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Evaluación del desempeño del sistema de riego: Un análisis global y local en Costa Rica

Performance evaluation of irrigation system: A global and local analyses in Costa Rica

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TÍTULO DE LA TESIS: Evaluación del desempeño del sistema de riego: Un análisis global y local en Costa Rica.

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INFORME RAZONADO DEL/DE LOS DIRECTOR/ES DE LA TESIS

(se hará mención a la evolución y desarrollo de la tesis, así como a trabajos y publicaciones derivados de la misma).

El doctorando ha tenido una excelente trayectoria en la realización del programa de doctorado de la UCO, partiendo de su gran interés y dedicación al mismo. Su compromiso con el programa ha sido total y completo y su evolución en el tiempo, extraordinaria.

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Artículo 1: A global analysis of irrigation scheme water supplies in relation to requirements, publicado por Juan Benavides, et al., en: Agricultural water management (IF> 4).

Artículo 2: Evaluating Irrigation Scheme Performance in a Tropical Environment: The Guanacaste Scheme, Costa Rica. Por Juan Benavides et al., enviado a Irrigation and Drainage.

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Por todo ello, se autoriza la presentación de la tesis doctoral.

Córdoba, 25 de septiembre de 2020

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Dedicada,

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Profesor, jefe, mentor y amigo

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Lista de símbolos

ETc	Evapotranspiración de cultivo
ETo	Evapotranspiración de referencia
t ha^{-1}	Tonelada por hectárea
$\boldsymbol{\beta}_{\mathbf{n}}$	Coeficiente de regresión para cada correspondiente efecto X_n
$\mathbf{X}_{\mathbf{n}}$	Efectos del modelo
$\boldsymbol{\alpha}$	Intercepto de la ecuación del modelo

Lista de abreviaturas

AC	Arable crops
Arr	Arrange schedule
Cl	Close collective distribution
Dem	Demand schedule
EU	Europe
Gh	Greenhouses
IND	Hindustan
LA	Latin America
Loc	Localized irrigation system
MENA	Middle East and North Africa
NIR	Net irrigation Supply
Op + Cl	Open and Close collective distribution
Op	Open collective distribution
RIS	Relative irrigation supply
Rot	Rotation Schedule
SEA	Southeast Asia
Spr + Loc	Sprinkler with Localized irrigation system
Spr + Sur	Sprinkler with Surface irrigation system
Spr	Sprinkler irrigation system
SSA	Sub-Saharan Africa
Sur	Surface irrigation system
Tr + AC	Fruit trees whit Arable crops
Tr	Fruit trees

Abstract

The growing demand for agricultural products worldwide focuses its attention on crop yield, understood as the weight of agricultural product per unit of harvested area. The increase in crop production is mainly determined by the increase in actual yields crops, until reaching their potential, which, in turn, is expected to continue to increase with new technologies, as it has been doing since the green revolution. The agricultural yield gap is a performance index strongly used to measure agricultural performance, whether at the parcel, irrigation district, watershed or region level. Yield gap refers to the difference between the potential yield of a crop and the actual yields of farmers on a specified spatial and temporal scale of interest. The performance of irrigation systems comprises the ratio between the irrigation water consumed by crops and the water diverted from the supply source. To improve the use of water in agriculture, the evaluation of irrigation performance is essential. One of the main indicators used to evaluate this performance considers the relationship between the amount of water supplied and the net irrigation needs of the crop, known as the relative irrigation supply (RIS).

This PhD thesis presents a global analysis of the performance of irrigation schemes through evaluating the key attributes that influence the RIS. In addition, an analysis was carried out that characterized the performance through the RIS and the yield gap of a tropical irrigation scheme in Costa Rica during a period of five years, from 2014 to 2018. The first analysis was based on a review of scientific reports and articles that collected 264 cases from 25 countries in six world regions. The database was subjected to two types of statistical analysis: a cluster analysis of k-means and analysis of covariance (ANCOVA). The cluster grouped irrigation schemes that were characterized by a low RIS and hight irrigation technology; as well as irrigation schemes with the highest RIS values, poor irrigation technologies and the prevalence of abundant rainfall. The ANCOVA showed that the RIS covaried significantly with the variation in precipitation, the delivery schedule, the irrigation systems on the farm, the distribution network and the region, but not with the crop. The ANCOVA also showed that modern on-farm pressurized irrigation systems and on-demand distribution systems significantly improve RIS.

The second analysis of tropical irrigation scheme, showed that the RIS ranged between 2.48 and 3.78, values much higher than those observed in temperate area schemes, but which are in the lower rank of the RIS values documented in other tropics schemes. Actual yields were determined through semi-structured surveys with farmers in the scheme who also gave information about other irrigation management issues. The yield gaps of the main crops (rice, sugar cane and fodder crops) ranged between 26-43%, 64-69% and 30-40%, respectively. The survey revealed that in this scheme the users show a high satisfaction degree with the service, in terms of the supply of irrigation water and its cost, there are ample opportunities to improve the irrigation scheme's performance and to close the yield gaps (e.g. update the water supply schedule to avoid shortages in the tail of the canals and improve drainage network).

Resumen

La creciente demanda de productos agrícolas a nivel mundial centra su atención en el rendimiento del cultivo, comprendido como el peso del producto agrícola por unidad de área cosechada. El incremento en la producción de cultivos es determinado, principalmente, por el aumento de los rendimientos actuales de cultivo, hasta alcanzar su potencial, el cual, a su vez, se espera que siga su incremento con nuevas tecnologías, como lo ha venido haciendo desde la revolución verde. La brecha de rendimiento agrícola es un indicador de desempeño fuertemente utilizado para medir el desempeño agrícola, ya sea a nivel de parcela, distrito de riego, cuenca o región. La brecha de rendimiento se refiere a la diferencia que existe entre el rendimiento potencial de un cultivo y los rendimientos actuales de los agricultores en una escala de interés espacial y temporal especificada. El desempeño de los sistemas de riego comprende la proporción entre el agua de riego consumida por los cultivos y el agua desviada desde la fuente de suministro. Para mejorar el uso de agua en la agricultura es fundamental la evaluación del desempeño del riego. Uno de los principales indicadores usados para evaluar este desempeño contempla la relación entre la cantidad de agua suministrada y las necesidades netas de riego del cultivo, conocido como suministro relativo de riego (RIS).

Esta tesis doctoral presenta un análisis mundial del desempeño de los esquemas de riego mediante la evaluación de los atributos clave que influyen en el RIS. Además, se realizó un análisis que caracterizó el desempeño a través del RIS y de la brecha de rendimiento de un esquema de riego tropical en Costa Rica durante un período de cinco años, de 2014 a 2018. El primer análisis se basó en una revisión de informes y artículos científicos que arrojaron 264 casos pertenecientes a 25 países en seis regiones del mundo. La base de datos se sometió a dos tipos de análisis estadístico: Un análisis de clústeres de k-medias y un análisis de covarianza (ANCOVA). El clúster agrupó los esquemas de riego que se caracterizaron por un bajo RIS y tecnología de riego avanzada; así como esquemas de riego con los valores de RIS más altos, pobres tecnologías de riego y presencia de abundantes precipitaciones. El ANCOVA mostró que el RIS covarió significativamente con la variación en la precipitación, el calendario de entrega, los sistemas de riego en la parcela, la red de distribución y la región, pero no con el cultivo. El ANCOVA también mostró que los sistemas modernos de riego presurizado en la finca y los sistemas de distribución a demanda mejoran significativamente el RIS.

El segundo análisis del distrito de riego en trópico, mostró que el RIS osciló entre 2,48 y 3,78, valores muy superiores a los observados en esquemas de áreas templadas, pero que se encuentran en el rango bajo de los valores de RIS documentados en otros esquemas de los trópicos. Los rendimientos actuales se determinaron a través de entrevistas semiestructuradas con los agricultores del esquema que también brindaron información acerca de otros temas de manejo del riego. Las brechas de rendimiento de los principales cultivos (arroz, caña de azúcar y cultivos forrajeros) oscilaron entre 26-43%, 64-69% y 30-40%, respectivamente. La encuesta reveló que en dicho esquema los usuarios muestran un alto grado de satisfacción del servicio en cuanto al suministro de agua de riego y su costo, existen amplias oportunidades para mejorar el desempeño del esquema y para cerrar las brechas de rendimiento (p.ej. actualizar el cronograma de suministro de agua para evitar escasez en la cola de los canales y mejorar la red de drenajes).

Capítulo 1. Introducción general

Capítulo 1. Introducción general

El conocimiento de la evolución, a lo largo del tiempo, del aprovechamiento del agua en la agricultura nos ayuda a entender la importancia que esta práctica ha tenido en el desarrollo de las civilizaciones, y brinda un punto de partida para comprender el valor que tiene la evaluación del desempeño del riego en la protección y buen uso que se le dé al agua. La alta variabilidad de las condiciones de suministro de agua que experimentan muchas áreas de producción agrícola en todo el mundo ha creado una dependencia del riego desde la época neolítica. Ha habido civilizaciones que crecieron y desaparecieron al fracasar sus sistemas de riego y otras que los han mantenido operativos durante milenios (Van Schilfgaarde, 1994). Angelakis et al. (2020) realizaron una descripción general de la evolución histórica global del riego de tierras agrícolas (Tabla 1.1), basada en una investigación bibliográfica centrada en técnicas antiguas de gestión del agua, prácticas de riego ingeniosas y la gestión de las tierras asociadas.

Table 1. Breve cronología del desarrollo histórico del riego agrícola. Adaptada de Angelakis et al (2020).

Periodo	Logros	Ubicación / Comentario
5000–2500 a.C.	Primeras evidencias confirmada de habitación y los primeros agricultores. El primer riego agrícola exitoso.	Mesopotamia, China
3050–2050 a.C.	Los primeros sistemas de riego en Egipto y Mesopotamia	
2200– 771 a.C.	Surgimiento de sistemas de canales agrícolas.	Antigua China
ca. 800 a.C.	Se desarrolló la tecnología *Qanat*, que se encuentra entre los métodos de riego más antiguos que se conocen y todavía se utiliza en la actualidad en varias partes del mundo.	Persia y otros lugares
167 a.C.–330 d.C.	Los romanos inventaron el hormigón romano (*opus caementitium*) que permitió la construcción de canales largos, puentes muy grandes y túneles largos en roca blanda.	Periodo romano
1200–1500 d.C.	Uso de Chinampas, que es un método de cultivo utilizado por la civilización azteca que consiste en pequeñas islas artificiales ubicadas en lagos en marismas sin necesidad de riego y optimizando el uso de tierras agrícolas, agua y desechos para aumentar los rendimientos.	México
1279–1911 d.C.	Los pólderes en el lago Poyang y el lago Dongting de la cuenca del río Yangtze y el recinto del dique en el delta del río Pearl entraron en el período de desarrollo a gran escala, que hizo que la cuenca del río Yangtze y la cuenca del río Pearl se convirtieran en centros económicos de China.	Antigua China
1900 – Hoy	Alrededor de 1800 la extensión de tierra irrigada era de aprox. 8 M ha, y alcanzó los 47 M ha alrededor de 1900 con un consumo de agua para riego de 500 mil millones de m^3 / año. Los cuatro países principales con la mayor superficie equipada para riego en 1900 fueron India, China, Pakistán y Estados Unidos. Se espera que la demanda total de agua aumente de 4000 en la actualidad a 5500 mil millones de m^3 / año en 2050, siendo el riego el uso principal.	Global

De la Tabla 1 se puede concluir que el riego es una práctica ancestral que tuvo su origen en muy diversas civilizaciones en los cinco continentes, al igual que la agricultura. El constante desarrollo del riego ha hecho posible proporcionar un suministro estable de agua a los campos, lo que ha mejorado drásticamente los rendimientos a la vez que mejoraba la calidad de vida de los agricultores. Además, la existencia de la agricultura de regadío ha cambiado mucho la vida de las personas, como la formación de aldeas, porque el trabajo conjunto es indispensable para la construcción y el manejo de canales de riego, drenaje y de formas altamente tecnificadas de aplicar agua al sistema suelo-planta.

El vínculo agua-energía-alimentos está guiando ahora nuevos enfoques para hacer del riego una práctica sostenible desde muchos puntos de vista. El más importante es quizás la capacidad de garantizar un suministro de alimentos suficientes y saludables para una población mundial en constante crecimiento, es decir, reforzar la seguridad alimentaria del Planeta. El agua para riego es un bien básico, pero no hay que olvidar que, sin suelos en buenas condiciones productivas, la agricultura no prosperaría incluso si hubiera suficiente agua para cultivar plantas para la producción de alimentos (Angelakis et al., 2020).

Estado actual e importancia del riego

Las mejoras en el rendimiento agrícola de las últimas seis décadas han sido impulsadas por dos factores clave: la adopción generalizada de nuevas variedades, insumos y prácticas agrícolas; y por avances en la tecnología y la expansión del riego (FAO, 2011). El riego ha contribuido, en gran medida, a mejorar la productividad y la producción agrícolas. La superficie de tierras agrícolas a nivel mundial representa el 37,1% de la superficie total, y de estas, sólo el 20 %

cuentan con sistemas de riego pero generan el 40% de toda la producción agrícola mundial, de ahí la importancia que tiene el riego (UNESCO, 2020). El agua para riego representa el 69% de la extracción de agua mundiales, seguido de la industria (incluyendo la generación de energía) que representa el 19%, y los hogares el 12% (UNESCO, 2020). Además, la demanda global de agua mantendrá un aumento constante hasta 20-30% para el año 2050, cuando gran parte de este crecimiento se atribuirá a los aumentos en la demanda de los sectores industrial y doméstico (Burek et al., 2016). Esto implica que la porción total de agua usada en la agricultura disminuirá en comparación con otros sectores, sin embargo, seguirá siendo el mayor usuario en general en las próximas décadas, en términos de extracción y consumo de agua. Por esto, la agricultura se enfrenta al reto de proveer la demanda creciente de alimentos, mientras garantiza el uso sostenible de un recurso hídrico cada vez más limitado. Este crecimiento en la demanda de alimentos centra su atención en la importancia que tiene la agricultura de regadío. La expansión de las tierras irrigadas en las próximas tres décadas, proyectada en 32 millones de ha, es un aumento en términos netos. Se asume que las pérdidas de tierras de regadío existentes debido, por ejemplo, a la escasez de agua o la degradación debido a la salinización y el anegamiento, se compensarán mediante la rehabilitación o sustitución de nuevas áreas (Bruinsma, 2009).

La práctica del riego

El control de las pérdidas de agua dentro de la práctica del riego es un tema fundamental para un manejo adecuado de los sistemas de riego, tanto para regiones con escasez generalizada de agua, como para regiones con alta demanda de agua en ciertos periodos del año, como ocurre en zonas del trópico húmedo. Sin embargo, Bruinsma, (2009) señala que el término "eficiencia en el uso del agua" implica pérdidas de agua entre la fuente y el destino, pero no toda esta agua se pierde en realidad, ya que la mayor parte de los flujos de retorno a la cuenca fluvial y los acuíferos se pueden reutilizar para el riego.

Conocer e identificar las pérdidas de agua en un sistema de riego permite evaluar las medidas necesarias y alcanzables para mejorar su desempeño. Las pérdidas de agua en el sistema pueden variar según su ubicación, sin embargo, se pueden identificar aquellas pérdidas en la fuente, durante la conducción de líquido, en el sistema de riego en la finca y también por un calendario de entregas de agua inadecuado.

Las pérdidas de agua operativas de manejo del riego pueden ser identificadas y localizadas utilizando medidores de flujo de agua en puntos clave del sistema. El lugar más adecuado para restablecer el control a estos efectos es la cabecera de los canales (Clemmens, 2006). Sin embargo, si queremos conocer primero las posibles pérdidas de agua que se producen en la fuente (p.e. lagos, ríos, embalses), es necesario medir o estimar los flujos de entrada y salida de agua y realizar un balance de agua.

Las pérdidas de agua debidas a la infiltración durante la conducción desde la fuente hasta el usuario se pueden contabilizar con la medición del caudal en la cabecera del sistema y la medición de las entregas que se hagan a todos los usuarios y a la salida del sistema, si este aporta agua a otro sistema. Las paredes de los canales abiertos sin revestimiento y los lechos de los ríos utilizados para transportar agua en regiones áridas suelen filtrar grandes cantidades de agua. Una de las principales acciones para mejorar la eficiencia en el transporte de agua es la mejora de la infraestructura hidráulica, mediante la sustitución de antiguas redes de distribución de canales abiertos por sistemas presurizados (Plusquellec, 2009), o en caso de no poder cambiar toda la red de distribución, se pueden revestir con materiales arcillosos, láminas enterradas, membranas sintéticas u hormigón. Sin embargo, a menos que se tenga mucho cuidado durante la construcción y el mantenimiento, las fugas generalmente se reducen solo en una pequeña cantidad (20-40%) (Rushton, 1986). Rodriguez-Díaz et al, (2012) analizaron el desempeño de una red de distribución de agua, que pasó de canales abiertos a nuevos sistemas presurizados. Los autores destacaron la reducción del uso de agua debida a nuevos sistemas de distribución, pero también señalaron el efecto que esto pudo tener a nivel de finca, como la introducción de cultivos de mayor valor y más demandantes de agua, así como el efecto en los mayores costos asociados a la operación, administración, y mantenimiento del nuevo sistema de bombeo (Camacho Poyato et al., 2011).

