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## Working paper

# Multidimensional analysis of nexus technologies II: dynamics of traditional and modern irrigation systems

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# Abstract

From a technological perspective, irrigation is a dynamic field undergoing a shift from a horizontal expansion of the area equipped for irrigation (or "total irrigation market") to a vertical transition of the technology mix in search of higher intensification and efficiency (more crop per drop). As a result, the "irrigation market" is currently experiencing a gradual transformation process from traditional flood irrigation towards more efficient pressurised irrigation technologies (sprinkler and drip). The results of this study suggest that these substitution dynamics will continue in the future, favouring the most recent and efficient technology, i.e. drip irrigation. A logistic projection of historical growth predicts drip to reach the highest growth rate among all technologies by 2035, and start a fast expansion over not only flood irrigated areas, but also sprinkler irrigated areas.

The cost and size dynamics of irrigation projects are less clear given the extremely high context dependency and variability of some critical factors determining irrigation project costs, as well as the important differences across regions. Economies of scale also vary across regions, and are estimated to be higher for rehabilitation and modernization projects than for new development projects, with scale factors of 0.6 and 0.97 respectively. Regarding the learning effects, the limitations in data quality and completeness do not allow to derive clear quantitative and technology specific estimates of learning trends. Nevertheless, some positive learning is detected in rehabilitation projects since 1990 and certain cost reductions at the application technology level are reported by consulted irrigation technology experts.

Focusing on the regions of interest for ISWEL case studies, South Asia may see a rapid expansion of drip irrigation through both private modernization initiatives at the small-medium scale and public large scale rehabilitation-modernization interventions on historical surface schemes. Thanks to the active local irrigation technology industry and off farm infrastructure stock, irrigation technology costs will remain lower than in other areas and could be subject for learning related cost reductions in the future. Meanwhile, projects in Africa may develop in the line of expanding the irrigation potential through mainly medium-large scale surface irrigation schemes. The costs of these new schemes are expected to be on the high edge of historical average ranges, due to the increasing complexity of suitable locations and thus of the systems offsetting the potential effects of economies of scale brought about by an increase in project size compared to the historical interventions. Meanwhile, sprinkler technology and particularly centre pivot seems to be a suitable option already expanding within the emerging commercial farming, due to the lower costs and the potential for technology sharing.

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## About the authors

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# Multidimensional analysis of nexus technologies II: diffusion, scaling and cost trends of irrigation

Beatriz Mayor

## 1. Introduction

### 1.1 Irrigation as a 'nexus technology' to address water, energy and land challenges

Within the framework of the United Nation's Sustainable Development Goals (SDGs) Agenda approved in 2015, understanding the interconnections between the different SDG goals and assessing the tradeoffs and synergies of potential technological and non technological solutions has become a priority to come up with sustainable development pathways. A particular focus has been put at both the international and regional levels on understanding the intrinsic interconnections between water, energy and land systems - the so called water-energy-land (WEL) nexus –, as these are transversal resources that underpin the achievement of most of the SDGs as well as the wellbeing and economic prosperity of regions. Several initiatives have been started by governments, international institutions and the research community with the aim to model and assess the water-energy-land implications of different policies and technology choices, e.g. FAO (2014), Mannschatz et al. (2016), Salam et al. (2017). It is imperative that such modelling exercises understand and integrate the historical trends and dynamics of those technology options in order to come up with realistic assumptions and estimations of technological change.

Amongst these initiatives, the International Institute for Applied Systems Analysis (IIASA) in cooperation with the United Nations Industrial Development Organization (UNIDO) and the Global Environmental Facility (GEF) launched in 2016 an ambitious cross-cutting project entitled 'Integrated Solutions for Water, Energy and Land (IS-WEL)'. IS-WEL aims to explore cost-effective nexus solutions to jointly meet water, land and energy demands under different development and climate pathways. The project involves the integration and upgrade of four robust IIASA models that target the different WEL dimensions – ECHO and CWAT (water), MESSAGE (energy) and GLOBIOM (land use) -, to generate an integrated framework that will be used to assess different nexus solutions across scales. At a global scale, a global hotspot analysis will allow to identify multi-sectorial scarcity hotspots and assess the synergies and trade-offs among sectors and countries; at the regional scale, different portfolios of integrated solutions for local water, energy and land challenges will be assessed in two case studies in the Zambezi and Indus basins (IIASA, 2016).

The work presented in this paper is the second part of a multidimensional assessment aimed to describe and quantify technological trends of a selection of critical 'nexus technologies', in order to support ISWEL integrated modelling and scenario building exercises. The term 'nexus technologies' refers to technologies that can exert potential trade-offs (high resource use, counteracting impacts or environmental externalities) or opportunities (resource efficiency, synergies between technologies or reduced externalities) for the integrated management of water, energy and land systems. The multidimensional analysis is comprised of three steps: first, a selection of a set of representative technologies to be analysed; second, an analysis of historical technological trends including diffusion at the industry and unit level, costs and cost reduction drivers (economies of scale and learning); and third, an analysis of technological performance against a series of nexus indicators. Some examples of relevant nexus technologies identified for the analysis span desalination technologies (Mayor, 2018; Mayor, 2019), irrigation systems (this paper), and as a potential next case wastewater treatment and reuse technologies .

This paper presents the multidimensional analysis applied to irrigation technologies. The analysis focuses on the three main irrigation technology groups encompassing both traditional (surface or flood) and modern or pressurized (sprinkler and drip) irrigation systems, and pursues the following goals: 1) to characterize the technologies' performance on water, energy and land resources use; 2) to analyze and quantify the diffusion and unit scaling (or increase in unit size) dynamics of the different technology types; 3) to analyze the trends and separated effects of economies of scale and learning on average irrigation project costs. The paper starts with an introduction to the history and features of the main irrigation technologies in section 1.2. Section 2 describes the methodological approach for the three dimensions considered. Sections 3, 4 and 5 present the results for each of those dimensions, followed by a discusion of the most outstanding findings in section 6. Finally, an overview of the most important conclusions is provided in section 7.

## 1.2 Irrigation technologies: types, historical trends and state of the art

Irrigation is a very ancient practice that has been carried out over centuries by different civilizations with different degrees of sophistication. The practice of irrigation has evolved from the cultivation of riverine lands naturally watered by seasonal floods during river flow peak periods (i.e. in Egypt and Mesopotamia some 5,000 years BC), through to the construction of water conveyance, distribution and application structures bringing water from the source to the field and even plant level.

An irrigation system is understood in this work as the set of infrastructures aimed to conduct water from the conveyance or diversion point (a dam, water well, etc.) to the plant root zone. Irrigation systems are comprised by two parts: an of farm part or network of pipes and channels that conducts water from the conveyance point to the individual fields; and an on farm part or "water application technology" that distributes water within the field. The characteristics, length and physical parameters (i.e. flow speed, pumping force, diameter, materials) are very variable and context specific depending on the topography, water source (surface or groundwater), system size and acreage coverage, among others. Within the on farm component or water application technology, there are three main types of technologies according to the type of flow driving force (gravity or pressurized pumping) and application method.

*Surface irrigation:* Also termed flood irrigation, it was the first technique ever used and currently the most widely expanded throughout the world. Surface irrigation encompasses all the irrigation systems (level basin, furrow and border strip[1]) where water is applied and distributed over the soil surface in an uncontrolled way by gravity, without need of any additional pumping force. The average depth of water that can be delivered on field cannot be less than 75-100 mm (ICID, 2019). The total crop requirement

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[1] Basin level irrigation: this type of surface irrigation is applied if a field is level in all directions, is encompassed by a dyke to prevent runoff, and provides an undirected flow of water onto the field, it is herein called a basin (Walker, 1989).

Furrow irrigation: this type of surface irrigation avoids flooding the entire field surface by channelling the flow along the primary direction of the field using 'furrows,' 'creases,' or 'corrugations' (Walker, 1989).

Border irrigation: can be viewed as an extension of basin irrigation to sloping, long rectangular or contoured field shapes, with free draining conditions at the lower end (Walker, 1989).

per rotation would be 75-100 mm plus the water lost due to deep percolation. Water application efficiencies are the lowest among all irrigation technologies, ranging between 40% and 60% (FAO, 1989; Sauer et al., 2010).

*Sprinkler irrigation:* sprinkler irrigation was the first type of pressurized-high efficiency irrigation application technology. In sprinkler or overhead irrigation, water is piped to one or more central locations within the field and distributed by overhead high-pressure sprinklers or guns (ICID, 2019). Therefore, this system requires external energy for pressurizing and pumping the water to be sprayed over the crops. There are different types of sprinkler systems depending on the pressure, the disposition (mobile or fixed) and the height (over canopy or under canopy), resulting in a wide variety of applications and costs ranges. The technique of water spraying involves some water losses due to wind evaporation or water retention on the leaves, resulting in average application efficiencies of 75-80% (FAO, 1989; Sauer et al., 2010).

*Drip irrigation:* Also known as trickle irrigation, micro irrigation or localized irrigation, this system was invented in Israel by the Netafirm company during the 1960s to become the most recent and efficient among pressurized irrigation systems. It applies water drop by drop directly onto the plant root through a network of valves, pipes, tubing, and emitters (ICID, 2019), reaching application efficiencies of 90% (FAO, 1989; Sauer et al., 2010). The system requires energy for the pressurization and controlled pumping of water, as in the case of sprinklers.

The implementation and diffusion of irrigation systems over its long history has taken in several phases characterized by different diffusion speeds and features. In an initial phase that lasted until the beginning of the 20th century, the diffusion of (traditional) irrigation systems took place over centuries at a gradual and slow pace. Around the 1950s, a period of intense irrigation project development started driven by the interest from international donors to promote irrigation as a means of rural and international development strategies. Finally, a third phase featured by the rehabilitation and modernization of degraded schemes and implementation of pressurized technologies started around the 80s-90s making the prelude of a slow down in the expansion but increase in the intensification of irrigation technologies (Alexandratos, Bruisma, 2012).

### *Irrigation projects funded with support of international donors: large surface irrigation schemes*

Since the 1960s, there has been a strong current of implementation of large-scale irrigation systems funded by governments with support of international donors. Particularly the World Bank lead a financing stream for irrigation and rural development projects that encompassed a range of interventions spanning the development of large scale surface water conveyance (dams) and irrigation schemes, land treatments, additional rural development infrastructure (roads, settlements), deployment of groundwater pumping and irrigation schemes, and later on rehabilitation of “degraded” systems. These interventions were developed at various scales (large scale vs small scale schemes) with differences across regions and over time.

The most relevant ex-post evaluation of these interventions in terms of project performance and cost efficiency were carried out by the World Bank (various years) and Inocencio et al. (2007). Table 1 presents a summary of the specific cost averages estimated by these assessments at the world scale and for ISWEL case study regions from projects implemented between 1960 and 2003.

Table 1. Average capital costs of irrigation projects reported by these two sources and by different sources.

| Concept | Cost range (2010$/ha) | Region | Time period | Source |
|---|---|---|---|---|
| Irrigation projects | 3,000-5,000 | World | 1960-1990 | Barghouti, S., Le Mogine, G., 1990 |
| Irrigation projects | 4,700 – new development<br>1,750 – rehabilitation | Developing regions | 1965-2000 | Inocencio et al., 2007 |
| Irrigation projects | 3,700-7,500 | Sub Saharan Africa (Zambezi) | 2010 | World Bank, 2010 |
| Irrigation projects | 3,000-3,500 | Sub Saharan Africa | 2008 | ZANCOM, 2008 |
| Irrigation projects (only successful) | 4,450 – new development<br>2,850 – rehabilitation | Sub Saharan Africa | 1965-2000 | Inocencio et al., 2007 |
| Irrigation projects | 4,200 – new development<br>1,250 – rehabilitation | South Asia | 1978-2000 | Inocencio et al., 2007 |

Some interesting trends and lessons highlighted by Inocencio (2006) and the last World Bank performance assessment report (World Bank, 2018) are presented here below.

