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WATER MANAGEMENT GROUP

Water Scarcity and Modern Irrigation

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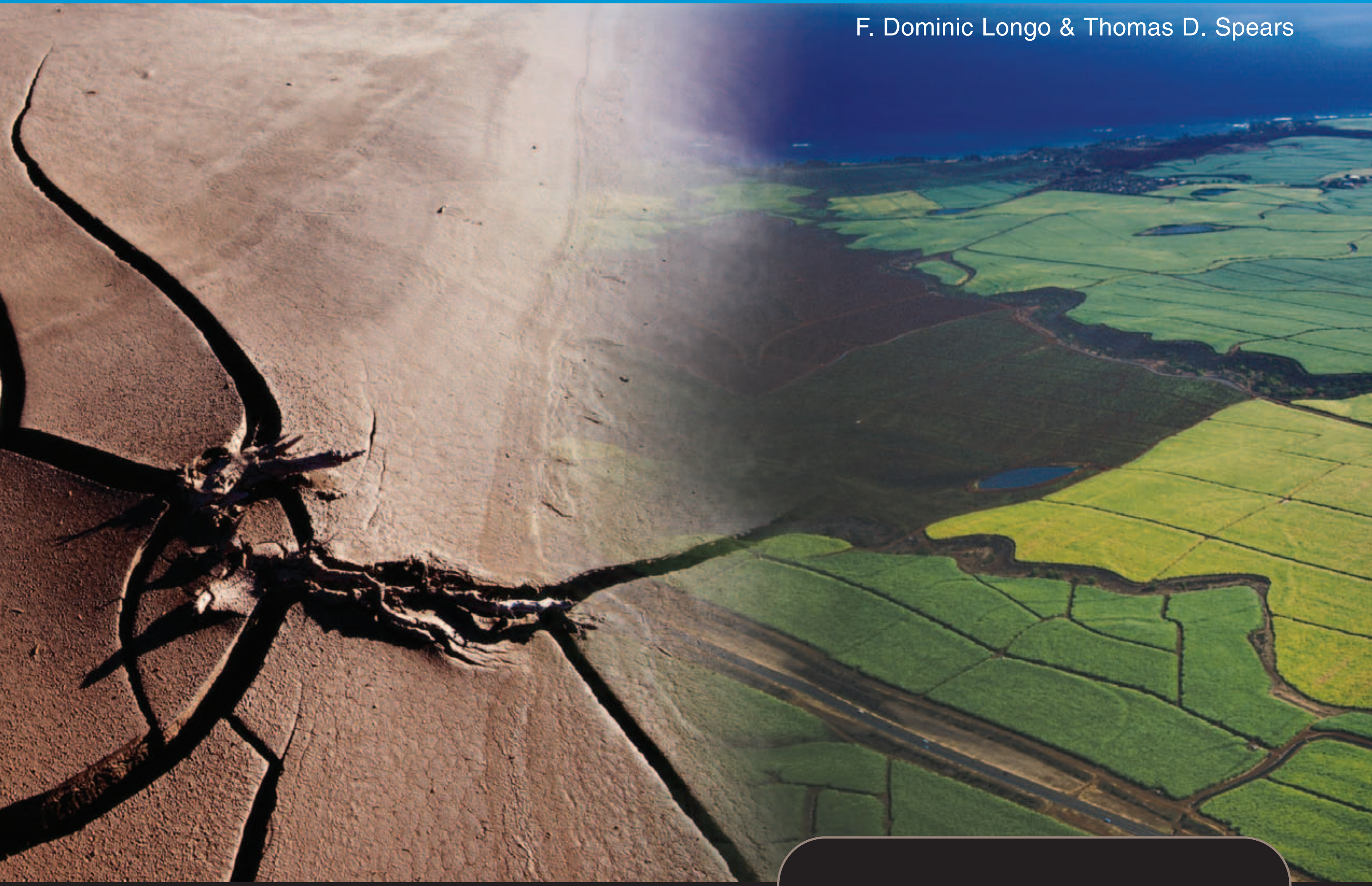


"Agriculture has the greatest potential for solving the problem of global water scarcity."

Gone is the era when humanity can pretend that water defies the principles of economics.

The water demand of our thirsty cities, factories, and farms will soon exceed the available water supply. Despite these pressures, society keeps water prices very low. The economics of water could soon lead to crisis or war in many parts of the world.

Agriculture has the greatest potential for solving the problem of global water scarcity. Since agricultural irrigation accounts for more than 65% of fresh water usage, improving irrigation efficiency is the most important step toward addressing human water needs.

Technology offers two modern methods for irrigating crops efficiently. Mechanical move and drip irrigation both use only half as much water as traditional flood irrigation and produce higher crop yields.

Employing these modern irrigation technologies appropriately is key to overcoming the critical challenge of global fresh water scarcity.

> “Irrigation is the primary consumer of water on earth”
>
> — Igor Shiklomanov[1]

I. Water Scarcity and Usage Trends

There is no shortage of water on earth.

There is, however, an increasing scarcity of fresh water relative to societal use. In fact, severe shortages already exist in the societies of key regions, especially ones with rapidly growing populations such as South Asia and the Middle East. Eminent hydrologist Igor Shiklomanov reports[2] that between 1850 and 1993 per capita global renewable water declined from 33,000km^3 to 8,500km^3.

As water becomes more scarce, water management must improve. In the historical development of water resource management, the last 150 years have been an important phase of advancement.[3] The industrial revolution and subsequent technological advances enabled us to control the natural hydrologic cycle to an impressive degree. Whereas in pre-industrialized pre-modern society, water had been considered a free gift relatively outside of human control, in modern times we have used our newfound engineering prowess to satisfy the burgeoning water demands of the growing human population.

The next developmental phase of water resource management will see society reach “the maximum attainable and acceptable level of stream flow regulation...in many major river basins.”[4] Societies in this stage of development must try to advance from an irrationally exuberant to a rationally conservative development of Earth’s water resources; from a profligate to an efficient usage of water; from showy engineering feats to integrated water management. One key to rational and integrated fresh water management will have to be efficient irrigation. Irrigation is today the primary consumer of fresh water on earth, but the twin drivers of human population and economic development exert pressure on our water resource management regimes to be more productive with less water. While human food needs are increasing, the fresh water available for agriculture is decreasing.

Fresh Water Availability

From the Earth’s oceans about 505,000 km^3 of water evaporate every year. Most of this fresh water, around 90%, returns to the oceans via atmospheric precipitation. The other 10%, about 50,500km^3 of precipitation, falls on land.[5] This 50,500 km^3, along with the 68,500 km^3 of atmospheric precipitation which originates on land, supplies all types of land water including rivers and aquifers. This rainfall on land, which renews the fresh water supplies, totals over 119,000km^3. From this still very large amount, we subtract the 72,000km^3 which evaporates to leave 47,000km^3 of what hydrologists call ‘run-off,’ that is, precipitation less evaporation. (In the agricultural water usage section of this paper, it will be discussed that what hydrologists call ‘run-off’ is different than what irrigators call ‘run-off’.) If we exclude the run-off in Antarctica, an effective ice flow of 2,230 km^3, or 5% of the total run-off, then we are left with 43,500km^3.

Of this 43,500km^3 of run-off, human society currently withdraws only about 3,765km^3, according to a recent estimate.[6] Thus our outtake is only about 8% of all surface run-off, a small portion of the total.

The portion of fresh water that we withdraw is small not because our need or rapaciousness for water is satiated. Rather, our proportionately small withdrawal is explained by the distribution of rainfall being exceedingly uneven—both geographically and temporally. For example, large amounts of rain fall so rapidly in monsoons and hurricanes that using their run-off is impractical or impossible.[7] We already noted the large quantity of water that falls over the Antarctic region, where there is no human population to benefit. We can also dismiss most of the 6,930 km^3, or 15% of the 47,000km^3 total, which the world’s largest river, the Amazon, carries to the sea each year, since that river basin with its dense rain forest does not lend itself well to human usage.[8] By Sandra Postel’s analysis, “[i]n most countries, it is only possible to store and control 20-50 percent of the total run-off, so only a fraction of the water resource is actually available for use.”[9] As human populations grow and economies advance, dealing with the natural inequality in the global distribution of accessible fresh water is a more and more pressing issue.