Las mejoras de la tecnología y la gestión del riego en finca pueden generar ahorros importantes de agua. Muchos de los problemas de la agricultura de regadío pueden mitigarse o evitarse mejorando la tecnología y la gestión de los sistemas de riego en la finca y abordando adecuadamente los aspectos sociales, culturales y ambientales. Esto permitirá aumentar la calidad del manejo en el riego y así optimizar los beneficios (Van Schilfgaarde, 1994). La utilización de sistemas de riego que sean más eficientes permite acercar la aplicación de agua a la demanda de los cultivos. Por ejemplo, cambiando del riego superficial o aspersión a riego localizado (goteo superficial, goteo subterráneo o micro-aspersor), cuando el cultivo lo permita. Es probable que todos los sistemas localizados eliminen la deriva y la evaporación directa que ocurren normalmente durante el riego por aspersión, además reducen la escorrentía y el drenaje, ya que disminuyen la cantidad de agua aplicada (por lo general por debajo de la saturación del suelo), permiten un mejor control de estas cantidades y proporcionan tasas más bajas de infiltración (Serra-Wittling et al., 2019). El riego por goteo reduce notablemente la evaporación del suelo, siendo esto importante en el caso del riego de árboles frutales (Bonachela et al., 2001).

La modernización de los sistemas de riego para reducir las pérdidas de agua debe considerar la relación que existe entre el uso del agua y la energía que demanda el sistema. Tarjuelo et al. (2015) señalan que este equilibrio es alterado con mayor fuerza cuando se reemplazan los sistemas de canal abierto, operados por gravedad, por redes de distribución presurizadas y se cambia el método de riego de superficie a uno presurizado, el cual, señalan, es el enfoque de modernización más común en España y otros países.

Los calendarios de entregas de agua a los usuarios son el sistema de asignación del tiempo (cuando y por cuanto) que determina una cantidad de agua en función de la flexibilidad permitida en el sistema de riego, fundamentalmente a partir de criterios agronómicos de riego o de acuerdo con el desarrollo de la actividad. En un sistema productivo agrícola, las demandas del mercado deben ser satisfechas a través del cultivo de una amplia variedad de productos en el momento adecuado de oportunidad. Para llegar a esto los agricultores necesitan flexibilidad para aumentar el valor de los cultivos producidos. Sin embargo, existe un compromiso entre flexibilidad y control. A medida que los agricultores exigen más flexibilidad, el control se vuelve más difícil porque los cambios en el flujo del canal son más grandes y frecuentes (Clemmens, 2006). Los calendarios de entrega flexibles podrían mejorar la eficiencia en la finca al permitir que los agricultores apliquen la cantidad correcta de agua en el momento adecuado (adaptada al cultivo y al método de riego) y limitar las incertidumbres que inducen el riego excesivo (Clemmens and Molden, 2007). Sin embargo, los servicios de entrega flexibles suelen estar asociados con sistemas de distribución y equipos de control más sofisticados y costosos.

La producción agrícola y el riego en el trópico

El trópico se ha caracterizado por un bajo rendimiento en la producción agrícola en comparación con regiones templadas (West et al., 2010). Este bajo rendimiento en el trópico, a pesar de las favorables condiciones térmicas y de radiación solar, se debe en gran parte a problemas agronómicos, las sequías periódicas, el bajo consumo de fertilizantes y la prevalencia de plagas y enfermedades debidas a fuertes precipitaciones durante la estación lluviosa (Chang, 1977; Gallup y Sachs, 2000) y problemas de anegamiento por drenajes inadecuados (Manik et al., 2019). Además, las diferencias en el gasto en investigación por trabajador agrícola son gigantescas: los países templados gastan diecinueve veces más en investigación por trabajador que los países de las zonas tropicales y secas (Gallup y Sachs, 2000).

El clima juega un papel importante en la baja productividad en zonas tropicales. Aunque los trópicos son generalmente más cálidos y soleados durante todo el año que las zonas templadas, la alta nubosidad bloquea la luz solar, afectando negativamente la fotosíntesis, y las altas temperaturas nocturnas provocan una alta respiración que ralentiza el crecimiento de las plantas. Durante los meses de verano, las zonas templadas tienen días más largos que los trópicos, lo que da una ventaja a los cultivos de temporada de verano en las zonas templadas (Gallup y Sachs, 2000). Los patrones de precipitación en la zona tropical varían desde los de áreas secas y semiáridas con distribuciones poco confiables, hasta aquellos con exceso de lluvia interrumpido solo por una breve estación seca. Esto último, junto con la ausencia de períodos de heladas, permite que las malas hierbas, plagas y enfermedades completen su ciclo muchas veces durante el año (Affholder et al., 2013), afectando no solo el rendimiento de los cultivos, sino también la salud de la mano de obra agrícola (ej. Malaria, Dengue).

Los suelos en el trópico se caracterizan por ser en gran medida oxídicos y caoliníticos, inherentemente pobres y fuertemente erosionados, ácidos y a menudo también suelos jóvenes formados sobre minerales resistentes presentes en texturas gruesas (Sanchez, 1976). En condiciones de alta precipitación con sistemas radiculares de cultivos poco profundos, especialmente en suelos ácidos en los trópicos húmedos, la tasa de lixiviación de nitrógeno es alta y en consecuencia la sincronía en la mineralización de nutrientes en suelos del trópico y la absorción por parte del cultivo se ve reducida, afectando negativamente la productividad (Van Noordwijk et al., 1991). Por ello, Agegnehu y Amede (2017) señalan que el mayor desafío para la agricultura tropical es la degradación del suelo y la reducción de la fertilidad del suelo para una producción agrícola sostenible, lo que es asociado a la erosión del suelo, la extracción de nutrientes, la competencia por la biomasa para usos múltiples, la aplicación limitada de fertilizantes inorgánicos y la capacidad limitada de los agricultores para reconocer la disminución de la calidad del suelo y sus consecuencias sobre la productividad.

El anegamiento es una limitación importante para la producción de cultivos en todo el mundo en áreas con lluvias abundantes y / o drenaje deficiente (Manik et al., 2019; Yaduvanshi et al., 2012). En la región del trópico, los factores de alta pluviosidad y alta presencia de suelos arcillosos, combinados con utilización de suelos aluviales o zonas bajas, presenta un problema asociado de encharcamiento por un manejo inadecuado o insuficiente de los sistemas de drenajes de evacuación del excedente de agua (Bationo et al., 2006; Chang, 1977; Yaduvanshi et al., 2012).

Ante este escenario, parece innegable que la aplicación de fertilizantes inorgánicos en suelos agrícolas tropicales sería la solución apropiada en esta región. Sin embargo, la dificultad de acceso a ellos y la alta probabilidad de que los nutrientes sean arrastrados por la erosión del suelo generalmente desalienta a los agricultores a aplicar fertilizantes (Agegnehu y Amede, 2017). Aunado a esto, el uso de fertilizantes nitrogenados en la región del trópico está limitado por una baja eficiencia agronómica, una relación costo / beneficio desfavorable, una escasa accesibilidad y una creciente preocupación por los efectos ambientales (Tittonell y Giller, 2013; Van Noordwijk et al., 1991).

Aunque la precipitación anual en la mayor parte del trópico es superior a la demanda evaporativa, la variabilidad interanual y estacional hace que el riego se vea como una opción deseable para mejorar la agricultura de la región. Sin embargo, la creciente competencia por el agua está ejerciendo una gran presión globalmente sobre la disponibilidad de agua de riego, y especialmente para cultivos que requieren mucha agua, como el arroz u otros cultivos propios de climas tropicales (Kima et al., 2014). La agricultura de regadío podría mejorar notablemente la productividad agrícola en la región tropical, suministrando agua al cultivo en la estación seca y en periodos secos. El riego en los trópicos húmedos suele ser un riego suplementario (Bristow et al., 1998), que busca satisfacer las demandas de agua durante la estación seca, y reducir al mínimo los costos asociados a prácticas de riego durante la estación de lluvia. Sin embargo, las limitaciones debidas al clima, a los suelos, las plagas, la baja inversión en la zona tropical y las pobres tecnologías de riego típicamente encontradas en estas latitudes obstaculizan el retorno que puede proporcionar el riego.

La agricultura del riego en ambientes tropicales permite intensificar la producción, introduciendo más cultivos y acortando la duración del ciclo, reduciendo su sensibilidad a los cambios estacionales. Lo más importante es aumentar el rendimiento por día, lo que puede hacerse debido a la posibilidad de utilizar cultivos múltiples, lo cual es posible en ausencia de restricciones por bajas temperaturas, típicas del clima tropical (Evans, 1986).

Sistemas colectivos de riego

Los sistemas de riego colectivos tienen como objetivo la captación, almacenamiento y regulación, tratamiento y transporte del agua desde su origen hasta cada una de las parcelas de distintos usuarios, para garantizar el correcto funcionamiento del riego (Arviza y Balbastre, 2003). El agua se puede extraer de fuentes superficiales como ríos, lagos o reservorios, o de pozos de agua subterránea. A partir de esta fuente, la distribución del agua través de la red del sistema se puede realizar a través de canales abiertos (revestidos o no), tuberías presurizadas o sistemas mixtos que integren ambos sistemas en diferentes tramos hasta la entrada de la parcela de cada usuario. La forma en que la administración de un sistema de riego colectivo entrega el agua depende de los acuerdos alcanzados con los usuarios y de las capacidades del sistema para sostener un determinado calendario de riego a través del tiempo. Estos pueden ser a demanda, donde el usuario dispone de la total libertad de manejar el agua que ingresa a su finca, y por tanto representa la mayor flexibilidad de los calendarios. Puede ser acordado, que es cuando cada regante solicita la cantidad de agua que quieren y el gestor compone un turno de reparto que intenta satisfacer lo solicitado por cada regante dentro de la capacidad del sistema. Si el sistema no lo permite, entonces el gestor tiene que acordar con los regantes otro programa de entregas que sí se ajuste al sistema. Y por último, puede ser rotación fija, donde se asigna las fechas y la cantidad de agua a cada usuario, y por tanto representa la menor flexibilidad de los calendarios de entregas (FAO, 2007).

El funcionamiento óptimo de los sistemas de riego colectivo se centra en que un grupo de agricultores que comparten los recursos hídricos cooperan en conjunto para maximizar los beneficios particulares del recurso (Muchara et al., 2014; Ostrom, 2010). La evaluación de desempeño en un sistema de riego colectivo, es fundamental para mantener un nivel de servicio aceptable. La evaluación permite comunicar al usuario del agua sus derechos (en términos de acceso y recepción de agua) y responsabilidades (pago o contribución en especie, por ejemplo, para mantenimiento), además de servir de control de la administración del servicio para que brinde los estándares de suministro acordado (Bos et al., 2005).

El desempeño de los sistemas de suministro de agua a menudo se expresa en términos relativos a la eficiencia. Este término se usa frecuentemente en el caso de los sistemas de riego y se aplica comúnmente a cada subsistema de riego (almacenamiento, transporte, distribución dentro y fuera de la finca y subsistemas de aplicación en la finca), y se puede definir por la relación entre el volumen de agua de riego usada beneficiosamente y volumen total (usos beneficiosos más los no beneficiosos) de agua de riego que sale de los límites del sistema (agua aplicada menos almacenamiento), normalmente expresada en porcentaje (Bos and Nugteren, 1990; Burt et al., 1997). En este sentido se debe tener claro que aumentar la eficiencia del riego no representa el aumento del agua disponible, sino una reducción de las pérdidas de agua que no se consume de manera beneficiosa. En algunos casos, la fracción de agua no consumida por los cultivos es utilizada por otros sistemas aguas abajo; entonces, mejorar la eficiencia no sería ventajoso para el sistema total.

La modernización de los sistemas de riego permite mejorar la eficiencia e incrementar la productividad de la tierra y del agua, una mejor operación y gestión de los sistemas de riego colectivos, así como las condiciones de trabajo de los usuarios. Sin embargo, estas mejoras implicarán una mayor demanda de energía (al mejorar el servicio de entrega de agua) y un monto de inversión que debe ser presupuestado. Tarjuelo et al, (2015) ponen el énfasis en mostrar que la viabilidad económica, social y ambiental del proceso de modernización del riego es particular para cada contexto.

Desempeño de los sistemas de riego colectivos.

La gestión de los sistemas de riego es el conjunto de actividades y medios necesarios para asignación, regulación y entrega del agua para riego a un grupo de usuarios de modo que ello permita a los usuarios el máximo beneficio tanto en términos económicos como sociales (Molden y Gates, 1990; Sagardoy et al., 2003). Dentro del conjunto de actividades de la gestión del riego, está la organización y la planificación de todas las acciones para alcanzar un objetivo (la asignación, regulación y entrega de agua), a través de los medios necesarios (infraestructura del sistema de riego, el recurso humano y los acuerdos, normas o reglamentos) en un sistema de riego (Jiménez, 2014).

La calidad de un servicio se refiere a la capacidad de un proveedor para satisfacer las necesidades de los clientes o usuarios. Si la expectativa está más allá del desempeño, la calidad del servicio se percibe como insatisfactoria (Lewis y Mitchell, 1990). La percepción de la calidad del servicio por parte de los usuarios de un sistema colectivo de riego es la relación entre las expectativas y el desempeño real que los proveedores de servicio brindan (Rustinsyah, 2019). Por lo tanto, la medición de la percepción de servicio es necesaria para determinar el efecto de la calidad del servicio en la satisfacción de los miembros de quienes los reciben.

Para caracterizar el comportamiento de los agricultores y comprender las razones detrás de las tendencias de desempeño observadas, es necesario recurrir a encuestas, especialmente semiestructuradas (García-Vila et al., 2008; Takeda et al., 2019), donde el entrevistador no sigue solamente una lista formal de preguntas. Este tipo de entrevistas permite recopilar información puntual del agricultor, como producción en determinado periodo, y también permite recopilar su perspectiva con respecto a la calidad de un servicio, y en muchos casos indagar cuestiones que no habían sido contempladas previamente.

Los impactos en los rendimientos agrícolas, los ingresos de los agricultores y la gestión del agua de distritos de riego colectivos se deben en gran medida a la calidad del servicio de suministro de agua. La evaluación del desempeño puede utilizar indicadores referentes a la confiabilidad, dependencia, adecuación o equidad de las entregas. Estos y otros indicadores son medidas de la capacidad de los sistemas de riego colectivos para el suministro oportuno de agua con descargas apropiadas, presión suficiente en la cabeza del sistema, intervalos de tiempo y duración suficiente para satisfacer los requisitos de las fincas agrícolas durante la temporada de riego.

Indicadores de desempeño en la evaluación de distritos de riego

Un indicador de desempeño incluye tanto un valor real como un valor previsto que permite evaluar la desviación que existe entre ellos. Además, debe contener información que permita al administrador determinar si esa desviación es aceptable. Por tanto, siempre que sea posible, es deseable expresar los indicadores en forma de una relación entre la situación realmente medida y la prevista (Bos, 1997).

La evaluación del desempeño del riego busca el uso eficiente y efectivo de los recursos, proporcionando una retroalimentación relevante a la administración en todos los niveles y ayuda para obtener información útil para tomar acciones correctivas con la finalidad de maximizar los beneficios (Bos et al., 2005).

Algunos de los indicadores utilizados para evaluar el desempeño de un sistema de producción agrícola son (Burt et al., 1997; Fischer and Kertesz, 1976; Molden et al., 1998): Eficiencia de riego, coeficiente de uso consuntivo de riego, uniformidad de distribución, eficiencia de aplicación, suministro relativo del riego, capacidad de entrega de agua, brecha de rendimiento, adecuación, satisfacción, fiabilidad, producción por área regada, producción por suministro de riego, producción por agua consumida, entre muchos otros. Bos, (1997) indica que la cantidad de indicadores que deben utilizarse depende del nivel de detalle con el que se necesita cuantificar el desempeño (por ejemplo, investigación, gestión, información al público) y de la cantidad de disciplinas con las que debe analizar el riego y el drenaje (balance hídrico, economía, medio ambiente, gestión). Estos indicadores se han convertido en una poderosa herramienta para evaluar el manejo del riego tanto a nivel de distrito de riego como de finca (Rodríguez-Díaz et al., 2008). Un conjunto importante de indicadores de desempeño están relacionados con uso del agua, de los cuales algunos requieren la estimación de la evapotranspiración del cultivo (ET). La precisión de estos indicadores podría mejorarse estimando la ET utilizando técnicas de teledetección (Bos et al., 2005; Salgado and Mateos, 2021). Los métodos utilizados para obtener la ET a escala de distrito de riego se basan comúnmente en modelos de simulación y/o algoritmos de teledetección, debido a la dificultad de obtención de la ET a escala regional (Bastiaanssen et al., 2005).

Los modelos de simulación de cultivos en la evaluación del desempeño del riego

La necesidad de predicciones confiables para calcular las necesidades hídricas de los cultivos y la posterior programación del riego así como el crecimiento del cultivo, ha llevado al desarrollo de modelos desde principios de la década de 1980, tras la publicación de FAO24 de Doorenbos and Pruitt (1977). Estos modelos (p.e. AquaCrop, ISAREG, CROPWAT, SIMDualKc, MONICA, SWAP, RELREG, WEBISAREG, BUDGET, IRSIS, PILOTE, WOFOS) pueden utilizarse para apoyar la toma de decisiones de riego. Estos modelos permiten entender y predecir el balance de agua en el suelo y/o la producción de biomasa, y como interactúan ambos factores ante los diversos vectores de estrés de un cultivo en una escala de tiempo requerida. Una de sus aplicaciones puede ser la determinación de la producción máxima alcanzable para establecer el límite superior de la productividad esperada del regadío.

