the charge controller, drawn from the battery, goes to the 240-V AC inverter (the blue box at the right). When the pump was off, we observed a peak charging power of about 400 W going to the battery. Before we finished the wiring, we couldn't resist running the line from the battery and charge controller to the lounge so that we could watch the semifinal and final matches of the 2010 FIFA World Cup, on July 10–11, using quiet and renewable battery power instead of the generator. I'm not sure that it had much influence on the outcome on the pitch, but it sure felt satisfying!

Figure 18: *Pump controller and charge controller.* [July 13]

6.2 The Classrooms

We planned to send 240-V AC from the powerhouse up to the staff office, to provide better lighting, to allow teachers to charge their cell phones conveniently, and to use a computer, if available. We also decided to use the powerhouse to provide electricity to the laboratory. However, the classrooms would be on a different circuit.

Two of the five classrooms already had dim fluorescent lighting operating on 12-V DC from a solar battery in the staff office. We wanted to bring light to all the classrooms and to the laboratory, which would also get a power outlet. Benson decided to expand this system with a new 80-W panel, doubling the available power, and a second solar battery. We had to decide whether to extend the existing DC lighting scheme or switch everything to 240-V AC.

Assuming that the main trunk from the office to the first classroom carries all the current, and that each classroom would be lit with three bulbs of about 12 W each, the total load for lighting at night would be roughly 15 A. The wire to the first classroom had a cross section of no more than 2.5 mm^2, corresponding to a resistance of 6.8 mΩ/m. Thus, the resistive loss in the wire from the battery to the first classroom would be roughly

$$P = I^2 R \approx (15\ \text{A})^2\,(0.0068\ \Omega/\text{m})\,(72\ \text{m}) = 110\ \text{W} \tag{1}$$

This should be compared with 180 W for lighting. Of course, further losses would arise in getting the current to the second classroom. Insofar as it seems likely that all classrooms will be lit from about 18:00 to 21:00 each evening, the combined daily load on the battery would be roughly 75 A h, which is three-quarters of the capacity of the new battery in the staff office. Installing an inverter to convert from 12-V DC to 240-V AC drops the current by a factor of 20, and the resistive loss by a factor of 400, trading the resistive loss of 110 W for the inefficiency of the inverter, which should be less than 10% of the 180 W expended on lighting. Furthermore, it allows the entire electrical system to operate at standard 240-V AC. It also allows the system to be extended more readily. So, we decided to switch everything to alternating current.

Rob oversaw the student effort to wire up the classrooms and the lab, but Ozzie, Isabel, Ethan, and Evann did much of the work. Dedicated parents dug trenches for the wires, and everything was ready for testing on July 14th—except that the cheap 350-W inverter we had bought in Wote didn't want to light more than two bulbs in a classroom. So, Rob wired the line heading to the classrooms to the one coming from the powerhouse, so the students would have light to study by.

Principal Peter threw on the switch at dusk. We were all down in the lounge, relaxing and writing in our journals. A bit later he came down to tell us that the classrooms looked like a small city and that we should wander up near nine o'clock, when the parents would be by to pick up their kids. What happened then is etched into all our memories. Some mothers started singing, and we all flooded into the bright classroom filled with students, grinning ear to ear. Students, parents, and teachers clapped, sang, and danced with infectious enthusiasm and profound gratitude. All our frustrations with the well just melted away. What a triumph!

Figure 19: *The new lights come on in a Form 4 classroom.* [July 14]

7. Troubles

Would that the story might end here! Sadly, the triumph was short lived. The next morning (July 15th) I noticed the "tank full" light was lit on the pump controller. Being a suspicious sort, but also old, I sent Ryan up to check the tank: he found it only half full (see Fig. 20). Bypassing the sensor failed to get the pump working again, so we opened up the controller when I returned from Wote at the end of the day. A component on the printed circuit board had clearly fried, leaving a trail of smoke going up the board (Fig. 21). With no schematic (and no electronic components or appropriate tools), there was no choice but to head off to Nairobi to try to get it repaired or replaced.