Dams and Wells: Supply Augmentation in the 20th Century

In the 20th century until the 1980s, the prevailing approach to water management was to “focus on supply-side solutions: [planners] assumed that projected shortfalls would be met by taming more of the natural hydrological cycle through construction of more physical infrastructure, usually reservoirs for water storage and new aqueducts and pipelines for interbasin transfers.”[10] Large dam building was the most important example of how humans employed technology to try to ‘tame’ water supplies. The idea was to increase our capacity to clutch onto the fresh water that comes within our reach before releasing it back into the natural hydrological cycle.

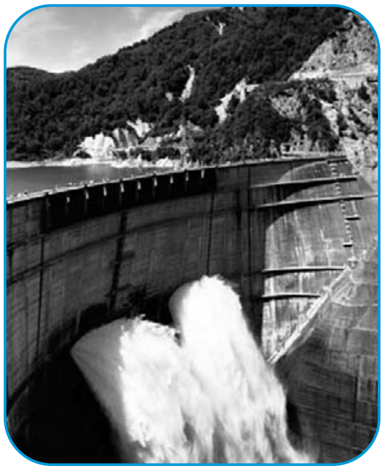
While dams date back thousands of years in human civilization, only 41 man-made reservoirs with storage volume of more than 0.1 km^3 existed before the year 1900. Between 1900 and 1950, 540 were constructed. To illustrate the vast scale of dam design plans in the heyday of large dams, we recall one of the most grandiose water management schemes – NAWAPA. Though never implemented, the North American Water and Power Alliance illustrates just how heady the ambitions of overreaching engineers in the early 20th century could be. The NAWAPA project was conceived in the early 1960s by Donald McCord Baker, a planning engineer for the Los Angeles Department of Water and Power.[11] Baker’s idea was to exploit the water of British Columbia, which boasts between 4% and 10% of the world's accessible, renewable fresh water, for the benefit of the thirsty American Southwest.[12] With 369 dams, this fantastical project would have added 5,000 km^3 of water storage capacity by damming the Yukon and diverting it 2,000 miles to the Southwest United States, through the Rocky Mountain Trench, a gorge stretching 800 km in the Canadian Rockies next to Banff and Jasper National Parks.[13] Canadians would have gotten 38 million KW of power and a shipping route connecting its mineral-rich north to the Mississippi and Great Lakes. Mexicans would also have benefited, receiving enough water to triple the amount of land they irrigate. Marc Reisner evokes the NAWAPA project as the epitome of the "Cadillac Desert" mentality in both the introduction and the epilogue of his 1986 book by that name. Reisner marvels at the "brutal magnificence" of this mother of mega-projects, by which "[e]very significant river between Anchorage and Vancouver would be dammed for power or water, or both."[14] Never quite reaching the scale of NAWAPA, global dam building after 1950 accelerated, peaked, then declined[15]:

Construction of Large Dams

Figure 1

Time Period	Number of Large Reservoirs (reservoirs larger than 0.1km^3)
Up to 1900	41
1901-1950	540
1951-1960	524
1961-1970	699
1971-1980	601
1981-1990	363
1991-2000	68

This record of reservoir building demonstrates that the more feasible projects with the greatest benefits were completed between 1950 and 1980, but then a point of diminishing returns was reached and reservoir building tapered. In *The World's Water: The Biennial Report on Freshwater Resources 1998-1999*, Peter Gleick surveys the negative effects of dams which have gradually driven public opinion to oppose what were once much favored projects. Such effects include "loss of riparian habitat, effects on aquatic species, and reservoir-induced seismicity, as well as the social impacts on people who must be uprooted and resettled." In addition to these environmental and social impacts, "more comprehensive regulatory procedures, and new complexities in financing major dam projects are all working to slow development."[16] Besides this most dramatic example of dam-building, we should not ignore the phenomenon of well digging, which constitutes another significant component of the supply augmentation efforts of the last century. Awareness of the environmental impact from over-pumping aquifers is increasing, and none too soon, since "a lot of the water being pumped out of the ground is as nonrenewable as oil."[17]



Supply-side solutions to the problem of the increased water needs of the 20th century erroneously treated consumption "as a simple technical issue, exogenous to other social changes."[18] In coming years, society will have to do something other than reduplicate its 20th century project of employing technology to store and control more water. In the place of increased water supply, we will need to substitute advanced technology and better management.[19] Whereas previously we used our ingenuity to take more water out of the natural cycle in order to use it profligately, now we must rather ingeniously utilize the limited fresh water supply that is available to us. Rather than "*extensive*" development of water resources, which water law expert Lawrence MacDonnell defines as "a process by which new demands were satisfied by extending control over more of the resource," our task for the 21st century is "more careful and efficient 'intensive' development and use of water."[20] Another way of framing this shift is to note that we must transcend the modernist strategy of domination and control of water resources. In the upcoming years, we must employ the post-modern strategies of social change and attention to the global realities of which humans are but one part.

Trends in Fresh Water Usage

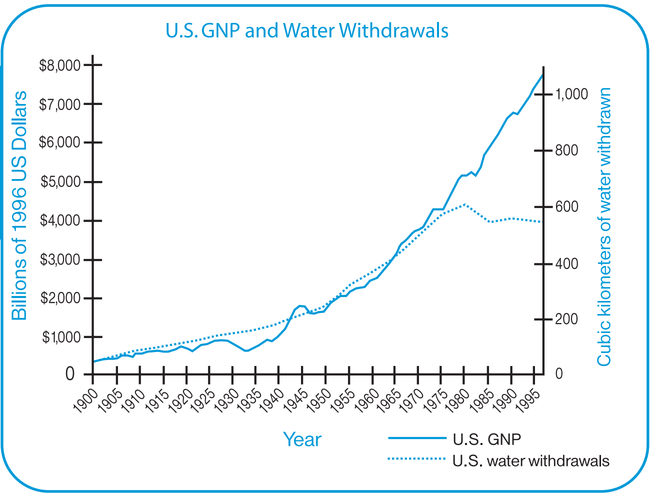
In terms of human usage, fresh water is generally analyzed in three categories: water for municipal or domestic usage, water for industrial usage, and water for agricultural usage. The two drivers affecting fresh water usage by humanity, namely population growth and economic development, have impacts on each of these three categories. In order to clarify the trends in societal use of fresh water, we will examine each of these categories in turn.

Municipal Usage: Water for Households

Domestic or municipal withdrawal of water is the simplest usage category to understand and also the smallest, accounting for 357 km^3 in 1995, less than 10% of all water withdrawals.[21] Urbanization has often been noted as among the most significant features of our most recent world history. Predictably, municipal water needs are ballooning along with our cities: "Agriculture is also losing some of its existing water supplies to cities as population growth and urbanization push up urban water demands. Worldwide, the number of urban dwellers is expected to double, to 5 billion, by 2025. Pressure to shift water from farms to cities is thus bound to intensify—as is already happening in China, the western United States, and other water-short areas."[22]

Individuals need approximately 50 liters/day[23] of water for personal use to sustain life at the poverty level. This 50 liters of water does not include the water used to grow the food to feed somebody, but rather the water used for drinking, cooking, personal hygiene and sanitation. The reality today, however, without significant progress in demand management, is that economically developed nations with infrastructure in place generate significantly more demand for municipal water. A graph of United States GNP and water withdrawals over the last 100 years (Figure 2[24]) shows a strong

Figure 2



correlation between the increase of water consumption and the growth of wealth.[25] A global perspective on the same correlation reveals that a few high wealth countries such as Kuwait and Saudi Arabia have lower per capita water consumption levels, while several water rich countries including Canada and the United States have above average consumption even for their wealth levels.

Growing world GDP and population will clearly increase in the future and drive up the consumption of municipal water. A reasonable forecast of the human population in the year 2050 is 10 billion people, which would be an increase of 43% above today's population. The U.S. Department of Energy projects that gross world product will double by 2020.[26] Nonetheless, the world GDP per capita will still average only half of 2000 U.S. GDP per capita.


As the global economy advances, industry will demand a greater portion of the available freshwater supply.

Industrial Usage: Water for Goods and Services

Industrial fresh water withdrawals (732 km^3)[27] accounted for about 19% of all water withdrawals in 1995.[28] The industrial sector of society uses water for "cooling, heating, processing, and transporting, as well as for drinking, air conditioning, and cleaning."[29] Examining industrial water consumption over time and comparing it to world GDP, however, shows that while growth in GDP results in increased water consumption, the water consumed per unit of GDP has actually declined in the last 50 years. For example, according to a UNESCO study, for a society with per capita income of US $3,000, the per capita industrial water usage was three times as much in 1965 as in 2000.[30] A reasonable explanation for this trend is that industry responds swiftly to economic drivers. During the last 50 years, the cost of water consumed by industry has increased significantly due to delivery charges, energy cost increases, and regulation of water discharge. With economic development creating more and more goods for a growing population, industrial water demand has continued to increase, but at a slower rate, due to both its price elasticity of demand and to technologies that have increased water productivity. Even with a continuation of the trends of the last 50 years, industrial water demand will most likely increase significantly in the future.

