Irrigation efficiency and water saving: scale and rebound effects

Improving on-farm irrigation efficiency have many benefits; however, it may mislead policies aiming to increase the availability of water at watershed scale. The effect of improving on-farm efficiency on global efficiency is highly dependent on the hydraulic arrangement of the irrigation units and the degree of reutilization of return flows. Moreover, an improvement of irrigation efficiency may entail an increase of evapotranspiration, contributing to the watershed water depletion. Water policies must take these issues into account.

Irrigation efficiency is associated to a specific scale of analysis

Irrigation water conservation may be approached at different scales with different objectives. The farmer may have a limited water supply, be interested in reducing energy cost or have drainage restrictions, all good reasons for water conservation. On-farm irrigation efficiency can be improved by various engineering solutions that reduce water use. Drip irrigation or site-specific variable rate irrigation are such solutions. However, system performance is affected by the degree of reuse of return flows, which depends on the system's hydraulic arrangement and the performance of the irrigation units (Mateos, 2008). An increment of unit irrigation performance will have more effect on system performance efficiency if the units are arranged in parallel than if they are in series (Figure ❶). In a system in series, there is a single water source at the head. This source supplies the upstream unit that, in turn, supplies the next downstream unit, and so on. The system irrigation efficiency increases rapidly as the number of irrigation units increases (the size of the units must decrease since each unit consumes part of its supply as evapotranspiration) (Figure ❶). Thus, an increase of unit efficiency would have little effect on system efficiency if the number of units in series were greater than 3. Contrary, in a system in parallel, where all units receive water directly from a common water sources (e.g., a river or irrigation canal), the excess of irrigation water that receives an irrigation unit flows out of the system. In this case, the system irrigation efficiency equals that of the individual units and an increment of unit irrigation efficiency would have an equivalent effect on system efficiency (Figure ❷). The most common situation, however, is an intermediate (mixed) arrangement, where the return flows of the irrigation units may be used in different ways. Depending on the water circulation and the degree of reuse, the system irrigation efficiency will increase with the number of units at one rate or another (Figure ❶). Summarising, engineering solutions for water conservation at farm level do not necessarily imply basin-scale water saving (Mateos, 2008). Mateos et al. (2000) and Vivas et al. (2016) gave examples of real cases where the global irrigation efficiency was notably higher than the efficiency of individual irrigation units. The former showed that an on-farm irrigation efficiency between 60 and 70% may be transformed into a global efficiency greater than 90% if the reuse of drainage water is as intense as it is in the Tulelake Irrigation District in Nothern California. Vivas et al. (2016) demonstrated that such integrated water management notion was already embedded in the mountain irrigation systems developed in the Medieval Age in Southern Spain. The corollary is that policies favouring on-farm irrigation performance may not result on the expected increase of water availability at basin scale.

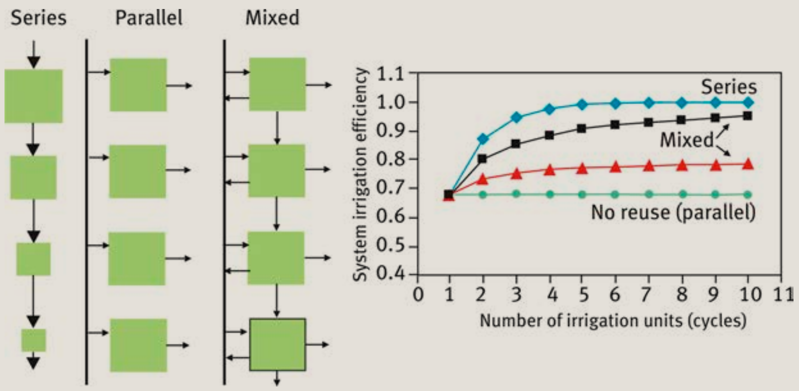
The rebound effects of improving irrigation efficiency

Figure ❷ displays the relationship between the deficit coefficient (defined as the proportion of the soil root zone that is not wetted during the irrigation event), the application efficiency and the distribution uniformity as well as the trajectory through that relationship of an irrigation modernization process. The introduction of pressurized on-farm irrigation (i.e., localized or sprinkler systems) allowed better distribution uniformity and thus higher application efficiency with less deficit. Modern systems, which may apply water with a distribution uniformity greater than 90%, have the potential of applying water with practically 100% efficiency while filling the entire root zone (Figure ❷).