Figure 20: *The students decided to have a "pool party" to check out the sensor in the tank. The sensor was fine, but the water sure looks murky!*

7.1 Circuit Board

Paul and I headed off early on the 16th. In contrast to the normal *pole pole* ride, Paul demonstrated that he could make good time when the situation really called for it. We were back in Nairobi at the Chloride Exide store where we bought all the other electronic components within three hours. However, they do not deal directly with Lorentz pumps and would have to work through the Center for Alternative Technologies, which was across town. As it turned out, I had a map to the center, which I had printed out before leaving California. However, this was my opportunity to experience midday Nairobi traffic. *Pole pole* doesn't begin to describe it.

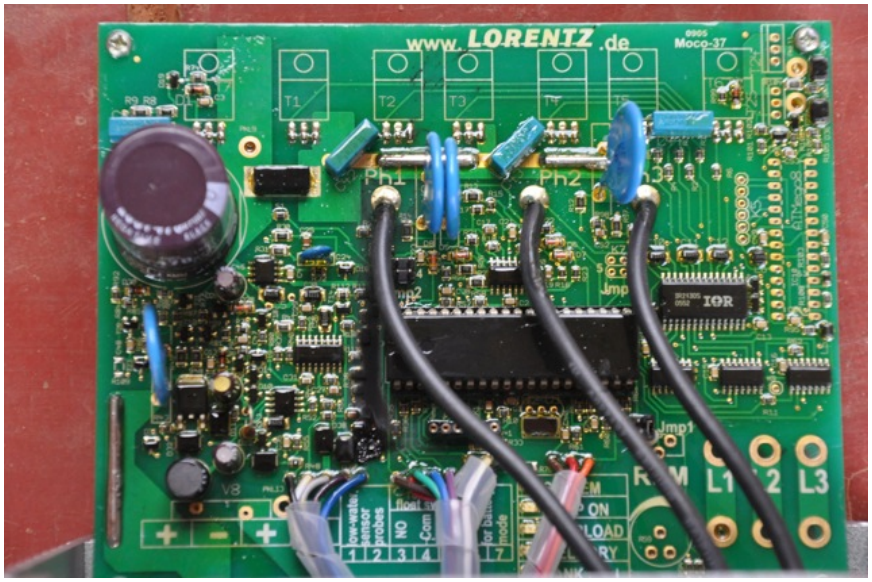


Figure 21: *The damaged printed circuit board.*

By lunchtime we managed to make it and find that they had a replacement board. However, I had to pay for it in cash since they don't deal with credit cards. Fortunately, there was a Barclay's with an ATM a short distance away, so just after noon we had the precious circuit board. However, it was getting dark by the time Paul and I returned to Ngomano.

The next morning Peter had arranged a celebration of our time at the school. Students, teachers, and parents would all be there, starting at 10. Shortly after dawn, I got up and tested the wires heading down to the well, to make sure that the replacement circuit board wouldn't get fried like the first one. To my immeasurable distress, I found that the lines were all shorted together. I could find not a single pair of wires that had a resistance greater than 3.3 Ω. How could the lines going to, and coming from, the water-level sensor be connected to the motor? I hustled down to the well and tried bypassing the lines between the powerhouse and the well. Now the resistances were lower, as expected if the short were in the well. Something was terribly wrong here. We would have to raise the pump and find where the lines were cut.

7.2 Raising the Pump

We no longer had the chain hoist. We had to get it back. Fortunately, Benson got ahold of his friend, who said we could borrow it again. (After all, I'd paid him fairly well for our previous use.) Paul went off to fetch it while I dressed for the celebration, which included performances from each of the classes, speeches and advice for the students, and lunch. It was great to have our work appreciated and to spend some time with the whole community, but in the back of my mind I knew that we had many hours of work at the well ahead of us. In all probability, the short was below the water line, which would mean that we would need to seal up the repair work very well and let it dry at least 24 hours before we could lower the pump again. The clock was ticking.