- Between 1950 and 1993 more than half the Bank's lending was for extensions, rehabilitation and upgrades of existing systems. Less than half was for new schemes.
- Large projects were more likely to be successful than smaller ones (except in Sub-Saharan Africa where the reverse was more common).
- Simple projects outperform more complex ones.
- Most poorly performing projects do so because of institutional problems. Poor performance suggests a need for more thorough appraisal and less ambitious goals for institutional change.
- Poor operation and maintenance (O&M) outweighed poor project design and planning in negatively affecting outcomes.
- There is rarely a link between irrigation water charges and better O&M.
- More beneficiary participation is required in project design and implementation. Water Users Associations (WUAs) that endure operate with clear boundaries and definition of functions. Financial autonomy for WUAs to set and collect service fees resulted in better collection rates.
- The impact of irrigation lending has been positive for borrowers and should be continued. Despite reduced funding agriculture and water management (AWM) projects remain relevant.
- Neither implementation duration, nor delays incurred, affected project outcomes significantly.
- Monitoring and evaluation (M&E) was often poor, with a lack of baseline studies and suitable performance indicators, especially for policy and institutional outcomes. Too many projects lacked a results chain linking interventions to outcomes and impacts.
- In systems: decrease in irrigation-power projects (dam rejection), increase in multi-sector projects. Increase in groundwater lift projects (with higher success rate), decrease in river-dam-reservoir and river-lift systems. Decrease in sugar cane-cotton towards trees.

### *Irrigation modernization: emergence of efficient irrigation technologies and national approaches to increase irrigation efficiency*

By the late 80s, the emergence and take-off of the pressurized irrigation technologies in water scarce regions along with the increasing degradation and obsolescence of existing infrastructure prompted a focus change by international donors towards a prioritization of rehabilitation and modernization of existing infrastructure (World Bank, 2018). A number of water scarce irrigation pioneering countries implemented ambitious national modernization programs with the aim to reduce agricultural water use (and thus the vulnerability against droughts), while fostering agricultural productivity. Examples include the Spanish irrigation modernization plan 2002-2008 and 2008-2015 (Lopez-Gunn et al., 2012; Berbel, J., Gutierrez-Martin, C., 2017), the *Australian Water for Future Program* (Mushtaq et al., 2013), the intense diffusion of drip irrigation in California (Taylor, Zilberman, 2015), or the case of the national modernization initiative in Morocco (Venot et al., 2014). Meanwhile, several initiatives and interventions to introduce low cost-efficient irrigation systems in Africa and Asia were promoted by international development agencies and NGOs, albeit with poor technology adoption results in several cases (Abric, S. et al., 2011).

An overview of average capital costs of mechanized efficient irrigation systems reported in the literature for different geographical locations is provided in table 2.

| Concept | Cost range (2010$/ha) | Region | Time period | Source |
|---|---|---|---|---|
| Fixed sprinkler system | 2,200-3,500 | Australia | 2002 | Mustaq, 2013 |
| Fixed sprinkler system | 2,700-4,200[1] | Spain | 2002-2015 | Berbel, 2017 |
| Fixed sprinkler system | 1,500 (only equipment) | Zambia | 2011 | World Bank project goo.gl/HKm52D |
| Mobile sprinkler system (pivot) | 1,250<br>1,250<br>2,500 | South Africa<br>US<br>Africa (CoFarm company prices) | 1981-2001<br>2004<br>2011 | FAO, 2001<br>Keller, 2004<br>World Bank project goo.gl/HKm52D |
| Drip system | 4,500-6,000 | Australia | 2013 | Mustaq, 2013 |
| Drip system | 1,900-4,500* | Spain | 2002-2015 | Berbel, 2017 |
| Drip system | 600-4,000 | US | 2004 | Keller, 2004 |
| Drip system | 1,800-3,000 | India | 2000 | Postel, 2001 |
| Drip system | 1,300-4,000 | Developing countries | 1998 | Cornish, 1998 |

[1] Only on farm application system. The whole cost including the adaptation of the distribution network would be 5,400-14,800 2010$/ha.

[2] Only on farm application system. The whole cost including the adaptation of the distribution network would be 6,500-10,500 2010$/ha.

Table 2. Average capital costs of mechanized efficient irrigation systems.

# 2. Methodological approach

The logic for selecting the methodological approach applied to the multidimensional analysis is explained in detail in Mayor (2018). For the irrigation analysis, the same dimensions were explored with the need to introduce some methodological variations to reflect data availability and format issues.

### *Data sources and treatment*

The analysis was carried out using three main types of data: data obtained from the literature through a review of irrigation reports and scientific papers, data retrieved from databases to carry out quantitative analyses, and qualitative insights obtained from interviews to irrigation experts from the Netafirm company and the World Bank (cited as personal communications). The name and details of the irrigation experts consulted are provided in Appendix 1.

Historical data on total area equipped for irrigation and irrigation deployment by technology for the diffusion analysis were obtained from Aquastat. In order to improve the representativity of sprinkler and drip irrigation deployment rates across regions, data series were downloaded at the country level and completed or updated with additional sources. These sources included data from ICID 2002, 2012, and 2016 for ICID reporting countries, as well as statistics from national sources for a number of countries with acknowledged developments in mechanized irrigation, namely Spain, France, Italy, Romania, Greece, United States, Canada, Australia and Brazil. An excel file with the resulting data series and sources is provided as supplementary material to this report.

For the unit scaling and cost analysis, a review of publicly available data sets gathering information on historical irrigation project costs across regions revealed the existence of three main data sources:

- a dataset of projects from the period 1970-2003 developed and analysed by IWMI and published in Inocencio (2007).
- an 'Investment cost database' containing cost information for a list of international donors-financed projects from the period 1960 – 2003 available at FAO's website
- the World Bank's projects database from which a list of projects financed by the World Bank since 1960 to date can be downloaded.

Additionally, a literature search for specific data sets on sprinkler and drip irrigation projects and associated costs was carried out, including through direct contact to drip irrigation companies. As a result, the following databases were obtained and selected for the study:

- A download of all irrigation related projects from the World Bank database for the period 1960-2017. This source was preferred over FAO and Inocencio (2007) for two reasons. First, it was the only source including projects implemented after 2003. Second, it offered the possibility to access more detailed information on the cost breakdown and isolate the irrigation component cost from the total project budget. Data required for the analysis were collected per project using the project completion report when available or the staff appraisal report otherwise. For time reasons, data collection was done for a selection of 180 projects that included all projects implemented after 1990, and a representative sample covering all regions and project types for the period 1959 - 1990. All the costs were actualized to 2010$ using the GDP deflator index available at the World Economic Outlook database[2]. This dataset allowed for a global and regional trend analysis on new development and rehabilitation surface irrigation projects, relevant for ISWEL global solutions and case study analyses. However, records on modern irrigation systems were rather limited. The list of projects and retrieved data on project characteristics is provided in a spreadsheet as supplementary material to this report.
- A dataset with Spanish modernization projects implemented over the period 2002-2015 as part of the National Irrigation Modernization plan retrieved from SEIASA's[3] website. Project costs were converted into US dollars using the 2010 conversion rate, but could not be actualized due to the lack of data on the project implementation date. Despite being country specific, this dataset enabled a more specific assessment focused on irrigation modernization projects in a pioneering country in modern irrigation technologies. It aims to provide a reference for possible extrapolations to other cases while allowing to calibrate or contrast the results from the World Bank dataset analysis.

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[2] International Monetary Found, World Economic Outlook database, February 2018. http://data.imf.org/regular.aspx?key=60998112

[3] SEIASA is the state-owned engineering company that has carried out the great majority of irrigation modernization projects in Spain. Website: http://www.seiasa.es

- A dataset on drip irrigation projects implemented by Netafirm was directly obtained from the company on a confidential basis, which included information on project size, geographical location and main crops. This dataset allowed to analyse project size aspects specific to drip irrigation technologies, albeit the lack of cost data did not allow to dig into the economic side.

### *Water, energy, and land tradeoff analysis*

This analysis provides an overview of a series of water, energy and land performance indicators for the different irrigation technologies based on resource demands and resource use efficiency. The assessment of the indicators was done through a literature review of cases in regions with high experience in irrigation and/or with high interest for ISWEL case studies, i.e. Sub Saharan Africa and South Asia. A description of the indicators is here provided:

- *Water withdrawals (m3/ha):* Water diverted or withdrawn from a surface water or groundwater source (Vickers, 2001; Hoekstra, 2011). According to this definition, WW makes reference to blue water abstraction, when water is physically diverted or taken from a water source, to be given either a consumptive or a non consumptive use.
- *Water consumption (% of water withdrawals)*: Water permanently withdrawn from its source that is no longer available because it has been evaporated, transpired by plants or incorporated into the crops (adapted from Vickers, 2001). This indicator is measured as percentage of water withdrawals and thus reflects the water use efficiency enabled by the irrigation system.
- *Energy requirements (KWh/m$^3$):* energy consumed by the irrigation system to pump and transport water on farm with the required pressure. This value reflects the energy used by the on farm system and does not include the energy used to transport water from the source to the field, which can be very variable depending on the distance, the topography, and the water source, i.e. surface water or groundwater.
- *Land use (ha/ton and % compared to surface):* Land required to produce one unit of agricultural product. Since this indicator depends on the yield and thus is crop specific, it is here assessed for maize as a typo crop. Maize was selected because it is a high value crop suitable for irrigation by the three irrigation systems - despite surface and sprinkler being the most commonly used -, while it is grown in both ISWEL case study areas.

### *Technological diffusion and unit scale analysis*

On the way towards wide market implementation, technologies go through a series of steps or phases known as the ‘innovation lifecycle’ (Grübler, Wilson, 2014). The analysis of growth trends for a large record of technologies across the technology innovation literature has shown that most of them follow a logistic growth fashion along this cycle. Once in the market and as they achieve higher penetration rates, they often substitute other technologies previously undertaking the same function, or in extraordinary cases conquer new unexploited markets, to be later substituted by new emerging ones (Grübler, 1998; Grübler, Wilson, 2014).

The technological diffusion analysis designed for this research aimed to model and parameterize the historical diffusion trends of the modern and traditional irrigation technologies, in order to derive projections of growth and substitution processes to 2050. The analysis was carried out using historical data series on area equipped for irrigation and the breakdown into flood (traditional) and sprinkler and drip (modernized) irrigated area for the period 1975-2015, retrieved from FAO Aquastat and improved as previously described. Additionally, the area equipped for flood irrigation was split into rice producing and non-rice producing flood irrigated area, as rice is the only crop that can only be irrigated by flooding and thus is not subject to modernization. The software used to generate the model fits and projections was the logistic substitution model (LSM2) developed by IIASA[4].

On this basis, growth projections were developed for two modelling scenarios:

- Logistic model scenario: it builds on the assumption that future growth will continue the historical trends with a logistic fashion. A logistic model was fitted to the historical data series constraining the total market growth or saturation potential (K) to 417 million ha, which is estimated as the maximum irrigation potential by FAO (Alexandratos, Bruisma, 2012). A sensitivity analysis was done to test the data range providing the best results to develop the logistic market shares of the technology breakdown (see Appendix 2). The results showed high sensitivity of the fits to the data range, and a fit range of 1991-2015 was selected in order to include a representative sample while avoiding the disturbance caused by a trend shift after 1990 as a result of the fall of the Soviet Union.

- FAO linear scenario: this scenario applies the LSM2 model to FAO's projections for area equipped for irrigation to 2050 as estimated in Alexandratos & Bruisma (2012). This projection assumes a linear growth at a slower pace than the historical rate due to a series of factors such as the concentration of investment in rehabilitation of existing infrastructure (up to 90% of investments), and the limitation of net expansion to developing countries (Alexandratos, Bruisma, 2012). For this scenario, growth rates projected by Alexandratos & Bruisma (2012) were applied to the latest value provided by Aquastat in order to actualize their projections to the most recent information, and a linear fit was forced for the total market to meet the resulting 2050 values. A sensitivity analysis was also done to test the data range providing the best results to develop the logistic market shares of the technology breakdown. The results showed that the data range providing the best fit for all the technologies was 2008-2015 (see Appendix 2). In order to allow for comparison, the projections were made for both the best fit data range and the data range considered for the logistic model (1991-2015).

The different assumptions and model parameters considered for each scenario are summarized in table 3 and further detailed in Appendix 2.

Table 3. Assumptions for irrigation diffusion scenarios.

| **Assumptions** | **Scenario** | |
|---|---|---|
| | Logistic model | FAO Linear |
| Projection model | Logistic | Linear |
| Fit range | 1991-2015 (best fit) | 2008-2015 (best fit)<br>1991-2015 (for comparison) |
| Maximum irrigation potential | 417 million | 417 million |

The unit scaling analysis explores trends in average unit size over time and across regions with the aim to identify patterns and possible upscaling phases both at the global and regional scale. The analysis

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[4] For further information on LSM2 and for downloads: http://www.iiasa.ac.at/Research/TNT/WEB/Software/LSM2/lsm2-index.html

was done for projects funded by the World Bank over the period 1960-2017 and for drip irrigation projects funded by Netafirm between 2012 and 2018 using the above described datasets.