Dentro de la diversidad de modelos existentes, se mencionan únicamente los dos modelos para obtener los requerimientos netos de riego y producción (CropWat y AquaCrop) que se han utilizado en esta tesis. El modelo CROPWAT (Smith, 1992) consistió en una base de datos construida a partir de datos de FAO24 (Doorenbos and Pruitt, 1977), una base de datos meteorológica complementaria (CLIMWAT), una calculadora de ET de referencia y una herramienta computacional de balance hídrico capaz de proponer una calendario de programación de riego para el cultivo, suelo y campo seleccionados (FAO, 2009). El programa informático CROPWAT permite calcular la ET_0, requerimientos netos de agua para cultivos, los requerimientos de riego y el suministro de agua del esquema de riego, para desarrollar programas de riego bajo diversas condiciones de manejo.

El modelo AquaCrop es el modelo de balance de agua y producción desarrollado por la FAO (Steduto et al., 2009). Este modelo además del enfoque de coeficiente de cultivo dual (el coeficiente del cultivo se divide en dos factores que describen por separado las diferencias en la evaporación y la transpiración entre el cultivo y el pasto de referencia) adopta un enfoque “Kc-ET_0” basado en la cobertura del dosel (CC) para calcular la ET y sus componentes (Hsiao et al., 2009; Steduto et al., 2009). AquaCrop simula la respuesta del rendimiento de los cultivos herbáceos al agua y responde de forma precisa cuando las condiciones en las que el agua es un factor limitante en la producción de cultivos. Ambos modelos (AquaCrop y CropWat) brindan el requerimiento neto de riego que es empleado en el indicador de suministro relativo del riego. Por su parte AquaCrop muestra la producción potencial bajo las condiciones que se deseen para ser empleado en el indicador de brecha de rendimiento.

Suministro relativo del riego

El RIS relaciona el suministro con las necesidades netas de riego, y brinda una perspectiva de la condición de abundancia o escasez de agua en un periodo de tiempo determinado, normalmente anual. El suministro relativo de riego se centra únicamente en el agua de riego, en contraste con otro indicador utilizado habitualmente conocido como el suministro relativo de agua (RWS), que incluye la lluvia. Cuando el riego completa la diferencia entre los requerimientos de agua de los cultivos y los aportes por la lluvia, el RIS está cerca de la unidad (Molden et al., 1998). Se debe tener cuidado en la interpretación del RIS, ya que un valor adecuado depende del entorno y del momento donde se encuentre el distrito de riego (Molden et al., 1998). Si el valor de RIS es inferior a 1, entonces la demanda es mayor que la oferta de suministro, y el riego es deficitario. Contrariamente, si el valor de RIS es superior a 1, entonces se está regando en exceso.

Brecha de productividad. Productividad en sistemas de riego colectivos

La productividad de la tierra es la producción de un cultivo por unidad de superficie. Los indicadores "externos" se utilizan para relacionar las salidas de un sistema con las entradas de ese sistema. Estos indicadores externos son una herramienta de comparación de rendimientos entre países y regiones, diferentes infraestructuras, tipos de gestión y entornos, y para evaluar a lo largo del tiempo la tendencia en el desempeño de un proyecto específico (Sakthivadivel et al., 1999).

La variabilidad del rendimiento global está fuertemente controlada por el uso de fertilizantes, el riego y el clima (Mueller et al., 2012). A través del riego, es posible reducir la exposición de los cultivos al estrés hídrico y, por lo tanto, mejorar la productividad.

La brecha de rendimiento es estimada como la diferencia que existe entre el rendimiento real de los agricultores en una determinada escala de interés espacial (finca, zona regable o región) y temporal, y el rendimiento máximo (potencial) alcanzado de una variedad de cultivo adaptado o híbrido cuando se cultiva en condiciones favorables sin limitaciones de crecimiento por agua, nutrientes, plagas o enfermedades (Evans, 1993; Lobell et al., 2009). El rendimiento potencial, a su vez, puede definirse y medirse de diversas formas, entre las que destacan el rendimiento potencial basado en modelos de cultivos, en experimentos de campo, en el máximo rendimiento obtenido por los agricultores de la zona (rendimiento alcanzable).

La oferta de productos agrícolas está ligada a dos factores, área de cultivo y rendimiento de los cultivos (producción por hectárea). Lobell et al. (2009) mencionan que en la actualidad existe un margen considerable para la expansión de las tierras de cultivo porque muchos ecosistemas naturales poseen condiciones adecuadas. Muchas proyecciones del suministro mundial de alimentos indican una cantidad considerable de conversión de tierras en América Latina y África (especialmente en la región tropical) (Bruinsma, 2003). Sin embargo, el objetivo de muchos avances en la ciencias agrícolas y legislaciones de todo el mundo apuntan a la mejora de los rendimientos para reducir la brecha de rendimiento que prevalece en muchas zonas del mundo. Lo que se busca es no solo aumentar la seguridad alimentaria, sino también preservar al máximo muchos ecosistemas que albergan gran parte de la biodiversidad del planeta.

Objetivo general de la tesis

Evaluación cuantitativa del desempeño de zonas regables a dos niveles: global y local en un ambiente tropical.

Objetivos específicos:

Objetivo 1. Evaluación del desempeño del riego en diferentes regiones del mundo mediante el indicador RIS y análisis de los atributos clave del sistema de riego que influyen en este indicador.

Objetivo 2. Desarrollar un modelo estadístico que prediga el desempeño del RIS en distritos de riego colectivos con diferentes características.

Objetivo 3. Cuantificar y analizar los factores internos del desempeño del riego en una zona regable en una región del trópico, concretamente el distrito de riego Arenal-Tempisque, en Guanacaste, Costa Rica.

Objetivo 4. Analizar las brechas del rendimiento en el distrito de riego Arenal-Tempisque, en Guanacaste, Costa Rica.

Capítulo 2. A global analysis of irrigation scheme water supplies in relation to requirements

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Capítulo 2. A global analysis of irrigation scheme water supplies in relation to requirements

Abstract of Chapter 2

The performance of irrigation schemes around the world has been below expectations. The assessment of irrigation performance is an essential step towards improving agricultural water use. One of the primary performance indicators is the relative irrigation supply (RIS, the ratio between the amount of water delivered and the crop net irrigation requirements). This study presents a worldwide analysis of irrigation scheme performance by evaluating key attributes that influence the RIS. The analysis was based on a review of reports and scientific papers that yielded 264 cases belonging to 25 countries in six world regions. The database was subjected to two types of statistical analysis: k-means clustering and analysis of covariance (ANCOVA). The cluster grouped irrigation schemes which were characterized by low RIS and advanced irrigation technology. The ANCOVA showed that the RIS co-varied significantly with the variation in precipitation, delivery schedule, on-farm irrigation systems, distribution network, and region, but not with the crop. The ANCOVA also showed that modern pressurized on-farm irrigation systems and on-demand distribution systems significantly improve RIS. The ANCOVA general linear model had a good capacity to predict RIS with a coefficient of determination of $R^2 = 0.83$.

Resumen del Capítulo 2

El rendimiento de los sistemas de riego en todo el mundo ha estado por debajo de las expectativas. La evaluación del rendimiento del riego es un paso esencial para mejorar el uso del agua en la agricultura. Uno de los principales indicadores de rendimiento es el suministro relativo de riego (RIS, la relación entre la cantidad de agua suministrada y las necesidades netas de riego del cultivo). Este estudio presenta un análisis mundial del desempeño de los esquemas de riego mediante la evaluación de los atributos clave que influyen en el RIS. El análisis se basó en una revisión de informes y artículos científicos que comprendía 264 casos pertenecientes a 25 países en seis regiones del mundo. La base de datos se sometió a dos tipos de análisis estadísticos: clústeres de k-medias y análisis de covarianza (ANCOVA). El análisis de k-medias agrupaba los sistemas de riego que se caracterizaban por un bajo RIS y una tecnología de riego avanzada. El ANCOVA mostró que el RIS covarió significativamente con la variación en la precipitación, el cronograma de entregas, los sistemas de riego en la finca, la red de distribución y la región, pero no con el cultivo. El ANCOVA también mostró que los sistemas modernos de riego presurizado en la finca y los sistemas de distribución a demanda mejoran significativamente el RIS. El modelo lineal general ANCOVA tuvo buena capacidad para predecir RIS con un coeficiente de determinación de $R^2 = 0{,}83$.

2.1 Introduction

The predicted growth of global population, the expected increase in food demand and the future climate are likely to constrain water use by agriculture (Clemmens and Molden, 2007; Bodirsky et al., 2015; Davis et al., 2016; Gerten et al., 2020; Pastor et al., 2019). Furthermore, the performance of irrigation schemes around the world has so far been below expected levels. Improving agricultural water use is therefore a necessary condition for sustainable development as optimal irrigation management is strongly associated with yield stability, income gains, and higher employment rates (Hussain, 2007).

The improvement of irrigation schemes must encompass both the delivery and the on-farm systems. Localized irrigation has become the world's most valued irrigation technology; however, both its potential for saving water (Perry et al., 2017; Van der Kooij et al., 2013) and its adaptability for smallholders in developing countries (Venot et al., 2018; Wanvoeke et al., 2015) are being questioned. There is less of a debate on the benefits of flexible delivery. In fact, many irrigation schemes around the world are being modernized with the aim of improving their efficiency, reliability and, above all, the flexibility of their delivery schedules (Burt and Styles, 2000). However, flexible delivery services are usually associated with more sophisticated and expensive distribution systems and control equipment.

The assessment of irrigation scheme performance is therefore an essential, primary step towards improving agricultural water use, particularly for making decisions on modernization investments and management changes (Bos et al., 2005). Molden et al. (1998) stressed the importance of benchmarking irrigation scheme performance to evaluate their internal and external processes in relation to best-practice schemes, usually within a peer group of schemes. This allows organizations to develop plans on how to make improvements or adapt specific best practices (Borgia et al., 2012; García-Bolaños et al., 2011).

Indicators are used to characterize the performance of complex irrigation systems, cropping patterns and organizational settings through few and apprehensible input data available. One of the primary performance indicators used to determine the suitability of the water irrigation supply for agricultural production is the relative irrigation supply (RIS), defined as the ratio between the amount of water delivered and the crop's net irrigation requirement. The RIS gives an indication of the condition of over- or under-irrigation, depending on how closely supply and demand are matched (Molden et al., 1998). Applying an amount of water greater or less than the net irrigation requirements does not imply good or bad irrigation. Deficit irrigation ($RIS < 1$) may be an intended strategy (Fereres and Soriano, 2007). Applying more water than the required to ensure potential crop evapotranspiration ($RIS > 1$) may be necessary to leach salts (Ayers and Westcot, 1985; Letey et al., 2011) or a planned groundwater recharge strategy to guarantee the water supply during periods of water shortage. However, the net irrigation requirement is an objective water depth, useful as a reference in contextual performance assessments, either as target irrigation depth or as a baseline on which over- or under-irrigation strategies are based.

The objective of this study was to carry out an analysis of irrigation performance across world regions by evaluating the key irrigation scheme attributes that may influence the RIS indicator. The analysis used data extracted from an extensive and systematic review of published reports and scientific papers. The goals were to understand where we currently stand with respect to the productive utilization of land and water, to compare the relative performance of the various types of systems, and to identify possible avenues for performance improvement.

2.2 Materials and methods

2.2.1. Literature search and review

The analysis consisted of a bibliographic review of scientific documents and technical reports conducted through the search engines "Google Scholar" (https://scholar.google.com) and "Scopus" (https://www.scopus.com). The first step was to make a search of documents that contained the exact phrase: "relative irrigation supply" in any part of the document. The second step was to filter all the documents providing quantitative information related to "relative irrigation supply". The search and filter yielded 343 documents, out of which only 29 presented quantitative RIS data for one or several cases. The information on the irrigation schemes found in the selected papers was organized in a matrix with quantitative and categorical variables in columns and cases in rows. One case consisted of one RIS value for a given irrigation scheme and year, plus the records of the variables. The variables commonly found in the selected papers were classified as:

- Documentary: reference (authors, year of publication, title, sources) and keywords.
- Geographical: country, region, latitude and longitude.
- Climatic: annual precipitation and reference evapotranspiration.

- Irrigation: water source, type of collective distribution system, on-farm irrigation systems, delivery schedule, crops and crop management, irrigation depth, relative water supply, relative irrigation supply (with irrigation water supply measured at the system entrance or the farms' inlet), water delivery capacity.
- Years of evaluation.

The common specific variables that we considered relevant as descriptive of the irrigation schemes and indicative of their performance were: relative irrigation supply, precipitation, latitude, region, type of distribution system, delivery schedule, on-farm irrigation systems, and crops (Table 2.1). Precipitation and latitude were continuous predictors and the rest were categorical predictors. Not all of the relevant variables were available for the selected cases. If the records of three or less of them were missing, they were treated as missing data in the statistical analyses. If more than three records of relevant variables were missing, the case was discarded. The final database comprised 264 cases.

Table 2. 1 Nomenclature and abbreviation for variables (categorical and continuous) used for statistical analyses.

Variable	Precipitation (mm)	Latitude (degrees)	Distribution network	Delivery schedule	Crops	On-farm irrigation system	Region
Independent (abbreviation)	Precipitation	Latitude	Open (Op)	Demand (Dem)	Rice (Rice)	Surface (Sur)	Europe (EU)
			Closed (Cl)	Arranged (Arr)	Fruit trees (Tr)	Sprinkler (Spr)	Latina America (LA)
			Open and Closed (Op+Cl)	Rotation (Rot)	Arable crop (AC)	Localized (Loc)	Middle East and North Africa (MENA)
					Fruit trees with Arable crop (Tr+AC)	Sprinkler and surface (Spr+Sur)	Hindustan (IND)
					Greenhous (Gh)	Sprinkler and Localized (Spr+Loc)	Sub-Saharan Africa (SSA)
							Southeast Asia (SEA)
Response (continuous)	Relative irrigation supply (RIS)						

2.2.2. Statistical analyses

The statistical analysis had two objectives. The first one was to group the cases with similar characteristics according to the set of relevant variables and their relation with RIS. For this purpose, we conducted a k-means cluster analysis preceded by a partial least square (PLS) regression. The second objective was to find the relationship between RIS and the independent variables describing the irrigation schemes. For this objective, we used a general linear model of covariance (ANCOVA). Both statistical analyses were performed using the statistics software package STATISTICA (TIBCO-Software, 2017).

The k-means clustering is a vector quantification method, which aims to divide n observations (our cases) into k groups in which each observation belongs to the group with the nearest mean, which acts as a prototype of the group. The coordinates used for the k-means clustering were previously obtained from a PLS regression. PLS reduces the large number of predictor variables to a few components, similarly to what is done by the Principal Component Analysis. PLS is used when the number of predictor variables is large, the amount of data is limited and there is multi-collinearity between the predictor variables. The objective function of the k-means clustering was to minimize the variance within the clusters, defined as the squared distance between each centre and its assigned data points (MacQueen, 1967). The dataset used for the PLS and cluster analyses contained 234 cases, resulting from the elimination from the full database (264 cases) of the cases with more than two missing data and 6 outliers (cases falling outside the limits of normality).

The ANCOVA was applied to evaluate the relationship between the RIS (dependent variable) and the categorical predictors (region, crops, on-farm irrigation system, delivery schedule and distribution network), having precipitation as a covariate. Categorical predictors that had an effect on RIS were subjected to a Tukey´s Post-Hoc analysis to test for differences between levels. In order to meet the normality and homoscedasticity assumptions, the ANCOVA was performed ignoring the 6 outliers detected in the PLS analysis. Cases with any missing data were also eliminated so that the resulting dataset used contained 115 cases.

2.3 Results

The database comprised 264 cases pertaining to 25 countries in 6 regions (Figure 2.1). The largest data set belonged to Europe (124 cases), followed by the Middle East and North Africa region (47 cases), Southeast Asia (38 cases), Latin America (28 cases), Sub-Saharan Africa (21 cases) and Hindustan (6 cases). We did not find any cases in North America, where the RIS indicator is rarely used in their irrigation literature. The final dataset is available as 'Supplementary material'.

Figure 2. 1 Global distribution of the irrigation schemes used for chapter 2.

2.3.1. k-means clustering

The PLS identified two significant components that together explained 41.9 % of the variance in RIS (Table 2.2): Component 1 explained 31.4% of the variance of RIS and Component 2 explained 10.5%. The contribution of other components was not significant.

Table 2. 2 Partial least squares analysis summary (n = 264). Number of components by cross validation is 3. 43.8 % of sum of squares of the dependent variables has been explained by all the components extracted.