On the plus side, we would no longer have to contend with the wrench, so I thought that it should take a lot less time to raise the pump this time. Indeed, we were able to remove some pipes in as little as 7 minutes. However, we needed to pull 23 of them out. Furthermore, the chain was quite heavy and difficult to raise by hand at the same rate that the chain hoist was raising the pipe and pump. Perhaps inevitably, the chain gang fell behind and the chain pooled up near the bottom, where it functioned just like the wrench. Furthermore, in the process of lowering the pump, the pump, chain, and pipe must have rotated a fair bit, because the chain ended up wrapped around the pipe and the wires. Our progress slowed to a crawl.

By nightfall we had only pulled up a bit more than half the pipes, and had found no convincing evidence of a short. However, it quickly became clear that the advice we had been given to use stainless steel cable ties was unwise. They had sharp edges and the wire insulation was nicked in several places, although never deep enough to cause the short we were observing. Despite the darkness, we knew we had to keep going if we were to fix the shorts and seal the problem areas in time to lower the pump before we had to leave. So, we rotated through dinner shifts and kept working.

From time to time the pipe would get stuck and we were unable to raise the chain by hand. So, we had to clamp the pipe, attach the hoist to the chain, and raise the chain until it caught up with the pipe. We realized that when we lowered again, we might save ourselves a lot of hassle when we lowered again by using just the chain. It would stay taut and the pipe would clearly remain stiff and behave itself. Unfortunately, I let this line of thought color my thinking about the problem at hand: raising the pump. Once the chain had drawn taut, and the pipe vise had been loosened, I kept pulling on the hoist. The chain must have been knotted around the pipe. Suddenly, it slipped, the pipe started to fall, and it gained enough momentum that it ended up snapping a link of the chain. Yet again, gravity had reared its ugly head. This time, it was Rob's hands that suffered significant cuts and a sprain in the plunge. We cleaned them out, applied a cold pack to the sprain, and crossed our fingers that he wouldn't need further medical attention.

This time, we had to admit defeat. There was no time to fish out the pipe and pump, even though we knew the Rocket would work—if we had had enough rod to make it work. However, the top of the pipe should be at a depth of about 73 m, so it would be entirely possible to lower a second pump above it. This time, we would use light, plastic piping, as recommended by the Lorentz pump manual, and a light safety rope, instead of the heavy chain. Benson and Mbithi could manage this by themselves; they wouldn't even need the chain hoist. Fortunately, there was money in the budget to cover this expense, and I later found out that it would be possible for me to pay for the new pump from the States using the Center for Alternative Technologies' affiliate in Arizona. Soon after returning to the Claremont, I did this, and Benson quickly confirmed that the money had arrived. It took the C.A.T. a couple of weeks to get the pump, but Benson picked it up on August 12th, and installed it on the 14th. After a couple of messages back and forth about the water-level sensor, water started coming up again on the 15th and soon started refilling the tank. We have our fingers crossed that the water gets progressively less salty and more usable.

8. Technical Details

Connections to the pump were wired with three-conductor wire of 2.5 mm^2 cross section. Its estimated resistance is 6.8 mΩ/m, so that on a 70 m + 75 m run down to the pump, its resistance should be roughly 1 Ω, or 2 Ω round trip. The pump runs on 240-V 3-phase from the controller, Lorentz model PS1200. The replacement circuit board carries the serial number **309012301**. It was purchased from the Center for Alternative Technologies in Nairobi.[1]

The pump controller draws current directly from the panels, which are 24-V, 170-W BP Solar panels, connected in series to yield a nominal 72 V. In practice, the voltage is often significantly higher, but the controller can handle up to 200-V input. When the pump is running, the controller appears to draw between 125 and 175 W. Its maximum pumping speed is 800 liters/h. Assuming the water level has dropped to 70 m below the top of the borehole, the work required to pump at this rate—neglecting frictional losses, which are small in the piping, but may be significant in the pump—is

$$P = (800\text{ kg})(70\text{ m})(9.8\text{ m/s}^2)(3600\text{ s})^{-1} = 152\text{ W} \tag{2}$$

The pump brochure claims that the maximum efficiency of the pump is 65%. This means that if the panels are performing at something like 400 W, there should be something like 175 W to charge the battery even while the pump is operating at full speed.

