

Cutting costs for farmers by improving irrigation efficiency

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Summary

A center pivot irrigation system is made up of a well, a pump and the pipework and pivot that distributes the water (Figure 1). When all components of the system operate as designed, it uses the least energy and is most efficient. Knowing the efficiency of an irrigation system is important because irrigation systems are energy intensive.[3] Some inefficiency in irrigation systems is unavoidable, but even small efficiency improvements can mean substantial savings for irrigating farmers. Here, we discuss this issue using a dataset from western Nebraska.

What is inefficiency?

Inefficiency in an irrigation system means that the system uses more energy than it needs. The greater the inefficiency, the more energy the system is wasting. Since electricity, diesel and natural gas are expensive, inefficiency means considerable costs for the farmer.

The cost of inefficiency

Pumping groundwater for irrigation in Nebraska uses on average about 400 kWh of electricity (or about 20 gallons of diesel fuel) per irrigated acre per year, depending on depth to groundwater, crop type and other factors. This is around $50 to $100 in annual energy costs per acre.

Inefficient pumps are a common problem in Nebraska. Testing by the University of Nebraska found that the average pumping plant in the state was operating at only 70% of the Nebraska Pumping Plant Performance Criteria (NPC) benchmark.[4] In other words, the average irrigation well in Nebraska is using about 40% more energy than one operating to NPC standards. This implies that the average Nebraska energy bill for pumping could be reduced by about 30% if pumping plant performance was improved to NPC standards.

[3] E.g., Sowby and Dicataldo (2022) estimate that irrigation uses about 1% (37.5 TWh) of total electricity in the USA, and the proportion in Nebraska is higher at about 5-10% of energy use in the state.

[4] See https://cropwatch.unl.edu/your-pumping-plant-doing-all-it-can/ for more details.

