Affordable Drip Irrigation for Small Farms in Developing Countries

By
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Abstract: Many farmers in India and elsewhere surface irrigate their small fields with water from wells having small average discharges. They are being assisted in converting to very low-cost drip systems that are non-proprietary and manufactured locally. These drip systems are affordable and payback is quick in view of the reported water savings of 50 to 80 percent and yield increases of 30 to 50 percent. The systems operate at pressure heads of less than 3 meters (10 feet), require minimal filtration, use cheap recycled plastic sub-mains (manifolds), and use simple drip-tape with short lengths of microtubes for emitters. This presentation covers the following aspects of these low-cost drip systems: a) farmers' experiences and profitability; b) technology development and marketing assistance; c) system specifications and component costs; d) local manufacturing requirements and costs; e) system performance characteristics; and f) design tools and procedures.

Background

It is estimated that three-quarters of the farmers in developing countries cultivate less than 2 hectares (5 acres) of land. For example, a typical farm in Bangladesh supports six people on what they can earn and eat from one acre of land. Typically the family income is only $200 to $300 a year, far too little to afford the modern irrigation devices that are often promoted by development experts. However, without improved irrigation, they cannot gain full access to green revolution inputs. Furthermore, many development experts expect that in an open marketplace, small inefficient farms will be taken over by larger and more efficient farms. But in the face of rapid population growth, actual farm size in developing countries is steadily decreasing! The failure of the development community to take these simple facts into account is a major factor constraining emergence of practical solutions to both improved irrigation performance and to hunger and poverty.

About twenty percent of the world's 6 billion people live in families with incomes of less than a dollar a day, and 800 million people regularly go hungry. Roughly eighty percent of this core group of 800 million hungry and poor people live in rural areas in developing countries and earn their livelihoods from agriculture. The green revolution, with its high yielding varieties of seeds combined with access to improved irrigation and fertilizer tripled global grain production and tripled the incomes derived by farmers with sufficient water supplies and relatively large land holdings. But for the most part it left farmers who only have access to small plots of land and limited water supplies standing on the sidelines. (See Postel, et al 2001.)

Introduction

An area of land that can be fully irrigated from a given volume of applied water can be significantly increased by converting from traditional surface irrigation to drip irrigation. Of even greater importance from a basin-wide water resources perspective, the production per unit of water depleted by evaporation, transpiration and salt-loading is often increased by 30 to 50%. Furthermore, the availability of drip irrigation systems in small affordable packages unlocks these potential benefits for literally millions of resource-poor farmers. In addition

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it opens the potential benefits of irrigation even where water supplies were considered insufficient or too costly to acquire for traditional irrigation methods to be practical.

The drip systems described herein are low-cost, available in small packages, operate at very low pressure, and are easy to understand and maintain. These features are what distinguish them from commercial "state of the art" drip irrigation systems. Compromises are made in operational convenience, manufacturing tolerances, and the uniformity of irrigation applications to achieve these advantages. However, the water conservation and productivity gains from converting from traditional small-scale surface irrigation to low-cost drip irrigation may even be greater than the comparative gains from converting large-scale commercial surface irrigation to state of the art drip irrigation systems.

Systems for Small Landholders

A potential drip irrigation customer who had limited access to capital can purchase an expandable drip system capable of irrigating a garden plot of 20 to 100 m^2 for from $2.00 to $10.00. Poor farmers who only have small plots can afford to invest in them and after they gain technical competence and sufficient financial capacity they can use the profit generated to expand the system. These systems are also affordable enough to be attractive to home gardeners with access to small patches of land adjacent to their dwellings (or elsewhere) to invest in them.

The "drip kits" that irrigate 20 to 40 m^2 only need a 20-liter (5-gallon) water supply bucket or tank. For intermediate sized drip kits that irrigate 100 to 400 m^2 (1/10-acre) a 50-to 200-liter water supply tank supported about 1.0 meter (3.3 feet) above the ground is sufficient (see Figure 1). It is practical to manually fill the water supply tanks of such drip kits. However, for larger systems a pumped or gravity fed water supply is needed to either periodically fill the tanks[3], or be directly connected to the sub-main. Still, these low-cost systems are only suitable for irrigating plots of 2 hectares (5 acres) or less.