Agricultural Usage: Water for Food

In 1995, agricultural withdrawals amounted to approximately 2,488 km^3, which is more than double the fresh water used by industries (732 km^3) and municipalities (357 km^3) combined.[31] In percentage terms, the agricultural sector is responsible for 66% of all water withdrawals and 86% of total consumptive use by humanity.[32] Most fresh water withdrawn by humanity, then, is used to produce food. The vast majority of this agricultural water usage is for irrigation, while a much smaller portion is used in raising livestock. These facts explain Shiklomanov's statement that "Irrigation is the primary consumer of water on earth."[33] A more in-depth review of how agriculture uses water is in order. We will see how the agricultural sector not only currently uses the most water, but how this sector is losing its water resources to the municipal and industrial sectors. At the same time that water is being taken from them, crop producers are being asked to grow more food due to the increasing nutrition needs of the burgeoning human population. Consequently, "An all-out effort to raise the water productivity of the global crop base—both irrigated and rain-fed—is urgently needed."[34] Agricultural water usage is where society needs to make the most progress in doing more with less. In the remainder of this paper, we will further explore this problem and its possible solutions.

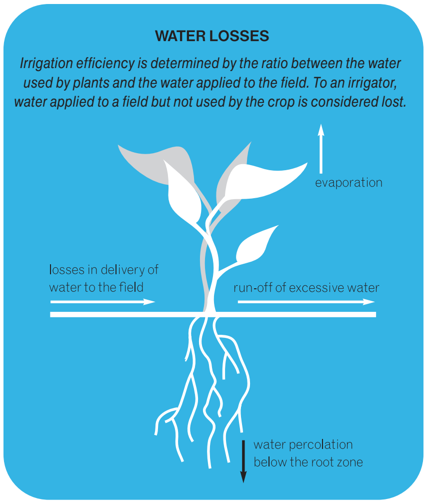
II. Agricultural Water Usage and Trends

Doing more with less water for agriculture is about improving the efficiency of agricultural water usage, which can be considered from several angles.[35] A financial analysis of agricultural water application and usage would examine "the financial return in relation to the investment in water supply." Physiologically, the efficiency of irrigation depends on "the amount of total plant growth, or of the harvestable yield, per unit volume of water taken up by the crop from the soil." A variety of factors affect efficiency, whether considered from a financial or from a physiological perspective. The financial efficiency of irrigation is highly dependent on the fluctuating costs and prices of water and crops in different locales. The physiological efficiency of irrigation depends on the crop, the variety, and the suite of agronomic practices in use on the field.

Our concern in this paper is primarily irrigation efficiency from the perspective of irrigation engineers. What they call "water application efficiency" or simply "irrigation efficiency" is defined as "the amount of water added to the root zone...as a fraction of the amount taken from some source." This kind of efficiency is our focus because when water is applied to the root zone of plants, it is in a usable form for uptake by the plant. Irrigation efficiency, in this sense, is impeded by evaporation, deep percolation into the soil below the root zone, and run-off due to excess instantaneous application rates.

The mechanism of evaporation of water into the atmosphere is directly related to the surface area per unit volume of water as well as to the duration of time during which water is exposed to air. The longer water is exposed to the atmosphere and the greater the surface area of exposure, the greater the evaporative loss. The rate of loss also varies with air temperature and humidity. Losses due to evaporation occur in storage bodies like reservoirs and canals, as well as in farm fields. While a reservoir may have a low surface area per unit of volume, the time of exposure can be quite long and significant losses can result. In fields, typical exposure times are relatively low, but water is quite spread out, resulting in high evaporative losses. Efficient water delivery systems must provide the appropriate amount of water to permit quick infiltration into the soil in order to limit the duration of atmospheric exposure.

While different methods have been suggested to reduce evaporation of water in storage and transportation systems, these proposals entail significant environmental impacts or costs that currently make them impractical. Reduced evaporation in agricultural fields, on the other hand, can be accomplished through the use of currently available technologies that simultaneously reduce water usage and improve crop yields, as shall be discussed in this paper.


WATER LOSSES

Irrigation efficiency is determined by the ratio between the water used by plants and the water applied to the field. To an irrigator, water applied to a field but not used by the crop is considered lost.

Besides evaporation, a second impediment to irrigation efficiency is what is called “deep percolation,” which occurs when water seeps below the level where plants can use it. Deep percolation can be a major problem in reservoirs and canals, but can be avoided through the use of impermeable linings. Lining reservoirs and canals, however, is costly and causes silt to accumulate. At the farm field, a great deal of deep percolation is often caused by the over-application of irrigation water. A correct water application rate for efficient irrigation is a function of the water holding capacity of the soil, which is determined by the soil type. Efficient irrigation practitioners the soil water holding capacity of their fields to determine both the water application rate and the frequency with which they should irrigate their crops. Deep percolation in farm fields is especially problematic where farms have light, sandy soils. In order to reduce this phenomenon of deep percolation, attention to the water holding capacity of a field’s soil is a good starting point. In addition, efficient irrigation practitioners also need to measure and control the amount of water which they apply as well as the uniformity of water application.

A third impediment to efficient irrigation is what irrigators call “run-off” by which they mean the water which was intended for the root zone but which instead flows off the field (as distinguished from the use of the term mentioned earlier in this paper by hydrologists who mean by “run-off” precipitation minus evaporation). Run-off is a problem primarily with fields irrigated using traditional gravity flow methods. It results from the over-application of water to a field. Run-off is also the greatest cause of water pollution by the agricultural sector, since agricultural run-off frequently carries with it nitrogen fertilizers, pesticides and herbicides. Reducing this irrigation run-off will thus also reduce water pollution by agriculture.

What is Water Conservation? The Basin Argument and Irrigators’ Perspective

Doing more with less requires both increased water productivity and water conservation. Irrigation efficiency, as explained above, is connected to both of these goals. Let us try to clarify, however, what ‘conserving’ water means: Hydrologists studying river basins theorize that water which remains within a river system or basin is not lost, but eventually re-appears somewhere else in the basin and hence is ‘conserved.’ On the other hand, from the point of view of irrigators, the relationship between rivers, lakes, and agricultural land in a basin is somewhat different. Water that deep percolates in an agricultural field may drain directly to a river, in which case according to the river basin manager, the water is conserved, except for whatever water evaporated from the field. However, to an irrigator, in order for water that has either deep percolated or run off from an over-watered field to be considered ‘conserved,’ the water would need to return in an acceptable quality, to an accessible place, and in time for the irrigator to use it again on his crops. This kind of return of irrigation water happens quite infrequently, much less often than the basin argument implies. Excess water applied to a farm field may become locked in deep aquifers; it may be diverted to an underground river; it can become locked in unusable storage basins such as remote lakes; or it might return to a river at a time of year when it is not usable. Sandra Postel contrasts these two viewpoints on water conservation in her book, *Pillar of Sand: Can the Irrigation Miracle Last?* (1999):

> “Saving water...is not as simple as it seems. It requires knowing where water goes and what functions it performs. It also depends on the geographic scale or vantage point we are concerned with. From a planetary perspective, it is impossible to save water because none is ever wasted. Earth is a big water-recycling machine, moving water between the land, the sea, and the atmosphere. No water gets lost, it merely changes location, quality, and form. To a river basin manager, however, water certainly can be wasted. If water evaporates from an expensive reservoir or from a farmer’s field, it leaves human control without having produced any benefits. Finally, an individual farmer who pays to pump water from a well might view any water that flows off the farm as a waste, even though that water may supply someone else downstream.”[36]

In general, while we acknowledge the theoretical correctness of the basin argument as well as the ‘planetary perspective’ to which Postel refers above, from a practical standpoint the utility of deep percolated or run-off water is much lower than water which remains in the river, lake or reservoir. Taking into account field application efficiencies alone might somewhat overstate how much water modern, efficient agricultural irrigation technologies conserve. However, assuming that all savings of water in the field lead to increases in the supply is likely closer to real world experience than the basin argument that only the water which evaporates is lost. Water conservation has to do with society increasing its benefit from withdrawn water before that water returns to the natural hydrologic cycle: "The broad policy objective of water conservation is to reduce unneeded uses of water where there are more benefits [than] can be produced by other uses of the water."[37]

Global Food Requirements

> "Water, long left out of the food security equation, may now be driving it."[38]

Having discussed irrigation efficiency and water conservation, we turn now to the underlying cause for the increased demand for agricultural water productivity, namely, the rapidly multiplying human population. Examination of population and food supply issues in the West has been greatly influenced by the so-called First Essay (1798) of Englishman Robert Malthus. Good Enlightenment thinker that he was, Malthus begins what he himself entitled *An Essay on the Principle of Population* by defining the method employed therein:

> "In an inquiry concerning the future improvement of society, the mode of conducting the subject which naturally presents itself, is
>
> 1. An investigation of the causes that have hitherto impeded the progress of mankind toward happiness; and
> 2. An examination into the probability of the total or partial removal of these causes in future.
>
> To enter fully into this question, and to enumerate all the causes that have hitherto influenced human improvement, would be much beyond the power of an individual."