8.1 Recharge Rate

Data from the 2007 report on the condition of the borehole was used to estimate the maximum daily amount of water that could be pumped from the well. The data were taken by pumping on the well until the water level was $h = 73.24$ m below the top of the well, and observing the height of the water over the course of four hours, as shown in Table 1. The equilibrium water level was measured to be 23.68 m. Assuming that the rate of influx is proportional to the pressure difference between the water in the borehole and the water in the aquifer, the influx should satisfy

$$\frac{dV}{dt} = -A\frac{dz}{dt} = \alpha(z - z_0) \tag{3}$$

where $z_0 = 23.68$ m is the equilibrium depth of the free surface of water in the well, α is a constant, and A is the cross-sectional area of the well. Solving for $z(t)$ gives

$$z(t) = z_0 + (h - z_0)e^{-\alpha t/A} \tag{4}$$

In other words, the water level relaxes to its equilibrium level in a decaying exponential with time constant $\alpha/A = \beta$. A fit to the data yields $\beta = \alpha/A = 0.0089\text{ min}^{-1}$ or $\beta = 0.54\text{ h}^{-1}$. Note that the final data point appears to have been misrecorded.

[1] Nawir Ibrahim, CEO. P.O. Box 64921, 00620 Nairobi. Location: from the intersection of Thika and Outer Ring Road, proceed one block clockwise around the Outer Ring Road. Turn left. There is a Dawa Building on the left, turn right on the first street and right into the first compound, called Jos Hansen (there are many business in this compound). Cell: 254 722 512004, 254 733 512004. Water pumping: 254 20 8562034; photovoltaics: 254 20 8000175; inverters and batteries: 254 20 8561253. `nawir@cat.co.ke`; `www.cat.co.ke`.

Time (min)	Water level z (m)	Rise (m)	$\ln(\Delta z)$	$d\ln(\Delta z)/dt$
0	73.24	0	3.90	
5	70.8	0.049	3.85	0.0101
10	68.87	0.088	3.81	**0.0084**
30	61.13	0.244	3.62	**0.0094**
90	45.65	0.557	3.09	**0.0089**
180	33.5	0.802	2.28	**0.0089**
240	25.2	0.969	0.42	0.0311
∞	23.68			

Table 1: *Well recharge data taken from the 2007 report.*

Overnight, the well will return to its equilibrium level. On turn on in the morning, the pump can remove water to the depth of the pump, after which it can pump at the recharge rate appropriate for that depth. The inside diameter of the borehole is 4.75 in = 12 cm, but the effective diameter may be greater, if water occupies the sand and gravel annuli surrounding the casing. A conservative estimate uses a radius of $r = 6$ cm, for a cross section of $A = 114\ \mathrm{cm}^2$, which means that the well holds one liter for every 6 cm of depth. Combining the area with the observed recharge time constant, we get

$$\alpha = A\beta = (114\ \mathrm{cm}^2)(0.53\ \mathrm{h}^{-1}) = 61\ \mathrm{cm}^2/\mathrm{h} \tag{5}$$

Assuming the pump is installed at a depth of $z = 70$ m, the steady-state pumping rate could