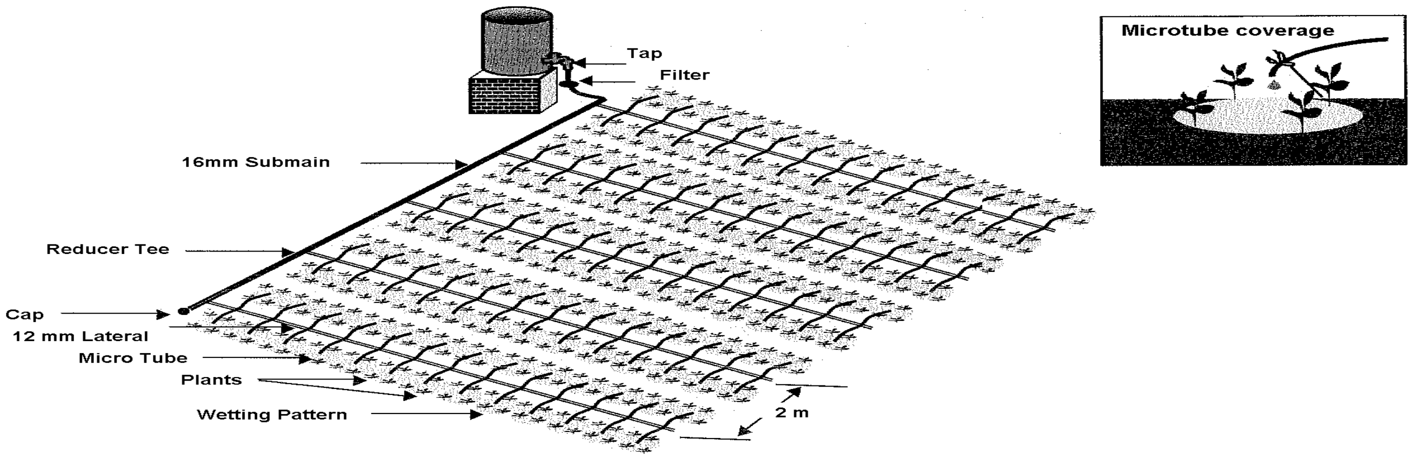

Figure 1. Schematic of a low-cost micro-tube drip irrigation system.

As a Board member (Jack) and a Professional Associate (Andrew) of International Development Enterprises (IDE), we periodically provide technical assistance to IDE-India[4]. A principal objective of IDE-India is to

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[3] Pressure-type manually operated treadle-pumps, which are easily capable of providing enough water to irrigate up to 2,000 m^2 (1/2-acre) of vegetable crops when operated about four hours per day during peak water use periods, are available for roughly $50.

[4] IDE and IDE-India are non-government development organizations (NGOs). IDE is the international entity and IDE-India is an associated organization that is managed separately and operates mainly in India.

refine, test, and promote *generic* low-cost irrigation technologies. These include low-cost microtube-drip kits (see Figure 1) and customized microtube-drip systems supplied directly from wells. This presentation is focused primarily on the customized low-cost microtube-drip (*L-Cm-drip*) systems. We have used a case study approach that covers the following aspects related to them: farmers' experiences and profitability; technology development and marketing; specifications including manufacturing requirements and costs; performance characteristics; and design tools and procedures.

Farmers' Experiences

In the semi-arid region of the state of Maharashtra, India the average small land holding is less than a hectare (2.5 acres). The following comments are based on discussions that occurred during the past year with over 25 purchasers of the low-cost microtube drip (*L-Cm-drip*) systems promoted by IDE-India[5]. Most of them had previous experience producing vegetable crops (such as tomatoes, eggplant, okra, squash, etc.) using traditional surface irrigation supplied from hand-dug, open wells fitted with electric or diesel powered pumps. Many smallholders were using portable small diameter (63 to 75 mm) flexible or rigid recycled-plastic pipe to convey the water to their vegetable plots. During the dry season their wells produced very little water[6], and the sizes of their vegetable plots ranged from roughly 200 m^2 (1/20-acre) to 2,000 m^2 (1/2 acre). All of the farmers interviewed said the conversion to drip irrigation was very cost-effective and many of them had increased annual net return from additional vegetable production that were several times the investment cost!

Farmers reported yield increases of roughly 50 to 100 percent and decreases in water use of 40 to 80 percent compared to experiences with traditional surface irrigation systems. Their gross returns from the typical vegetable crops grown under *L-Cm-drip* systems ranged between \$0.25 and \$1.00 per m^2 for each crop season, with a typical annual return of roughly \$0.50 per m^2 for a single crop and \$1.00 per m^2 per year for double cropping. The net returns from a given area under double cropping were roughly \$0.50 per m^2 greater under the *L-Cm-drip* systems than with their traditional surface irrigation systems. However, in most cases water was the limiting resource and they have been able to double or even triple the irrigated area by converting from surface to *L-Cm-drip* irrigation[7] and generate increased net returns of \$1.00 per m^2 of newly irrigated land. In addition to the increased crop production they found the *L-Cm-drip* systems to be much easier and less time consuming to operate than traditional surface systems, particularly where water supplies were very limited.

A farmer[8] who also had some regular drip-tape with built in emitters said he knew the uniformity of application from his newly purchased *L-Cm-drip* system was not as good, but he had observed that the water savings and productivity were almost the same. He also noted the sophisticated drip-tape required relatively high pressure heads with careful filtration and special acid treatment to keep it operating properly; but the *L-Cm-drip* system can be operated at much lower pressure heads and it does not need such special filtration and care. Therefore, considering its ease of use and low-cost (less than 20% of a sophisticated system cost) he intends to continue buying *L-Cm-drip* systems to expand his irrigated area. (He also noted that the sophisticated drip-tape would probably last three times as long but it was still not worth the difference in cost.)