### *Cost trend analysis*

Costs are one of the main factors conditioning the widespread adoption of a technology, and thus its feasibility as a technological solution. The analytical focus is put on the study of investment or capital costs, which constitute one of the main variables included by modelling frameworks, while presenting lower regional and context dependency than operation costs.

The cost trend analysis looks at three different aspects:

*Current average cost trends*. Average cost ranges for irrigation projects reported in the literature and previously summarized in section 1.2 have been estimated using a historical record of World Bank projects implemented around the period 1970-2000. These averages neither include recent projects nor reflect possible variations over time due to improvements in technology, materials, etc. (technological learning). Meanwhile, these averages are computed using total project costs, which in most World Bank projects include some side infrastructure and rural development components besides the main irrigation target, thus reducing the representativeness and homogeneity as a proxy for irrigation system capital cost. In this context, this study aims to provide a better proxy for present average capital costs for different irrigation technologies based on the available and accessible data. This improvement is based on two actions: first, an update of the average cost estimations with a more recent sample of World Bank funded projects including the latest projects granted up to 2018. Second, an increase in the accuracy of the irrigation infrastructure cost estimate through the isolation of the irrigation component cost from the total project budget to increase homogeneity.

*Economies of scale and learning effects on cost trends.* One of the main limitations of global and regional irrigation cost averages found in the literature, particularly with views to modelling, is that they are computed from projects implemented over a time span of 40-50 years. Being the best available proxy, these averages do not reflect the possible improvements in technology and project implementation (learning effects) that may have had an effect on both infrastructure and implementation costs. Meanwhile, they also provide an unclear notion of how to consider economies of scale. The economies of scale and learning effects and how they may have influenced the evolution of irrigation capital costs are also explored and described quantitatively when possible, or qualitatively otherwise.

Economies of scale effect is a common engineering concept that describes the falling marginal costs of production as production capacity or output increases (Joskow, Rose, 1985; McCabe, 1996; Wilson et al., 2012). They are given by the evolution of capital costs as a function of unit size, and can be estimated by means of formula 1

$$[1]\ \text{Cost}(2) = \text{Cost}(1) * (\text{Size }2/\text{Size}1)^{p}$$

where cost and size are the absolute investment cost and total sizes of plants 1 and 2, and p is the exponential scale coefficient with $p<1$ denoting positive economies of scale effects, i.e. specific costs decline at larger scales. An analysis was done for the World Bank project dataset and the Spanish modernization project dataset, allowing to distinguish and compare between traditional irrigation projects and interventions (surface new development projects and surface rehabilitation projects) and irrigation modernization projects.

The ‘learning by doing/using’ phenomenon refers to the improvements achieved through the continuous replication and upgrading of the manufacturing process and/or use of the technologies, which together with economies of scale plays the main role in technological cost reductions (Grübler, 1998; Nemet, 2006; Wilson et al., 2012). It is given by the evolution of specific capital costs as a function of experience or installed capacity, and can be estimated by means of formula 2.

$$[2]\ Cost_t = Cost_{t0} * (CC_t / CC_{t0})^{\alpha}$$

$$[3]\ LR = 1 - 2^{\alpha}$$

where $Cost_t$ is project cost at time t, $Cost_{t0}$ is the project cost at the previous time step, $CC_t$ is the cumulative installed capacity by time t, $CC_{t0}$ is the initial installed capacity, and $\alpha$ is the learning coefficient. However, traditional capacity-based learning curves have been argued to overestimate the effects of learning due to the inclusion – or non ex-ante exclusion – of other drivers of cost reductions that conflate with experience (Coulomb, Neuhoff, 2006; Weiss et al., 2010; McNerney et al., 2011; Wilson, 2012). Particularly, in several cases the effect of economies of scale has been found to explain an important part of cost reductions that were usually attributed to learning (Dutton, Thomas, 1984; Nemet, 2006; Qiu, Anadon, 2012; Healey, 2015). Healey (2015) proposed an alternative version of learning curves that solved this problem by applying a process of ‘de-scaling’ to average specific cost data series – namely removing the economies of scale effects arising from changes in average unit sizes – and using the resulting de-scaled data series for the learning rate estimation. The methodological steps applied for the cost de-scaling are described in detail in Healey (2015).

# 3. Water, energy and land implications of irrigation technologies

Table 4 provides a compilation of main water, energy and land use parameters for the different categories of irrigation technologies based on evaluation studies of irrigation modernization initiatives around the world (FAO, 1997; Narayanamoorthy, 2004; Corominas, 2010; Mushtaq et al., 2013; Arunjyoti et al., 2016; Ahmad, Khan, 2017; Berbel, J., Gutierrez-Martin, C., 2017).

Table 4. Water, energy, and land use parameters for irrigation technologies.

| | **Surface irrigation** | **Sprinkler irrigation** | **Drip irrigation** |
|---|---|---|---|
| Water withdrawals ($m^3$/ha) | 8,800 (Australia)<br>7,400 (Spain) | 4,600-7,600 (Australia)<br>5,000-6,000 (Spain) | 4,500-5,600 (Spain) |
| Water consumption (efficiency) (% of withdrawals) | 45-60% | 75-80% | 90% |
| Energy requirements (KWh/$m^3$) | 0 | 0.18 (Australia, Spain) | 0.18-0.21 (Australia)<br>0.24 (Spain)<br>0.75 (India)[1] |
| Land use (Maize)<br>(ha/ton)<br>(% compared to surface) | 0.14 (Zimbabwe)<br>-- | 0.11 (Zimbabwe)<br>-20% (Zimbabwe) | 0.09 (Zimbabwe)<br>-40% (Zimbabwe) |

[1] In India a great portion of the irrigation water supply comes from groundwater, which is more energy costly than surface water. This explains why the average energy requirements for drip irrigation in India are higher than in Spain and Australia.

The amount of irrigation water consumed in agriculture per ha is a crop specific parameter that will vary with the crop pattern, rainfall and temperature conditions, among others. However, looking at regional averages can give a sense of the magnitude that also enables comparing between irrigation technologies. The results in table 4 show that the increase in application efficiency across irrigation systems results in a reduction in water withdrawals and an optimization of land use thanks to the productivity improvements. However, this gains in water and land efficiency come at the expense of an increase in energy consumption, and therefore an increase in the carbon footprint of irrigation.

# 4. Diffusion and scaling analysis

## 4.1 Diffusion trends and scenarios for irrigation technologies

The results from applying the LSM2 model to derive future growth projections for the total area equipped for irrigation and the irrigation systems mix under the proposed growth scenarios and fit data ranges are presented in figures 1 to 3. The resulting model parameters and fits, as well as the sensitivity analysis performed for the different fit ranges, are provided in Appendix 2.

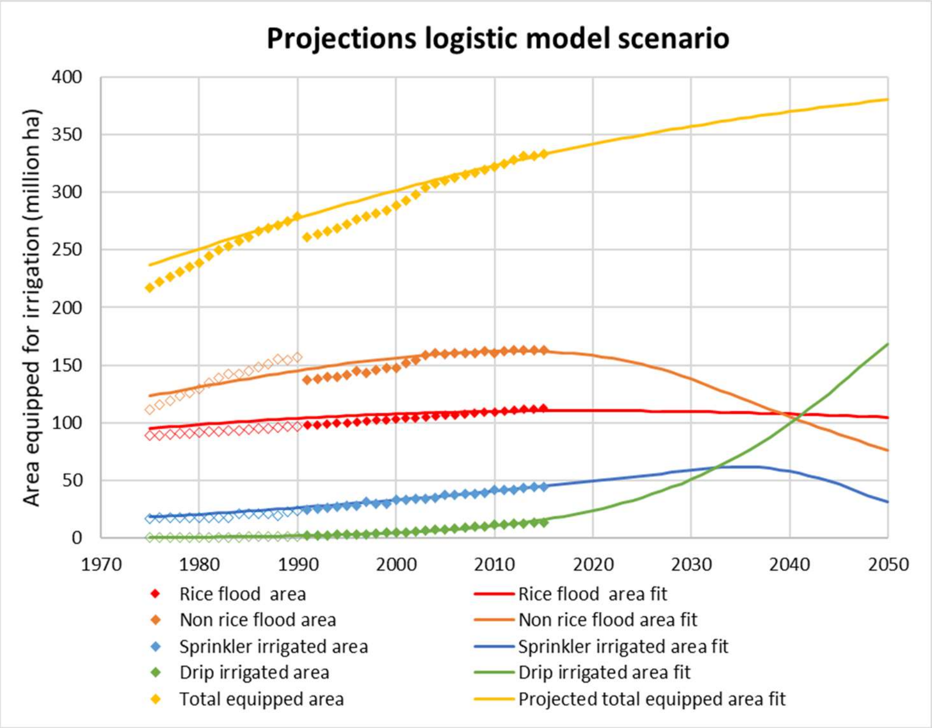

Figure 1. Logistic curves and projections for the logistic model scenario. Markers without filling correspond to data excluded in the fit.

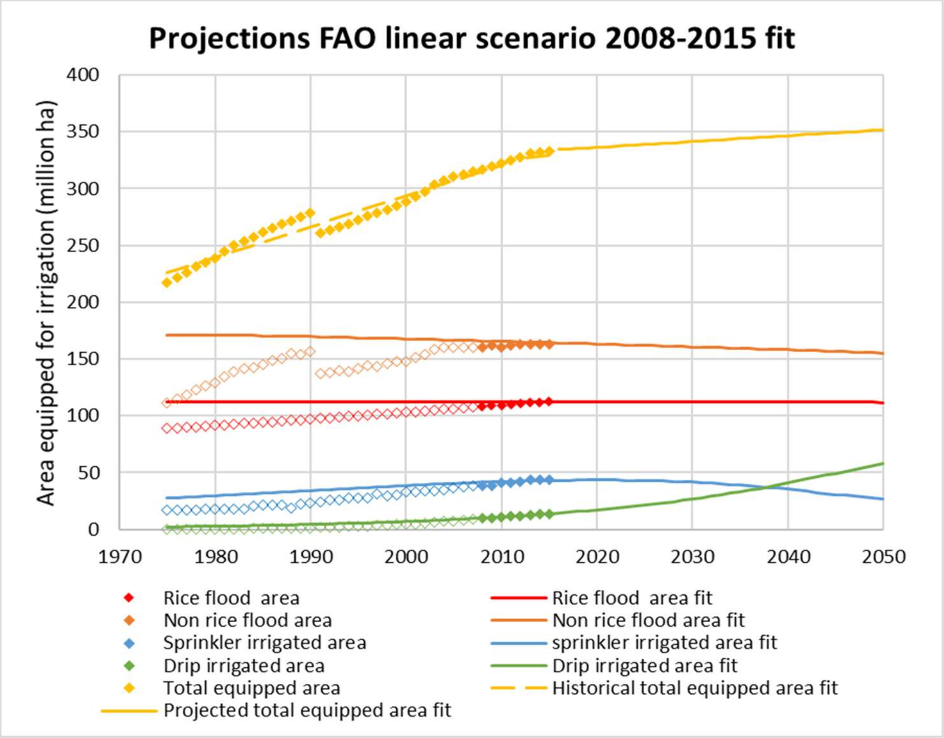

Figure 2. Logistic curves and projections for the FAO linear scenario with data range 2008-2015. Markers without filling correspond to data excluded in the fit.