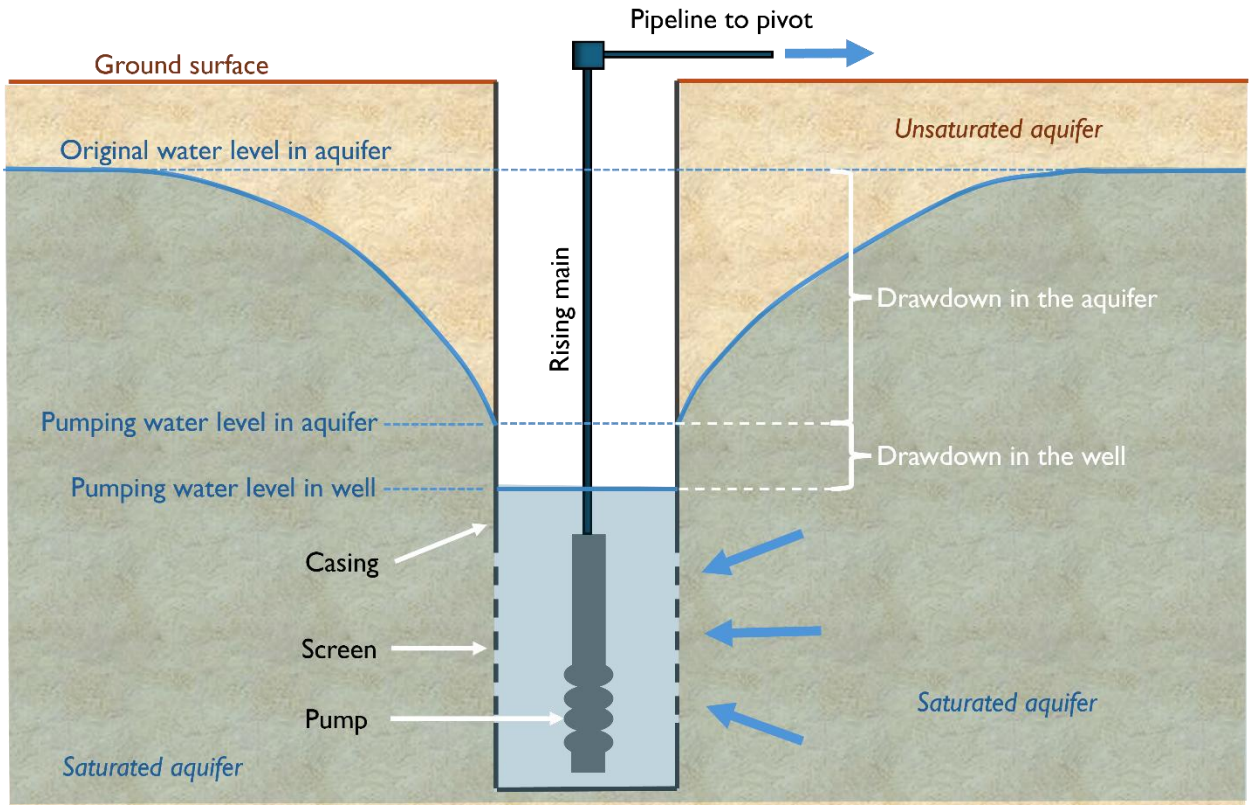

Figure 1. Sketch of a typical irrigation well (not to scale).
Source: J. Cobbing

Sources of inefficiency

The well, pump, rising main (or drop pipe) and center pivot are components that operate together as a system. Inefficiency can be found in any or all components. Inefficiency in one part can cause or worsen inefficiency in other parts of the system. Some sources of inefficiency are easy to fix (e.g. a pump adjustment), while some are not (e.g. a poorly designed well). It's not always easy to find the exact cause of inefficiency in an irrigation system, but there are ways to help narrow it down.

First, let's divide inefficiency in center pivot irrigation systems into three components. These are 1) problems with the pump and rising main; 2) problems with the well; and 3) problems with the center pivot. We'll look at each of these components and examine possible solutions.

1. Inefficiency problems with the pump and rising main

More than 80% of the energy needed by center pivot irrigation systems is used to lift the water from the pumping water level in the well to the ground surface, so the efficiency of the pump and the pipework (rising main) matter a lot. Sources of inefficiency here include:

- Inefficient pump type, inefficient electric motor or both.
- Improper pump impeller adjustment or other mechanical adjustment.
- Worn pump or motor or other damage.
- High friction losses due to rising main diameters that are too narrow (submersible pumps) or badly adjusted and worn driveshafts (top-drive pumps).
- Leaks in the pump rising main.
- A pump that is poorly matched to the well and pivot system (i.e. pump not operating at or near best efficiency point on its pump curve – see box below) – in the worst cases leading to rapid wear or cavitation.[5]

Wear or deterioration in the pump or rising main happen naturally over time and the gradual loss of efficiency can be hard to spot.

The efficiency of a pump and rising main is often considered as the ratio between the input power to the pump/motor, and the "water horsepower" or hydraulic power available at the pump discharge. In other words, efficiency is the ratio between input power drawn by the pump (kW or hp) and the theoretical power required to lift a specific volume against a specific head. This ratio is sometimes known as a "power conversion coefficient" or PCC. The PCC ratio ignores pivot problems and clogging and design issues of the well (we'll talk about these later), but it is still a good way to gauge the efficiency of the irrigation system and to narrow down causes of inefficiency.

There are several templates for farmers to perform this calculation themselves.[6] The following measurements are needed to calculate the PCC ratio:

- Pump discharge pressure.
- Pumping water level.
- Flow or discharge rate.
- Electricity (or other fuel) consumption.

Using the PCC ratio, the overall efficiency of the pump and rising main can be compared with the Nebraska Pumping Plant Performance Criteria (NPC). The criteria were developed in the 1950s and provide an efficiency baseline against which irrigation wells can be judged, accounting for different fuels. Finding a system's PCC ratio is a good first step towards knowing whether a system is operating efficiently and deciding what to do if it is not.

[5] In practice, pumps must operate within a range of conditions, often sacrificing optimal efficiency for some flexibility. Sometimes a variable frequency drive (VFD) is used to keep the pump near its best efficiency point.
[6] See https://bookstore.ksre.ksu.edu/pubs/evaluating-pumping-plant-efficiency-using-on-farm-fuel-bills_L885.pdf for example.

Remedying an inefficient pump, rising main or drive shaft is relatively simple, but usually means pulling out the pump for inspection, adjustment, repair or replacement. The PCC ratio can also allow us to estimate the costs and possible savings of doing this.

2. Inefficiency problems with the well

More than 80% of energy is used to lift the water to the surface, but even if the pump and rising main are efficient, further energy savings can be made by reducing drawdowns (i.e. the difference between the rest water table and the pumping water level in the well).