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[5] The IDE development strategy focuses on utilizing a business or market approach for assisting farmers with small land holdings (smallholders) in improving their incomes and livelihoods.
[6] A typical hand-dug-open well might only produce 5 to 20 m^3 per day. This will only last for one or two hours of pumping at a rate of 2 to 4 liters per second (30 to 60 gpm).
[7] A note of caution is in order here. By increasing the irrigated area the total water consumed by crop ET will increase proportionally. From a basin-wide water resource perspective this will not increase the production per unit of water consumed if the so called 'losses" from the less efficient traditional surface irrigation were being reused. The losses are only "real losses" if the water is discharged to salt sinks or consumed by salinization or unwanted evaporation and transpiration.
[8] Mr. B. Harat whose farm is near Jalina, Maharashtra.

We observed that microtube clogging was not a problem[9] with any of the *L-Cm-drip* systems in Maharashtra that were using short microtubes with internal diameters between 1.2 and 1.5 mm even though they were being supplied directly from open wells and not equipped with filters. Most of them did not even have simple in-line screens for safety purposes. The few microtube emitters that clogged were simply replaced if flushing did not unclog them.

Expected Longevity of *L-Cm-drip* Systems

We estimate that the longevity of the lay-flat lateral tubing (called drip-tape hereafter) that IDE-India recommends for *L-Cm-drip* systems serving row and vegetable crops is up to four vegetable cropping seasons or roughly two years. The estimated longevity of the heavier wall tubing recommended for horticultural crops is roughly four years. These estimates are based on discussions with IDE-India field agents and the following observations in the field:

- A farmer's[10] experience with a 1.6-hectare (4-acre) field where he has used an *L-Cm-drip* system for three different crop seasons beginning in 2001 (cotton followed by two crops of watermelon). The system was actually operated for a total of 12 months. It had 16 mm diameter drip-tape with a wall thickness of 110 micron (4+ mils). He had just replaced it (in March 2003) with the recommended drip-tape, which has 125-micron (5-mil) wall thickness because the original lateral tubing was mechanically damaged (not because of weathering). He is confident that new drip-tape will last for four cropping seasons or at least two years. He also installed an *L-Cm-drip* system in a banana planting using the recommended heavier 250-micron (10-mil) drip-tape and is confident it will last for four to five years.
- The experience of a farmer[11] who used 140-micron drip-tape with punched holes instead of microtubes. He only had a lateral for every six rows to irrigate his 1-hectare (2.5-acre) lentil field. The drip-tape was shifted six times per irrigations and he applied four irrigations to the lentils. Thus each lateral was moved dozens of times, but the drip-tape is still in excellent condition with practically no signs of deterioration and he was planning on using it in a similar manner next cropping season.

Technical Development and Marketing

The marketing approach to development used by IDE and others is beautifully presented and explained in the Swiss Agency for Development and Cooperation's Report by Heierli (2000). This report includes program descriptions with examples of successes along with the performance indicators used. This and other reports describing the marketing approach to development as well as smallholder irrigation technologies are available on the Small Irrigation Market Network (SIMI-net) web site: http://www.siminet.org/fs_start.htm.

The strategy of subsidizing the cost of conventional drip irrigation systems so farmers with small plots can afford and use them has generally proven to be unsustainable. It has not been a very efficient mechanism for addressing the needs of smallholders, nor has it resulted in the expected improvements in irrigated agricultural performance. For economically sustainable success, the uptake of drip irrigation systems by smallholders should be demand driven and without direct subsidies. Thus the systems must be financially feasible (or affordable), and farmers should be willing to pay the full ongoing cost (including reasonable profit margins) associated with producing and marketing them once the market demand is well established. There are circumstances resulting from extreme poverty, disasters, and socio/economic/political situations when farmers

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[9] A few farmers elected to simply punch holes in their thin wall drip-tape instead of using microtubes as emitters and they were experiencing sever problems with clogging.
[10] The farm is near Jalgon, Maharashtra and it is owned and operated by Mr. Uttam Digambar Bari.
[11] Mr. Narayan Bahi Jeram Bahi Dogariya, whose farm is near Rajkot, Gujarat.

are unable to pay the "full ongoing costs" and are thus subsidized. But experience has generally been that system uptake and continued use are not sustained in such circumstances when the subsidies are discontinued.

General Design Strategy

L-Cm-drip systems provide subsistence farmers with an affordable means for irrigating their small plots in order to reap the associated potential crop production increases and water savings. The general technical and economic criteria IDE-India employed in this successful development effort are:

- The systems are designed around the best available components, with preference given to local manufacturing that only require relatively unsophisticated facilities, but not at the expense of affordability and functionality.
- The assemblage, sales, and service tactics required for the systems are compatible with local micro-enterprises and require limited skill and capital to design, service, and maintain.
- The systems are designed to optimize economic returns based on the availability and opportunity costs of both local capital (which may be higher than 100% per year) and labor (which is often ≥ $1.00/day).
- The income generation potential of the systems (compared to the systems they replace) at least covers the investment cost in one irrigation season.
- The systems are available in a range of small packages (from as little as 20 square meters to a couple of hectares). They are also expandable so the area served can be enlarged as farmers gain confidence in the technology and become more financially capable.
- The systems are simple and easily understood, operated, and maintained by unsophisticated users.
- The required inlet pressure head for *L-Cm-drip* systems ranges from 1 to 4 meters.
- They provide the potential for high irrigation efficiencies and superior crop yields.