Malthus proceeds from a statement of method to a statement of purpose:

> "The principal object of the present essay is to examine the effects of one great cause [impeding the progress of mankind toward happiness]...which, though it has been constantly and powerfully operating since the commencement of society, has been little noticed by the writers who have treated this subject...The cause to which I allude is *the constant tendency in all animated life to increase beyond the nourishment prepared for it*"(emphasis added).[39]

The whole of Malthus' opus – some 388 pages in a recent abridged edition – unfolds various aspects of this idea, that life tends to multiply beyond what the available food supply can support, or, in his words, "population has this constant tendency to increase beyond the means of subsistence."[40] Nobel Prize-winning economist Amartya Sen notes that the Malthusian idea that "the world food output [is] falling behind world population in what is seen as a 'race' between the two...has had remarkable staying power despite relatively little evidence in its favor."[41] In fact, according to Sen, "There is...no significant crisis in world food production at this time."[42] However, Sen is keenly aware of the existence of famine, hunger, and undernourishment, and he acknowledges food production as "one of the variables that can, inter alia, influence the prevalence of hunger."[43]

For different reasons, then, than those imagined by Malthus,[44] the on-going sufficiency of food production to meet human needs is a vexed economic question with uneven supply and demand curves. In recent years, overall the world has actually produced more food than the human population needs. The typical surplus, however, is slight, around 10% in a good year. Surplus food production is desirable, because shortfalls in food production result in steeply higher prices which have their greatest impact on the world's poorest populations. Food shortages in some regions and excesses in others occur because achieving alimentary or nutritional self-sufficiency is a politically and economically motivated goal.

Even in periods of excess global production, countries continue to subsidize local food production to ensure the conservation of foreign currency reserves, political independence, and rural employment. On the other hand, some growers in food poor countries push the food supply curve in the opposite direction than government subsidies, by planting cash crops, such as cotton, for export when their compatriots lack bread. Unfortunately, widespread starvation still occurs today, though it is due to economic, political, and social issues more complex than mere sufficiency of food supply. In his book *Development as Freedom*, Amartya Sen draws on his scholarship on the topic of famine causation and prevention to elucidate the economic nature of hunger, malnutrition, and starvation.

> "For the elimination of hunger in the modern world, it is crucial to understand the causation of famines in an adequately broad way, and not just in terms of some mechanical balance between food and population. What is crucial in analyzing hunger is the substantive freedom of the individual and the family to establish ownership over an adequate amount of food..."[45]

Crops respond differently to different irrigation methods. Maize, for example, is among the crops that respond best to irrigation from MMI systems

This idea that famine is not merely about a balance between food supply and population is supported by Sen's analysis of famines in history, where he repeatedly finds the rather surprising phenomenon, that "famine can occur without any decline in food production or availability."[46] Instead, famine results from a variety of causes, such as economic shifts in the value of certain commodities, occupations, and national currencies. "The main issue," then, for famine prevention, "concerns overall economic growth, since food is purchasable in the world market."[47] Nonetheless, food production is clearly an important issue, and it does indeed play some part in the problems of hunger, malnutrition, and famine. Afterall, "when we consider food problems at the global level (rather than at the national or local level), there is obviously no opportunity of getting food from 'outside' the economy. For these reasons, the often aired fear that food production per head is falling in the world cannot be dismissed out of hand."[48]

Food demand is increasing. As GDP per capita increases, people consume more calories. The average world citizen consumes approximately 2,800Kcal a day[49], while the average American consumes 3,800Kcal/day.[50] Moreover, because Americans consume a high proportion of their calories as meat, it takes almost 60% more grain to support an American's diet than to support the diet of a typical world citizen. In the future, as Gross World Product (GWP) increases, so will the per capita calorie consumption. Moreover, if the population of the developing world increases the proportion of calories it consumes from meat relative to grain, agricultural production would be under additional pressure to increase.[51]

Diminishing Resources for Food Production

The resources historically used to increase food production are becoming less available. A brief examination of the pressures affecting the availability of arable land, fresh water, and technology for food production will demonstrate how water for food will be an even more vexed question for the years to come.

Before describing the pressures on arable land, we should note that in terms of its relationship to irrigation, arable land can be categorized as follows:

1. unirrigated or 'dry land,'
2. land which requires irrigation, and
3. land where irrigation is not required but supplemental.

Dry land represents 82% of the farmed area in the world and grows 60% of the food tonnage.[52] The land area where irrigation is supplemental is relatively small today, so it can be added to the much larger area of land where irrigation is required to form a single category of 'irrigated land.' The total land under cultivation today is about 1,510 million hectares, according to the United Nations Food and Agriculture Organization (FAO).[53] Crops could be grown with reasonably successful yields on over 2,600 million hectares, and so according to FAO estimates "expansion of arable land could account for 21 percent of the necessary increase in food production for future populations by 2010."[54] However, significantly boosting food production through cultivating more arable land is in our opinion unlikely for a number of reasons. Like dam-building projects, the top quality sites are developed first, so the land which FAO and others claim could be brought into production are likely to yield less crop per hectare due to lower quality soil, as Gleick notes.[55] Moreover, to develop this arable land for agriculture often incurs very high environmental costs such as deforestation or the reduction of nature conservation sites. Urbanization and commercial and industrial development are also taking land away from the agricultural sector.[56]

We have already mentioned the likely water transfers from the agricultural sector to the municipal sector, due to increasing household needs for water. In addition, with the current water market structure, it often makes financial sense for industry to pay the true price for water while it does not for agriculture. Because the prices which agriculture pays for water are usually much lower than water's true price, agriculture in many cases will be the first to lose its supply when society withdraws less water, either because of drought or other reasons. One of these other reasons comprises newly awakened environmental concerns, such as the preservation of river ecosystems. Seeing the destruction which over withdrawals have caused in places such as the Colorado River Delta and the Aral Sea, society is beginning to recognize parts of the non-human world as a legitimate user of water. Unfortunately, water consumption already exceeds the limit required to sustain natural ecosystems in many areas of the world. As a result, we can expect the water withdrawn for use by society to be reduced due to a societal choice to leave more water in its natural systems. The agricultural sector will probably be the sector most affected by this reduction.

In addition to arable land and agricultural water, chemical technology has been an important resource used by society to increase its food production, with especially dramatic results in the last half of the 20th century. However, it seems that the "green revolution" of the 1965-1980 era is nearing its end. Yield improvements for cereal production have slowed globally to roughly 1.6% per year from an annual 2.6% increase between 1967 and 1982, at the height of the green revolution.[57] So far despite high expectations, genetic engineering has produced no similarly impressive increases in crop yields.

Despite all these problems related to the supply and demand of food, the markets accord water used for agriculture less economic value than water used for municipal or industrial purposes. "Most irrigators believe, rightfully in many cases, that they cannot compete economically with other new demands for water that would generate higher returns than their irrigation use."[58] Municipal and industrial water are more economically productive than agricultural water. The price elasticity of municipal and industrial demand for water is also less than agricultural demand, meaning that the water demand of the agricultural sector is more sensitive to price. When water prices go up, municipalities and industry are willing and able to keep buying water, whereas the agriculture sector is not. Freshwater scarcity, that is, decreased supply, results in higher water prices, and thus reductions of irrigated agriculture. Shortages in food production and increases in food prices can then ensue from water shortfalls. "The difference between the value of water in agricultural, industrial, and municipal uses is largely due to the limited use of markets for allocation of water among users."[59] If the free market were allowed to determine the allocation of water, either food prices would increase beyond the reach of low-income populations or most agricultural uses of water would be eliminated, since they would not be justified economically.