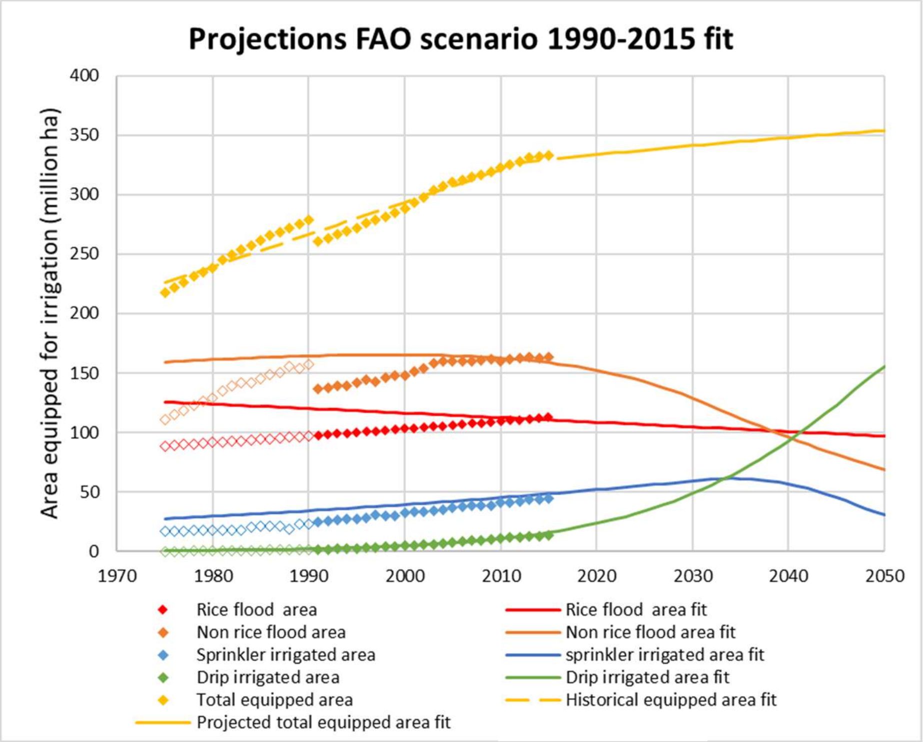

Figure 3. Logistic curves and projections for the FAO linear scenario with data range 1990-2015. Markers without filling correspond to data excluded in the fit.

In terms of total area equipped for irrigation, the graphs show that the logistic model provides higher growth prospects than those projected by FAO, with a difference of about 27 million ha by 2050 (381 vs 352 million ha respectively). It is remarkable noting that the model fit to the historical data is considerably better for the logistic model than for the linear FAO scenario regardless of the data range selected for the projections, as shown in Appendix 2. This is partly due to the fact that the growth rate proposed by FAO actually involves a sudden shift and slow-down of the historical trend, which is reported to account for some additional factors such as the lower growth rate of crop production, the increasing scarcity of suitable areas for irrigation and of water resources in some countries, the rising costs of irrigation investments, and the need for deriving some of the investment efforts to the rehabilitation of existing systems (estimated in 2.5% of current irrigation capacity per year) (Alexandratos, Bruisma, 2012). The difference between scenarios involves an expansion of irrigation infrastructure to currently unirrigated land 1.5 times higher under the logistic scenario compared to FAO's estimate of 20 million ha of irrigated area to be expanded by 2050 (Alexandratos, Bruisma, 2012).

When analysing the technology breakdown, the logistic model scenario projects a rapid increase of drip irrigation speeding up after 2025 and growing to dominate the market by 2050 (see figure 1), with 173 million ha or 45% of total equipped area. Such growth occurs in two stages. In a first stage, drip irrigation expands together with sprinkler at the expense of non-rice flood irrigated area, presumably as a result of the rehabilitation and modernization of surface schemes. An inflexion point is detected around 2035 marked by an acceleration of drip irrigation's growth rate and the beginning of a downturn in sprinkler irrigation. This change suggests the beginning of a substitution process not only out of traditional flood irrigation, but also within the modern technologies from sprinkler to drip irrigation, being the later the most recent and advanced technology. This substitution does not affect rice flood irrigated area, which remains almost stable. This result is consistent with the provided assumption that rice cannot be irrigated by other systems but flood irrigation, as well as with FAO's forecast of a 2% reduction in global rice surface by 2050 (Alexandratos, Bruisma, 2012).

Regarding the FAO linear scenario, the projection with the best fit data range (figure 2) shows a more conservative evolution of the technology mix. Drip irrigation would grow at a significantly slower pace than in the previous scenario, reaching a total market share of 58 million ha or 16.3% by 2050, with sprinkler and drip irrigation together summing 24% of the total irrigated surface. Meanwhile, sprinkler irrigation would peak and start the downturn around 2020, showing a faster substitution rate than flood irrigation. In turn, both rice and non-rice flood irrigated areas remain relatively stable with a slight decrease until 2050. Nevertheless, it should be noted that given the rather low fit qualities in the flood irrigation technology curves and the high sensitivity of the projections to the selected fit ranges (see Appendix 2), these results should be taken with caution. When projected for the same data range as in the logistic model scenario (1991-2015) in figure 3, the resulting dynamics for the technology mix are very similar than those of the logistic scenario, only with slightly lower diffusion extents of drip irrigation due to the lower total market growth. In this case, drip irrigation would reach the same market share as in the logistic scenario, with 160 million ha or 45% of the total equipped area.

Overall, the proximity of the projections obtained from the logistic and FAO linear models for the period 1991-2015 suggests that the variability in the evolution of the total equipped area does not affect consistently the dynamics of the trends, and provides a scenario that is consistent with the observed trends above mentioned. The logistic scenario is recommended over the FAO linear one for integrated modelling and scenario building exercises for three reasons: 1) it shows remarkably better fit qualities, thus capturing the historical trends, 2) it stays within the natural boundary of total irrigation potential, and 3) it reflects the internal substitution dynamics consistent with observed and expected trends. The FAO linear projection with the best fit can be used as an alternative-more conservative scenario to explore the possible consequences of a more gradual and limited penetration of modern irrigation technologies due to e.g. cost constraints or promotion of soft water conservation policies in agriculture focused on raising the productivity of rainfed systems in water scarce areas, such as Africa (Molden et al., 2007).

## 4.2 Unit scaling trends

An analysis to search for possible trends over time in average unit capacity was carried out for the World Bank projects dataset and the list of drip irrigation projects provided by Netafirm. This analysis could not be performed for the Spanish modernization projects due to the lack of information on the project implementation date. The resulting evolution of average project size trends sampled over five-year intervals for the two mentioned datasets is presented in figures 4 and 5. Additional figures plotting annual averages can be found in Appendix 3 for more detailed documentation.

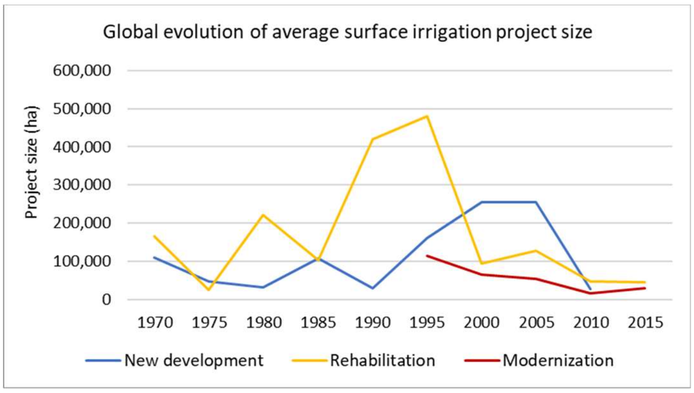

Figure 4. Global evolution of average irrigation project size for new development and rehabilitation surface irrigation projects and modernization projects implemented by the World Bank.

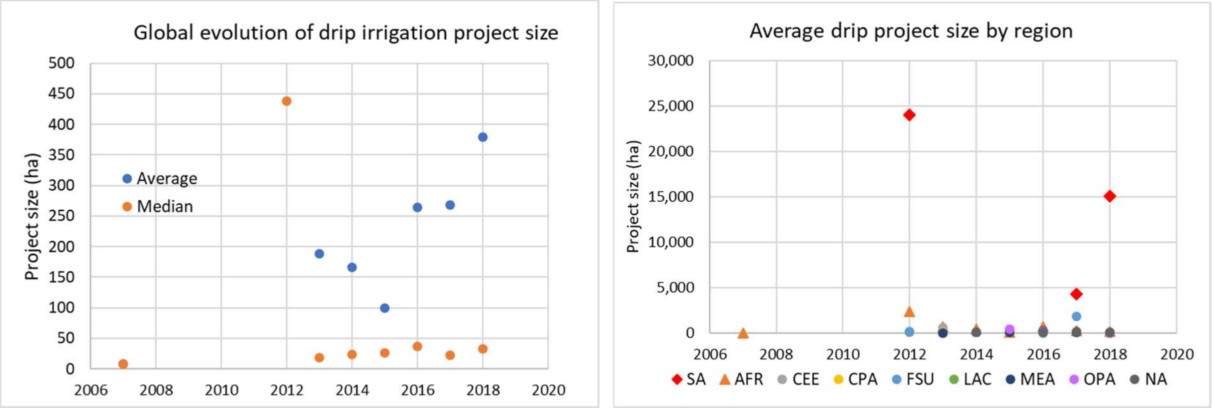

Figure 5. Evolution of drip irrigation project size at the global scale (left) and by regions (right), based on projects implemented by Netafirm company.

A first observation is the overall absence of clearly defined trends in any of the datasets. Different types of regressions were tried resulting in $R^2$ based fit qualities below 0.5, and thus not even worth reporting. These results reflect the remarkably high variability and context dependency of irrigation projects regardless of the technology type.

In the case of World Bank irrigation projects, a project upscaling phase can be observed in both new development and rehabilitation projects in the period 1985-2000, although no mathematical curve fittings provided acceptable results. This phenomenon reflects an age of extremely large scale World Bank initiatives that were evaluated as economically profitable due to the benefits of economies of scale, but functionally unsuccessful due to the management complexities and low long term adoption and use rates (World Bank, 2018). After year 2000, there is a trend shift followed by a downscaling of project size in all project categories. This second trend mirrors a new period in which the investment efforts were focused towards rehabilitation of medium scale projects, a decrease in new development actions, and modernization of smaller schemes or parts of big schemes in order to test new technologies. This phenomenon was especially relevant in Latin America where most of the modernization projects funded by the World Bank were implemented.

The analysis of drip irrigation projects in figure 5 shows no clear trends in the evolution of average project size over time. Average sizes are considerably lower than in the case of surface irrigation projects, albeit with remarkable regional differences. South Asia has considerably higher averages than the rest of the regions with values up to 24,000 ha, which to date constitutes the capacity frontier in drip irrigation projects. Average project size in the rest of the regions falls below 2,500 ha, and hoovers around 25-50 ha as indicated by the median values in the graph on the left in figure 5. This fact could be explained by several factors. First, drip irrigation projects are usually implemented at the plot or irrigation community scale (on farm interventions) and benefit from an already established off farm distribution infrastructure, which reduces the target size as compared to large district wide interventions. Second, the type of crops usually irrigated with drip systems are intensive high value crops such as vegetables and woody crops, which are grown in small or medium size intensive exploitations.

# 5. Economic analysis: an approximation to economies of scale and learning trends in irrigation

## 5.1 Cost analysis of irrigation projects financed by the World Bank

The cost analysis presented here below was carried out using data on projects implemented by the World Bank in the period 1990-2017 from the World Bank Project Database. The time period was selected to allow capturing the most recent trends (last 30 years) while keeping a representative sample in number, geographical location and technology/project typology.

### *Global cost analysis: new development, rehabilitation and modernization project costs*

Some statistics to describe the average specific costs for new development surface irrigation and rehabilitation projects are provided in table 6. These costs reflect only the cost of the irrigation component, which usually comprises the required land treatment, implementation of main channels and on farm water distribution and pumping (if applicable) infrastructure. The cost of dams and other large scale conveyance structure when present was not included in order to maintain data comparability across many different projects and regions.

Table 6: Statistics for average specific costs of new development surface irrigation and rehabilitation projects financed by the World Bank. Values are rounded to the hundreds position in order to avoid a false feeling of accuracy.

| | World | | |
|---|---|---|---|
| **Statistical parameter** | **New development** | **Rehabilitation** | **Modernization** |
| Average | 2,700 | 1,900 | 3,700 |
| Standard Deviation | 1,700 | 1,900 | 1,750 |
| Median | 1,800 | 1,200 | 4,200 |
| Max | 7,000 | 10,300 | 5,200 |
| Min | 700 | 80 | 2,150 |
| Q1 | 1,500 | 600 | 1,470 |
| Q3 | 4,000 | 2,300 | 4,210 |
| Range (Q1-Q3) | 1,500-4,000 | 630-2,300 | 2,500-4,700 |
| Size ranges (ha) | 8,500 – 60,000 | 16,750 – 134,000 | 100-94,000 |

To provide insights on the most recent trends, average specific costs and sizes for projects approved after 2010 are provided in table 7. The smaller size of the sample did not allow to derive meaningful trends at the regional scale.