Developing the *L-Cm-drip* System Market Demand

Rather than direct subsidies, IDE-India provides what are in effect indirect subsidies to farmers by covering the costs of developing and promoting *L-Cm-drip* systems and establishing the market demand for them. The strategy they used prior to establishing the production capacity and implementing the marketing program included the following:

- Identifying promising technologies that had the potential to improve productivity if packaged for small plots of land and affordable to the potential smallholders. While the *L-Cm-drip* systems may appear simple, developing this affordable and user-friendly product line required inventive concepts followed by talented engineering.
- Promising low-cost drip systems were then field-tested and modified to trim cost, increase functionality, and better address field requirements so they would be more acceptable to smallholders.
- The most promising systems were again field-tested and then market-tested prior to initiating supply chain development and promotional programs for them.
- The design strategy is described above, but it essentially never ends because of remaining possibilities for reducing costs and increasing the functionality of *L-Cm-drip* systems in response to suggestions and insights gained from the manufacturers, dealers, assemblers, and farmers who work with them.

This role played by IDE-India using donor funding was necessary since the *L-Cm-drip* system was designed around more or less generic (without patent protection) components. Thus micro-enterprise manufacturers (or importers and assemblers) and vendors could not have afforded to invest in the necessary product and market development activities because these costs would not be recoverable after the market demand was established. If the innovators attempted to maintain sufficient profits to cover these development costs, competitors would arrive on the scene and undercut their prices. However, this competition is actually a positive aspect of the market creation approach that led to development of the *L-Cm-drip* system. It continuously stimulates inventiveness by attempting to increase cost-effectiveness and functionality.

Specifications and Costs

One might consider the *L-Cm-drip* systems recommended and promoted by IDE-India to be a regression back to systems previously used in the US and elsewhere. This is because the laterals are simple plastic tubing and microtubes are used for emitters. But this is not the whole story of *L-Cm-drip* systems. They represent refinements by utilizing modern plastic technologies, generic off-the-shelf auxiliary components that have been developed for modern drip systems, and various innovations that utilize simple manufacturing techniques and increase layout flexibility.

The ideas underlying the development of *L-Cm-drip* systems resulted form a blend of: a) IDE-India's experience using standard wall polyethylene (PE) tubing with long microtube emitters such that a single lateral could serve two crop rows (see Figure 1); and b) some innovative farmers' experiences using drip laterals made from very thin-wall clear plastic tubing produced for packaging a confectionary treat called "Pepcee or Pepsi". Instead of using emitters, holes are punched in the "Pepcee" tubing with a needle. The resulting water application is not uniform and the tubing begins to disintegrate in a few weeks; furthermore, algae grow in it. But these systems are successful because they only cost about \$0.01 per m^2 (\$40 per acre) and last long enough to germinate a cotton crop six weeks before the monsoon rains begin, which increases yields by 25 to 50 percent.

IDE-India recognized the cost advantages of the "Pepcee" systems but they were not suitable for irrigating a vegetable crop for a full season. So IDE-India focused on blending the cost effectiveness of the thin-wall tubing using modern plastic technologies and microtube emitters with relatively large internal diameters in developing the *L-Cm-drip* systems. The lay-flat tubing is a mixture of linear low density PE (LLDPE) and low density PE (LDPE) with carbon-black so it is strong and resists stress cracking, deterioration from ultraviolet light, and internal algae buildup. Under low operating pressure heads the discharge rates from the microtube emitters are about ideal, clogging problems are minimal, and on relatively level small fields the application uniformity is high. Furthermore, the systems are very affordable, with the laterals plus sub-main (see Figure 1) costing less than \$0.04/m^2 (\$400/hectare or \$160/acre) installed.

Recommended Specifications

The general specifications recommended by IDE-India for *L-Cm-drip* system components are:

- **Lay-flat lateral tubing:**
  - The recommended composition is 80 units of LLDPE, 20 units of LDPE and 2.5 units of Master Batch containing 50% carbon black. Virgin film grade plastic should be used and the tubing scrap should not be recycled in the process, but used for making other products.
  - Recommended wall thicknesses:
    - For regular row and vegetable crops use 125 ± 5 microns (5 ± 0.2 mils); and
    - For horticultural crops (such as banana, vines and fruit trees) use 250 ± 5 microns (5 ± 0.2 mils).
  - The width of the tubing when flat should be 26 ± 0.5 mm, which gives a minimum inflated inside diameter of 16 mm.
- **Microtube emitters:**
  - Recommended internal diameters (IDs):
    - For regular row and vegetable crops use 1.2 mm ID microtubes; and