It's often not possible to do much about the distance that water must be lifted – the water table is at a certain depth, and the pumping water level increases a certain amount when the pump is running. Add the two, and you have a vertical distance or "head" that the pump must lift. However, two sets of issues that contribute to the drawdown are at least partly within a farmer's control:

i. Well losses due to clogging of the well screen (mineral encrustation, biofouling, etc.); clogging of the gravel pack or area around the well; turbulent flow into the well; insufficient length of screen; inadequate screen slot size; inadequate well development; or other well design, construction and maintenance issues. Pumping water levels are deeper in poorly designed wells, or wells that have clogged screens or gravel packs. Pumping water levels in these wells can be much deeper than the level in the surrounding aquifer, resulting in higher pumping costs.

ii. Excessive drawdown in the aquifer and well due to unnecessarily high pumping rates. It may be possible to pump the same volume of water (at lower rates for longer periods) while keeping water levels higher and lessening head pumped, depending on aquifer transmissivity and water demand.

A simple diagnostic for the first set of issues (well design, construction and maintenance issues) is a well's "specific capacity." The specific capacity of a well is simply its discharge divided by the drawdown, and it's easy to measure.[7] Deterioration of the well screen or gravel pack often causes specific capacity to decline over time. When a well is new, its specific capacity is usually the best it will ever be. Measuring a well's specific capacity on a regular basis can show when it is time to clean or rehabilitate a well. If well maintenance is left too late, it can be much more difficult to reverse the deterioration.

The specific capacity of a well depends on the aquifer conditions (transmissivity and water level), as well as on the construction and overall condition of the well. Comparing the specific capacity of different wells to diagnose well health is only useful if the construction of the wells and the aquifer conditions are very similar. Local drillers and other specialists who know the area can usually tell whether a specific capacity number is reasonable.

[7] See https://sehydrogeology.com/using-specific-capacity-monitor-well-performance/ for example.

Improving the specific capacity of a well may be possible using cleaning techniques like surging, jetting or acidification. However, this requires specialized equipment and removal of the pump. If a poor specific capacity is due to a badly designed or constructed well there is not much that can be done apart from drilling a new well. Local expert advice helps decide the costs and benefits of various courses of action.

Deteriorating well inefficiency, apart from being a problem of its own, can make the pump less efficient too. Every pump is designed to operate close to a particular combination of flow and pressure. If the pumping water level in the well changes substantially due to clogging, changed pivot pressures or other reasons, the pump won't operate as designed and will be less efficient. It may wear more quickly or even be damaged, making the inefficiency worse.

Addressing the second set of issues (reducing pumping rates) will depend on the water requirement of the crop; the design pumping rate and head of the pump and pivot; and the drawdown in the aquifer. Tackling these issues is best done once the specific capacity of the well and any clogging issues are understood, in collaboration with local specialists such as drillers and pivot suppliers. It may be possible to reduce pumping rates while still pumping the same daily volume of water, reducing drawdowns in the well and saving energy and wear-and-tear on equipment.

Pumps and pump curves

Irrigation pumps need to be chosen for a particular head (i.e. height and pressure) to lift water against and the required flow rate, known as the duty point. Pump manufacturers publish diagrams called pump performance curves (or just "pump curves") for each of their pumps. Pump curves show the performance of the pump at various heads and flow rates. The point on a pump curve where the pump is most efficient is called the best efficiency point. The pump should be operated close to this point (i.e. the duty point should be close to the best efficiency point).

Just as each pump has a unique pump curve, so each irrigation system has a unique "system curve." The system curve describes how friction losses in the well, pipes and center pivot increase at higher flow rates. The pump curve and the system curve can be plotted on the same chart. The system duty point is where these two lines cross. The selection of a pump for a given duty point should also consider the best efficiency point of the pump. When a pump duty point is close to the best efficiency point it will operate most efficiently, reliably, and this will contribute to the longest possible life. This is why pumps need to be carefully selected for the head, pressure and flow rate they'll be expected to deliver.

When the aquifer conditions, flow rates, water table levels, pivot operating pressures and pipeline specifications (length, diameter, material) are known or estimated, the pump and system curves help specialists to choose the best pump for the job. This is why big changes to flow rates, water table depths or operating pressures can introduce a lot of inefficiency into a system that was originally efficient, silently costing the farmer a lot of money and reducing pump life.