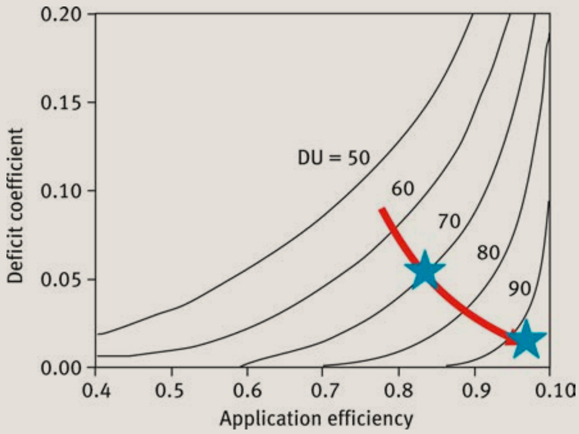
However, the introduction of irrigation systems that apply water more uniformly may actually increase evapotranspiration and therefore watershed depletion. Figure ❸ presents the yield response to irrigation and evapotranspiration under two conditions, supposedly representing the situation before and after modernization (i.e., the introduction of pressurized irrigation systems that augmented distribution uniformity, DU, from 70% to 95%). The yield response to evapotranspiration is usually a linear function. However, the response to applied irrigation is curvilinear, with a curvature that increases as the distribution uniformity decreases. For a given yield, the horizontal distance between the straight line (the response to ET) to the curvilinear function represents the water losses. These water losses are notably greater for the DU=70% curve than for the DU=95% curve (Figure ❸), which is the expected result of the modernization of irrigation systems. However, Figure ❷ indicated that the deficit coefficient before modernization was significantly greater than zero, meaning that crop evapotranspiration under those conditions was slightly limited (Figure ❸). Therefore, while the modernization brought a decrease of water usage, it also implied an increase of evapotranspiration, the main consumptive use in irrigated agricultural systems. This is one face of the so called "rebound effect" (Berbel and Mateos, 2014).

Moreover, if land is not a limiting factor, an improvement on irrigation efficiency may provoke expansion of the irrigated area using "water savings". This would be the response of farmers aiming to maximize profit. Figure ❹ presents the income and cost response to applied water and indicates the maximum benefit under water limiting and land limiting conditions (English, 1990). Note that the maximum benefit under land limiting conditions is greater than under water limiting conditions and it is obtained with more applied water. Therefore, if the farmer has dryland that cannot be irrigated because of the limitation of water resources, an improvement of irrigation efficiency could free some water and allow the expansion of the irrigated area and therefore the benefit. This expansion would imply an increase of evapotranspiration, the second face of the "rebound effect". Furthermore, since yield and benefit would increase if additional irrigation water were allocated to the new irrigated area, farmers will be tempted to lobby with the goal of obtaining more water resources. This is the beginning of a spiral that may explain the constant increase of irrigated

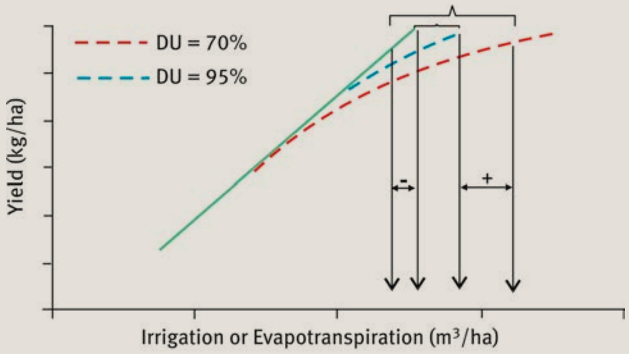
❶ Ideal arrangements of irrigation units (green squares) in an irrigation system (scheme, basin): series, parallel and mixed. System irrigation efficiency as a function of the number of cycles (or irrigation units) and the arrangement of the irrigation units: series (blue diamonds), parallel (green circles), and two examples of mixed systems with different type and degree of reuse (black squares and red triangles). Adapted from Mateos (2008).



❷ Relationship between the deficit coefficient (defined as the proportion of the soil root zone that is not wetted during the irrigation event), the application efficiency and the distribution uniformity (DU, %) in on-farm irrigation systems and trajectory of improvement from DU=70% to DU=95%.