    - For horticultural crops use 1.5 mm ID microtubes.
  - Recommended microtube lengths:
    - For regular row and vegetable crops use 20-cm (8-inch) long pre-cut microtubes with a tight overhand knot[12] when a lateral is used for each crop row. The microtubes should be 10-cm (4-inches) longer than half the row-width where two rows are served by each lateral as shown in Figure 1.
    - For horticultural tree crops use 1.0 to 1.5 m (3.3 to 5 feet) long tubes. For bananas and papayas use 0.75 to 1.5 m (1.5 to 5 foot) long tubes, depending on the plant and drip-tape spacing and microtube layout. (Typically, there are four microtubes per tree for citrus and deciduous tree fruit and only one per plant for bananas and papayas.
  - Microtubes must be installed in the field when the drip-tape is inflated and inserted so 2.5 to 5 cm (1 to 2 inches) are inside the drip-tape with their inlet ends pointing downstream.

Costs[13]

The cost of *L-Cm-drip* systems is very low. Some insights into how this low cost is achieved in India are:

- *L-Cm-drip* tape is a simple continuous tube and with microtube emitters installed in the field rather than standard drip-tape with integral emitters that requires expensive manufacturing machinery. Although installing *L-Cm-drip* is labor intensive, in India a skilled installer can install about 1000 m^2 (one-fourth acre) of *L-Cm-drip* per day at a labor cost of \$2.00/day.
- The *L-Cm-drip* tape without emitters and the simple emission devices are economical because they can be manufactured using inexpensive machinery. Furthermore, the rolls of drip-tape and microtubes are very compact and easy to transport, even on a motor bike. The drip-tape is manufactured using the same blow extrusion process used to make plastic films and bags. In India the locally made extruders range in price from \$3,200 to \$6,400 and produce from 1.25 to 5 Kg of drip-tape per hour respectively. They require two operators, each earning roughly \$0.25 per hour– one to manually maintain the required width and wall thickness of the drip-tape and the other to manage and change the take-up reels.
- The cost and profit margins in the supply chain are very low in India. For example, the cost of the virgin plastic in a kilogram (Kg) of the drip-tape is about \$1.30 and the cost to the farmer including installation is about \$2.60/Kg, only twice the raw material cost.
- Approximately 160 m of 125-micron (5-mil) drip-tape can be extruded form 1 Kg of plastic, so the drip-tape costs 2.60/160 = \$1.60/100 m (\$0.50/100 ft). Bulk microtube stock cost about \$15.00 per 1,000 meters, which when cut into 20-cm (8-inch) lengths makes 5,000 microtube emitters. Thus the installed cost of drip-tape with 30-cm (12-inch) between microtube emitters is only \$2.60/100 m (\$0.80/100 ft).
- The smallholders IDE-India focuses on seldom have fields over one acre and the typical row length ranges from 30 m to 100 m[14].
- The drip-tape has a 16 mm ID and the friction head loss at a given flow rate is only half[15] that of regular 16 mm drip tubing with an ID of 14 mm.
- The required inlet pressure head is usually only 1 to 3 meters so very simple pipe fittings and connections can be used. For example, the sub-main pipes can be made using recycled plastic and the

[12] The overhand knots are tied so about 5 cm of the microtubes are inserted inside of the drip-tape pointing downstream. The knots produce an angular bend in the microtubes so they lay flat along the drip-tape.
[13] As of March 2003 the conversion rate for \$US to Indian Rupees was: \$1.00 = 46Ru; however, in India's rural sector, when the purchasing price parity of a Rupee is considered, 46Ru will buy roughly \$4.00 worth of services.
[14] Row lengths up to 50 m can be served from one end, but for longer rows, pairs of drip-tape laterals must be fed from a sub-main laid across and near the middle of the rows.
[15] The tubing friction head loss is a function of $1/ID^{4.75}$ and $(14/16)^{4.75} = 0.5$.

pipe sections do not need to be glued, which further reduces costs and makes it is easy to rearrange the system after each crop cycle. Some other advantages of low pressure operation include:

- There are no problems with leakage or splitting of the drip-tape at the sub-main connections or where the microtubes are inserted.
- Microtube with wide flow paths are used for the emitters, thus minimizing screening and filtration requirements.
- Low quality standard sized irrigation fittings and pipe extruded from recycled plastic can be used for the sub-mains and drip-tape connections to them. For example:
  - Both flexible semi-lay-flat and rigid pipes made from recycled plastic are suitable for sub-mains. The 75-mm semi-lay-flat tubing only costs $0.20/m but only lasts for 2 to 4 years, while 63-mm rigid pipe cost $0.40/m and lasts from 6 to 8 years.
  - Regular 16-mm grommet connectors that cost $0.03 each are used for connecting the drip-tape to the sub-mains. Short pieces of light weight 16-mm by 0.5-mm wall drip tubing are ideal for securing the drip-tape on the grommet connectors with a knot.