Component	R^2X	R^2X (Cumul.)	Eigenvalues	R^2Y	R^2Y (Cumul.)	Q^2	Limit	Q^2 (Cumul.)	Significance	Iterat
1	0.252	0.252	5.516	0.314	**0.314083**	0.226	0	0.226	S	1
2	0.107	0.359	2.186	0.105	**0.419493**	0.006	0	0.231	S	1
3	0.125	0.484	2.083	0.019	**0.438380**	-0.062	0	0.184	NS	1

The attributes contributing positively to Component 1 were (in this order): pipe distribution network, sprinkler plus localized on-farm irrigation system, on-demand delivery schedule, latitude, and tree crops (Table 2.3). The attributes contributing negatively were (in this order): rice crops, surface and surface plus sprinkler on-farm irrigation system, open channel distribution network, and arranged delivery schedule (Table 2.3). Negative values of Component 1 were associated with low values of RIS and technologies that, in principle, favour the efficient use of water, while positive values were associated with higher RIS and on-farm irrigation systems with less efficient technologies. Therefore, it could be interpreted that Component 1 represented the irrigation technology level.

The main attributes positively contributing to Component 2 were tree crops, open distribution network, and precipitation, whereas the main negative contributors were a combination of open and closed conduits in the distribution network, greenhouse crops, and tree plus arable crops (Table 2.3). We could not find such a clear interpretation of Component 2 as we did for Component 1, which was expectable given its scant contribution to the explanation of the variance (Table 2.2).

Table 2. 3 Weights for each component spreadsheet. Variables: precipitation, latitude, region, delivery schedule (Arranged, rotation and demand), On-farm irrigation system (sprinkler, localized or surface), distribution network (open, closed or mixed) and crop (Rice, fruit trees, arable crops, fruit trees with arable crops, and greenhouse. See Table 2.1 for abbreviations of variables values.

Variable	**Component 1**	**Component 2**	**Component 3**
Precipitation	-0.267	0.208	0.245
Latitude	0.297	-0.188	-0.150
Delivery Schedule {Arr}	-0.221	0.090	-0.080
Delivery Schedule {Rot}	-0.088	-0.056	0.131
Delivery Schedule {Dem}	0.299	-0.046	-0.026
Irrigation system {Sur}	-0.279	0.036	-0.582
Irrigation system {Spr + Loc}	0.362	0.161	0.438
Irrigation system {Spr + Sur}	-0.268	-0.257	0.273
Irrigation system {Spr}	0.007	0.080	-0.263
Irrigation system {Loc}	0.137	-0.097	0.222
Distribution network {Op}	-0.247	0.295	0.075
Distribution network {Op + Cl}	-0.158	-0.530	0.013
Distribution network {Cl}	0.364	0.023	-0.089
Crops {AC}	0.099	0.150	-0.215
Crops {Tr+AC}	0.096	-0.260	0.111
Crops {Rice}	-0.306	0.081	-0.054
Crops {Gh}	0.001	-0.330	0.206
Crops {Tr}	0.253	0.473	0.230

The k-means clustering allowed the grouping of the cases into three distinctive clusters (Figure 2.2). Cluster A was in the quadrant of positive Component 1 and Component 2; Cluster B was located in the quadrant corresponding to positive Component 1 and negative Component 2; and Cluster C was in the negative side of Component 1. Table 2.4 summarizes the main characteristics of the three clusters identified. Cluster C grouped the cases with the more advanced irrigation technologies (localized and sprinkler irrigation, frequently associated with pipe distribution networks and on-demand delivery), most of them located in Europe. Mean RIS in Cluster C was 0.79. Clusters A and B were less distinctive. They included the cases with rice as the main crop; localized irrigation and on-demand delivery were uncommon (reported only in a few cases in Southern Italy). In Clusters A and B, RIS took higher values (means of 2.34 and 1.90 in Clusters A and B, respectively) and were much more variable than in Cluster C.

Table 2. 4 Attributes that characterized the irrigation scheme in each of the three groups defined by k-means clustering. Categorical units are in percentage of occurrence, continuous variables are in mean value with their standard deviation.

	Region	**Delivery Schedule**	**Irrigation system**	**Distribution network**	**Latitude ° (std dev)**	**RIS (std dev)**	**Crops**	**Precipitation (mm)(std dev)**
Cluster A	LA 47% EU 47% MENA 6%	Rot 35.3% Arr 29.5% Dem 23.5% No Data 11.7%	Spr + Sur 38.2% Sur 26.5% Loc 20.6% No Data 11.7% Spr 3%	Open 61.8% Op+Cl 38.2%	28.4 (10.7)	**2.34 (1.41)**	AC 35.3% Tr+AC 23.5% Rice 20.6% Gh 20.6%	744 (382)
Cluster B	MENA 38% SEA 37% SSA 15%	Arr 69% Rot 20% Dem 8%	No Data 69% Surface 31%	Open 90% No Data 10%	20.1 (14.8)	**1.90 (1.31)**	AC 56 % Rice 44%	1163.6 (834)
Cluster C	EU 96.8% MENA 3.2%	Dem 61.7% No Data 29.8% Arr 5.3%	Spr+Loc 44.7% Spr 28.7% Loc 19.1% No Data 1%	Closed 67% Open 20% No Data 13%	38.33 (2.16)	**0.79 (0.32)**	AC 52% Tr+AC 33% Gh 8.5% Tr 6.4%	512.3 (157)

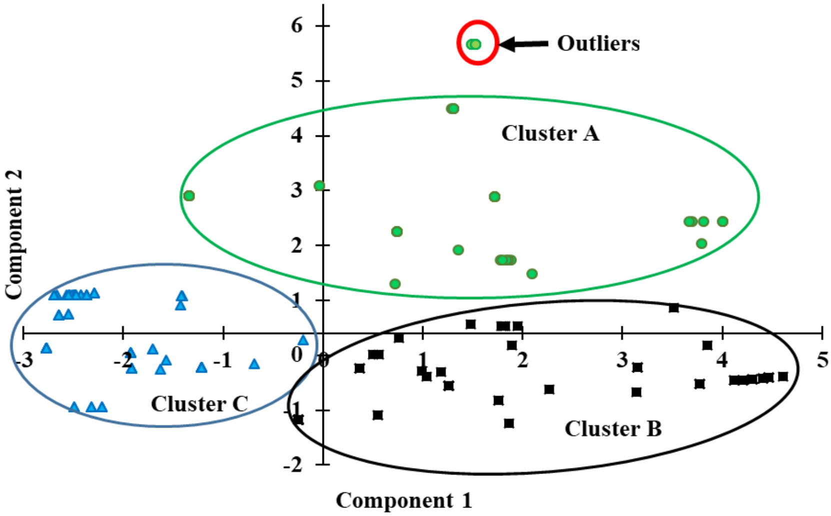

Figure 2. 2 Scatterplot of the scores for Component 1 against the scores for Component 2 resulting from the partial least square regression and clusters results of the k-means cluster analysis.

Figure 2.2 also shows six outliers detected by the PLS. These six cases belonged to Southern Italy and were characterized by a mix of surface and sprinkler on-farm irrigation systems, a rotation water delivery schedule, a combination of pipes and open c in the distribution network and a mix of fruit trees and arable crops (Zema et al., 2018).

2.3.2. ANCOVA

The model explained 83 % of the variance (R^2) in RIS. Precipitation, delivery schedule, on-farm irrigation systems, distribution network, and region were significantly related to RIS, whereas no effect of crop was detected (Table 2.5).

Table 2. 5 ANOVA test (type III) for the general linear model on the effects of irrigation scheme (delivery schedule (Arranged, rotation and demand), On-farm irrigation system (sprinkler, localized or surface), distribution network (open, closed or mixed) and crop (Rice, fruit trees, arable crops, fruit trees with arable crops and greenhouses), climate (precipitation) and geographic (Region) variables on RIS values.

	F	**Degrees of freedom**	**p**
Intercept	17.11	1	0.0001
Precipitation (mm)	25.10	1	< 0.0001
Delivery Schedule	3.59	2	0.03
Irrigation system	2.82	4	0.03
Distribution network	5.68	2	0.005
Region	3.12	5	0.01
Crops	0.18	3	0.9

Regarding the on-farm irrigation system, the average RIS in the cases using a combination of localized and sprinkler systems was below one (0.62) and significantly lower than in any other irrigation system (Figure 2.3). The cases with localized or sprinkler on-farm systems showed similar average RIS and close to unity (1.08 and 1.57, respectively). By contrast, the cases with surface irrigation presented the highest average RIS (on average, water supply was more than twice the net irrigation requirements).

The group of cases with on-demand delivery showed a mean RIS below one (0.95) which was significantly lower than the RIS of the group of cases with arranged rotation or fixed rotation delivery schedules (Figure 2.4). Interestingly, the mean RIS for the cases under fixed rotation (2.11) was less than that of the cases with more flexible delivery (mean RIS of 2.68 for arranged rotation).

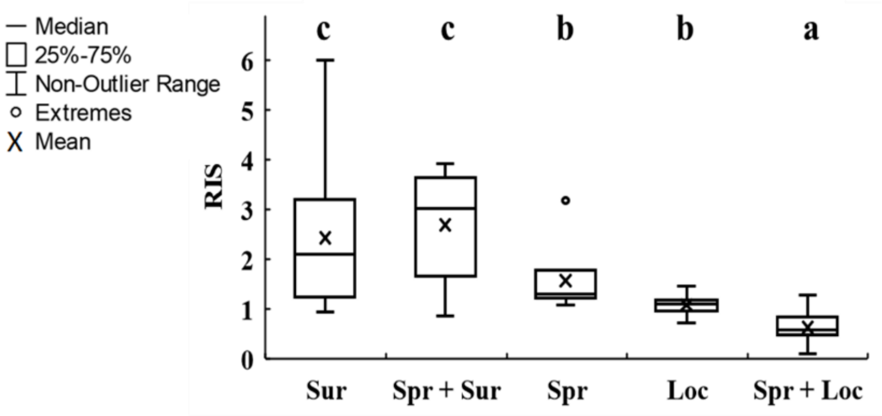

Figure 2. 3 Box plot of on-farm irrigation systems vs RIS. Different letters above the boxes denote significant differences ($p < 0.05$) between the data groups in Tukey's post hoc analysis.

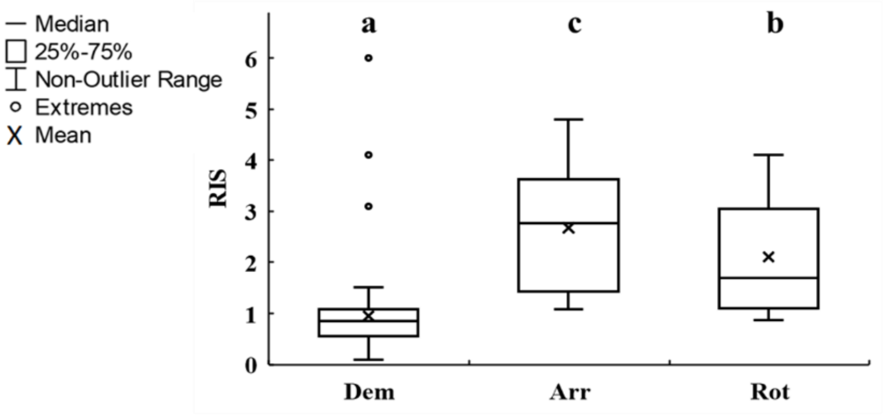

Figure 2. 4 Box plot of delivery schedules (Demand, rotation and arranged) vs. RIS. Different letters above the boxes denote significant differences ($p < 0.05$) between the data groups in Tukey's post hoc analysis.

The analysis revealed that the type of water distribution network also significantly influences the RIS (Figure 2.5). The irrigation schemes with pipe distribution systems gave the lowest mean RIS (0.79). Networks composed of open channels and closed pipes had a mean RIS of 2.14, and distribution networks only with open channels showed an average of RIS of 2.59, although the mean RIS of these two groups were not statistically different. The results in Figure 4 were coherent with those in Figure 2.5 since on-demand delivery usually requires closed distribution networks, whereas most open channel networks are operated under rotation schedules. However, this comparison should be taken with caution because, while in the 63 cases of piped distribution systems the water supply was measured at the farm entrance, in the cases with distribution systems composed of open channels or of open channels and pipes, the water supply was measured either at the farm entrance (17 cases) or at the system head (35 cases). We recognize that the measurements at the system head integrate some upstream water losses that do not take place when the measurements are taken at the farm entrance. In the cases with open channel distribution system, the measurement of the water supply at the head of the system or at the farm entrance did not imply significant differences in RIS. However, the 10 cases with open channels combined with pipes and water supply measured at the system head presented an average RIS that was significantly higher than the average RIS of the 7 cases with the same type of distribution system but water supply measured at the farm entrance (a RIS of 2.9 vs. a RIS of 1.1).

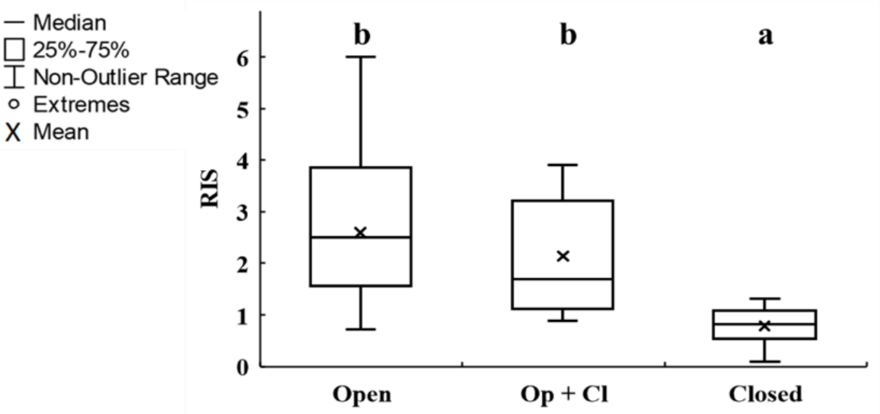

Figure 2. 5 Box Plots of distribution network (Open, Closed and Mix Open and Closed) vs. RIS. Different letters above the boxes denote significant differences ($p < 0.05$) between the data groups in Tukey's post hoc analysis.

RIS differed between regions, with Europe and Southeast Asia showing the lowest (1.07) and the highest (4.73) RIS values, respectively (Figure 2.6). The EU dataset presented 4 outliers, that were 4 of the 10 cases reported by Zema et al. (2018). It should be remembered that the other 6 cases were not included in the ANCOVA after being signalled as outliers by the PLS.

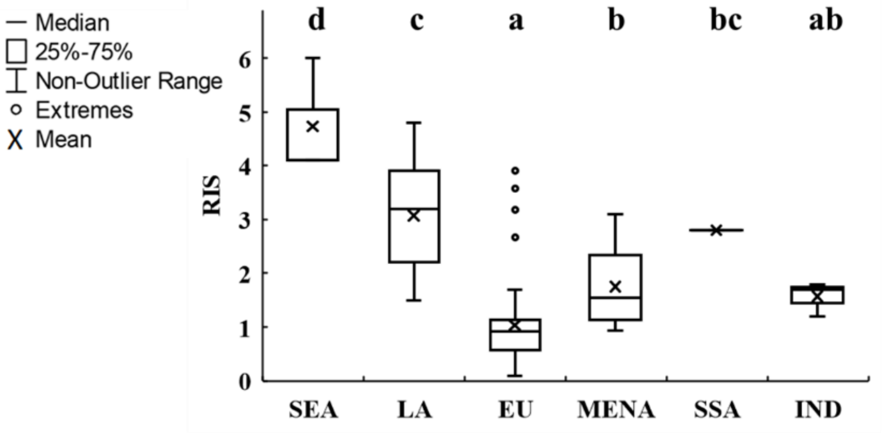

Figure 2. 6 Box plot of region (Southeast Asian, Latin America, Europe, Middle East and North Africa, Sub Saharan, and Hindustan) vs. RIS. Different letters above the boxes denote significant differences ($p < 0.05$) between the data groups in Tukey's post hoc analyses.

Finally, RIS increased with precipitation, as shown in Figure 2.7. Higher RIS when rainfall is significant is an expected result; for instance, if it rains after a well-timed irrigation, then RIS appears high but irrigation scheduling was actually good.

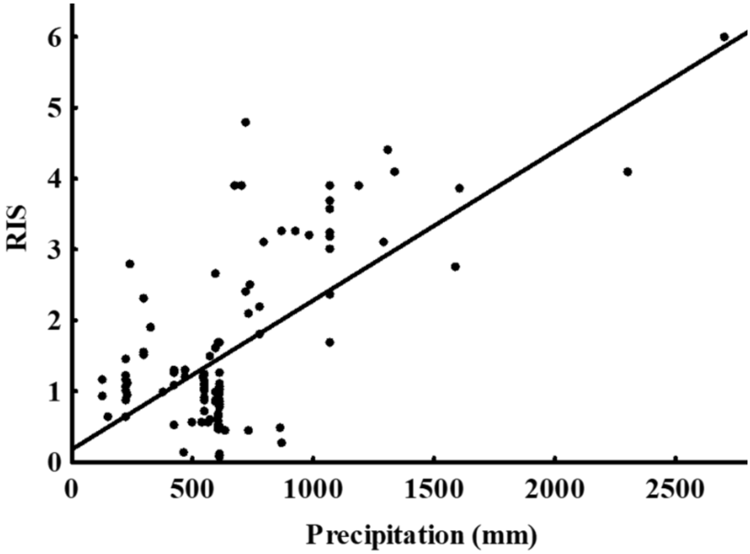

Figure 2. 7 Scatterplot of precipitation (mm) vs. RIS.