Table 7: Average specific costs and sizes for projects approved after 2010. Values are rounded to the hundreds position in order to avoid a false feeling of accuracy.

| | **Surface new development** | | **Surface rehabilitation** | | **Modernization** | |
|---|---|---|---|---|---|---|
| Statistical parameter | Cost (2010$/ha) | Size (ha) | Cost (2010$/ha) | Size (ha) | Cost (2010$/ha) | Size (ha) |
| Average | 3,600 | 40,000 | 1,600 | 60,000 | 4,700 | 30,000 |
| Standard Deviation | 2,000 | 50,000 | 1,700 | 75,000 | 506 | 36,000 |
| Range (Q1-Q3) | 1,400-4,300 | 1,500-75,000 | 200-3,300 | 10,000-120,000 | 4,200-5,200 | 2,300-48,000 |

*Regional cost analysis: average investment costs, sizes and irrigated crops by regions*

Statistics on specific surface project costs were also generated for the regions of interest for ISWEL case studies, namely South Asia and Sub Saharan Africa (see table 8).

Table 8. Statistics for specific surface project costs in South Asia and Sub Saharan Africa. Values are rounded to the hundreds position in order to prevent a false feeling of accuracy.

| | South Asia | | Sub Saharan Africa | |
|---|---|---|---|---|
| **Statistical parameter** | **New development** | **Rehabilitation** | **New development** | **Rehabilitation** |
| Average | 2,500 | 1,250 | 4,200 | 3,400 |
| Standard Deviation | 1,700 | 1,900 | 2,300 | 1,900 |
| Median | 1,750 | 950 | 4,300 | 2,900 |
| Max | 5,550 | 4,150 | 7,000 | 7,300 |
| Min | 700 | 100 | 1,400 | 1,200 |
| Q1 | 1,500 | 750 | 2,500 | 1,950 |
| Q3 | 3,200 | 1,500 | 5,950 | 4,600 |
| Range (Q1-Q3) | 1,500-3,200 | 750-1,500 | 2,500-5,950 | 1,950-4,600 |
| Size ranges (ha) | 13,000-180,000 | 18,000-136,000 | 1,450-20,000 | 3,450-8,600 |

Additionally, an overview of region-specific average cost and size ranges for the different types of technologies, as well as the most common irrigated crops, is provided in table 9.

Table 9. Region-specific average cost and size ranges for the different technology types.

| **Technology** | **Cost range (2010$/ha)** | **Size ranges (ha)** | **Region** | **Crops** |
|---|---|---|---|---|
| Surface-new development | 2,500-7,000 | 976-23,200 | Africa | Maize, paddy rice, wheat, millet |
| | 2,500–4,200 | 21,000-40,000 | East Europe-Central Asia[1] (1980-1990) | Cotton, winter cereals, nuts, sesame, fruits |
| | 4,900 | 44,000 | Middle East[2] (Egypt) | Winter cereals and vegetables, maize, rice, cotton |
| | 1,700 | 139,000 | South Asia (India) | Rice, oil seeds |
| Surface-rehabilitation | 1,200-7,300 | 1,797-50,000 | Africa | Maize, paddy rice, wheat, millet |
| | 100-2,500 | 14,000-220,000 | East Europe-Central Asia | Same as new development |
| | 1,100-4,150 | 9,450-88,000 | Middle East | Same as new development |
| | 100-4,150 | 825-300,000 | South Asia | Rice, wheat, maize |
| Fixed sprinkler<br>Sprinkler | 1,500[3] | 3,000 | Southern Africa (Zambia) | Wheat, maize, potato, sugar beans, tobacco, Banana |
| | 1,500-4,000 | 900-180,000 | Eastern Europe | Cereals, maize, sugar beet, tubers, oil seeds |
| Drip + micro sprinkler | 4,300[4] | 30,000 | Middle East | Winter cereals (sprinkler) and vegetables (drip), maize |
| Mobile sprinkler | 2,500 | 3,000 | Southern Africa (Zambia) (CoFarm company prices) | Wheat, maize, onion, potato, tobacco, seed maize, soya beans, sorghum, banana |

[1] The database had no records of new development surface irrigation projects after 1990. The information provided corresponds to the only available records corresponding to projects implemented between 1980 and 1990.

[2] This value corresponds to the only project registered within this category in the database.

[3] On farm equipment only.

[4] On farm equipment + off farm system modernization.

Regarding the crop distribution, some patterns can be observed. Surface irrigation projects span the whole range of most typical crops across regions. Sprinkler irrigation projects tend to be used for extensive crops such as cereals, maize, oils seeds, sugar beet, and occasionally tubers, for which a diffuse spray water application is suitable. This suggests that the natural trend in modernization of an irrigation system aimed to grow these types of crops usually goes from surface to sprinkler systems. Regarding drip irrigation, despite the low number of projects of this type in the database, it can still be observed that this system is mostly applied to vegetables and trees, namely localized crops that can be planted in rows. Meanwhile, these crops usually have a higher market value and thus require less production (and cropping surface) to achieve the same economic return.

In this line, the last World Bank Projects Audit Report concluded that vegetable and fodder crops were a more successful alternative from an economic and sustainability point of view, since they have lower investment costs and higher performance than rice, while allowing for the use of efficient irrigation systems (World Bank, 2018).

### *Analysis of economies of scale*

The results for the economies of scale analysis for World Bank financed projects are gathered in table 10. In this case, the scale parameter was estimated for both the isolated irrigation component cost and the total project cost, in order to allow for intra-comparison between cost types and inter-comparison with values reported in the literature.

Table 10. Economies of scale of World Bank financed projects.

| **Region** | **Type of cost** | **New development** | | **Rehabilitation** | | **Modernization** | |
|---|---|---|---|---|---|---|---|
| | | Economies of scale parameter | $R^2$ | Economies of scale parameter | $R^2$ | Economies of scale parameter | $R^2$ |
| **World** | Irrigation component | 0.97 | 0.83 | 0.6 | 0.51 | 0.82 | 0.87 |
| | Total project | 0.65 | 0.64 | 0.48 | 0.43 | 0.63 | 0.85 |
| **Sub Saharan Africa (SSA)** | Irrigation component | 1.08 | 0.84 | 1.02 | 0.71 | NA | NA |
| | Total project | 0.78 | 0.83 | 0.74 | 0.6 | NA | NA |
| **South Asia (SA)** | Irrigation component | 0.83 | 0.81 | 0.54 | 0.52 | NA | NA |
| | Total project | 0.51 | 0.6 | 0.53 | 0.6 | NA | NA |

At the world level, new development surface irrigation projects have almost no economies of scale. This is especially so in Sub Saharan Africa, probably due to the low average project size and the historical focus on small scale interventions. In contrast, South Asia shows higher economies of scale than the world average, due to the higher average project sizes and sharp differences between the minimum and maximum scales (see table 10). When considering the total project cost, the economies of scale are considerably higher due to the inclusion of many costly additional elements such as dams, additional buildings and other heavy infrastructure that are highly scale-sensitive. The impact of such investments on specific project cost gets lower as the project size increases.

Rehabilitation projects have higher economies of scale in both the irrigation component and the total project cost (0.6 and 0.48 respectively), with smaller difference between them. However, fit qualities are lower than in new development and modernization projects. This fact mirrors the diversity and heterogeneity of rehabilitation projects that entail very different types of interventions, though mostly aimed at the improvement of the irrigation system. Therefore, differences between total project costs and irrigation component costs are smaller.

Modernization projects have moderate economies of scale with small differences between the irrigation component and the total project cost (0.90 and 0.63 respectively). Modernization projects have a similar nature to rehabilitation projects albeit with smaller average sizes. Therefore, economies of scale play out less intensively. For further insights, the analysis for this category will be contrasted with the results from the Spanish modernization project analysis in the next section.

## 5.2 Cost analysis of modernization projects implemented by the Spanish government between 2002 and 2012 as part of the National Irrigation Modernization plan.

### *Average specific costs and unit sizes*

An analysis of the different size ranges and associated specific cost variations according to the size is shown in table 11.

Table 11: Average specific cost and sizes of Spanish modernization projects.

| **Project size (ha)** | **Average Specific cost (2010$/ha)** | **Specific cost range (2010$/ha)** | **Number of projects** |
|---|---|---|---|
| <200 | 12,500 | 7,300-14,300 | 9 |
| 200-1,000 | 6,100 | 4,500-7,800 | 51 |
| 1,000-10,000 | 5,250 | 2,000-7,300 | 89 |
| >10,000 | 800* | 550-1,700 | 9 |

*This value corresponds to the median instead of the mean due to the need to correct for the influence of an outlier. The difference between median and mean values in the other categories is not significant.

The results show a clear decrease in average specific costs with increasing project sizes, which points out the influence of economies of scale as further analysed in the next section. The maximum project size in the Spanish sample is 42,000 ha, with 90% of the projects comprised within a range of 200 to 10,000 ha. These results are below the averages obtained at the world scale for the World Bank modernization projects, which registered an average size of 30,000 ha and a scale frontier of 94,000 (see table 11). An important factor influencing this difference is that Spanish modernization projects were usually implemented at the "Irrigation Community"[5] scale rather than targeting the whole Irrigation district or channel. Nevertheless, the variability in irrigation community sizes is still considerable, allowing for economies of scale to play out.

As a result, average costs range from around 12,500 2010$/ha for small scale farms down to around 800 2010$/ha for the largest sizes. The overall average accounting for the size ranges encompassing the core of the samples is around 5,250 – 6,100 2010$/ha, which is higher than the world average (around 4,000). An important factor determining this difference lies on the high mechanization level of Spanish modernization projects, especially those implemented in the last period 2010-2015 (Berbel, 2017). Spanish modernization works usually included both the rehabilitation and pressurization of the off farm conveyance and piping infrastructure, and the installation of the on farm application infrastructure (sprinkler or drip systems), as in the case of most of the World Bank modernization projects. However, in most of the latest projects there was an additional component of water metering and control infrastructure that included i.e. water meters at the channel head, or tele-control systems for remote irrigation control and operation (SEIASA, 2018). Therefore, these average costs could be used as a proxy for a *high-tech* irrigation with strong water control capabilities and thus very high water use efficiencies, but also higher investment costs.

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[5] A Spanish Irrigation community comprises a series of nearby farms usually served by a sub-branch of a main irrigation channel and where farmers have associated to adopt the Irrigation Community status.

*Economies of scale*

The economies of scale effect detected in table 11 was further analysed and quantified applying the methodology described in section 2, obtaining an economies of scale factor of 0.63 with an R2 of 0.50 (see figure 6). This result perfectly matches that obtained for the World Bank modernization projects when considering the total project costs (see table 10), which suggests that Spanish projects may have also included some additional components that are more scalable than just the irrigation technology itself. The lower fit quality in the case of the Spanish projects (0.49 compared to 0.85 in World Bank projects) is probably due to the considerably higher size of the sample, which increases the variability.

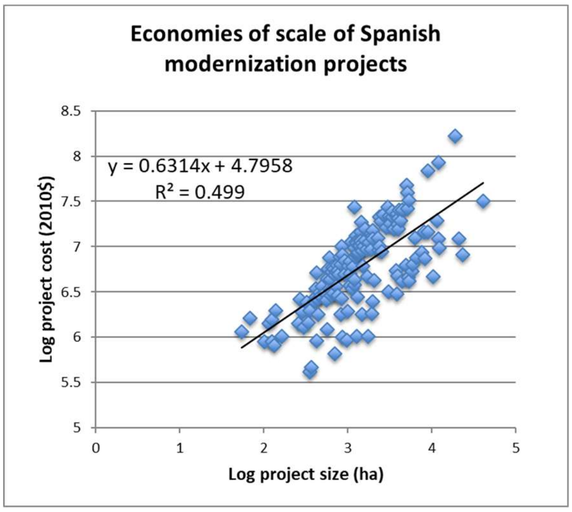

Figure 6. Economies of scale of Spanish modernization projects.

## 5.3 Learning analysis

An attempt to quantitatively estimate a presumable learning effect of irrigation technologies using the World Bank project database was carried out. This analysis could not be tested with the Spanish modernization projects due to the lack of data on project implementation dates. The analysis based on the methodological approach explained in section 2 required plotting the temporal evolution of average specific investment costs over cumulative installed capacity in a log-log scale. In order to undertake this step, a five year moving average of investment costs over time was first plotted on a five year interval for the whole series of surface new development and rehabilitation projects. A second series excluding the African projects (which had the highest occurrence of cost overrun anomalies) was also included, seeking to clarify the trend. The results are shown in figures 7a and b. Further representation of the averages on an annual basis for all types of projects can be found in Appendix 3.