Performance Characteristics

We recommend that the micro-irrigation performance standards, such as those proposed by the American Society of Agricultural Engineers, be relaxed for *L-Cm-drip* systems designed for smallholders in developing countries. Thus we propose the following performance standards be institutionalized and "officially accepted" so smallholders are eligible for bank loans and government assistance to finance *L-Cm-drip* systems.

Uniformity Standards for Smallholder Drip Systems

The uniformity of water distribution or Emission Uniformity (EU) (Keller and Bliesner, 1990) is typically used as a primary measure of the potential performance of drip irrigation systems. EU is dependent on the combined effects of:

- The water supply head available;
- The elevation differences throughout the irrigated area;
- The friction losses in the pipe distribution network; and
- The discharge characteristics and manufacturer's (and assembler's) coefficient of uniformity of the water emission devices.

Usually systems serving small plots can be laid out so that elevation differences throughout the irrigated area are relatively small and both ground slopes and flows are in the same direction. Thus elevation decreases that increase the available head can be used to offset pipe friction losses. The "rule of thumb" criteria for designing a sub-unit of a *L-Cm-drip* system is to try to maintain the pressure head difference due to pipe friction losses and elevation differences between –25% and +50% of the average microtube emitter pressure, H_a..

Coefficient of Variation Uniformity, *CvU*

We recommend using the *coefficient of variation*, v, of the individual emitter discharges from the field test data as the measure of uniformity for post-installation evaluation of *L-Cm-drip* systems:

$$v = sd/q_a \qquad (1)$$

Where q_a is the average rate (lph) of catch for the population and sd is the estimated standard deviation of the catch rates (lph) of the population.

The v is easy to calculate using a calculator or a computer spreadsheet program. Furthermore, it is a useful parameter with consistent physical significance[16] for populations of normally distributed data and it is a generally known and accepted measure of the variability within a population. Therefore, we subscribe to the use of a term we refer to as the Coefficient of Variation Uniformity (*CvU*)[17] as the standard measure of application uniformity for smallholder drip irrigation systems:

$$CvU = 100(1.0 - v) \quad (2)$$

The relationship between the field emission uniformity, *EU'*, presented by Keller and Bliesner (1990) and *CvU* for relatively normally distributed field catch data is:

$$EU' \approx 100(1.0 - 1.27v) \quad (3)$$

Combining equations 1 and 2 gives:

$$EU' \approx 100 - 1.27(100 - CvU) \quad (4)$$

Recommended Values of CvU for *L-Cm-drip* Systems

According to Keller and Bliesner (1990) conventional drip irrigation systems serving relatively small fields with uniform topography should be designed to produce *EU'* values above 85%, which is equivalent to a *CvU* of 88%. However, they also suggest that for systems serving relatively large fields with undulating topography design *EU* values as low as 70%, which is equivalent to a *CvU* of 76%, are acceptable. Thus it is clear that system acceptability is dependent on site, equipment selection, and cropping conditions rather than a rigid adherence to fixed *EU* values.

In view of the above we recommend adapting the following general performance criteria, originally presented by Keller, et al, 2001, for field evaluation of *L-Cm-drip* systems serving smallholder plots:

- *CvU* above 88% is excellent;
- *CvU* between 88% and 80% is good;
- *CvU* between 80% and 72% is fair; and
- *CvU* between 72% to 62% is marginally acceptable.

Design Tools

Many of the people in the supply chain for *L-Cm-drip* systems have little knowledge of pipeline hydraulics and the use of the typical equations engineers use for designing irrigation systems. In view of this we are developing pre-engineered design tables that are intuitive and convenient to use. We anticipate that by using these design tools it will be relatively easy to train inexperienced IDE-India staff and other field personnel as well as assemblers and dealers so they can provide rather expert designs for their farmer clients. The purpose of this section is to provide a sample of the types of design tools we are developing for *L-Cm-drip* systems.

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[16] The physical significance of v is derived from the classic bell-shaped normal distribution curve in which approximately 68% of the catch rates fall within $(1 \pm v)q_a$; approximately 95% of the catch rates fall within $(1 \pm 2v)q_a$; essentially all of the observed catch rates fall within $(1 \pm 3v)q_a$; and the average of the low one-quarter of the catch rates is approximately equal to $(1 - 1.27v)q_a$.

[17] Wu and Barragan (2000) have also proposed using the equivalence of *CvU* for micro-irrigation systems and recognized the above relationship between *EU* and *Cv*.

L-Cm-drip Lateral Design Tables

We have already developed a unique program for designing *L-Cm-drip* lateral design tables. The tables are designed to enter with the lateral inlet pressure head, H_L, lateral length, L_L, and microtube emitter spacing, S_e. Development of the tables requires an iterative process to compute the total lateral flow rate, Q_L, given H_L, L_L, and S_e. Starting with H_L values is most convenient for designing *L-Cm-drip* systems since the design strategy is to begin with the system operating pressure head, H_S, that satisfies the desired system flow rate, Q_S, and uniformity, EU_L, under the given field conditions. Entering design tables with H_L may seem unusual for designers in the US because we usually begin our design by computing the required q_a to meet peak crop water requirements assuming some desired *EU.* Also developing design tables for different q_a values does not require an iterative solution because if q_a, L_L, *and* S_e are given, then Q_L, and the remaining hydraulic characteristics can be computed directly by assuming $q = q_a$ at all emitters. In addition to the lateral design tables for level rows, which we have already developed (see Table 1), we are also developing tabular tools for the design of sub-mains and for positioning sub-mains on sloping fields.