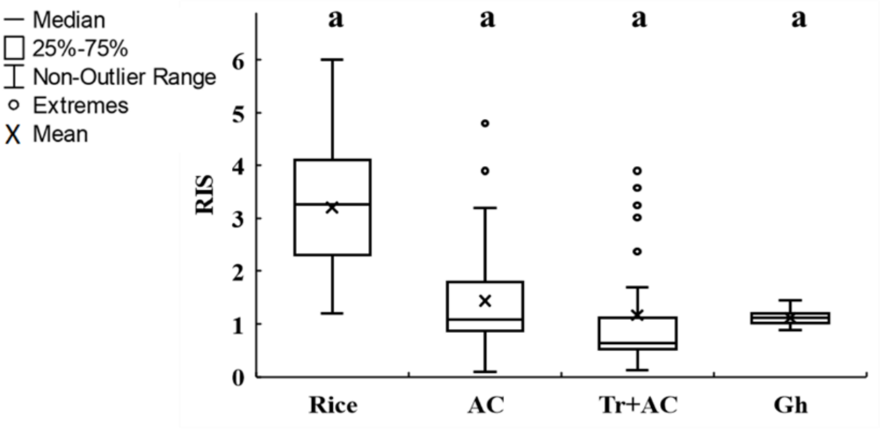

Figure 2. 8 Box plot of crops (Rice, AC (arable crops), Tr + AC (fruit trees plus arable crops) and Gh (greenhouses). There are no significant differences in crop, between the data groups in Tukey's post hoc analysis.

The ANCOVA indicated that the RIS did not statistically differ between types of crops (Table 2.5). Nonetheless, in Figure 2.8 we present the median values of RIS and their variation for the 4 types of crops considered in the analysis. The median value of RIS of the cases in which rice was the main crop was higher than the RIS in those in which it was not. The lack of a "crop effect" could be because rice is commonly associated to tropical regions (e.g., Southeast Asia and Sub-Saharan Africa) and regions of high rainfall, two variables whose effects were already detected by the ANCOVA.

The general linear model (ANCOVA) resulted in the RIS predictive equation:

$$\mathbf{RIS = \alpha + \beta_p P + \beta_1 X_1 + \beta_2 X_2 + \cdots + \beta_n X_n} \qquad \text{(Ec. 2.1)}$$

where α is the intercept, P is annual precipitation (mm), β_p is the regression coefficient for P, and $\beta_{1, 2, \ldots, n}$ are the regression coefficients for corresponding effects $X_{1, 2 \ldots n}$ that for categorical attributes may take the values of 1 or 0 if the effect applies or not, respectively.

The coefficients were adjusted using 86 randomly selected cases out of the 115 cases used in the ANCOVA. Coefficients are shown in Table 2.6. The remaining 29 cases were used for validation of the model.

Table 2. 6 Coefficients and standard error (std. Error) of the ANCOVA general linear model relating RIS with irrigation scheme, climate and geographic variables. See Table 1 for abbreviations. Reference type for delivery schedule was Rot, for Irrigation system was Spr, for Distribution network was Open, for Region was IND and for Crop was Rice

Effect	**Level**	**(β) Regression coefficient**	**std. Error**
Intercept		**1.372598**	0.526213
Precipitation (mm)		**0.001324**	0.000382
Delivery Schedule	Dem	**-0.391402**	0.350544
Delivery Schedule	Arr	**0.362181**	0.205221
Delivery Schedule	Rot	**0**	0
Irrigation system	Spr + Loc	**-0.322238**	0.253633
Irrigation system	Spr + Sur	**0.109392**	0.363592
Irrigation system	Sur	**0.444339**	0.265191
Irrigation system	Loc	**-0.091778**	0.419778
Irrigation system	Spr	**0**	0
Distribution network	Closed	**-0.212732**	0.172460
Distribution network	Op + Cl	**0.409839**	0.147939
Distribution network	Open	**0**	0
Region	EU	**-0.501028**	0.564246
Region	MENA	**-0.530605**	0.296583
Region	SSA	**0.526288**	0.617401
Region	LA	**0.207718**	0.244817
Region	SEA	**1.219978**	0.818190
Region	IND	**0**	0
Crops	Tr + AC	**-0.186089**	0.196263
Crops	AC	**-0.051342**	0.175128
Crops	Gh	**0.260862**	0.390081
Crops	Rice	**0**	0

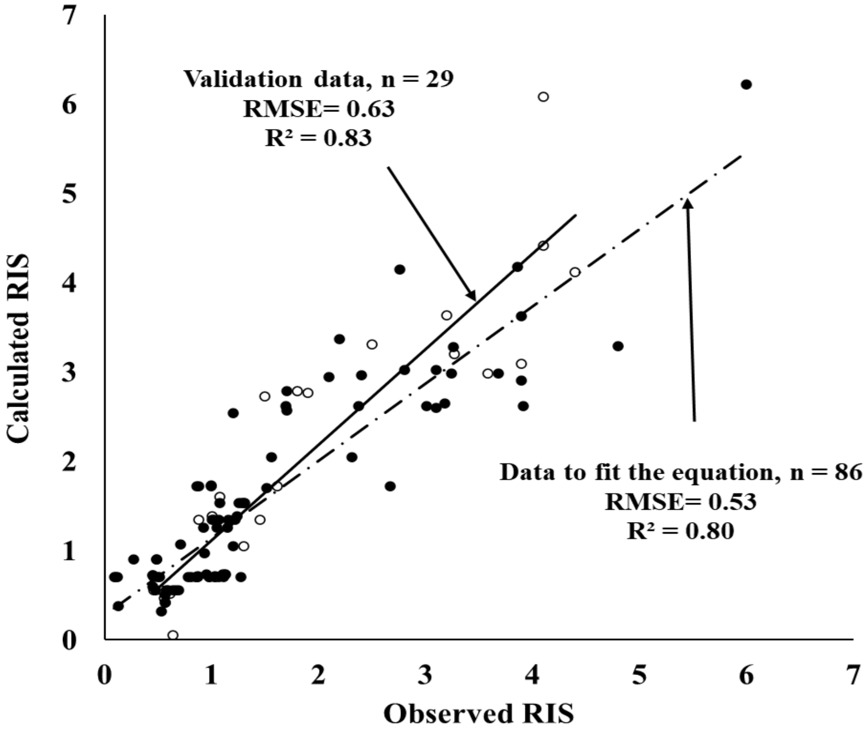

Figure 2. 9 Scatter plot RIS observed vs. RIS calculated with the ANCOVA general linear model. Observed and validation values represented with filled and open symbols, respectively.

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2.4 Discussion

The PLS technique was applied to a large dataset of cases using RIS as a dependent variable and key irrigation scheme features as predictor ones. The clusters of similar cases that were identified based on the principal components obtained by the PLS regression were characterized by their technological level (Figure 2.2, Table 2.4). Moreover, the ANCOVA detected significant differences in RIS between groups of cases sharing key irrigation scheme technological features (Table 2.5). Therefore, RIS, an indicator of relatively recent usage (Molden et al., 1998), has proven to be able to detect the differential performance of irrigation schemes around the world. Although it does not capture all the nuances that the well-established irrigation efficiency does (Burt et al., 1997; Israelsen, 1950), it is easier to determine, and it offers a first general approximation of irrigation performance; namely, it points to the possibility of significant water losses or overirrigation (RIS > 1) or underirrigation (RIS < 1).

The on-farm irrigation system clearly affected the RIS. Sprinkler and localized systems performed similarly and much better than the surface system (Figure 2.3). The superiority of the two pressurized systems vs. surface irrigation was expected and in consonance with the results in other regional comparative assessments (Gonçalves et al., 2015). However, Serra-Wittling et al. (2019) reported that in all the French experiments comparing localized with sprinkler systems, the former never used more water than the latter, and in most experiments it used significantly less. This was not contradictory with our results, although it was interesting that in the irrigation schemes in which sprinkler and localized systems coexisted, RIS was lower than in the irrigation schemes with only one of two systems (Figure 2.3). The other noteworthy finding that could have a common basis was that the use of water with sprinkler irrigation that Serra-Wittling et al. (2019) reported to be normally higher than with drip irrigation, ceased to be so as rainfall decreased, while we observed that the RIS increased as rainfall increased (Figure 2.7).

Although modern on-farm irrigation technology is being questioned lately (Alonso et al., 2019; Perry et al., 2017; Wanvoeke et al., 2015), our analysis showed that application uniformity and the ability to apply the required water depth, characteristic of sprinkler and localized irrigation systems, clearly helped to adjust the irrigation supply to the needs. To expect benefits beyond the precise and uniform application of water (e.g., to expect a reduction in consumptive use) is to misunderstand irrigation engineering and agronomy; moreover, rebound effects are to be expected (Berbel and Mateos, 2014; Pfeiffer and Lin, 2014). To blame irrigation technology for failure in environments where the conditions for its appropriation are not met is to ignore the basic principles for the selection of an appropriate technology (Burt and Styles, 2000). Irrigation technology cannot substitute rural development or water governance planning. It is true that modern technology like localized irrigation does not imply good performance (Venot et al., 2018), but our global analysis showed a closer match between water supply and requirements where modern technology has been adopted. As usual, the challenges lie in selecting the appropriate technology and closing the irrigation performance gap by promoting professional advisory services (Mateos et al., 2018).

The global analysis also reflected the effect on the RIS of the characteristics of the collective distribution system. Plusquellec (2009) stated that one of the main actions towards improving water productivity is the upgrading of hydraulic infrastructure, replacing open channel networks by pressurized pipe lines. Even though our study lacks the necessary depth to analyse the water productivity mentioned by Plusquellec (2009), it shows clearly that the adjustment between the water supply and the irrigation requirements in piped distribution networks was better than in open channel networks. (Figure 2.5). However, the substitution of open channels by pressurized pipes can be very expensive. The group of European cases in our analysis showed the lowest RIS (Figure 2.6), but this was thanks to considerable public investment in irrigation modernization (Berbel et al., 2019). We do not advocate the systematic replacement of open channels by pipes, but making a tailor-made examination. Hsiao et al. (2007) proposed a chain of efficiency framework to identify the component steps whose improvement would have the greatest impact on overall efficiency. This could be a good approach for some irrigation schemes, although the hydraulic complexity of others might require a deep understanding of their hydraulic connectivity (Mateos, 2008).

Flexible delivery schedules could enhance on-farm efficiency by allowing the farmers to apply the right amount of water at the right time (adapted to the crop and the irrigation method), and to limit uncertainties that induce over-irrigation (Clemmens and Molden, 2007). Our global analysis showed this effect (Figure 2.4). However, greater flexibility is usually associated with pressurized pipe networks, which, as mentioned above, are expensive. Two alternatives are the examination of existing open channels to exploit their full capacity for flexible delivery (Lozano et al., 2010a; Lozano and Mateos, 2008), and the suggestion by Clemmens (2006) to break complex networks down at key intermediate locations to reduce chaos and improve the delivery service to users. On the same causality chain, flexibility should be correlated with the economic performance of irrigation schemes (Styles and Mariño, 2002; Clemmens, 2006), although our database did not include economic performance to prove it.

The response of the RIS with respect to the region (Figure 2.6) showed that the regions with acute water scarcity (e.g. MENA), or the regions with substantial investments in modernization (e.g. EU) presented the lowest values of RIS, while the regions with limited access to irrigation technologies (e.g. SSA, AL and SEA), showed a higher RIS. RIS tended to increase with precipitation (Figure 2.7) and it had also a negative relationship with latitude (Figure 10). This pointed to the effect of climate factors, but it could be an interaction with the fact that the countries with less access to irrigation technology are closer to the equator than the countries with more developed irrigation technology. Another reason could be the prevalence of rice cultivation in the tropical areas which is associated with high RIS values.

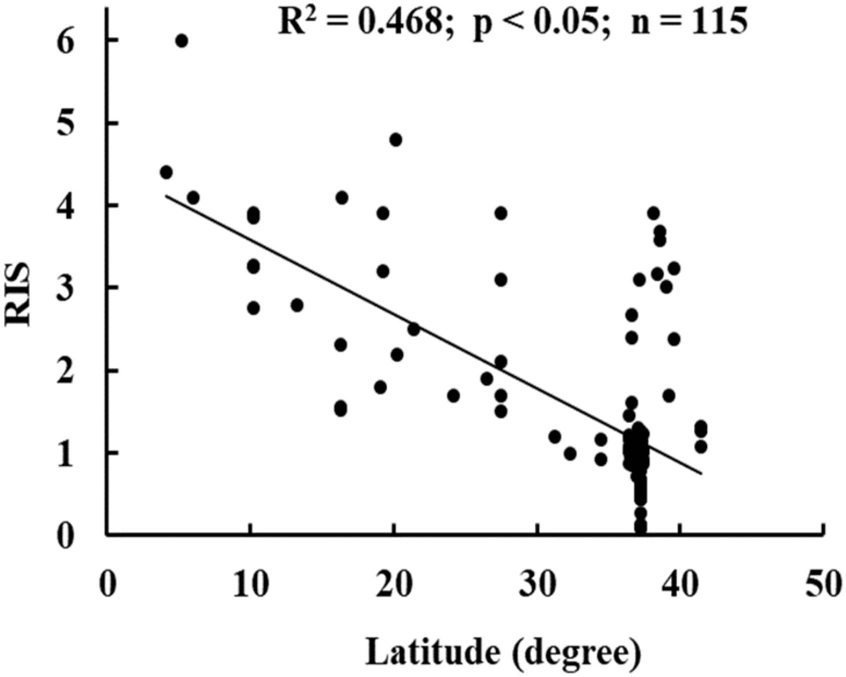

Figure 2. 10 Scatterplot of latitude (degrees) vs. RIS.

Besides the ANCOVA and the cluster analysis that revealed a distinctive irrigation performance in relation to the key attributes of irrigation schemes, the most relevant contribution in this global analysis was that of the General Linear Model in which the predictive capability of Eq. (2.1) was remarkable (Figure 2.9). A similar approach has recently been made by the U.S. Government

Accountability Office (2019) responding to congressional requests on the impact of irrigation technology on situations of water scarcity. We believe that our GLM may be useful for national and international development agencies aiming at making decisions on irrigation interventions.

2.5 Conclusions

The Relative Irrigation Supply indicator served to discriminate the performance of very different irrigation schemes worldwide. The PLS regression and the k-means cluster analysis demonstrated that low RIS values are one of the characteristics of the most technologically advanced irrigation schemes. The ANCOVA helped to understand which attributes of the irrigation schemes are contributing to RIS being higher or lower. The ANCOVA demonstrated that modern pressurized on-farm irrigation systems and on-demand distribution systems significantly improve RIS. However, the variation in the RIS under the conditions in which it takes higher values was considerable, indicating that there may be opportunities for improving some systems under those conditions, thus closing the performance gap. The predictive capability of the ANCOVA General Linear Model (Eq. 2.1) should be useful for national and international development agencies making decisions on appropriate on-farm irrigation technology or on the modernization of collective irrigation systems in different countries.