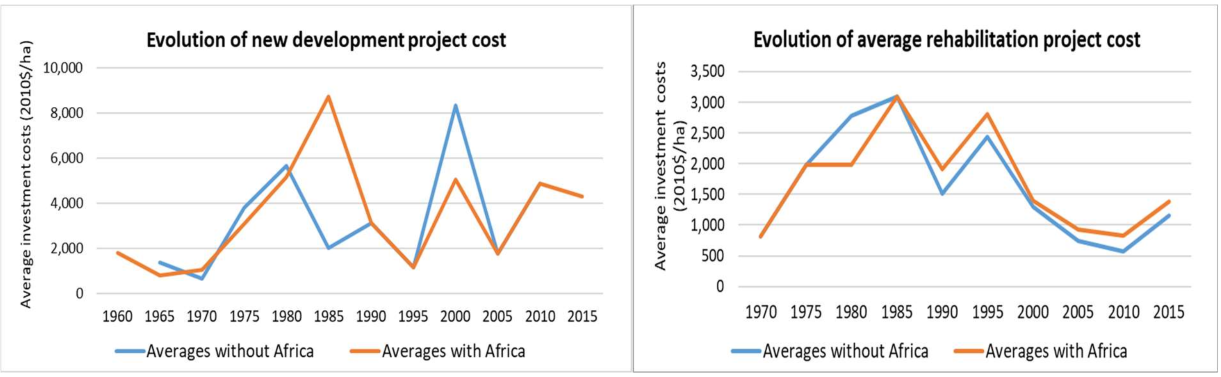

Figure 7a (left). Evolution of average new development project costs. Figure 7b (right). Evolution of average rehabilitation project costs.

New development projects show no clear trend. An apparently sharp decrease in world averages is observed between 1985 and 1995; however, the series without the African projects suggests that such decrease may have been softer in most regions. After 1995, the trend oscillates - with ups and downs - within the range of 2,000-4,000 2010$/ha, as reflected in more detail in figure A5.1. Meanwhile, rehabilitation projects reveal a clearer descending trend from 1985 to 2010 confirmed by both time series, which initially could be thought to be linked to or affected by the project size upscaling detected over the same period in figure

When the effects of economies of scale are removed, the resulting cost trends are shown in figure 8, which plots in orange the original average costs shown in figure 7 and in green the de-scaled cost for new development and rehabilitation projects. New development projects show almost no difference between the original and the de-scaled cost trends, as it could be expected given the high economies of scale factor (0.97, see table 10). Rehabilitation projects had more substantial economies of scale, with a factor of 0.6, and thus the difference between cost series is higher. The average cost downfall detected after 1990 is even more pronounced in the de-scaled cost series, which suggests against the hypothesis of this cost downfall being driven by the project size upscale detected around the same period in figure 4. Instead, it opens the door to a hypothesis of a presumable period of higher learning linked to the focus shift from new development to rehabilitation projects starting around that period (World Bank, 2018).

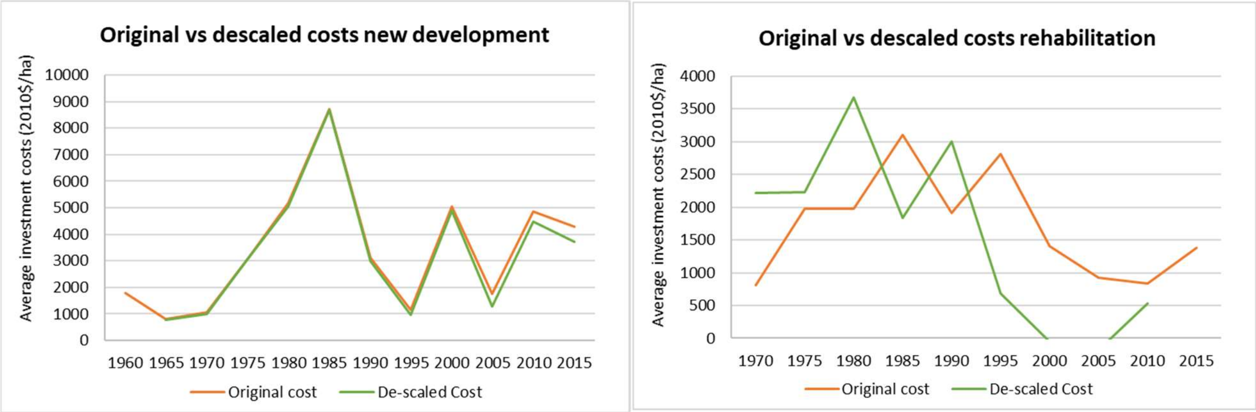

Figure 8a (left). Actual versus de-scaled average costs for new development project. Figure 8b (right). Actual vs de-scaled average costs for rehabilitation project.

Despite the limitations to apply the learning rate methodology due to the incomplete representation of total cumulative capacity (only World Bank financed and reported rehabilitation projects) and the variability of the annual average costs, an experiment to calculate the learning rate was carried out (see Appendix 4, figures A4.1-A4.4). The results showed no trend for the whole time period in both new development and rehabilitation projects both when plotting original costs and de-scaled costs, with fit qualities below $R^2=0.3$. Within rehabilitation projects, a specific fit was done for the period 1990-2015 for the original and de-scaled cost time series. The regressions showed more feasible results, with learning rates of 36% and 31% for original and de-scaled cost respectively, although the fit qualities were still very poor ($R^2 = 0.37$ and 0.35 respectively). As a result, these values could be considered the best possible approximation to a quantitative estimation of the recent learning rates for rehabilitation projects, acknowledging a high level of uncertainty due to the high data variability.

Regarding the specific learning dynamics for sprinkler and drip irrigation technologies, the considerable growth experienced in the last decades suggests that these technologies may have benefitted from some learning effects. However, the difficulties to estimate them lie in the separation of the on farm and the off farm components of a pressurized irrigation project. The development of the pressurized off farm network, or the modernization and pressurization of an existing one, is a large scale intervention that is usually undertaken and financed with support of the governments and international donors, and information on project characteristics and costs is more accessible (e.g., the World Bank and Spanish modernization databases). However, the on farm component consisting of the sprinkler and drip irrigation technologies per se is usually purchased directly by the farmer to an engineering company, and thus a track of historical data on cost evolution is much more sparse and less accessible, or subject to confidentiality issues. Therefore, despite the learning trends on the off farm part could be assumed similar to the presented rehabilitation projects analysis, more specific data series with on farm project costs for the two types of systems would be required in order to infer any technology specific learning trends and potential cost evolution.

## 5.4 Qualitative cost trends reported by irrigation experts

A series of qualitative insights on past and expected trends for irrigation systems deployment and costs were gathered from irrigation experts from the World Bank and the Netafirm company. This qualitative information is aimed to help refine the quantitative results and recommendations based on expert knowledge, in order to reduce the level of uncertainty and data limitations.

First, related to international donor financed irrigation projects, the following trends were highlighted (World Bank, personal communication).

- Currently most of the efforts are focused on the rehabilitation of degraded or old schemes rather than on the development of new ones, and this trend is expected to continue. Only SubSaharan Africa and some parts of South East Asia (e.g. Indonesia) hold a higher potential for development of new projects. However, the easy locations have already been tapped and the remaining potential is located in rather remote areas where the complexity of the system design will substantially increase the capital cost.
- The main factors determining irrigation project costs variability and associated trends are the following:
  - Distance to the source: the higher the distance, the higher the construction and operational costs involved. Nowadays most of the irrigation potential located close to water sources has been developed, and thus the new development projects will require more complex water conveyance and transportation networks that will increase the project costs.

  - Availability of local suppliers: India has plenty of local manufacturers whereas countries like Indonesia or Zambia need to import the materials, resulting in transport related increases of the final project cost.
  - Type of crop: rice systems are on average cheaper than any other crop.
  - Farmer preferences: shared systems (e.g. shared sprinkler lines vs individual sprinkler systems) can reduce up to 1/3 the cost of the systems.
  - Type of irrigation system: sprinkler and drip require denser configurations in the secondary and tertiary lines than surface irrigation, besides the need for pressurization.

- Average cost trends observed over time and expected for the future:
  - There have been improvements over time in sizing and reduction of cost overruns during the design and implementation phases, leading to a decrease in final unitary costs (Inocencio, 2007). The decrease in cost overrun has been especially pronounced in the Sub Saharan Africa region.
  - There could be historical cost reductions due to the shift from public to private funded and implemented projects, which enhances competition and time and cost efficiency. The role and main interest of governments lies on the rehabilitation of large scale existing schemes, particularly in the off farm part of the systems, leaving the canal lining and on farm modernization to private initiatives funded by the users with or without support of international financing.
  - The price of materials has decreased, which may also reflect in some cost reductions over time.
  - Micro irrigation systems have also benefited from lowering costs of materials (e.g. pipes) that may have reflected in cost reductions over time.
  - In Africa, costs are higher and will further increase due to the increasing complexity of the locations and distance from water sources, and thus of the designs and lengths of the systems. Africa will need to develop medium and large scale systems, but this is not always the wish of the local people. Currently many initiatives are working at the small scale, including some initiatives of "commercial agriculture" and "tier based" models promoted by the World Bank (see Appendix 5).
  - Surface irrigation with improved efficiency (rehabilitated) will remain the major method, over pressurized systems. The main advantages are that most farmers understand it and capacity building is simple, the cost of operation is less than in pressurized irrigation, and the replacement of equipment is less expensive. The shift to pressurized systems will only take place for high value crops.
  - In Asia all new developments will be small and specific (niche crops) because most of the water sources are already in use. Meanwhile, no new big dams will be developed because of resettlement constraints. The opportunities there lie on specific new schemes for high value crops, mainly with sprinkler and drip irrigation.

    Currently rice production is very protected and considered strategic at the national scale. However, the economic return is not very high and farmers are getting more aware, skilled and strong, so a shift away from rice cultivation or a higher diversification may come in the future.
  - The irrigation potential around most of the perennial rivers has already been tapped. Therefore, new schemes will increasingly require additional water storage infrastructure (dams, ponds, etc.) which also increase project costs (e.g. a 60 million m3 dam has an average cost of 20 million dollars).

Second, in the particular case of drip irrigation projects, the following trends were highlighted (Netafirm, personal communication):

- Increase in the technological level and sophistication of the projects to achieve better yields, consistency and quality.
- Irrigation projects can be subdivided into two major parts: on farm part comprised by pumps, filters, valves, pipes, automation, etc.; and off farm part or bulk water supply from the water source to the field. The latter cost may vary significantly depending on the water source type and the distance to the field; furthermore, it can sometimes increase by up to ten times the cost of the on farm part.
- Limitations in the quantity and quality of irrigation water at the source have a negative influence on the project costs, resulting in a more complex and costly bulk water supply of irrigation projects.
- There has been an increase in labour costs over time across all regions.
- Any mild reductions in technology costs due to industrial improvements have been by far overcompensated by these factors, thus resulting in an overall increase in irrigation project investment costs over time.

# 6. Discussion

## 6.1 Insights and recommendations on presumable future irrigation technology mix and cost trends

The future irrigation development scenarios and technology mix projections presented are coherent with the overall trends and driving factors predicted by FAO. These include the allocation of most of the funding to rehabilitation and modernization of existing schemes, as well as the seek for higher efficiency and added value in agriculture, which is usually associated with crops suitable for drip irrigation rather than sprinkler irrigation, i.e. woody crops and vegetables. Evidences of this trend can be found in most of the highly water stressed regions with a long agricultural tradition such as California, the Mediterranean region, Australia, India and the Middle East, where drip irrigation currently finds its main markets (see figure 9). Particularly, India and Pakistan are giving signs of an increasing interest and speeding up process of agricultural transformation towards higher value crops. This is linked to a bid for the rehabilitation of traditional large scale off farm irrigation infrastructure implemented in 1960-1980 and the conversion into drip irrigation, as shown by the commissioning over the last decade of some of the biggest drip irrigation projects worldwide (Netafirm, 2017). Latin America is also experiencing a gradual transformation into drip irrigation, which has been particularly intensive in countries like Peru, Brazil, Argentina and Mexico in the last two decades. Meanwhile, the loss of flood irrigated area may be partially offset by some new developments in Africa, which holds the highest untapped irrigation potential and the need to increase agricultural productivity and resilience (Alexandratos, Bruisma, 2012). However, the large project costs linked to the distance from water sources and the complexity of the systems (as mentioned in the previous section), may lead to the preference for optimized flood systems that avoid additional costs of pressurization (World Bank, personal communication). Based on these observed trends, the dynamic technology mix evolution projected by both the logistic and the FAO linear scenarios when taking the 1990-2015 range fit seems consistent. Given the better fit provided by the logistic scenario, which captures both the historical trend and the foreseeable evolution, this is the recommended scenario for prospective modelling purposes.