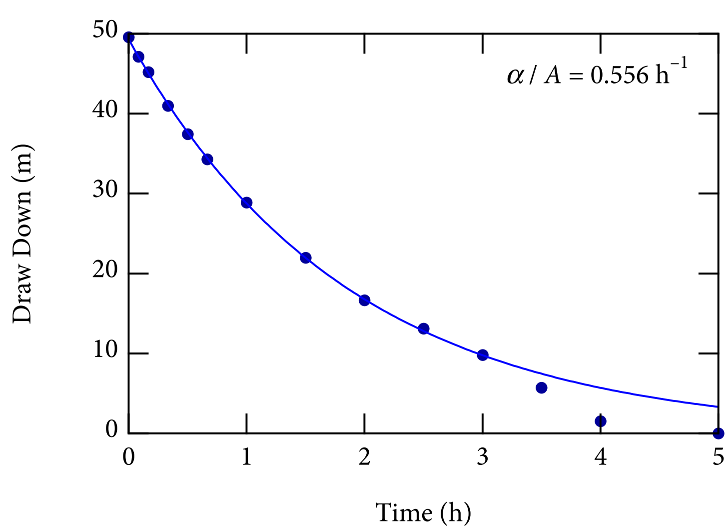


Figure 22: *Well recharge data from 2007 report. In view of the fit, I suspect that the final data point was misreported.*

be

$$\dot{V} = \alpha(z - z_0) = (61\ \mathrm{cm}^2/\mathrm{h})(70\ \mathrm{m} - 23.68\ \mathrm{m}) = 282\ \mathrm{liter/h} \tag{6}$$

which is well below the capability of the pump. Accounting for the volume in the well at dawn, which can be pumped out as soon as there is sufficient daylight, and estimating six hours per day of effective operation at the recharge rate, the daily take from the well would be roughly 2200 liter. If these rates hold up, it would seem that there should be significant power left over from pumping to recharge the battery in the power house. Assuming six hours of sun at 400 W, and a 67% efficiency of the pump, there should be 2 kW h of energy to charge the battery, or roughly 165 A h.

8.2 Charge Controller

The charge controller is an Outback Power Systems model FLEXmax 60, wired in parallel with the pump controller. It is a MPPT (maximum power point tracking) controller that takes input DC, converts it to moderate-frequency AC (20–80 kHz) and then back to DC at a voltage suitable for charging the battery. I believe the charge controller should be better than 90% efficient. The output of the charge conroller is wired to a Phoenix Victron Energy pure sine wave inverter capable of sustained output of 750 W AC. Unlike the cheap inverters we have purchased in Wote, this one cost KSH 27,000 ($338) and appears to be properly protected against excessive loads. It also doesn't appear to complain about the level coming from the charge controller, which presumably limits the power drawn from the battery to prevent damaging the battery.

8.3 Classrooms

The 350-W inverter we purchased at Mighty Wave in Wote beeped and failed when more than two lights were operated, so we returned it for a 300-W inverter. Both were modified sine type inverters, as opposed to the 750-W pure sine inverter installed in the power house. The 300-W inverter would operate more lights, but had a beeper that came on when the load exceeded a few light bulbs and the supply voltage dipped below 11.5 V (despite the manual's claims that the beep should come on at 10.5 V). To open the inverter to disable the beeper, we had to saw through the end plates. Thereafter, placing a piece of tape over the beeper didn't seem to solve the problem. So, I recommend buying a higher-quality ~ 400-W inverter to power the classrooms. The price at the Center for Alternative Technologies was much higher than what we had paid for our 750-W Phoenix inverter, so I have sent money for Benson to buy another of these. The lab has been wired to the inverter in the power house.

9. Acknowledgments

This adventure would not have been possible without generous support from a number of donors, to which we express our deep appreciation.

Donor	Donation
Shanahan Fund	$10,000
Center for Environmental Studies	9,000
Jenzabar	5,000
Strauss Fund	3,000
HMC 2020	2,668
Brian Eberle	1,800
Rotary Club	500
Total	$31,968

In addition, Don Mergens flew over ahead of us and smoothed our way from Nairobi to Ngomano. He also visited Kisii ahead of us and identified a suitable hotel. Finally, the Clays provided all our in-country transportation, which was handled by Benson and Paul.