2.6 Material suplementario del capítulo 2

Table A. 1 Collected global data used for PLS statistical analysis with 264 samples of irrigations schemes, related to the management of irrigation water supply (Country, Region, RIS, Delivery Schedule, On-farm Irrigation system, Distribution network, Latitude, Crop and precipitation

Region	Delivery Schedule	Water source	Irrigation system	Distribution network	Latitude	RIS	Crops	Precipitation (mm)	Autor
Algeria	Arranged	Groundwater	Drip	Pressurized pipe	34°42' N	**1.77**	Greenhouse	128	Laib et al. 2018
Algeria	Rotation fixed	Groundwater	Drip	Pressurized pipe	34°42' N	**0.93**	Greenhouse	128	Laib et al. 2018
Argentina	Rotation fixed	Surface	Surface	Open	27°50' S	**1.50**	Arable crops	572	Prieto 2006
Argentina	Rotation fixed	Surface	Surface	Open	27°50' S	**1.70**	Arable crops	611	Prieto 2006
Argentina	Rotation fixed	Surface	Surface	Open	27°50' S	**2.10**	Arable crops	732	Prieto 2006
Argentina	Rotation fixed	Surface	Surface	Open	27°50' S	**3.90**	Arable crops	700	Prieto 2006
Argentina	Rotation fixed	Surface	Surface	Open	27°50' S	**3.10**	Arable crops	794	Prieto 2006
Colombia	Combination	Surface	Surface	Open	3°55' N	**7.70**	Mainly rice	1442	Burt & Styles. 1998
Colombia	Combination	Surface	Surface	Open	4°17' N	**4.40**	Mainly rice	1306	Burt & Styles. 1998
Costa Rica	Arranged	Surface	Combination	Open	10°25' N	**3.33**	Mainly rice	868.23	*
Costa Rica	Arranged	Surface	Combination	Open	10°25' N	**3.31**	Mainly rice	925.38	*
Costa Rica	Arranged	Surface	Combination	Open	10°25' N	**3.72**	Mainly rice	1185.79	*
Costa Rica	Arranged	Surface	Combination	Open	10°25' N	**2.82**	Mainly rice	1584.56	*
Costa Rica	Arranged	Surface	Combination	Open	10°25' N	**3.96**	Mainly rice	1603.2	*
Dominican Republic	Arranged	Surface	Surface	Open	19°23' N	**3.2**	Arable crops	984	Burt & Styles. 1998
India	Rotation fixed	Other or mix	Surface	Open	31°23' N	**1.20**	Mainly rice	545	Burt & Styles. 1998
India	Rotation fixed	Other or mix	Surface	Open	24°18' N	**1.70**	Arable crops	604	Burt & Styles. 1998
India	Rotation fixed	Other or mix	Surface	Open	19°11' N	**1.80**	Arable crops	774	Burt & Styles. 1998
Iran	Demand	Surface	Surface	Open	37°16' N	**3.10**	Mainly rice	1290	Burt & Styles. 1998
Iran	Combination	Surface	Surface	Open	32°15' N	**5.00**	Arable crops	250	Burt & Styles. 1998
Italy	Rotation fixed	Other or mix	Combination	Other or mix	39°54' N	**2.38**	Trees + others	1070	Zema et al. 2018
Italy	Rotation fixed	Surface	Combination	Other or mix	39°19' N	**1.70**	Trees + others	1070	Zema et al. 2018
Italy	Combination	Surface	Combination	Other or mix	39°53' N	**3.24**	Trees + others	1070	Zema et al. 2018
Italy	Rotation fixed	Surface	Combination	Other or mix	39°04' N	**3.01**	Trees + others	1070	Zema et al. 2018
Italy	Combination	Surface	Combination	Other or mix	38°58' N	**3.68**	Trees + others	1070	Zema et al. 2018
Italy	Combination	Surface	Combination	Other or mix	38°54' N	**3.58**	Trees + others	1070	Zema et al. 2018
Italy	Rotation fixed	Surface	Sprinkler	Other or mix	38°40' N	**3.18**	Arable crops	1070	Zema et al. 2018
Italy	Rotation fixed	Surface	Combination	Other or mix	38°29' N	**9.98**	Trees + others	1070	Zema et al. 2018
Italy	Rotation fixed	Other or mix	Combination	Other or mix	38°10' N	**3.91**	Trees + others	1070	Zema et al. 2018
Italy	Rotation fixed	Other or mix	Combination	Other or mix	38°05' N	**7.28**	Trees + others	1070	Zema et al. 2018
Malaysia	Demand	Surface	Surface	Open	5°17' N	**6.00**	Mainly rice	2700	Burt & Styles. 1998
Malaysia	Combination	Surface	Surface	Open	6°05' N	**4.10**	Mainly rice	2300	Burt & Styles. 1998
Mali	Arranged	Surface	Surface	Open	13°28' N	**2.80**	Mainly rice	238	Burt & Styles. 1998
Mauritania	Combination	Surface	Surface	Open	16°30' N	**1.56**	Mainly rice	298	Borgia et al. 2013
Mauritania	Combination	Surface	Surface	Open	16°30' N	**2.31**	Mainly rice	298	Borgia et al. 2013
Mauritania	Demand	Surface	Surface	Other or mix	16°30' N	**1.52**	Mainly rice	298	García-Bolaños et al. 2011
Mexico	Arranged	Other or mix	Surface	Open	26°53' N	**1.90**	Arable crops	323	Burt & Styles. 1998
Mexico	Arranged	Surface	Surface	Open	19°24' N	**3.90**	Trees + others	671	Burt & Styles. 1998
Mexico	Arranged	Other or mix	Surface	Open	21°44' N	**2.50**	Arable crops	737	Kloezen & Garcés-Restrepo. 1998
Mexico	Arranged	Other or mix	Surface	Open	20°28' N	**2.20**	Arable crops	777	Kloezen & Garcés-Restrepo. 1998
Mexico	Arranged	Other or mix	Surface	Open	20°12' N	**4.80**	Arable crops	721	Kloezen & Garcés-Restrepo. 1998
Morocco	Rotation fixed	Other or mix	Surface	Open	32°29' N	**1.00**	Arable crops	376	Burt & Styles. 1998
Spain	Demand	Surface	Combination	Pressurized pipe	37°24' N	**0.45**	Trees + others	729	Lorite, Mateos & Fereres. 2004
Spain	Demand	Surface	Combination	Pressurized pipe	37°24' N	**0.49**	Trees + others	860	Lorite, Mateos & Fereres. 2004
Spain	Demand	Surface	Combination	Pressurized pipe	37°24' N	**0.64**	Trees + others	150	Lorite, Mateos & Fereres. 2004

Table A1. Collected global data used for PLS statistical analysis with 264 samples of irrigations schemes, related to the management of irrigation water supply (Country, Region, RIS, Delivery Schedule, On-farm Irrigation system, Distribution network, Latitude, Crops and precipitation). (continued)

Region	Delivery Schedule	Water source	Irrigation system	Distribution network	Latitude	RIS	Crops	Precipitation (mm)	Autor
Spain	Demand	Surface	Combination	Pressurized pipe	37°24' N	**0.57**	Trees + others	499	Lorite, Mateos & Fereres. 2004
Spain	Demand	Surface	Combination	Pressurized pipe	37°23' N	**0.46**	Trees + others	606	Moreno-Pérez & Roldán-Cañas. 2013
Spain	Demand	Surface	Combination	Pressurized pipe	37°23' N	**0.64**	Trees + others	606	Moreno-Pérez & Roldán-Cañas. 2013
Spain	Demand	Surface	Combination	Pressurized pipe	37°23' N	**0.59**	Trees + others	606	Moreno-Pérez & Roldán-Cañas. 2013
Spain	Demand	Surface	Combination	Pressurized pipe	37°23' N	**0.48**	Trees + others	606	Moreno-Pérez & Roldán-Cañas. 2013
Spain	Demand	Surface	Combination	Pressurized pipe	37°23' N	**0.58**	Trees + others	606	Moreno-Pérez & Roldán-Cañas. 2013
Spain	Demand	Surface	Combination	Pressurized pipe	37°23' N	**0.67**	Trees + others	606	Moreno-Pérez & Roldán-Cañas. 2013
Spain	Demand	Surface	Combination	Pressurized pipe	37°23' N	**0.69**	Trees + others	606	Moreno-Pérez & Roldán-Cañas. 2013
Spain	Demand	Surface	Combination	Pressurized pipe	37°23' N	**0.53**	Trees + others	606	Moreno-Pérez & Roldán-Cañas. 2013
Spain	Demand	Surface	Drip	Pressurized pipe	36°53' N	**1.16**	Greenhouse	227	Sánchez et al. 2015
Spain	Demand	Surface	Drip	Pressurized pipe	36°53' N	**1.13**	Greenhouse	227	Sánchez et al. 2015
Spain	Demand	Surface	Drip	Pressurized pipe	36°53' N	**1.07**	Greenhouse	227	Sánchez et al. 2015
Spain	Demand	Surface	Combination	Pressurized pipe	37°24' N	**0.45**	Trees + others	636	García-Vila et al. 2008
Spain	Demand	Surface	Combination	Pressurized pipe	37°24' N	**0.13**	Trees + others	465	García-Vila et al. 2008
Spain	Demand	Surface	Combination	Pressurized pipe	37°24' N	**0.27**	Trees + others	866	García-Vila et al. 2008
Spain	Demand	Surface	Combination	Pressurized pipe	37°24' N	**0.45**	Trees + others	730	García-Vila et al. 2008
Spain	Demand	Surface	Combination	Pressurized pipe	37°24' N	**0.49**	Trees + others	860	García-Vila et al. 2008
Spain	Demand	Surface	Combination	Pressurized pipe	37°24' N	**0.64**	Trees + others	151	García-Vila et al. 2008
Spain	Demand	Surface	Combination	Pressurized pipe	37°24' N	**0.57**	Trees + others	499	García-Vila et al. 2008
Spain	Demand	Surface	Combination	Pressurized pipe	37°24' N	**0.57**	Trees + others	568	García-Vila et al. 2008
Spain	Demand	Surface	Combination	Pressurized pipe	37°24' N	**0.53**	Trees + others	422	García-Vila et al. 2008
Spain	Demand	Surface	Combination	Pressurized pipe	37°24' N	**0.56**	Trees + others	535	García-Vila et al. 2008
Spain	Demand	Surface	Combination	Pressurized pipe	37°24' N	**0.61**	Trees + others	571	García-Vila et al. 2008
Spain	Demand	Surface	Combination	Pressurized pipe	37°24' N	**0.64**	Trees + others	224	García-Vila et al. 2008
Spain	Demand	Other or mix	Drip	Other or mix	36°44' N	**1.02**	Greenhouse	220	Fernández et al. 2007
Spain	Demand	Other or mix	Drip	Other or mix	36°44' N	**1.07**	Greenhouse	220	Fernández et al. 2007
Spain	Demand	Other or mix	Drip	Other or mix	36°44' N	**1.01**	Greenhouse	220	Fernández et al. 2007
Spain	Demand	Other or mix	Drip	Other or mix	36°44' N	**0.88**	Greenhouse	220	Fernández et al. 2007
Spain	Demand	Other or mix	Drip	Other or mix	36°44' N	**1.45**	Greenhouse	220	Fernández et al. 2007
Spain	Demand	Other or mix	Drip	Other or mix	36°44' N	**1.22**	Greenhouse	220	Fernández et al. 2007
Spain	Demand	Other or mix	Drip	Other or mix	36°44' N	**1.16**	Greenhouse	220	Fernández et al. 2007
Spain	Demand	Surface	Combination	Pressurized pipe	37°24' N	**1.03**	Arable crops	610	Santos et al. 2010
Spain	Demand	Surface	Combination	Pressurized pipe	37°24' N	**0.98**	Arable crops	610	Santos et al. 2010
Spain	Demand	Surface	Combination	Pressurized pipe	37°24' N	**0.46**	Arable crops	610	Santos et al. 2010
Spain	Demand	Surface	Combination	Pressurized pipe	37°24' N	**0.98**	Arable crops	610	Santos et al. 2010
Spain	Demand	Surface	Combination	Pressurized pipe	37°24' N	**0.09**	Arable crops	610	Santos et al. 2010
Spain	Demand	Surface	Combination	Pressurized pipe	37°24' N	**1.07**	Arable crops	610	Santos et al. 2010
Spain	Demand	Surface	Combination	Pressurized pipe	37°24' N	**0.87**	Arable crops	610	Santos et al. 2010
Spain	Demand	Surface	Combination	Pressurized pipe	37°24' N	**1.11**	Arable crops	610	Santos et al. 2010
Spain	Demand	Surface	Combination	Pressurized pipe	37°24' N	**0.51**	Arable crops	610	Santos et al. 2010
Spain	Demand	Surface	Combination	Pressurized pipe	37°24' N	**1.27**	Arable crops	610	Santos et al. 2010
Spain	Demand	Surface	Combination	Pressurized pipe	37°24' N	**0.12**	Arable crops	610	Santos et al. 2010

Table A1. Collected global data used for PLS statistical analysis with 264 samples of irrigations schemes, related to the management of irrigation water supply (Country, Region, RIS, Delivery Schedule, On-farm Irrigation system, Distribution network, Latitude, Crops and precipitation). (continued)

Region	Delivery Schedule	Water source	Irrigation system	Distribution network	Latitude	RIS	Crops	Precipitation (mm)	Autor
Spain	Demand	Surface	Combination	Pressurized pipe	37°24' N	**0.81**	Arable crops	610	Santos et al. 2010
Spain	Demand	Surface	Combination	Pressurized pipe	37°24' N	**0.85**	Arable crops	610	Santos et al. 2010
Spain	Demand	Surface	Combination	Pressurized pipe	37°24' N	**0.86**	Arable crops	610	Santos et al. 2010
Spain	Demand	Surface	Combination	Pressurized pipe	37°24' N	**0.49**	Arable crops	610	Santos et al. 2010
Spain	Demand	Surface	Combination	Pressurized pipe	37°24' N	**1.03**	Arable crops	610	Santos et al. 2010
Spain	Demand	Surface	Combination	Pressurized pipe	37°24' N	**0.11**	Arable crops	610	Santos et al. 2010
Spain	Demand	Surface	Combination	Pressurized pipe	37°24' N	**0.78**	Arable crops	610	Santos et al. 2010
Spain	Rotation fixed	Surface	Combination	Open	36°58' N	**2.67**	Arable crops	595	Lozano & Mateos. 2008
Spain	Rotation fixed	Surface	Combination	Open	36°58' N	**1.61**	Arable crops	595	Lozano & Mateos. 2008
Spain	Rotation fixed	Surface	Combination	Open	36°58' N	**1.00**	Arable crops	595	Lozano & Mateos. 2008
Spain	Rotation fixed	Surface	Combination	Open	36°58' N	**0.99**	Arable crops	595	Lozano & Mateos. 2008
Spain	Rotation fixed	Surface	Combination	Open	36°58' N	**0.99**	Arable crops	595	Lozano & Mateos. 2008
Spain	Demand	Other or mix	Drip	Pressurized pipe	37°06' N	**1.20**	Greenhouse	467	Garcia-Morrillo et al. 2015
Spain	Demand	Other or mix	Drip	Pressurized pipe	37°06' N	**1.30**	Greenhouse	467	Garcia-Morrillo et al. 2015
Spain	Demand	Surface	Combination	Pressurized pipe	37°40' N	**1.05**	Trees + others	550	Fernández-García et al. 2014
Spain	Demand	Surface	Combination	Pressurized pipe	37°40' N	**1.03**	Trees + others	550	Fernández-García et al. 2014
Spain	Demand	Surface	Combination	Pressurized pipe	37°30' N	**1.15**	Trees + others	550	Fernández-García et al. 2014
Spain	Demand	Surface	Combination	Pressurized pipe	37°30' N	**1.1**	Trees + others	550	Fernández-García et al. 2014
Spain	Demand	Surface	Combination	Open	37°00' N	**0.71**	Arable crops	550	Fernández-García et al. 2014
Spain	Demand	Surface	Combination	Pressurized pipe	37°40' N	**0.92**	Trees + others	550	Fernández-García et al. 2014
Spain	Demand	Surface	Combination	Pressurized pipe	37°40' N	**0.87**	Trees + others	550	Fernández-García et al. 2014
Spain	Demand	Surface	Combination	Pressurized pipe	37°40' N	**1.24**	Arable crops	550	Fernández-García et al. 2014
Spain	Arranged	Surface	Sprinkler	Pipe	41°47' N	**1.26**	Arable crops	422.9	Andrés & Cuchí. 2014
Spain	Arranged	Surface	Sprinkler	Pipe	41°47' N	**1.31**	Arable crops	422.9	Andrés & Cuchí. 2014
Spain	Arranged	Surface	Sprinkler	Pipe	41°47' N	**1.30**	Arable crops	422.9	Andrés & Cuchí. 2014
Spain	Arranged	Surface	Sprinkler	Pipe	41°47' N	**1.08**	Arable crops	422.9	Andrés & Cuchí. 2014
Spain	Arranged	Surface	Sprinkler	Pipe	41°47' N	**1.28**	Arable crops	422.9	Andrés & Cuchí. 2014
Thailand	Combination	Surface	Surface	Open	16°36' N	**4.10**	Mainly rice	1336	Burt & Styles. 1998
Turkey	Arranged	Surface	Combination	Other or mix	36°57' N	**2.40**	Arable crops	721	Burt & Styles. 1998

Capítulo 3. Evaluating Irrigation Scheme Performance in a Tropical Environment: The Guanacaste Scheme, Costa Rica

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Capítulo 3. Evaluating Irrigation Scheme Performance in a Tropical Environment: The Guanacaste Scheme, Costa Rica

Abstract of Chapter 3

Irrigation is expanding in the tropics and it could make an important contribution to the intensification of production in the tropical areas where a dry season limits productivity. A study was carried out to characterize irrigation performance and the yield gaps of a tropical irrigation scheme that covers more than 41 000 ha in northern Costa Rica. The study covered a five-year period, from 2014 to 2018. The performance indicator Relative Irrigation Supply (RIS) ranged between 2.48 and 3.78, values higher than those typically observed in schemes of temperate areas, but in the low range of those documented in the tropics. Despite the excess of water usage, it was found that there were farms with water shortages, especially in the canal tails during the dry season, but there was also damage caused by excess of water in the rainy season. The potential yield of the two main crops (rice and sugarcane) was determined with the AquaCrop simulation model. Actual yields were determined via a farmers' survey that also inquired about irrigation management issues. Yield gaps were determined for each of the two sectors that make up the irrigation scheme (South and West canals). The mean yield gap of rice in the South canal sector

(3.34 t ha^{-1}) was smaller than that of the West canal sector (4.84 t ha^{-1}). The highest yield gap of rice occurred in the rainy season in the West canal sector. The yield gap of sugarcane in the West canal sector was significantly larger than that in the South canal sector. A farmers' survey, combined with an examination of soil maps revealed that poor drainage through the heavy soils that predominate in the West canal sector is one of the main causes of the large yield gap. While users are relatively satisfied with the provision of irrigation water and its cost, several opportunities for improving scheme performance and for closing the yield gaps are discussed.