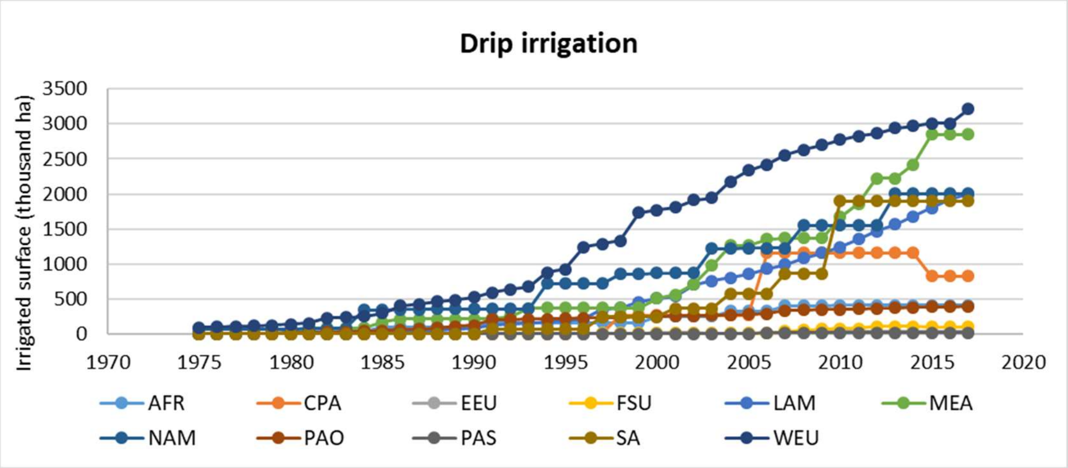

Figure 9. Historical evolution of drip irrigation deployment by regions. Abbreviations: AFR: Africa, CPA: Central Asia and China, EEU: Eastern Europe, FSU: Former Soviet Union, LAM: Latin America, MEA: Middle East, NAM: North America, PAS: Other Pacific Asia, PAO: Pacific OECD, SA: South Asia, WEU: Western Europe.

Regarding trends on the average project scale and costs, a clear conclusion is that a single overall trend at the global scale cannot be drawn, as scale and cost dynamics, trends and challenges are very different across regions. Therefore, a set of insights and recommendations will be provided specifically for the IS-WEL regions and for the front runner regions in agricultural technification.

In the case of South Asia, where the Indus basin is located, the main irrigation related interventions are expected on the 'vertical rather than horizontal expansion of irrigation' (World Bank, personal communication). This means that most of the interventions will focus on increasing the efficiency and economic returns of agriculture through crop diversification at the small and medium scale plot size. This will come together with the intensification and conversion into drip irrigation driven by the cost competitiveness of the technology in the region thanks to, on the one hand, the availability of local suppliers and, on the other hand, the governmental initiatives to reduce the intensive groundwater mining already causing serious water and soil quality issues. In this sense, two types of irrigation projects could be expected:

- An increasing number of privately driven small to medium scale drip irrigation projects implemented at the individual or irrigation community level in groundwater irrigated farms. These farms already have the connection to the water source and pumping system setups, thus reducing the investment cost to the purchase and installation of the on farm drip infrastructure.
- A reduced number of publicly driven large scale rehabilitation projects to restore unused large scale surface schemes, where economies of scale will play a considerable role. These may be accompanied by a modernisation of part of the systems and conversion into drip irrigation supported by the government, in line with the last projects registered in the Netafirm database.

A summary of the recommended assumptions for future irrigation scenarios in South Asia is provided in table 12.

Table 12: Recommended assumptions for future irrigation scenarios in South Asia.

| Parameter | Small scale drip irrigation with groundwater | Large scale surface rehabilitation projects | Modernised large scale drip irrigation projects |
|---|---|---|---|
| **Average size 2050 (ha)** | 50-500 | 50,000-150,000 | 10,000-30,000 |
| **Economies of scale** | 0.82 | 0.52 | 0.82 |
| **Historical learning** | NA | 31%* | NA |
| **System cost 2050 (2010$/ha)** | 2,000-3,000 | 700-1,200 | 3,700-4,500 |

*This best approximation to the learning rate cannot be applied due to the lack of regional projections on the evolution of cumulative capacity. Therefore, the recommended cost estimates do not reflect the learning effect. However, the value is included in the table to allow modellers take it into account based on their assumptions on future irrigation development.

In the case of Sub Saharan Africa, where the Zambezi basin is located, the expected trend is the expansion of the irrigation infrastructure to enable access to irrigation and increase the productivity of agriculture, as well as the rehabilitation of existing underused surface schemes (World Bank, 2010). In this context, three types of projects could be expected:

- Publicly driven large scale new development irrigation projects associated to an existing dam or otherwise requiring the construction of a dam or water storage system. In the second case, the cost of the project would be increased by around 20 million dollars for a 60 cubic meters dam (World Bank, personal communication). These projects would probably increase the average historical size of interventions in Africa, due to the push of governments to substantially increase irrigation with medium to large projects. Increasing the average scale would allow for some economies of scale that small interventions in Africa usually lacked. The global economies of scale parameter for new development projects can be considered as a reference. However, project size would be limited by the physical configuration and the project cost. Costs would be on the higher edge of the historical ranges due to the need to go to more difficult locations with larger distances from the water conveyance point. The most probable on farm systems are high efficiency flood systems (furrow) for the largest projects and centre pivot sprinklers for the smaller ones. Here the choice for the modellers could be based on the level of efficiency assumed by the scenario (e.g. surface irrigation for state of the art efficiency, sprinkler for high efficiency). There are no records of drip irrigation initiatives in the Zambezi, which suggests that sprinkler is the preferred/most cost-effective modern irrigation technology. The hypothesis of technology sharing within irrigation communities could be used as an assumption to develop a scenario of low-cost efficient irrigation. In such case, the investment cost for the on farm sprinkler infrastructure could be assumed as 1/3 per ha (World Bank, personal communication).
- Publicly driven large-scale rehabilitation projects to restore underused or degraded off farm infrastructure. These projects would be similar to the rehabilitation projects traditionally undertaken by the World Bank. The scale of the projects would vary given the wide range of scheme sizes in the basin, usually ranging between 1,000-50,000 ha. The evaluation of existing equipped area in the Zambezi basin and potential for rehabilitation projects proposed by the World Bank (World Bank, 2010) suggest a possible increase in average project sizes to around 10,000-50,000 ha (maximum rehabilitation project size registered in Africa). This would allow economies

of scale to play, which did not happen in the historical record of African projects due to the small size of the interventions. The global economies of scale parameter for new development projects can be considered as a reference. These projects could include an additional on farm component of implementation of sprinkler pivot systems along the same lines as in the previous type. The choice would depend on the assumptions on irrigation efficiency targets taken by the modellers.

A summary of the recommended assumptions for future irrigation scenarios in Sub Saharan Africa and especially the Zambezi basin is provided in table 13.

Table 13: Recommended assumptions for future irrigation scenarios in Sub Saharan Africa.

| **Parameter** | **On farm sprinkler system** | **Medium - large scale new development surface irrigation projects (only irrigation component)** | **Medium- large scale surface rehabilitation projects** |
|---|---|---|---|
| **Average size (ha)** | Variable depending on the efficiency target assumptions | 10,000-50,000 | 5,000-50,000 |
| **Economies of scale** | 1/3 if sharing | 0.97 | 0.6 |
| **Historical learning** | NA | NA | NA |
| **System cost 2050 (2010$/ha)** | 2,500<br>830 if shared | 6,600-7,000 | 1,400-3,500 |

Finally, here follows some insights on the expected irrigation trends in frontrunner regions with highly specialized agriculture such as the Mediterranean, Middle East, the US or Australia. As mentioned in the introduction, most of these regions have a long historical deployment of irrigation infrastructure and have undergone or are currently undergoing intense irrigation modernization processes - often promoted by the national governments - that include the implementation of pressurized irrigation technologies. The potential to increase equipped irrigated area in these regions is almost depleted, and most of the interventions will be focused on further increasing the efficiency and precision of existing irrigation infrastructure. The modernization process will acquire increasing sophistication and higher degree of complexity of the implemented systems, including irrigation automatization, telecontrol, sensor based monitoring and tele-metering. Meanwhile, the higher energy footprint associated to this modernisation process will be increasingly addressed through the installation of on farm or irrigation community shared decentralized solar power systems, an emerging trend that is already seen across the world (World Bank, personal communication, FAO, 2018). Overall, this will presumably translate in an increase in the average cost of modernization projects, due to the increasing number of components. However, it will also result in considerably higher economic turnovers from irrigation, thus enabling farmers to pay-off the upfront investment when appropriate financing mechanisms are facilitated by the governments.

## 6.2 Data quality, limitations and implications

Data availability and quality has been a major limitation in this study in order to properly apply the described methodologies and get meaningful results. This limitation has particularly affected the analysis of the learning effect, for which only a best approximation could be obtained. The main data limitations and identified knowledge gaps are here described.

Regarding data on irrigation deployment, the best available dataset on historical irrigation deployment by technology type, i.e. flood, sprinkler and drip irrigated area, is contained in FAO's Aquastat platform. However, data is only available for certain years and countries, being some regions particularly underrepresented, as in the case of Africa or Latin America. Therefore, the estimates and scenarios of total irrigation deployment generated by the present and similar studies should be considered best approximations based on currently available data acknowledging a high level of uncertainty, as highlighted by Venot (2014). Nevertheless, in this study an effort to improve the completeness and accuracy of data series included in Aquastat has been done by consulting national sources for a series of countries with presumable high irrigation deployment. This completed dataset is provided as a supplementary excel file and it is considered as a relevant contribution to improve the currently available data.

Regarding data on irrigation project costs for the different technology types, the only available data comes from international donors and national governments who promote interventions usually at the off farm scale and mainly for surface irrigated schemes. This is the case of the World Bank database and the Spanish modernization project database. However, off farm interventions are only partially correlated with the on farm technology (as far as they allow or not for a pressurised system), and thus data on the on farm system is required in order to generate comparable analyses between sprinkler, drip and flood application technologies. Meanwhile, drip and sprinkler irrigation projects are usually commissioned and implemented by private actors (users and companies), and thus more difficult to access due to the local or distributed nature of retailers or to confidentiality issues. This limitation constrains the conduction of trend or statistical analyses, such as those aimed to explore economies of scale or learning effects, which require a representative enough technology specific sample in order to provide consistent and meaningful results. Therefore, the elaboration or facilitation of databases gathering this type of data through e.g. partnerships or win-win agreements with important retailers in the sector could be of high relevance to the broad scientific community working on irrigation - land use modelling and scenario building within the SDG agenda and sustainability assessment frames.

# 7. Conclusions

From a technological perspective, irrigation is a dynamic field undergoing a shift from a horizontal expansion of the area equipped for irrigation (or "total irrigation market") to a vertical transition of the technology mix in search of higher intensification and efficiency (more crop per drop). As a result, the "irrigation market" is currently experiencing a gradual transformation process from traditional flood irrigation towards more efficient pressurised irrigation technologies (sprinkler and drip). The results of this study suggest that these substitution dynamics will continue in the future, favouring the most recent and efficient technology, i.e. drip irrigation. A logistic projection of the historical growth predicts drip to reach the highest growth rate among all technologies by 2035, and start a fast expansion over not only flood irrigated areas, but also sprinkler irrigated areas.

The cost and size dynamics of irrigation projects are less clear given the extremely high context dependency and variability of some critical factors determining irrigation project costs, as well as the important differences across regions. Focusing on the regions of interest for ISWEL case studies, South Asia may see a rapid expansion of drip irrigation through both private modernization initiatives at the small-medium scale, and public large scale rehabilitation-modernization interventions on historical surface schemes. Thanks to the active local irrigation technology industry and off farm infrastructure stock, irrigation technology costs will remain lower than in other areas and could be subject for learning related cost reductions in the future. Meanwhile, projects in Africa may develop in the line of expanding the irrigation potential through mainly medium-large scale surface irrigation schemes. The costs of these new schemes are expected to be on the high edge of historical averages, due to the increasing complexity of suitable locations and thus of the systems offsetting the potential effects of economies of scale brought about by an increase in project size compared to the historical interventions. Meanwhile, sprinkler technology and particularly centre pivot seems to be a suitable option already expanding within the emerging commercial farming, due to the lower costs and the potential for technology sharing.