3. Inefficiency problems with the center pivot

The center pivot itself normally uses less than 5% of the total energy used by a center pivot irrigation system, so it doesn't get much attention when efficiency is being discussed. But every little bit helps, and in some cases, a problem with the pivot can mean substantially higher energy costs. Causes of pivot inefficiency include:

- A buried pipeline that is constricted or too narrow
- Leaks
- Wrong sprinkler package
- Wrong pressure
- Overwatering

Older pivots are not necessarily less efficient than newer ones (see example below), but problems do creep in when sprinkler packages are not updated for a new crop, or where pivot operating pressures are changed by altering a valve rather than adjusting the pump. Pivot companies or agents can provide advice and recommendations on pivot efficiency, together with cost-benefit figures.

Overwatering is a major source of inefficiency and a waste of money. It can be remedied by finetuning the irrigation volume to the crop requirements. Crop water requirements can change due to a surprisingly long list of factors, and there are techniques available to farmers to help them estimate the crop water requirement, such as evapotranspiration data or soil moisture sensors. Leaks in the system or excessive evaporation or drift are effectively the same as overwatering and can be costly.

Irrigation system efficiency in Nebraska: An example from the Republican River Basin

We looked at a dataset of 959 pivot irrigation systems in the Republican River Basin in western Nebraska (Figure 2) and found a large range of irrigation system efficiencies.

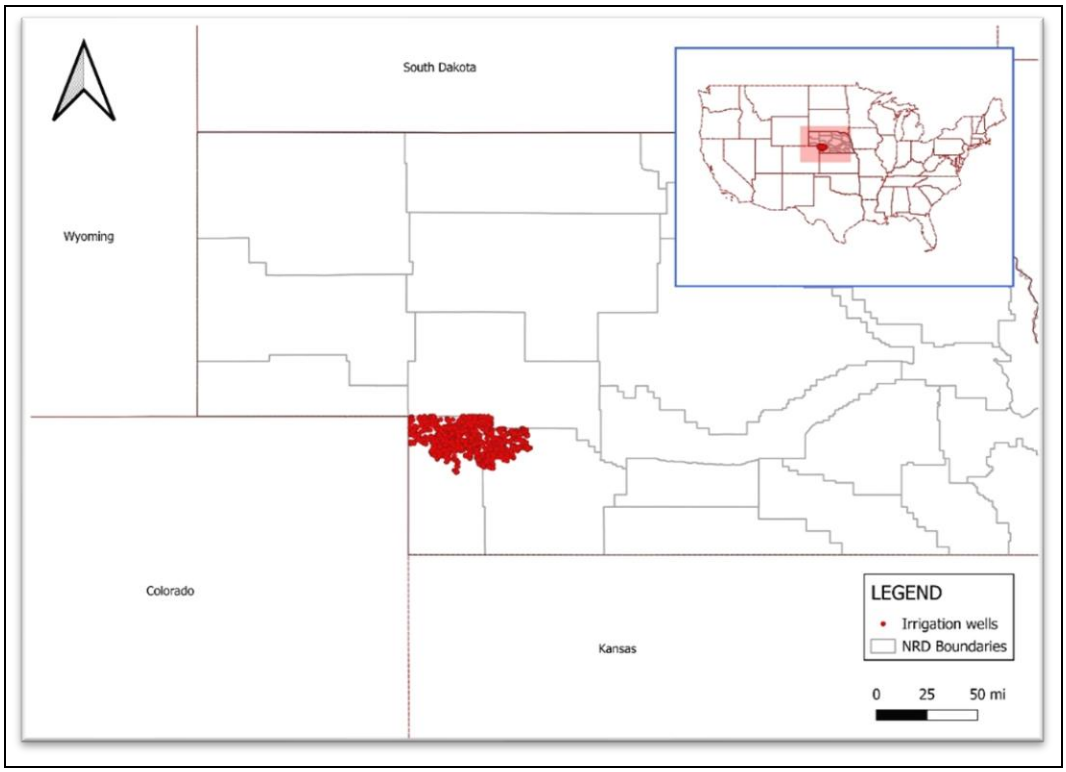

Figure 2: Location of wells in the Republican River Basin in western Nebraska.
Source: J. Cobbing

The dataset included electricity consumption for each system, volume of water delivered and the pumping water level recorded when the well was drilled. A calculation was done that showed the range of system efficiencies in the dataset. The dataset shows that there is roughly a three-fold difference[8] between the most and least efficient systems (Figure 3).