Resumen del Capítulo 3

El riego se está expandiendo en los trópicos y podría hacer una contribución importante a la intensificación de la producción en las áreas tropicales donde una estación seca limita la productividad. Se llevó a cabo un estudio para caracterizar el rendimiento del riego y las brechas de rendimiento de un esquema de riego tropical que cubre más de 41 000 ha en el norte de Costa Rica. El estudio abarcó un período de cinco años, de 2014 a 2018. El indicador de desempeño del Suministro Relativo de Riego (RIS) osciló entre 2,48 y 3,78, valores superiores a los típicamente observados en esquemas de zonas templadas, pero en el rango bajo de los documentados en los trópicos. A pesar del uso excesivo de agua, se encontró que hubo fincas con escasez de agua, especialmente en las colas de los canales durante la época seca, pero también hubo daños por exceso de agua en la época de lluvias. El rendimiento potencial de los dos cultivos principales (arroz y caña de azúcar) se determinó con el modelo de simulación AquaCrop. Los rendimientos reales se determinaron mediante una encuesta a los agricultores que también preguntó sobre cuestiones de gestión del riego. Se determinaron brechas de rendimiento para cada uno de los dos sectores que conforman el esquema de riego (canales Sur y Oeste). La brecha de rendimiento medio del arroz en el sector del canal Sur (3,34 t ha^{-1}) fue menor que la del sector del canal Oeste (4,84 t ha^{-1}). La brecha de rendimiento más alta en arroz se produjo en la temporada de lluvias en el sector del canal Oeste. La brecha de rendimiento de la caña de azúcar en el sector del canal Oeste fue

significativamente mayor que la del sector del canal Sur. Una encuesta a los agricultores, combinada con un análisis de mapas de suelos, reveló que el drenaje deficiente a través de los suelos pesados que predominan en el sector del canal Oeste es una de las principales causas de la gran brecha de rendimiento. Si bien los usuarios están relativamente satisfechos con el suministro de agua de riego y su costo, se analizan varias oportunidades para mejorar el desempeño del esquema y para cerrar las brechas de rendimiento.

3.1 Introduction

World food demand continues to increase due to the accelerated increase in population, the increase in the amount of protein consumed per capita (FAO, 2017) and, the need to feed the hungry, one key goal among the SDG's (FAO, 2019). Given the limitations to expanding agricultural lands in many of the temperate areas, there is a need to increase the agricultural production coming from the tropics, a region characterized by high rainfall (Radulovich, 1989), and a potential for increasing its productivity. Evans (1993) assessed the productivity of different world regions based on production rate per day on a yearly basis. With the high radiation and favorable temperatures year-long of the tropics, this region is by far the one with the highest potential primary productivity on Earth. Furthermore, there are regions in the tropics that have strategic location and climate features to satisfy the timing and quality of the agricultural products demanded by international markets worldwide.

Generally, the tropical area has two well defined seasons, a rainy season and a dry one, and little noticeable changes in temperature during the year (Malhi and Wright, 2004). To approach any potential productivity, it is essential to have access to irrigation that would guarantee agricultural production throughout the year. With the use of irrigation, tropical areas can compete with subtropical and semi-arid areas, where there are increasing water supply constraints. One tropical country that is strategically located with access to major world markets is Costa Rica, in Central America. The area of Costa Rica is

5.11 million ha, out of which 1.77 million ha are agricultural land. Its cultivated area (arable land plus area under permanent crops) was 570 000 ha in 2017, and the area equipped for irrigation was 102.000 ha (FAO, 2020, 2015).

Regarding the water resources of Costa Rica, in 2015, the total water extraction of surface and underground water resources was 21 873 hm^3, of which 85% (18 679 hm^3) was extracted for non-consumptive uses (mainly hydroelectric power generation) and the remaining 15% (3 194 hm^3), was devoted to consumptive uses, the largest user being agriculture (72%), followed by municipal use (20%) and, finally, for mining, construction manufacturing, trade and services in their production processes (8%) (BCCR, 2017). Of the total water extracted in 2015, only 1 294 hm^3 (5.9% of the total of 21 873 hm^3) were used in irrigation districts for agricultural production (BCCR, 2017), mainly in the province of Guanacaste, which has experienced a strong growth in water demand, partly due to the increase in tourism. This province has the largest irrigation infrastructure in the country, and some of the biggest hydroelectric projects, which also compete for water, especially before the onset of the rainy season (BCCR, 2017).

Irrigation and drainage development and management in Costa Rica is run by the National Irrigation and Drainage Service (SENARA, acronym in Spanish). This entity is responsible for the administration of the Arenal-Tempisque Irrigation District (DRAT, acronym in Spanish), located in Guanacaste (GWP, 2016). The main water source of DRAT is Lake Arenal, which also supplies the Arenal-Corobicí-

Sandillal hydroelectric complex consisting of three hydroelectric power plants arranged in cascade. Downstream is the Manuel Pablo Dengo Benavides (MPDB) diversion dam, where DRAT begins.

The use of irrigation water in Costa Rica has hardly been investigated. A recent study has shown that the common practice in irrigation schemes in tropical regions is oversupplying (Benavides et al., 2021). The rationalization of irrigation in these schemes requires, therefore, performance assessment and in-depth analysis to identify the scope for improvement. Substantial research has been carried out in recent decades on irrigation performance assessment (Bos et al., 2005). This research led to identifying a number of performance indicators which have been used, standardized and improved throughout the years (Burt and Styles, 1998; García-Bolaños et al., 2011; Kloezen and Garcés-Restrepo, 1998; Lorite et al., 2004; Malano and Burton, 2001; Molden et al., 1998; Qureshi et al., 2010). The performance indicators have been related to aspects such as water delivery, water use efficiency, productivity, maintenance, sustainability of irrigation, environmental aspects, socio-economics, and water resources management (Bos, 1997; Bos et al., 2005). Assessing the irrigation performance of collective schemes requires significant efforts in collecting data, which are often unavailable and/or of uncertain quality. Estimates of water consumption from cultivated areas and the water delivery records are frequently used to calculate the water delivery performance indicators at the system level. One of the primary performance indicators used to determine the suitability of the water irrigation supply for agricultural production is the relative irrigation supply (RIS), defined as the relationship between applied irrigation and irrigation requirements (Molden et al., 1998). The RIS value gives an indication of the irrigation condition, showing how closely supply and demand coincide (Molden et al., 1998).

Most irrigation scheme performance assessment indicators focus on water management and economic aspects, and only deal with the evaluation of agricultural productivity in a summary fashion. There is a need to place more emphasis on productivity (land, water, energy, labor) indicators in the assessment of irrigation performance. Cassman, (1999) highlighted the interest in quantifying the potential for the sustainable intensification of production in agroecosystems by assessing the gaps between actual production and maximum or potential production. The yield gaps are estimated as being the difference between the potential yield and the actual farmers’ yields on some specified spatial and temporal interest scale. The potential yield, in turn, can be defined and measured in several ways (Lobell et al., 2009). Once those gaps are quantified, one way to understand the causes behind the observed performance trends, is to characterize farmers' behavior through field surveys (Tanaka and Sato, 2005). This characterization helps to identify the underlying factors affecting irrigation scheme performance.

The aim of this work was to conduct an irrigation performance assessment at the scheme level in the Arenal-Tempisque Irrigation District (DRAT) in Guanacaste, Costa Rica. The RIS performance indicator was determined for five years using district data and simulation models, and a yield gap analysis was also carried out in the areas served by the two main canals of DRAT.

3.2 Materials and Methods

3.2.1 Area description

The study area is the Arenal Tempisque Irrigation District (DRAT), located in the province of Guanacaste, in the north Pacific region of Costa Rica (Figure 3.1). It comprises 43 000 hectares of which, in 2017, about 41 000 hectares were cultivated and under irrigation. The climate is tropical dry, with an average annual rainfall of 1 711 mm (BCCR, 2017). Rainfall concentrates from May to November, while the dry season is from December to April (Figure 3.2). The average monthly temperature varies between 22 and 33 ºC (Solano Quintero and Villalobos Flores, 2001). The soils in DRAT belong to five taxonomic orders (Soil Survey Staff. 2014): Alfisols, Entisols, Inceptisols, Molisols and Vertisols (Table 3.1) (Mateo-Vega, 2001).

Figure 3. 1 Location, weather stations and soil orders of the Arenal-Tempisque irrigation district (DRAT). North Pacific, Guanacaste, Costa Rica. Source: Unit DRAT surveying and drawing. SENARA.

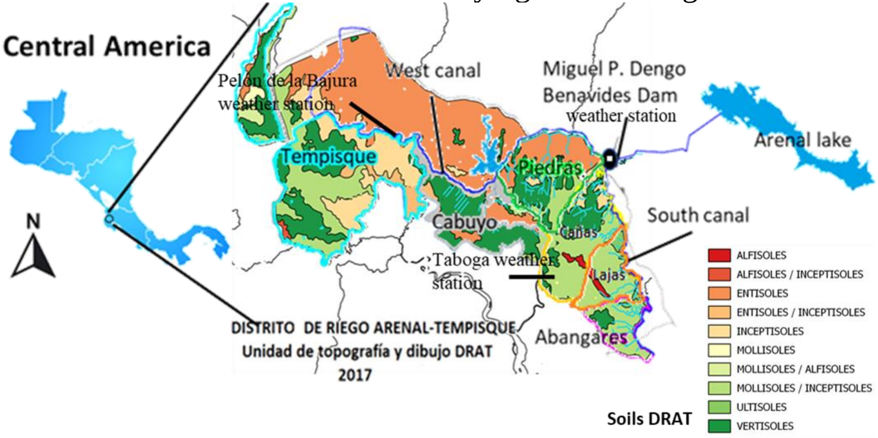
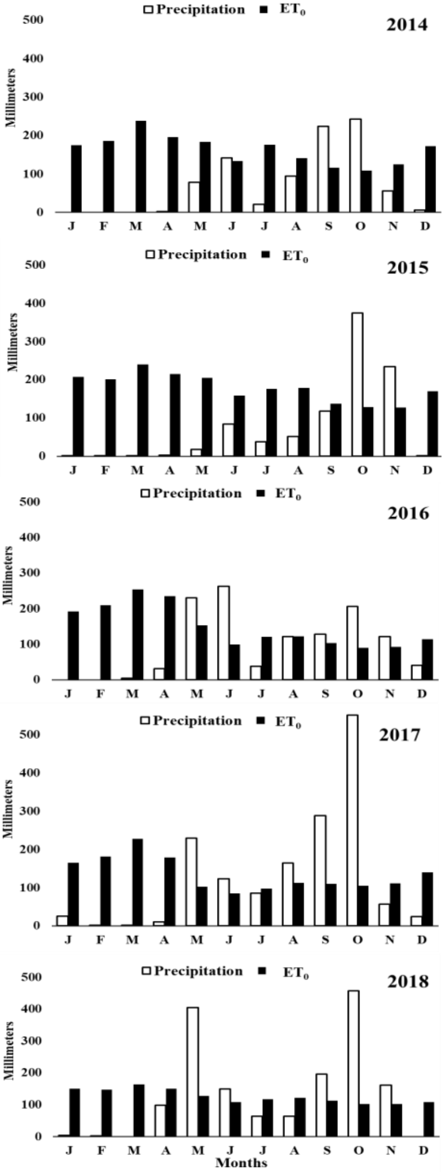


Table 3. 1 Description of the six predominant soil orders in the DRAT area: texture, pH, cation exchange capacity (CEC), organic material content (OM), total available water (TAW) and bulk density.

Soil order	**Texture**	**pH**	**CEC ($cmol kg^{-1}$)**	**OM (%)**	**TAW (%) (0-1.5m)**	**Bulk density ($g cm^{-3}$)**
Alfisol	Clay / Loam Clay / Loam	6.1	46	1.8	17	1.22
Ultisol	Loam Silty Clay / Clay	5.9	32	0.9	13	1.04
Entisol	Sandy clay loam / Sandy loam / Clayey	7.3	35	2.2	13	1.36
Vertisol	Clay Loam / Silty Clay / Loam Silty Clay	7.8	62	1.6	17	1.29
Inceptisol	Clay Loam / Clay	6.6	28	1.2	15	1.07
Mollisol	Clay / Sandy Clay Loam	7.1	40	3.6	16	1.14

The two mains DRAT canals, West Canal and South Canal, derive from the MPDB dam (10° 27’52’’ N, 85º 06”28’ O). The sub-districts of Cabuyo, Piedras and Tempisque, that take water from the West Canal, represent 68% of the DRAT area, while the sub-districts Lajas, Cañas and Abangares, irrigated with water from the South canal, cover 32% of the irrigation district area (DRAT, 2017) (Fig. 3.1). The Lajas sub-district receives also a relatively small water supply from the Cañas River (estimated on an average of 0.527 m^3 s^{-1} during the dry season), to supplement irrigation during that dry season. The first half of the West canal has a flow capacity of 55 m^3 s^{-1}, and the second half of 15 m^3 s^{-1}. The first and second halves of the South canal have flow capacities of 30 and 12.5 m^3 s^{-1}, respectively. Water in DRAT is distributed through a network of open canals with arranged water delivery schedules.

Figure 3. 2 Monthly averages of reference evapotranspiration ETo (mm) and Precipitation (mm) of the Taboga weather station in Cañas sub-district, for the years 2014, 2015, 2016, 2017 and 2018.



The irrigation scheme has about 1 000 users, out of which 73.7% have a farm of less than 10 ha in size, 23.2% have a farm of between 10 and 100 hectares, and the remaining 3.1% have a farm larger than 100 ha. The main crops in 2018 were rice (55 %), sugarcane (38 %) and fodder crops (5 %), and, to a lesser extent, melon, watermelon, papaya, corn, cotton, onion, sorghum, citrus and pineapple. In addition, the irrigation scheme provides water to 700 ha of ponds dedicated to aquaculture. The predominant irrigation system is surface (flood and furrows), followed to a lesser extent by sprinkler (less than 10%). The price for the DRAT water supply service changed in 2016, and in 2020 the water charge was of 0.0037 €/m^3 for all crops.

Previously, water charges for rice, sugarcane and fodder crops were 0.0026, 0.005 and 0.0065 €/m^3, respectively (ARESEP, 2015). This study covered the years 2014, 2015, 2016, 2017 and 2018.

3.2.2 Performance indicators

3.2.2.1 Relative Irrigation Supply (RIS)

One of the primary performance indicators used to determine the suitability of the irrigation water supply is the relative irrigation supply, defined as the ratio between the volume of irrigation water supplied and the volume of the crop's net irrigation requirements (NIR) (Malano and Burton, 2001):

$$\text{Relative irrigation supply (RIS)} = \frac{\text{Total annual volume of irrigation supply (m}^3\text{)}}{\text{Net irrigation requirement (m}^3\text{)}} \quad \text{(Eq. 3.1)}$$

In our analysis, the total annual volume of irrigation supply was the water diverted at MPDB dam to the West and South canals, while the volume of the net irrigation requirements was estimated for the cultivated area in DRAT using two water balance models (Section 3.2.4) and local weather, soil and crop data (Section 3.2.3).

The RIS gives an indication of the condition of over- or under-irrigation, depending on how closely supply and demand are matched (Molden et al., 1998). In our analysis, the total annual volume of water diverted for irrigation was the water diverted at MPDB dam to the West and South canals, while the volume of the net irrigation requirements was estimated for the cultivated area in DRAT using two water balance models (AquaCrop and CropWat) and local weather, soil and crop data. This study extended to the years 2014, 2015, 2016, 2017 and 2018.

3.2.2.2 Yield gap

Yield gap was defined here as the difference between the potential or the attainable yield under the conditions of the DRAT sub-districts and the actual yield obtained by individual farmers. Data on actual yields were collected in a farmer's survey (Section 3.2.3.3). Potential yield was simulated with the AquaCrop model for rice and sugarcane (Section 3.2.4), crops which cover about 90 % of the DRAT area. For fodder crops, that are not parametrized in the AquaCrop model, the attainable yield was defined as the highest fodder crop yield reported by farmers in the survey.

3.2.3 Data collection.

3.2.3.1. Weather, soil and crop data.

Weather data were obtained for the five years of analysis from three weather stations located in DRAT (Taboga, Pelón de la Bajura and MPDB; Fig. 3.1). The weather stations record daily data of precipitation and weather variables (solar radiation, maximum and minimum temperature and relative humidity and wind speed), that are necessary for computing reference evapotranspiration (ET_o) using the FAO standardized Penman-Monteith equation (Allen et al., 1998). The data from the Taboga weather station were used for the Lajas, Cañas, Abangares and Cabuyo sub-districts; the data from the Pelón de la Bajura weather station were employed for the Tempisque sub-district; and the data from the MPDB weather station were used for the Piedras sub-district.

Sandoval and Mata (2014) developed a database of georeferenced soil profiles descriptions across the DRAT. It included basic information per horizon, including depth, texture, bulk density, organic matter content, pH, cation exchange capacity, electrical conductivity and available soil water content. Table 3.1 synthesizes some of these properties for the soil orders present in DRAT that are mapped in Fig. 3.1.

The cultivated area per crop, sub-district and year were taken from the DRAT annual reports (DRAT, 2014, 2015, 2016, 2017, 2018) and are summarized in Table 3.2 for the years of the analysis. Typical planting dates and growing cycles were facilitated by the DRAT managers, and confirmed by the field survey (Section 3.2.3.3). Rice planting dates ranged from December to February (dry season) and from May to August (rainy season). Sugarcane was planted from January to March.