As a final remark, it should be noted that representative data on historical deployment and costs of the different irrigation technologies are incomplete and in the case of cost data not publicly available. Therefore, a suggestion for further research on the topic is the engagement and collaboration with the private sector to work on the elaboration or improvement of existing or new databases, which would allow further precision and robustness in the generation of land use scenarios and modelling assumptions including irrigation at the global and regional scale.

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# Appendixes

## Appendix 1. List of irrigation experts consulted for the qualitative analysis

Table A1.1. List of experts consulted for the qualitative analysis.

| Name | Position | Insitutions |
|---|---|---|
| Avi Schweitzer | CTO | Netafirm |
| Michael Schultzer | Agricultural water management analyst | 0.97 |
| Joop Stoutjesdijk | Lead irrigation engineer | World Bank |
| David Rivas | Postdoctoral researcher | Technical University of Madrid |

## Appendix 2. Logistic function parameters, assumptions and fit qualities for the irrigation diffusion scenarios

### *Model parameters, fit qualities and sensitivity analysis for the logistic model scenario*

Box A2.1. Logistic function formula and parameters.

y=  K/1+e^(-b(t-tm))  and  Δt=log81 ×b^(-1)
With:
K  = asymptote (saturation level)
b = diffusion rate (steepness)
Δt (delta t) = time period over which y grows from 10% to 90% of K
tm = inflection point at K/2 (maximal growth)

Table A2.1. Model parameters and fit quality for the logistic model.

| Model parameters | K | Tm | dt | R2 | Fit range |
|---|---|---|---|---|---|
| Total market (Equipped irrigated area) | 417 | 1965 | 160 | 0.96 | 1991-2015 |
| Rice flood irrigated area |  | 1922 | -582 |  | 1991-2015 |
| Non rice flood irrigated area |  | 2011 | -798 |  | 1991-2015 |
| Sprinkler irrigated area |  | 2133 | 279 |  | 1991-2015 |
| Drip irrigated area |  | 2053 | 55 |  | 1991-2015 |

Table A2.2. Sensitivity analysis for different data ranges.

| **Fit range** | **2050 value (Million ha)** | | | | **Percentage deviation from full range value (%)** | | | |
|---|---|---|---|---|---|---|---|---|
| | Rice flood | Non rice flood | Sprinkler | Drip | Rice flood | Non rice flood | Sprinkler | Drip |
| **1965-2015** | 110 | 52 | 5 | 214 | --- | --- | --- | --- |
| **1980-2015** | 115 | 168 | 5 | 92 | -4.55 | -223.08 | 0.00 | 57.01 |
| **1990-2015** | 108 | 76 | 23 | 173 | 1.82 | -46.15 | -360.00 | 19.16 |
| **2000-2015** | 113 | 101 | 44 | 122 | -2.73 | -94.23 | -780.00 | 42.99 |

### *Model parameters, fit qualities and sensitivity analysis for the FAO linear scenario*

Box A2.2. Linear function formula and parameters.

$y = ax + k$

With:

a = slope coefficient

K = constant

Table A2.3. Model parameters and fit quality for the FAO linear model.

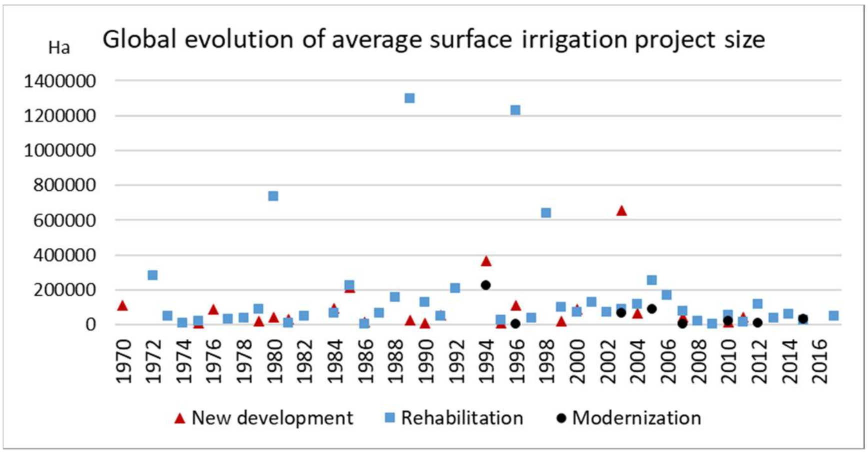
| **Model parameters** | **K** | **a** | **Tm** | **dt** | **$R^2$** | **Fit range** |
|---|---|---|---|---|---|---|
| Total market (Equipped irrigated area) | 417 | | 1965 | 160 | 0.96 | 1991-2015 |
| Rice flood irrigated area | | | 1922 | -582 | | 1991-2015 |
| Non rice flood irrigated area | | | 2011 | -798 | | 1991-2015 |
| Sprinkler irrigated area | | | 2133 | 279 | | 1991-2015 |
| Drip irrigated area | | | 2053 | 55 | | 1991-2015 |
| Total market (Equipped irrigated area) | 0.515 | -704 | | | 0.96 | 2008-2015 |
| Rice flood irrigated area | | | 1736 | -1814 | | 2008-2015 |
| Non rice flood irrigated area | | | 2010 | -754 | | 2008-2015 |
| Sprinkler irrigated area | | | 2140 | 310 | | 2008-2015 |
| Drip irrigated area | | | 1973 | -136 | | 2008-2015 |

Table A2.4. Sensitivity analysis for different data ranges.

| **Fit range** | **2050 value (Million ha)** | | | | **Percentage deviation from full range value (%)** | | | |
|---|---|---|---|---|---|---|---|---|
| | Rice flood | Non rice flood | Sprinkler | Drip | Rice flood | Non rice flood | Sprinkler | Drip |
| **1965-2015** | 101 | 40 | 6 | 204 | --- | --- | --- | --- |
| **1980-2015** | 106 | 154 | 6 | 85 | -4.77 | -285.61 | -6.74 | 58.29 |
| **1990-2015** | 100 | 67 | 24 | 160 | 1.56 | -68.29 | -314.30 | 21.61 |
| **2000-2015** | 104 | 96 | 39 | 113 | -2.96 | -140.36 | -553.92 | 44.82 |

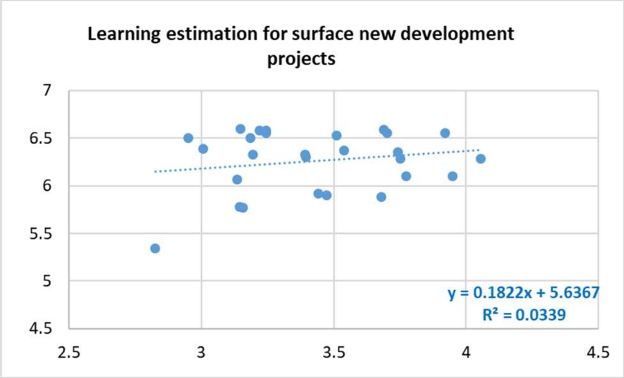
# Appendix 3. Evolution of annual average surface irrigation project sizes at the world scale

Figure A3.1. Annual average surface irrigation project sizes at the world scale



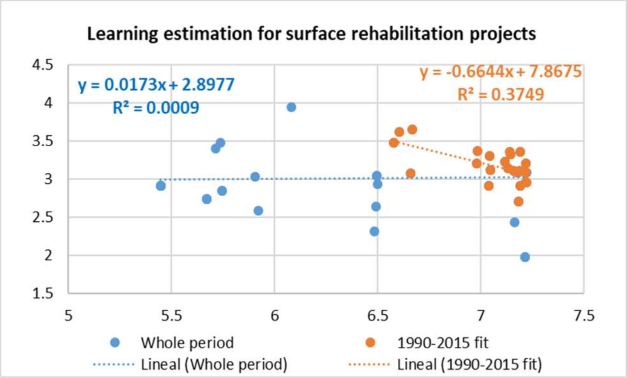
# Appendix 4. Supplementary materials for the learning analysis

Figure A4.1. Estimation of learning rate for surface new development World Bank projects



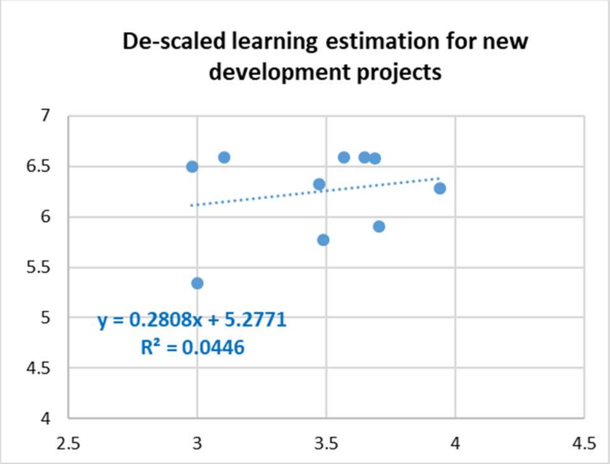
| Parameter | Value |
|---|---|
| Coefficient (a) | 0.28 |
| Progress Rate ($PR=2^a$) | 1.21 |
| Learning rate (1-PR) | -0.21 |
| Learning rate (%) | -21% |
| R2 | 0.03 |

Figure A4.2. Estimation of learning rate for surface rehabilitation World Bank projects



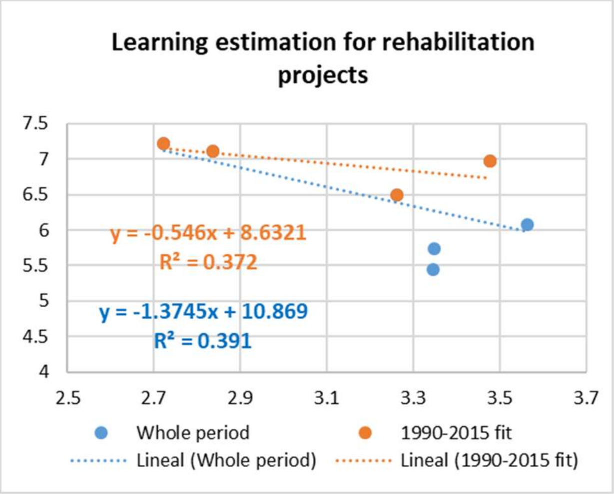
| Parameter | Value Whole period | Value 1990-2015 fit |
|---|---|---|
| Coefficient (a) | 0.017 | -0.66 |
| Progress Rate ($PR=2^a$) | 1.01 | 0.6328783 |
| Learning rate (1-PR) | -0.01 | 0.3671217 |
| Learning rate (%) | -1% | 36% |
| R2 | 0.0009 | 0.37 |

Figure A5.3. Estimation of de-scaled learning rate for surface new development World Bank projects



| Parameter | Value |
|---|---|
| Coefficient (a) | 0.28 |
| Progress Rate ($PR=2^a$) | 1.21 |
| Learning rate (1-PR) | -0.21 |
| Learning rate (%) | -21% |
| R2 | 0.04 |

Figure A5.4. Estimation of de-scaled learning rate for surface new development World Bank projects



| Parameter | Value Whole period | Value 1990-2015 fit |
|---|---|---|
| Coefficient (a) | -1.37 | -0.54 |
| Progress Rate ($PR=2^a$) | 0.39 | 0.69 |
| Learning rate (1-PR) | 0.61 | 0.31 |
| Learning rate (%) | 61% | 31% |
| R2 | 0.26 | 0.37 |

## Appendix 5. New models of small scale irrigation initiatives in Africa supported by the World Bank

**Box. A1. Commercial agriculture in Malawi**

This model consists of blocks of farmers forming a commercial entity. A group of neighbouring farmers align their plots together to form a block and hire a commercial company to manage and work the land on their behalf. Then, they get a dividend of the benefits at the end of the year. They usually contribute with labour but they cannot use or sell the production directly. Most of these plots have pivot, sprinkler or drip irrigation systems depending on the crop. You commercialize the management of the scheme.

**Box. A2. Tier based agriculture in Africa**

The agriculture value chain is composed of farmers operating at three levels:

- **Tier 1:** small holder farmers who have a plot and practice irrigation at the individual scale.
- **Tier 2:** emerging commercial farmers who do not have the experience to run a big farm but may have the capital or the capacity to run a 5-10 ha farm with commercial purposes.
- **Tier 3:** commercial farmers who run large exploitations and provide support to tiers 1 and 2 to become profitable irrigators as well as support to market products.