Population growth and economic development account for the increases in society's water demand

Projection of Future Needs for Irrigated Agriculture

By analyzing projections for the future water needs of irrigated agriculture, we can summarize some of the water issues we have covered thus far in this paper. Predictions about future water requirements are governed by the two drivers mentioned earlier–economic growth and population growth. Predicting these phenomena, or anything else about the future, is fraught with peril and uncertainty. However, with some conservative assumptions as a base, a reasonable assessment of future global irrigation requirements can be made.[60] The central question driving this projection is:

How will society produce enough food to meet the calorie demands of 2050?

Premise 1: Population Increases

The global human population will grow to between 9 and 10 billion people by 2050.[61]

Premise 2: Calorie Demand Increases Follow Wealth Increases

Based on current trends, it is reasonable to project that (in fixed US dollars) global GDP per capita will grow from $5,000 (in 2000) to $12,500 in 2050. As GDP per capita increases, so does the per capita calorie demand. As people climb out of poverty and become wealthier, they eat more. Therefore, we estimate that per capita calorie demand will increase from 2,700 in 2000 to 3,300 K cal daily in 2050. As a result, the world will need around 11,750 trillion K cal in 2050 versus the approximately 6,300 trillion K cal consumed by humans in 2000.

Premise 3: Agricultural Production from Unirrigated Land Increases at Historic Rate

The trend for non-irrigated crop yield increases in recent years has been 0.8% annually. These increases are the result of genetic improvements and better farming practices. We will assume that this trend continues, aside from the increases in the land area of irrigated agriculture.

Premise 4: No Net Increases in Cultivation of Dry Land

Since most land that can economically be farmed without irrigation is already cultivated, we will assume that there will be no further increases in so-called 'dry land' farming between 2000 and 2050. Whatever new land might be dry farmed will be balanced out by urban encroachment into currently cultivated areas, as has been the case from 1990-2000, according to FAO.[62]

Premise 5: Agricultural Production from Irrigated Land Increases at Historic Rate

Increases in the percentage of irrigated land versus non-irrigated cultivated land also increase crop yield growth, accounting for roughly one-third of the total yield growth of 1.2% annually in recent years. Although the modern methods of drip and mechanical move irrigation lead to increased yields in some cases, no yield increase driven by the modernization of irrigation methods is taken into account in these calculations.

Potential Solution: Irrigated Agriculture Can Meet the Food Needs of the Future

Based on the premises above, the world calorie demands of 11,750 trillion K Cal could be met by increasing the amount of irrigated agriculture from the year 2000 level of 272 million hectares to approximately 582 million hectares by 2050 as illustrated by the graph in Figure 3 below.

Increasing the area of land cultivated with irrigation is clearly a key component to dealing with the climbing caloric demands of the prolific human population. Let us re-emphasize that it is not possible to predict the exact numbers of people in 2050 nor precisely how many calories will be needed to feed them all nor the precise number of hectares of cultivated land that will be required to produce those calories. However, the trends are clear. Because there is only a negligible amount of undeveloped land that could be farmed without irrigation and because the yields on irrigated land are greater than on non-irrigated land, farming more land using irrigation will become a necessity in the coming decades. Irrigated cultivation of much more land is a very plausible solution to the problem of how to meet the food needs of the world in 2050.

Irrigated Land Requirements

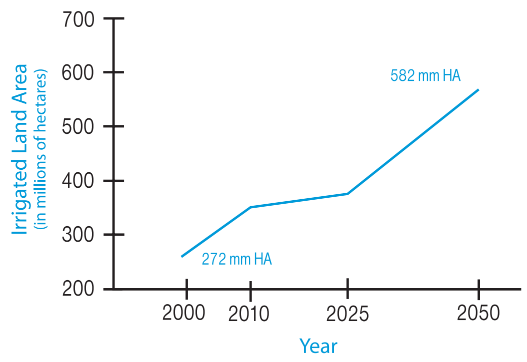
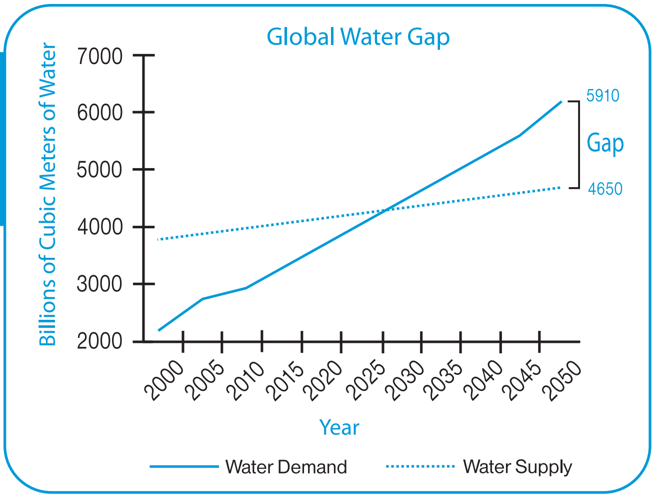


Figure 3

More irrigation, however, demands more water. How much more water depends on the type of irrigation used. If we were to continue using gravity irrigation and other inefficient methods in 2050 at the same level as we use them today, agriculture would consume virtually all of our available fresh water. Besides this projected increase in agricultural demand for water, we will also witness increases from the other demand sectors of industry and municipalities.

In addition, society could decide that more water needs to be allocated to keep wetlands alive or for other environmental needs, but for the purposes of this projection, we shall ignore this contingency. Our estimates presume that industrial water demand keeps to its historic trend of water per US $1 of gross domestic product per year. We likewise estimate the municipal water demand at 283 m^3 per person per year. Figure 4 takes these rates of demand growth into account and projects that growth to the year 2050. On the supply side, we presume that today we are withdrawing from available sources as much water as we possibly can and that our maximum withdrawals grow at the same modest rate as in the last decade of the 20th century. Figure 4 illustrates the result of these projections. Our estimates show that, if current water usage practices continue, before 2050 a sizable gap will develop between the water available for human use and the water required by the agricultural, industrial, and municipal demand sectors.

Figure 4



We emphasize once again our main point, that agriculture is far and away the greatest water user, and that to keep up with global alimentary requirements, more crop production will be needed using less water. Agriculture will not, however, be allowed to guzzle the percentage of our water that its current inefficient irrigation practices would require in order to meet the projected food needs of fifty years from now. Both industry and cities are willing to pay more for the water they use than agriculture can pay. Furthermore, with population growth and economic development, cities and industry will actually demand more than their current share of the world's finite water resources. More output with less input – that is the predicament of the agricultural sector in the years ahead.

III. Demand Management

In his book *Introduction to the Economics of Water Resources: An International Perspective*, scholar and consultant Stephen Merrett carves out a discipline which he calls "hydroeconomics". This "political economy of water resources" concerns itself primarily with "water that is abstracted, stored, and distributed by human labour," "the use of that water," and "the disposal of wastewater."[63] Like so many active water scholars today, Merrett recognizes the need for a shift from focusing on water supply augmentation to focusing on the management of water demand. After examining water supply from the perspective of engineers and then from the perspective of economists, Merrett conducts an instructive investigation of the hydroeconomics of demand. In order to put into proper perspective our main concern in this paper, namely, improving irrigation efficiency, we take note here of the major kinds of demand management which Merrett describes. These five forms of demand management techniques are by no means exhaustive, but they represent a useful overview of what total demand management could entail.