The pre-engineered *L-Cm-drip* system design tables we have developed for IDE-India are based on the following input variables:

- Lateral inlet pressure head, H_L, such as: 0.50 m, 0.75 m; 1.0 m, 1.5 m, 2.0 m; 2.5 m, and 3.0 m;
- Microtube emitter spacing, S_e ,such as: 45 cm (1.5 ft), 60 cm (2.0 ft), 75 cm (2.5 ft), and 90 cm (3 ft);
- Lateral length, L_L ,such as: 20 m, 30 m; 40 m, and 50 m;
- Lateral drip-tape inside diameter, which is 16.00 mm for 125-micron drip-tape and 15.75 mm for 250-micron drip-tape;
- Minor loss due to the insertion of the microtube emitters into the drip-tape, which is expressed as an equivalent length estimated to be 0.1 m;
- Microtube emitter pressure head/discharge relation based on bench tests and entered either as a curve or equation; and
- Coefficient of variation of the microtube emitters, v, based on bench test data.

The following information is developed for each of the above lateral configurations assuming the *L-Cm-drip* laterals are lying along crop rows that are nearly level:

- Total lateral discharge, Q_L, in liters per minute (lpm);
- Average emission device discharge, q_a, in liters per hour (lph);
- Lateral friction head loss, h_f, in meters (m); and
- Design emission uniformity of the *L-Cm-drip* lateral, EU_L, as a percentage, %.

The EU_L is computed using the same equation for the design emission uniformity developed by Keller and Keller (1974) and Keller and Bliesner (1990), which is commonly used for drip irrigation system design purposes in the US and elsewhere. However, EU_L is a metric for lateral uniformity rather than for the whole system or sub-unit of a system, which would include pressure variations due to elevation differences along the laterals as well as pressure differences along the sub-main supplying them. The equation for computing EU_L is:

$$EU_L = 100(1.0 - 1.27v)\, q_n/q_a \qquad (5)$$

Where EU_L is the design emission uniformity, %; v is the microtube emitter coefficient of variation; q_n is the minimum microtube emission rate computed from the minimum pressure along the lateral based on the emitter's nominal flow rate versus pressure curve, lph; and q_a is the average microtube emission rate, lph.

Table 1. Row and vegetable microtube drip-tape hydraulic design tables for laterals on zero slope.