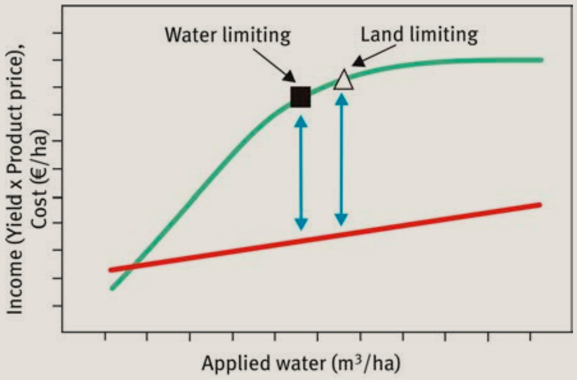


❸ Yield response to evapotranspiration and to irrigation with distribution uniformity, DU, of 70% and 95%. The green straight line represents yield response to evapotranspiration and the blue and red dashed lines represent yield response to irrigation with distribution uniformity (DU) of 95% and 70%, respectively. The keys represent the difference between applied and evapotranspirated water for idealized modern (DU=95%) and traditional (DU=70%) irrigation scenarios, respectively. The positive sign (+) indicates irrigation water reduction (positive gain) due to modernization; the negative sign (-) indicates evapotranspiration increase (negative gain) due to modernization.

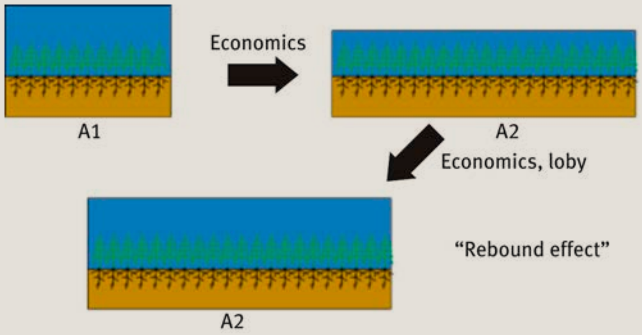


areas (Figure ❺) observed in many regions, for instance in Spain. This third face of the "rebound effect" is probably the main cause of overexploitation of water resources that it is observed worldwide.

❹ Income (green curve) and cost (read line) responses to applied water under water limiting and land limiting conditions. The black square and open triangles indicate income for the applied water that gives maximum benefit under water and land limiting situations, respectively. The blue arrows indicate the respective maximum benefits.



❺ Representation of the spiral expansion of irrigated land using "water savings" result of improved irrigation efficiency and of "lobbing" to obtain additional water resources. Economic reasons lead to transform dryland into deficit-irrigated land to use water savings due to modernization (first arrow in the figure). Benefit would increase by reducing the degree of deficit, thus farmers will lobby to obtain additional water resources (second arrow in the figure).



Conclusions

- The effect of improving unit irrigation efficiency on watershed irrigation efficiency is highly dependent on the hydrological arrangement of the irrigation units.
- In closed basins, water is conserved only by reducing evapotranspiration.
- The improvement of irrigation efficiency may entail an increase of water consumption ("rebound effect").
- There is the temptation of investing "water savings" into an expansion of irrigated area, further increasing water consumption ("rebound effect").
- However, there are good reasons to improve on-farm irrigation efficiency that have not been addressed in this paper. ■

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FURTHER READING...

BERBEL, J., MATEOS, L., 2014, Does investment in irrigation technology necessarily generate rebound effects? A simulation analysis based on an agro-economic model, *Agricultural Systems*, vol. 128, pp. 25-34, **https://doi.org/10.1016/j.agsy.2014.04.002**

ENGLISH, M., 1990, Deficit irrigation. I: analytical framework, *J. Irrig. Drain. Eng.*, vol. 116, pp. 399-412, **https://doi.org/10.1061/(ASCE)0733-9437(1990)116:3(399)**.

MATEOS, L., 2008, Identifying a new paradigm for irrigation system performance, Irrigation Science, vol. 27, pp. 25-34, **https://doi.org/10.1007/s00271-008-0118-z**

MATEOS, L., YOUNG, C.A., WALLENDER, W.W., CARLSON, H.L., 2000, Simulating spatially distributed water and salt balances, *Journal of Irrigation and Drainage Engineering*, vol. 126, pp. 288-295, **https://doi.org/10.1061/(ASCE)0733-9437(2000)126:5(288)**

VIVAS, G., GIRÁLDEZ, J.V., MATEOS, L., 2016, Water management in an ancestral irrigation system in southern Spain: a simulation analysis, *Irrigation Science*, vol. 34, pp. 343-360, **http://doi.org/10.1007/s00271-016-0507-7**

Irrigation canal in Spain.

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