[8] This is consistent with a study done in Kansas (KGA, 1990; quoted in Rogers and Alam, 2006) that found pumping plant performance ratings ranged from 15 to 120 percent of the NPPPC standard.

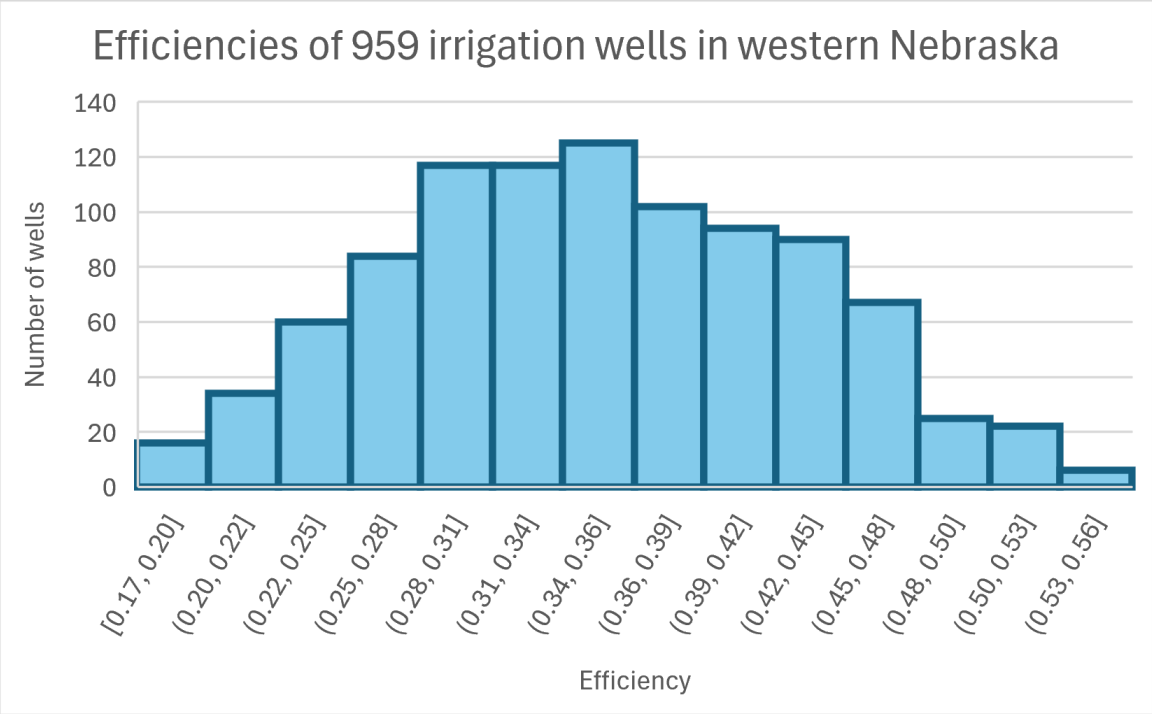

Figure 3. Histogram showing the relative efficiencies of well/pivot systems in western Nebraska. *Source: J. Cobbing*

The depth from which water is pumped is the main determinant of how much energy wells use to deliver a particular volume of water. To compare system efficiencies, the variation introduced by different pumping water levels must be removed. This is done by knowing the pumping water level for each well so that the theoretical power needed by the system can be calculated and compared with the actual energy use. In the dataset above, only the original pumping water level recorded when the well was drilled was available. Using this water level allows approximate comparisons between wells in the same aquifer to be made.

It might be expected that clogging of the well screen would get worse as a well ages. But the western Nebraska data showed almost no correlation between well age and well efficiency (r^2 <0.1). This suggests that a well's age has little to no effect on its efficiency. Many other factors are likely to be at play. Well clogging is partly related to the groundwater quality in the aquifer and this changes from one place to the next. The location of the pivot may be more important than its age when it comes to clogging.

Takeaways

- Pivot irrigation systems in the Midwest use a lot of energy, either through electricity or fuels like diesel or natural gas. This energy costs farmers around $50 to $100 per irrigated acre per year. Even small improvements in efficiency can save thousands of dollars per year on the average energy bill.