According to Merrett, demand management includes "internal and external re-use, consumption technology, land-use planning, educational initiatives and water pricing."[64] The first of these forms of demand management is *water re-use,* which Merrett divides into two kinds, internal and external: "With internal re-use, a specific consumer first uses the water supplied to it from a water service company, then returns its wastewater internally for [an additional] round of use...For example, the installation of water storage during housing construction can make the one-off re-use of bath and shower water for flush-toilets perfectly feasible, reducing total household water use by perhaps 15 per cent. With external re-use, a consumer, whether household, farmer or industrialist, uses its water supply, and then the wastewater is supplied as an input to another institution. With both internal and external re-use, the wastewater often requires treatment. Re-use can be seen as supply-side innovation. At the same time, it brings about a lower aggregate consumption of water by the community as a whole than would happen in the absence of re-use, and, in that sense, re-use can also be regarded as a form of demand management."[65]

Efficient means of irrigation, such as mechanical move and drip irrigation systems, fit into the second category of Merrett's schema, *consumption technology*. Consumption technology is "similar to internal re-use, in that both deploy technical measures that reduce consumption of the external water supply."[66] We shall delve into aspects of this category of consumption technology in the final sections of this paper. The third kind of demand management, *land-use planning*" concerns catchments where consumption is pushing at the very limits of supply capacity,...and where increased extraction would impose relatively high economic or environmental costs. In such cases,...land-use planning can restrain urban development – and the consumption that accompanies it – and divert its location to other regions not facing the same supply/consumption imbalances."[67] "The fourth form of demand management is to use a variety of *educational measures* to persuade the population as citizens, farmers and managers in industry, to use water wisely...US studies suggest that engineering audits, technical workshops, and best practices manuals can save 20-35 per cent of total annual water use with a short average payback period."[68] Merrett's fifth form of demand management, *water pricing*, includes "[t]he metering of water use and setting a price per unit quantity consumed."[69] Water pricing is complementary to re-use, consumption technology, land-use planning, and educational measures: It "underpin[s] all the first four demand management forms." These five kinds of demand management outlined by Stephen Merrett could form a solid basis for an integrated water demand management program for human society. We focus on improving the way irrigation systems use water, one part of the 'consumption technology' category in Merrett's schema, because we believe that is where the biggest gains can be made through economically viable steps.

In the last century great energy and ingenuity was directed by society toward controlling natural rivers by building dams in order to augment the fresh water supply available to society, thus increasing the supply of fresh water available to keep up with society's burgeoning water demand. At the beginning of this 21st century our energy and ingenuity must instead be directed toward managing our demand for fresh water. Because demand for water by the domestic and industrial sectors is "relatively inflexible," it is the agricultural sector which must make adjustments in the face of pressures on fresh water availability from both the demand and supply sides.[70] The agricultural sector is 'thirstier' than the municipal and industrial sectors, so it is the prime candidate to reduce its fresh water demand. One salient example of a society facing both supply and demand pressures is the stymied society of Palestinians living in the Gaza Strip. Israeli soil scientist Daniel Hillel describes the water situation in Gaza as follows:

> "Salinization of well water in the Gaza Strip [due to seepage from the Mediterranean caused by aquifer overpumping] has occurred at an average rate of 15-20 parts per million per year. Most of the local water in the Gaza Strip now exceeds the salinity level of 500 ppm considered the upper threshold for safe drinking water and in some areas the salinity has even reached 1,500 ppm. Consequently the situation regarding water there is nearly intolerable. Irrigation consumes about 100 MCM/Y [million cubic meters per year]. Domestic use, now amounting to some 20 MCM/Y, is forecast to increase to 35 MCM/Y by the year 2000 and to 55 MCM/Y by the year 2010. At the same time, industrial consumption, now negligible, is likely to increase to 5 MCM/Y or more. Inevitably, therefore, the amount of water used in irrigation (especially of citrus, which has long been the principal crop) must be reduced."[71]

The situation in Gaza and elsewhere is desperate. The "combination of increasing demands on finite freshwater resources makes them ever scarcer. More efficient use of resources, especially in the agricultural sector, and rational allocation between the various demand sectors are called for."[72] A consensus is developing that "the aggregate amount of water used in irrigated agriculture must and will decline."[73] Let us, however, underscore the point that this is "not to say that irrigated agriculture should cease or even that it should shrink." Rather, "Irrigated agriculture cannot continue to be practiced in the manner in which it has been."[74] Fortunately, significant improvements are already technologically possible in water delivery and application efficiency.

Surface drip irrigation system on tomato crop in Florida, USA.

IV. Getting "More Crop Per Drop" with Modern Irrigation Equipment

Efficient irrigation equipment generally comes in two broad categories—drip and sprinkler irrigation. Both of these areas have several sub-types of equipment in them. Within drip irrigation are surface drip equipment, subsurface drip equipment and micro sprays/sprinklers. This category of drip irrigation and particularly subsurface drip irrigation (SDI) is one of the most exciting and newest technologies in irrigation. Drip irrigation has attracted tremendous interest by academics, who measure the performance of drip systems and promote drip as a water savings technology.

Sprinkler equipment can also be broken down into several subcategories including wheel lines, solid set and hand move pipe, traveling guns, and mechanical move irrigation (MMI) systems, which include center pivots and linear move equipment. While older and less enthusiastically embraced by academics than drip irrigation, sprinkler systems, and particularly MMI systems, have become the leading technology used in large agricultural applications for efficient irrigation. With the advent of Low Energy Precision Application (LEPA) configurations in the 1980's, MMI systems achieve irrigation efficiencies rivaling subsurface drip.

Both of these 'best in class' technologies have been extensively compared to traditional gravity flow irrigation. Both systems can demonstrate significantly better overall performance than traditional irrigation methods. Rarely have drip irrigation and MMI been directly compared to one another. The balance of this paper will draw comparisons between these two types of irrigation systems, and explore how appropriate each technology is for various types of farming operations.

Irrigation System Performance

Up to this point, our discussion of modern irrigation has focused on water savings. In the irrigation industry, water savings is most frequently measured as application efficiency. Application efficiency is the fraction of water stored in the soil and available for use by the crop divided by the total water applied. For subsurface drip irrigation (SDI), this theoretical efficiency can be as high as 100%, and LEPA applications in MMI similarly result in application efficiency of up to 98%.[75] While application efficiency is a good starting point in understanding irrigation performance, efficiency measurements under ideal conditions on a test plot hardly tell the whole story about irrigation performance. In general, we can analyze irrigation performance in five categories as shown in Figure 5.

Water Efficiency

Researchers generally give the edge to subsurface drip irrigation SDI when they evaluate water efficiency. According to the Irrigation Association, subsurface drip irrigation (SDI) installations, properly managed, can achieve 95% water efficiency.[76] This high level of water efficiency is

Figure 5

Analyzing Irrigation System Performance

Water Efficiency
- Theoretical application efficiency
- Predisposition toward over watering
- Cleaning/Flushing requirements

Crop Yield Drivers
- Physical layout/Design quality
- Uniformity of application
- Availability
- Controllability
- Fertigation/Fertilizer application

Cost Drivers
- Initial Costs
- Equipment and installation
- Expected life and resale value
- Scalability/Flexibility
- Operating Costs
- Energy/Labor
- Maintenance and repair

Crop Specific Considerations
- Crop height/Planting pattern
- Germination
- Wetting of fruit
- Flexibility for crop rotations
- Crop cooling
- Foliar herbicides/Insecticides

Farm Management
- Adaptability to existing farm operations
- System Reliability
- Special issues (plugging, roots, rodents)
- Theft
- Forgiveness of poor management practice

approximately the same as what a LEPA center pivot or linear system achieves, at 90-95%, and definitely better than the 75-85% efficiency of center pivot with the obsolete water application method of impact sprinklers mounted to the top of the MMI system's pipe. Gravity flow installations are typically around 40%-50% efficient. For the purpose of a farmer's consideration, LEPA and SDI systems can be thought of as having equivalent potential efficiency. Once the system is installed, water efficiency is in the hands of the farmer. While data on this topic is difficult to find, it seems that farmers habitually over-apply water to their fields with all types of irrigation equipment including gravity flow. Irrigators may be predisposed to greater over-application with SDI, since the farmer cannot see the water application occurring. Both systems will benefit from more sophisticated information on evapo-transpiration and plant health to allow more precise application of water and reduce over-application. SDI systems typically require periodic cleaning and flushing to prevent root ingression and plugging. Such flushing is not a requirement with MMI equipment. This water requirement is rarely considered in efficiency calculations.

Crop Yield Driver

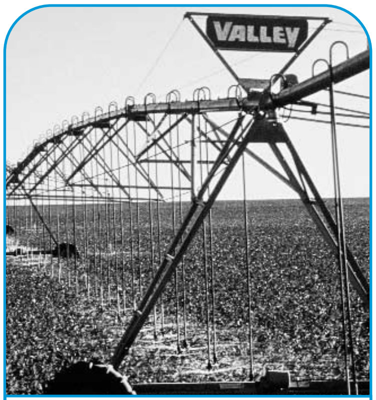
In most cases, the contribution that an irrigation system can make to reaching optimal crop yields is by delivering water to plants when they need it and by applying water uniformly over the area of the field. However, when the available water supply is insufficient to fully meet the water needs of a crop, then the highest crop yields will be achieved by the irrigation system with the highest application efficiency.