Inlet Head, H_L (m)	Microtube Spacing S_e (cm)	Lateral/Row Length 20 m				Lateral/Row Length 30 m				Lateral/Row Length 40 m				Lateral/Row Length 50 m			
		Q_L (lpm)	q_a (lph)	h_f (m)	EU_L (%)	Q_L (lpm)	q_a (lph)	h_f (m)	EU_L (%)	Q_L (lpm)	q_a (lph)	h_f (m)	EU_L (%)	Q_L (lpm)	q_a (lph)	h_f (m)	EU_L (%)
0.50	**45**	2.17	2.96	0.04	94	3.04	2.72	0.11	91	3.62	2.44	0.18	87	3.98	2.15	0.26	81
	60	1.66	3.01	0.02	95	2.38	2.86	0.07	93	2.95	2.65	0.13	90	3.34	2.41	0.19	87
	75	1.37	3.04	0.02	95	1.96	2.93	0.05	94	2.45	2.78	0.09	92	2.88	2.58	0.15	89
	90	1.12	3.06	0.01	96	1.64	2.98	0.03	95	2.10	2.86	0.07	93	2.51	2.69	0.12	91
0.75	**45**	2.91	3.97	0.07	94	4.05	3.63	0.18	91	4.78	3.22	0.30	86	5.22	2.82	0.41	80
	60	2.23	4.06	0.04	95	3.19	3.83	0.11	93	3.93	3.52	0.21	90	4.41	3.19	0.30	86
	75	1.84	4.09	0.03	95	2.63	3.94	0.08	94	3.28	3.71	0.15	92	3.81	3.42	0.24	89
	90	1.51	4.12	0.02	96	2.20	4.01	0.06	95	2.81	3.83	0.11	93	3.34	3.58	0.19	90
1.00	**45**	3.59	4.90	0.10	94	4.96	4.44	0.25	90	5.82	3.92	0.41	85	6.32	3.42	0.56	79
	60	2.76	5.01	0.06	95	3.93	4.71	0.16	93	4.80	4.30	0.30	89	5.37	3.88	0.43	85
	75	2.28	5.06	0.04	95	3.23	4.85	0.11	94	4.02	4.55	0.21	91	4.66	4.17	0.34	88
	90	1.87	5.10	0.03	96	2.72	4.94	0.08	94	3.45	4.71	0.16	93	4.09	4.38	0.27	90
1.50	**45**	4.82	6.58	0.16	94	6.60	5.91	0.41	90	7.67	5.17	0.67	84	8.28	4.47	0.89	77
	60	3.71	6.74	0.10	95	5.25	6.30	0.27	92	6.37	5.70	0.48	88	7.07	5.11	0.68	84
	75	3.07	6.81	0.07	95	4.34	6.50	0.19	94	5.36	6.07	0.35	91	6.16	5.52	0.55	87
	90	2.52	6.87	0.05	95	3.65	6.64	0.14	94	4.61	6.29	0.27	92	5.43	5.82	0.44	89
2.00	**45**	5.94	8.10	0.23	94	8.07	7.23	0.58	89	9.32	6.28	0.93	83	10.01	5.41	1.22	76
	60	4.58	8.32	0.14	95	6.44	7.73	0.38	92	7.77	6.96	0.68	88	8.59	6.21	0.95	83
	75	3.79	8.42	0.10	95	5.34	8.01	0.27	93	6.56	7.43	0.50	90	7.51	6.73	0.77	86
	90	3.11	8.49	0.07	95	4.50	8.19	0.20	94	5.66	7.72	0.39	92	6.64	7.11	0.62	89
2.50	**45**	6.98	9.52	0.31	94	9.43	8.45	0.76	89	10.83	7.30	1.20	83	11.60	6.27	1.57	75
	60	5.39	9.79	0.19	95	7.55	9.06	0.50	92	9.07	8.12	0.89	87	9.98	7.22	1.23	82
	75	4.46	9.91	0.14	95	6.27	9.40	0.36	93	7.68	8.69	0.66	90	8.75	7.84	1.00	86
	90	3.67	10.01	0.10	95	5.29	9.62	0.26	94	6.64	9.05	0.51	92	7.75	8.30	0.81	88
3.00	**45**	7.96	10.86	0.39	93	10.71	9.59	0.94	89	12.25	8.26	1.48	82	13.08	7.07	1.92	75
	60	6.15	11.19	0.24	95	8.60	10.32	0.63	92	10.29	9.21	1.10	87	11.29	8.16	1.52	82
	75	5.10	11.33	0.17	95	7.15	10.72	0.45	93	8.73	9.88	0.82	90	9.91	8.88	1.24	85
	90	4.20	11.45	0.12	95	6.04	10.99	0.33	94	7.56	10.30	0.64	92	8.79	9.42	1.01	88
4.00	**45**	9.80	13.36	0.56	93	13.08	11.71	1.33	88	14.86	10.02	2.06	81	15.80	8.54	2.64	73
	60	7.59	13.80	0.35	94	10.54	12.65	0.90	91	12.53	11.22	1.55	86	13.69	9.90	2.11	81
	75	6.30	13.99	0.25	95	8.78	13.18	0.65	93	10.67	12.08	1.16	89	12.06	10.80	1.73	85
	90	5.19	14.15	0.18	95	7.44	13.53	0.48	94	9.27	12.64	0.90	91	10.73	11.49	1.43	87
5.00	**45**	11.51	15.69	0.74	93	15.26	13.67	1.74	88	17.26	11.63	2.66	80	18.28	9.88	3.37	72

Table 1 shows a portion of a pre-engineered lateral for an *L-Cm-drip* system. It is based on an average $v = 0.031$ and pressure head versus emitter discharge curves determined for a series of bench tests at pressure heads ranging from 0.5 to 2.0 m for 20-cm (8-inch) long microtube emitters with an internal diameter (ID) of 1.2 mm installed in drip-tape. The ID used for the drip-tape laterals was 16.0 mm and the microtube/drip-tape connection loss was assumed to be equal to an equivalent length of 0.1 m of drip-tape.

To use the table for designing an *L-Cm-drip* system the designer enters it with the plant spacing and lateral length that fits the field size and shape. Then the designer searches for the combination of H_L, Q_L, and EU_L that appears most reasonable for the field layout while considering the following:

- Microtube emitters with large unobstructed passageways have relatively high discharges even under very low operating pressure heads. Therefore, it is not practical to use laterals much longer than 50 m for *L-Cm-drip* systems. If rows are longer than 50 m the sub-main must be laid out to bisect the field rather than being placed at the head of the rows. If rows are longer than 100 m, a second sub-main is needed.
- The ideal pressure head for *L-Cm-drip* systems is between 1 and 3 m.
- The system discharge, Q_S, is equal to the lateral discharge, Q_L, times the number of laterals along the sub-main. Thus to find a reasonable Q_L, divide the available Q_S by the number of laterals that will be required to irrigate the field. If the available Q_S is insufficient irrigate half the field at a time. .
- It is desirable to have the design emission uniformity, EU_L, as high as practical. Assume that in view of minor elevation variations and losses in the sub-main, the *CvU* of field test data will be close to the EU_L. Thus the designer can use EU_L values from the table in place of recommended *CvU* presented earlier as a guide to evaluating the anticipated system performance with the lateral configuration selected.

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