- The well itself can be inefficient (e.g. clogging), the pump can be inefficient, or some combination of the two can be true. The pivot and sprinklers can also be inefficient, but this is usually a lesser problem.
- Most irrigation systems fall short of Nebraska efficiency standards (NPC). The most efficient systems in Nebraska and the Midwest are three times more efficient than the least efficient systems.
- Very inefficient systems are much more expensive to run than the most efficient systems, and it is worth knowing a pump's efficiency (PCC) and a well's specific capacity to see if there's a problem. Farmers can perform these calculations themselves. Savings can be hundreds or even thousands of dollars per irrigation system per year.[9]
- There are various causes of inefficiency. Some are easy to fix (like adjusting an operating pressure), some are more difficult (like cleaning the well or overhauling the pump), and some are nearly impossible (like replacing well screen). It is not always easy to tell what is causing inefficiency, but local expert advice can help.
- Inefficiency problems can creep higher with time. Regular (annual) measurements of PCC and specific capacity act as "health checks" on an irrigation system and are well worth doing.
- Most of the energy used in an irrigation system is used to lift water from the pumping water level in the well to the ground surface. So, anything that reduces drawdown in the well (e.g. cleaning the well screen or pumping at a lower rate for longer) will save money.
- Leaks and overwatering mean more water is lifted than needed, wasting money.
- Although not covered in this note, time of energy use can also be important to saving energy costs since peak time energy is usually more expensive. In some cases, farmers can save a lot of money by agreeing not to irrigate at peak times of day or by reaching other agreements with their energy providers. Costs and savings incentives depend on the energy provider's pricing structures.

[9] See https://extension.okstate.edu/fact-sheets/print-publications/bae/understanding-the-results-of-master-irrigator-center-pivot-energy-efficiency-test-a.pdf for more information.

Glossary

Best efficiency point	A point on a pump's pump curve (i.e. a particular combination of pumping rate and head) at which a pump is most efficient.
Cavitation	Excessive pressure changes in a hydraulic system that causes shock waves and other damaging effects. It can happen when pumps are operated outside of their design specifications.
Drawdown	The difference between a rest water level and a pumping water level in an aquifer or well.
Driller	A specialist contractor able to drill and construct irrigation wells, as well as test and rehabilitate them.
Driveshaft	In many systems the pump is at the bottom of the well, and the motor driving the pump is on the ground surface. A vertical steel driveshaft connects the two.
Efficiency	A measure of how much of the energy used by an irrigation system is converted to useful work.
Head	Engineers prefer to express the power of a pump not in pressure, but in the vertical distance or "head" that it can lift a fluid. Head is measured in distance units such as feet.
Impeller	The rotating part of a pump that accelerates and moves the water. Some pumps have several impellers that work together.
NPC	The Nebraska Pumping Plant Performance Criteria (NPC), a benchmark for irrigation pump efficiency established in the 1950s. Checking against the NPC is a way to tell whether a pump is efficient.
Power Conversion Coefficient (PCC)	The ratio of the power drawn by a pump (e.g. electricity used or diesel burned) and the power embodied in the volume, height and pressure of the water it delivers. PCC is a simple measure of the efficiency of the pumping system.

Pump curve	A chart showing the relationship between pumping rate and the lift (head) of a particular pump. A pump is designed to operate most efficiently at a point on its pump curve called the best efficiency point.
Pump inefficiency	The component of inefficiency in an irrigation system due to the pump. Pumps that are worn, damaged or are operating far from their best efficiency point are less efficient.
Pumping rate	The volume of water that a pump delivers per unit of time, measured in gallons per minute.
Pumping water level	During pumping, the water level in the well and surrounding aquifer drops until it reaches a new equilibrium. This new level is called the pumping water level. The pumping water level in the well can be lower than the pumping water level in the surrounding aquifer, depending on the well's efficiency.
Rising main	The pipe leading up from a submersible pump to the ground surface that conveys the water. Also called a drop pipe.
Specific capacity	The pumping rate divided by the water level drawdown in a well. A high specific capacity means a well is more productive – i.e., the well delivers a lot of water for only a small drawdown.
Submersible pump	Many electric submersible pumps combine the pump and motor in one unit submerged near the bottom of the well. Some submersible pumps, however, are driven by a motor on the ground surface via a driveshaft.
System inefficiency	The total inefficiency of a whole irrigation system (well, pump, pipework and pivot). The more inefficient a system, the more it costs to deliver the same irrigation performance.
Well inefficiency	The component of inefficiency in an irrigation system due to the well. Wells that are badly designed (e.g. inadequate screen length) or are clogged (e.g. by mineral encrustation) are less efficient.