Uniform water application by MMI systems is determined by sprinkler package design and by the rate at which the equipment moves across the field. Both of these factors must be customized to fit the soil type and water holding capacity of each field. MMI experts today have a very good understanding of the relationship between soil type, water holding capacity, equipment speed, and sprinkler package design, and they have even developed several computer programs to generate highly uniform patterns of water distribution for low pressure and LEPA systems. Changes in the elevation of terrain can be accommodated by the use of pressure regulators. Uniformity of MMI systems is fairly constant over time. Variations among individual nozzles is significantly reduced by the movement of the equipment and by the overlap between the wetted diameters of soil irrigated by each individual sprinkler head. Typical water application uniformity levels are in the 90-95% range and are fairly constant over time.[77] In applications with high levels of abrasives present in the water, sprinkler packages must be replaced and redesigned every few years to maintain watering uniformity.

Drip systems can also be designed to have high levels of uniformity. A typical design targets uniformity levels in the 85% range. SDI design is not as standardized as MMI system design is, and consequently the water application of any drip system is highly dependent on the skill and knowledge the technician who designed it.

Unlike MMI systems, drip system uniformity can change substantially over time if proper maintenance is not performed to the drip installation. This is particularly difficult for subsurface systems, whose emitters are more likely to suck in soil which cannot then be easily removed by hand since the emitters are buried underground. According to a South African study published in 2001, field examinations of drip systems show that water application uniformity deteriorates significantly over time. The study was done on surface drip installations, and in the opinions of the authors, indicates a problem which may be even more severe in SDI applications.[78]

System availability and controllability is generally good with both MMI and SDI systems, since both offer the ability to irrigate at least once every 24 hours. The exception to this can be with towable pivots, where use of the equipment on multiple fields may limit its availability. Both systems support the use of sophisticated automatic controls and remote control and monitoring. Both systems support the 'spoon feeding' of fertilizer to the crop, but special care must be taken with SDI systems to make sure that injected fertilizers do not cause clogging of the system.



Low-hanging sprinkler nozzles deliver water close to the soil surface to minimize evaporation and wind drift.

For SDI systems, soil salinization is also a significant problem in areas where salts are present in irrigation water. As salts build up in soil, crop yields decrease. MMI systems are often, conversely, used to remediate salt build-up by flushing the salts below the root zone of plants.

Based on a review of available literature, it appears that in non-water limited applications, SDI and MMI systems produce equivalent yields, although the center pivot will use slightly more water in those comparisons due to losses from

The soil under this onion crop at a research farm is white due to extreme salt build-up from the irrigation method utilized.

surface evaporation. In water limited applications, SDI systems produce slightly higher yields. Over time, SDI system maintenance is of great importance. A lapse in system maintenance can result in a significant and permanent degradation of watering uniformity, which in turn causes permanently higher water consumption and lower crop yields.

Cost Drivers

A lot of conflicting information exists concerning the costs of both SDI and MMI systems. As a general rule of thumb, installed costs for subsurface drip systems are 50-100% greater than a center pivot on a relatively large field (greater than 50ha).[79] Cost depends on a number of factors including: availability of proper power, filtration type used in the drip system, the value of installation labor, towable vs. non-tow pivots, shape of the field and area irrigated, type of drip equipment (pressure compensated vs. non-pressure compensated) and the use of linear move equipment, or corner arm extensions on a center pivot.

Also important to the long-term cost is the expected life. Center pivots have an average life expectancy of 25 years with minimal maintenance expenses, typically less than 1% per year of the original price. In a few installations where the source water is corrosive to galvanized steel, it is important for the buyer to move to corrosion resistant products such as aluminum, stainless steel, or polyethylene lined systems. Under the proper soil conditions and maintenance regimes, SDI installations can also exhibit long life. Some research installations have surpassed 20 years of usage with still functioning systems. Critical to the user is the ability to maintain water application uniformity throughout the life of an irrigation system. In most commercial installations, drip systems performance degrades with time due to plugging, root intrusion, and pest damage. Diagnosis and repair of SDI system problems can be expensive and challenging to perform. Typical maintenance costs range from 3% to 10% per year of the original system cost.

Another advantage of MMI technology is its portability. It is not uncommon for a center pivot to be moved several times during its expected service life. Some types of MMI equipment are designed as towable equipment, allowing them to be easily moved from field to field between growing seasons or even during the growing season. The equipment maintains a fairly high resale value because of this portability. SDI systems, with the exception of some filtration and control elements, are generally not salvageable or resellable at all.

In addition to maintenance and repair costs, the other significant system operating cost is energy used to pump water and field labor. Energy costs are related to the volume of water pumped and the pressure required. Research shows that these two costs are nearly equal for SDI and MMI systems. Center pivot and linear systems at research plots typically pump slightly more volume of water then SDI systems, but SDI pump outlet pressures are typically higher (3 bar vs. 1.5-2 bar).

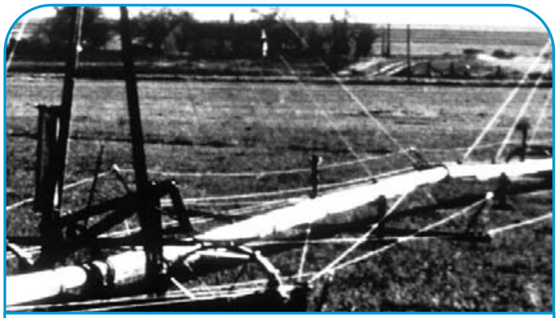
Labor costs vary depending upon the in-field conditions and the choice of control systems. One 1990 article shows pivots to require 3 hours per hectare, while drip requires 10 hours per hectare.[80] Even in trouble-free installations of equal control sophistication, SDI seems to require more labor because of its regularly required maintenance cycle. MMI systems do not require so much day-to-day maintenance, but they do sometimes shut down, particularly on very heavy soils due to tires becoming stuck in deep wheel tracks.

Crop Specific Considerations

Different crop specific characteristics favor one system type over another. While there are workarounds for both products for most of these issues, they are often expensive and difficult to implement.

Drip systems or micro-irrigation are often preferred by growers when crop height may be an issue for mechanical systems as over cashew nut trees, or with planting patterns not conducive to above ground mobile irrigation equipment as with vineyards. Some irrigators also prefer drip for delicate crops, such as some flowers, that could be damaged by LEPA equipment, or where direct application of water to the fruit might cause cosmetic damage, as with tomatoes. Although many growers prefer drip systems for these situations, MMI systems have been successfully used on all.

MMI systems are preferred where surface water application is required to germinate seed as with carrots and onions, particularly in sandy soils. MMI systems also have an advantage in applying foliar herbicides and pesticides, and can be used for crop cooling in temperature sensitive crops such as corn. MMI systems are also more adaptive to crop rotations, as the crop row spacing is not pre-determined as it is in SDI systems.



Nebraska farmer Frank Zyback sold this 1953 model of mechanical move irrigation equipment to Valmont, which held the patent until its expiration in 1968.

Farm Management Practices

While both types of systems require significant departure from traditional irrigation practices, SDI systems clearly require a higher level of discipline and regular maintenance than MMI systems. The consequences of not adapting to new management practices are generally more dire for SDI systems also.

High profile center pivots can irrigate trees as high as 5 meters tall.

SDI farms must commit to the regular cleaning and flushing procedures described by the system designer and the equipment manufacturers. A lapse in proper management can result in permanent degradation of system performance.

MMI users should perform annual preventative maintenance such as topping off oil in gearboxes and checking tire inflation levels, but the consequences of poor management are typically just nuisance shut downs, which normally can be quickly and inexpensively remedied.

A special problem that faces owners of MMI equipment in some third world countries is theft, particularly theft of motors, controls and copper wire. To combat this problem, a number of adaptations have been made to reduce the risk of theft on the system. Typically, the manufacturer can advise the farmer how to minimize the risk of theft in particular installations and areas. MMI systems are less flexible when it comes to field configuration and water infrastructure. Farmland laid out in 2 hectare plots with canals serving the individual fields, for example, are difficult to adapt to MMI systems.

Figure 6 provides a tabular summary of the previous discussion comparing the MMI and SDI technologies.

V. Conclusion

Both subsurface drip and mechanical move irrigation systems have a legitimate place in agricultural water conservation plans for the future. Both systems offer significant potential water application reduction, as well as yield improvements over traditionally managed irrigation fields. Over traditionally managed irrigation fields in general, mechanized systems are most suitable for: broad area crops in large fields, new land development, and sandy soils. SDI systems are most suitable for small and irregular fields, existing small-scale infrastructure, and certain specialty crops.

These innovative technologies require significant investment. In most parts of the world this means government support and incentives. Mexico and Brazil are two leading countries in providing effective incentives to farmers to invest in modern efficient agricultural irrigation.

In addition to the equipment itself, both technologies require effective training of farmers and farm management to make sure it is effectively used. Poor management can easily offset most of the water saving and yield gains made possible by the equipment.

Employing the modern technology available for water-efficient irrigation is clearly key to overcoming the global challenges of water scarcity. Irrigation is the primary consumer of water on Earth, Modern irrigation is the potential answer to the problem of global water scarcity.

Figure 6

Analysis of SDI and MMI System Performance

Water Efficiency

- SDI has slightly higher efficiency than LEPA (95% vs. 90-95%) in research installation.
- No known studies yet compare actual on-farm efficiency.

Crop Yields

- SDI performs better in research tests when water availability is the limiting factor, otherwise yields are equivalent between the two systems.
- Uniformity of SDI systems appear to degrade over time, favoring MMI.
- Design of SDI systems are critical to achieving good initial water uniformity.
- Where salinity is a problem, MMI systems have a clear edge.

Cost

- Center pivots and linears are less expensive to install on large plots, and have a higher resale value.
- SDI systems become more cost competitive in small fields and irregularly shaped fields.
- MMI systems have long lives (25 years on average). SDI can have a life of 10-15 years if proper maintenance is performed.
- Ongoing maintenance costs of SDI are 3-5 times higher than MMI.
- Operating costs for energy are similar between the two technologies, but MMI systems typically require much less labor.

Crop Specific

- SDI is often favored on tall permanent crops, particularly when the field is not laid out to use mechanized systems.
- MMI systems are preferred in sandy soils where surface application is necessary for germination.
- Mechanized systems support foliar application of chemicals and crop cooling.
- Mechanized systems are preferred where there are frequent crop rotations.

Farm Management

- SDI systems are less adaptive and forgiving to poor management practices.
- Theft is an issue for mechanized systems in some third world markets.
- SDI is more flexible for some existing infrastructure.

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[7] Shiklomanov reports 60%-70% of run-off occurring in the flood or high water period. Shiklomanov in Gleick, *Water in Crisis*, 16.

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[11] Marc Reisner, *Cadillac Desert: The American West and Its Disappearing Water* (New York: Viking, 1986), 507.

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[20] Lawrence J. MacDonnell, *From Reclamation to Sustainability: Water, Agriculture, and the Environment in the American West* (Niwot: University Press of Colorado, 1999), 239. On p. 346 n. 23, MacDonnell attributes this distinction to Gilbert White.

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[22] Sandra Postel, *Last Oasis* (New York: W.W. Norton & Company, 1997), xv.

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[25] *Ibid.*

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[27] Shiklomanov, in Gleick, *The World's Water* 2000, 53.

[28] *Ibid.*

[29] Falkenmark and Lindh, "Water and Economic Development," in Gleick, *Water in Crisis*, 80.

[30] Orloci, Szestay, and Varkonyi, "National Infrastructure in the Field of Water Resources," in Gleick, *Water in Crisis*, 81.

[31] Shiklomanov, in Gleick, *The World's Water 2000*, 53.

[32] *Ibid.*

[33] Shiklomanov, in Gleick, *Water in Crisis*, 19.

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[42] *Ibid.*, 206.

[43] *Ibid.*, 204.

[44] Malthus' analysis was based on what from our 21st century perspective might seem a fantastically simplistic scenario: "These effects [of subjecting the lower classes of society to distress and of preventing any great permanent amelioration of their condition], in the present state of society, seem to be produced in the following manner. We will suppose the means of subsistence in any country just equal to the easy support of its inhabitants. The constant effort towards population, which is found to act even in the most vicious societies, increases the number of people before the means of subsistence are increased. The food, therefore, which before supported eleven millions, must now be divided among eleven millions and a half. The poor consequently must live much worse, and many of them to be reduced to severe distress. The number of labourers also being above the proportion of work in the market, the price of labour must tend to fall, while the price of provisions would at the same time tend to rise. The labourer therefore must do more work to earn the same as he did before. During this season of distress, the discouragements to marriage and the difficulty of rearing a family are so great, that population is nearly at a stand. In the meantime, the cheapness of labour, the plenty of labourers, and the necessity of an increased industry among them, encourage cultivators to employ more labour upon their land, to turn up fresh soil, and to manure and improve more completely what is already in tillage, till ultimately the means of subsistence may become in the same proportion to the population as at the period from which we set out. The situation of the labourer being then again tolerably comfortable, the restraints to population are in some degree loosened; and, after a short period, the same retrograde and progressive movements, with respect to happiness, are repeated." Malthus, 25-26.

[45] Sen, 161.

[46] *Ibid.*, 165.

[47] *Ibid.*, 175-176.

[48] *Ibid.*, 204.

[49] United Nations Food and Agriculture Organization (UNFAO); available from http://apps.fao.org/lim500/wrap.pl?FoodBalanceSheet& Domain=FoodBalanceSheet&Language=english; Internet; accessed 26 Feb 2003.

[50] *Ibid.*

[51] UNFAO, "FAO: Large Gap In Food Availability Between Rich And Poor Countries - New Map On Nutrition Released," FAO [home page on-line]; available from http://www.fao.org/WAICENT/OIS/PRESS_NE/PRESSENG/1998/pren9870.htm; Internet; accessed 31 January 2003.

[52] Gleick, *The World's Water 2000*, 64.

[53] UNFAO, FAOSTAT database (http://faostat.fao.org) 1999, in Gleick, *The World's Water 2000*, 70.

[54] UNFAO, Ed. N. Alexandratos, "World Agriculture: Toward 2010, an FAO Study," in Gleick, *The World's Water, 2000*, 70.

[55] *Ibid.*, 73.

[56] *Ibid.*, 71.

[57] *Ibid.*, 64.

[58] MacDonnell, 258.

[59] National Research Council, *New Era for Irrigation* (Washington D.C. National Academy Press, 1996), 67.

[60] The premises and calculations in this section are explored much more thoroughly in a separate paper, "Irrigating Efficiently to Feed the World in 2050" by Thomas D. Spears (Valmont 2003).

[61] According to the IIASA Population Growth Model with a midline projection for birth rate, mortality, and interregional migration (CCC 2050 f+m 9.874e+009) as viewed on 3 Feb 2003 on http://www.iiasa.ac.at/Research/POP/Population Data/A.14.

[62] UNFAO; available from http://apps.fao.org/page/form?collection=LandUse& Domain=Land&servlet=1&language=EN&hostname=apps.fao.org&version=default; Internet; accessed 26 Feb 2003.

[63] Merrett, 2.

[64] *Ibid.*, 63.

[65] *Ibid.*, 64.

[66] *Ibid.*

[67] *Ibid.*

[68] *Ibid.*, 64-65.

[69] *Ibid.*, 65.

[70] Hillel, 230.

[71] *Ibid.*, 311-312, endnote 4.

[72] Young et al., *Global Water Resource Issues* (Cambridge: Cambridge University Press, 1994), 113-114.

[73] *MacDonnell*, 263.

[74] *Ibid.*, 290.

[75] D. Rogers, et al., "LEPA Irrigation Management for Center Pivots," *Irrigation Association Online*; available from http://www.oznet.ksu.edu/library/ageng2/l907.pdf; Internet; accessed 5 February 2003.

[76] James Hardie Irrigation, "Drip Irrigation for Landscaping, An Introductory Guide," 26, in Irrigation Association, "Agricultural Hardware," *Agricultural School of Irrigation*, 17.

[77] Scherer et al., *Sprinkler Irrigation Systems* (Ames, IA: Midwest Plan Service, Iowa State University, 1999).

[78] Koegelenberg, F. and R. Reinders, *Performance of Drip Irrigation Systems under Field Conditions* (South Africa: Agricultural Research Center-Institute for Agricultural Engineering).

[79] O'Brien et al., "An Economic Comparison of Subsurface Drip and Center Pivot Sprinkler Irrigation Systems," *American Society of Agricultural Engineers*, vol. 14(4), (1998): 391-398.

[80] Kruse et al., "Comparison of Irrigation Systems," in *Irrigation of Agricultural Crops*, ed. B.A. Stewart and Donald R. Nielsen (Madison, WI: American Society of Agronomy, 1990), 475-505.

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