Table 3. 2 Area in hectares of the main crops (rice, sugarcane and fodder crops) and fish farms in the DRAT, years 2014 to 2018.

Sector		**2014**	**2015**	**2016**	**2017**	**2018**
South canal	Rice	2 820	2 641	3 939	5 478	4 574
	Sugarcane	5 489	5 655	5 539	7 107	7 392
	Fodder crops	802	733	712	789	809
	Fish farm	372	372	372	372	372
West canal	Rice	16 588	17 143	17 252	17 726	17 072
	Sugarcane	9 062	8 695	10 477	8 614	7 396
	Fodder crops	1 464	1 647	1 733	1 572	1 223
	Fish farm	323	328	328	328	328

Source: (DRAT, 2018, 2017, 2016, 2015, 2014)

3.2.3.2 Water supply

The water supply was determined at the radial type head gates of the West and South canals using locally calibrated discharge equations and hourly measurements of gate opening and water levels in the canals. The head gate of the South canal operates under free flow, while the one at the West canal is normally submerged. The respective discharge equations are:

$$West\ canal\ flow\ rate\ \left(\frac{m^3}{s}\right) = 11.4814\ \times A^{0.9083} \times\ H^{0.5758} \quad \text{(Eq. 3.2)}$$

$$South\ canal\ flow\ rate\ \left(\frac{\mathrm{m}^3}{\mathrm{s}}\right) = 15.589\ \times\ \mathrm{A}^{1.0639}\ \times\ \Delta\mathrm{H}^{0.4989} \quad \text{(Eq. 3.3)}$$

where A is the gate opening (m), H is the upstream water level (m) and ΔH is the difference in water level upstream and downstream of the gate (m).

The workers guarding the canal head structures also measure, hourly, the opening of the gates and the water levels in the canals. Measurements are taken on scales attached to the structures. If the water flow fluctuates more than is normal (usually due to operations in the hydroelectric plant upstream), then the measurements are taken more frequently.

3.2.3.3 Farmers' survey

Semi-structured farmers' interviews were conducted to characterize on-farm irrigation management, crop productivity and farm management, as well as farmers' perception of the DRAT water service. The semi-structured questionnaires allowed guided conversations by asking open questions that encouraged answers with further information. A stratified random sampling of an optimal allocation was adopted (Snedecor and Cochran, 1989). The total population of farmers (994) was divided into four strata based on farm size, which was considered, *a priori*, as the main factor that could affect irrigation and farm management: stratum I with farm size (FS) ≤ 10 ha; stratum II, 10 < FS < 100 ha; stratum III, 100 < FS < 500 ha; stratum IV, FS> 500 ha. Within each stratum, we took a simple random sample, whose size was chosen based on its population size. The sample size of each stratum was: stratum I, 37 farmers; stratum II, 11; stratum III, 3 and stratum IV, 1. Some farms had more than one field, with different crops and irrigation strategies, so they were recorded as separate samples, although only one farmer's opinion about the DRAT's service was registered. Therefore, the number of farmers interviewed was 52 and the number of fields characterized was 72. The survey questionnaire included questions about i) land tenure; ii) crops area and yield; iii) irrigation method, land grading and drainage issues; iv) crop and irrigation management; v) DRAT irrigation service, regarding adequacy, flexibility and reliability of water delivery, water price, and other perceptions. Actual yields of rice, sugarcane and fodder crops were also reported by the farmers interviewed, for the years 2014, 2015, 2016, 2017 and 2018.

3.2.4 Estimation of irrigation water requirements and potential or attainable yield.

The net irrigation requirements and potential yield of rice, sugarcane, cotton, corn and sorghum (which represented more than 90% of the area grown in DRAT) were estimated with the AquaCrop model (Steduto et al., 2009). The CORPWAT software 8.0 (FAO, 2009) was used to estimate the net irrigation requirements of the crops not included in the AquaCrop application (namely, fodder crops, watermelon, onion, citrus, papaya and pineapple, which represented less than 10% of the area grown in the DRAT). It was assumed that the attainable yield of fodder crops was the maximum one reported in the farmer's survey. Water consumed in the fish farms (that represented a very small fraction of area in DRAT) was estimated from the area of the ponds and assuming an evaporation rate equal to the reference evapotranspiration. AquaCrop simulates the crop-soil–atmosphere continuum by including the soil, with its water balance; the crop, with its growth, development, and yield processes; and the atmosphere, with its thermal regime, rainfall, evaporative demand, and carbon dioxide concentration (Steduto et al., 2009). CROPWAT performs a daily soil-water balance and estimates the net irrigation requirements according to a given irrigation schedule (Smith, 1992). Both models require the following input data: i) meteorological data, such as solar radiation, maximum and minimum temperature and relative humidity, wind speed (variables needed to compute ET_o), and precipitation; ii) soil hydraulic characteristics; iii) sowing date and life cycle describing all the developmental stages; and iv) irrigation timing and amounts. The AquaCrop model requires additional parameters related to crop and irrigation management practices (Steduto et al., 2012).

Simulations were carried out for each sub-district, crop and planting date in the five years of the analysis, using sub-district-level information on climate, crops, soil, and typical planting dates. Weather data were taken from the three weather stations assigned to the different sub-districts. Soil hydraulic characteristics were up-scaled to sub-district level by taking the soil profiles in Sandoval and Mata, (2014) database located within each sub-district and computing the averages of field capacity, wilting point, saturation water content, and saturated hydraulic conductivity from the soil surface to a depth of 1.5 m (Table 3.3). Rice crops were simulated for the two growing seasons, with the planting date of each crop varying per year and sub-district from December to February (dry season) and from May to August (rainy season). The sugarcane planting date varied from January to March. Rice and sugarcane potential yields simulated with AquaCrop as dry matter were converted into fresh mass, considering 12% moisture for rice and a sucrose content in the sugarcane stalks of 13% (Steduto et al., 2012).

Table 3. 3 Soil information used in AquaCrop and CropWat for subdistrict-scale simulations: soil order, saturated hydraulic conductivity, permanent wilting point (PWP), field capacity (FC) and saturation water content.

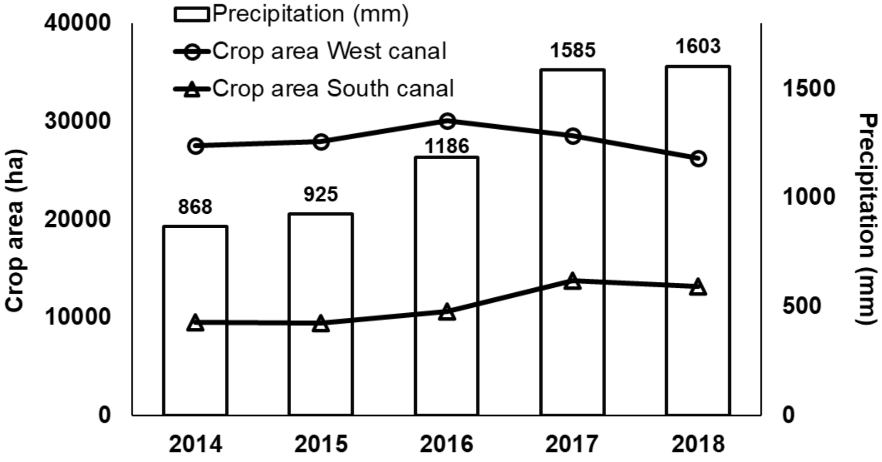
Sector	**Sub district**	**Soil order**	**Hydraulic conductivity K_{sat} (mm/day)**	**Soil water parameters (%)**		
				PWP	**FC**	**Sat**
West canal	Cabuyo	Vertisol, entisol	40	33	50	55
	Piedras	Vertisol, mollisol-inceptisol	40	33	50	55
	Tempisque	Entisol, Inceptisol-mollisol, vertisol	35	25	39	50
South canal	Abangares	Mollisol-alfisol	50	32	50	54
	Cañas	Molisol-inceptisol, vertisol	50	33	50	55
	Lajas	Ultisol, mollisol-inceptisol	50	32	50	54

The actual yields reported by each farmer were compared to the corresponding simulated potential yield or estimated attainable yield to obtain the corresponding yield gaps. The net irrigation requirements were aggregated at the level of the South and West canals and compared with the water supply measured at the respective canal entrances to compute RIS.

3.3 Results

Figure 3.2 shows the year-to-year precipitation and ET_o variability during the period of the analysis. ET_o during the dry season was higher than in the rainy season, mainly due to cloudiness differences; however, monthly values did not differ notably from year to year. By contrast, rainfall, which was concentrated between March and November, varied greatly from year to year. October, the rainiest month, recorded precipitations between 206 and 551 mm. Annual rainfall was lowest in 2014 (868 mm) and highest in 2018 (1 603 mm) (Figure. 3.3).

Figure 3. 3 Distribution of annual precipitation (mm) and the crop area (ha) in both canals, West and South, years: 2014, 2015, 2016, 2017 and 2018 in the DRAT.



The rice and sugarcane areas in the South canal sectors increased in the last two years (2017 and 2018) of the analysis (Table 3.2). We do not know the specific reasons for this variation, but it was apparently not related to the greater rainfall of those years, since the variation in the area of these crops in the West canal sector was the opposite (Fig. 3.3). The area of fodder crops fluctuated from year to year in both canal sectors, while the area devoted to fish farms remained constant (Table 3.2).

The variation in rainfall and the cropping pattern affected the estimated net irrigation requirements, that were highest in 2015 and lowest in 2016 and 2017 in the West and South canal sectors, respectively (Table 3.4).

Table 3. 4 Net irrigation requirements (NIR) in millimeters of each DRAT open canal, for the years 2014, 2015, 2016, 2017 and 2018.

Sector	**2014**	**2015**	**2016**	**2017**	**2018**
South canal	851	1 142	766	841	779
West canal	919	1 024	691	783	726

3.3.1 Relative Irrigation Supply

The RIS in DRAT was greater than 2 in the five years of the analysis (Figure 3.4), clearly indicating irrigation oversupply. The lowest RIS values were recorded in 2017, i.e., 2.48 for the South canal and 2.72 for the West canal. The highest RIS values were observed in the South canal in 2014 (3.78), and in 2018 in the West canal (3.71). In 2014, the RIS in the South canal was notably higher than in the West canal. This difference was reduced and reversed in the following years.

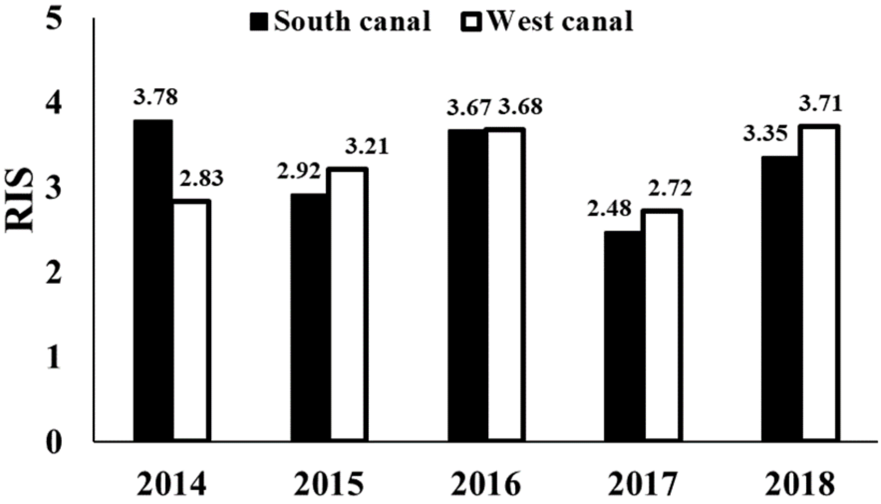


Figure 3. 4 Relative irrigation supply, for South and West open canals in DRAT. Years: 2014, 2015, 2016, 2017 and 2018.

3.3.2 Yield gaps

Figure 3.5 presents the potential and the actual yields (Fig. 3.5a) and the calculated yield gaps (Fig. 3.5b) of the three mains crops (rice, sugarcane and fodder crops) in the South and West canal sectors. The actual rice yield showed statistically significant differences (Tukey $p < 0.05$) between the South and West canal sectors (6.38 and 4.87 t ha^{-1} respectively), with high variability, mainly in the West canal sector, where the largest and the smallest actual yields were recorded. The rice potential yield did not show significant differences between the two sectors, with an average value of 9.74 t ha^{-1}. Consequently, the mean yield gap in the South canal sector (3.34 t ha^{-1}) was smaller than that of the West canal sector (4.84 t ha^{-1}). The boxplot showed that the largest yield gaps occurred in the crops grown in the rainy season (Fig. 3.5b). The yield gap of rice grown in the West canal sector in the rainy season was significantly larger (Tukey $p < 0.05$) than the gap observed during the dry season (5.45 vs. 4.25 t ha^{-1}). This significant difference was not observed in the South canal sector (with an average yield gap of 3.34 t ha^{-1}) (Figure 3.5b).

The actual yields of sugarcane were more homogeneous across the district than the actual rice yields (Fig. 3.5a). Nevertheless, the yield gap of sugarcane in the West canal was significantly larger than that in the South canal (Tukey $p < 0.05$), 170 and 148 t ha^{-1}, respectively, although the potential yield was similar in both canals (Fig. 3.5a).

Contrary to what we observed in the rice and sugarcane crops, the actual yield of fodder crops was higher in the West canal than in the South canal sector (Fig. 3.5a). The maximum yield observed was 29.2 t ha^{-1}, which we used as the attainable yield for the entire district. The estimated fodder crops yield gap in the South canal sector was 18.4 t ha^{-1}, significantly larger (Tukey $p < 0.05$) than the 11.2 t ha^{-1} gap in the West canal sector (Fig. 3.5b).

In an attempt to find an explanation for the significant differences (Tukey $p < 0.05$) in yield gap variations, we investigated whether the size of the farm affected them, as some authors had hypothesized (Helfand and Taylor, 2017; Key, 2019; Paul and wa Gĩthĩnji, 2018;

Rada and Fuglie, 2019; Ren et al., 2019). However, we found no relationship between farm size and yield gap (data not shown).

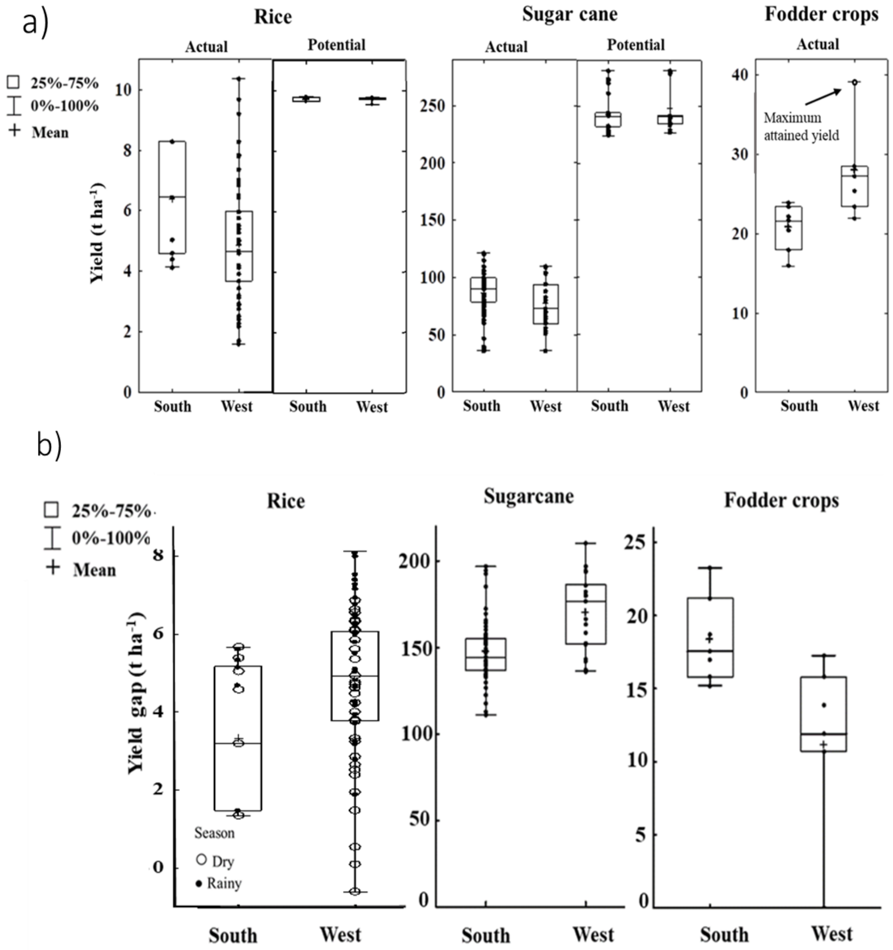


Figure 3. 5 Box plot of yield (t ha-1) of rice, sugarcane and fodder crop reported by users in survey for South and West open canals in figure a, and the Yield gap for same crops and years in figure b.

3.3.3 Farmers' Practices in DRAT

Field leveling and drainage work were considered in the survey to be the most important practices to improve surface irrigation in DRAT. Regular field leveling maintains a favorable soil condition by allowing uniform infiltration along irrigation furrows, uniform water depth across paddy fields, and uniform surface water runoff into drains, thus reducing the impact of waterlogging, especially in the rainy season. All DRAT farmers carried out drainage work in their fields (Figure 3.6). The majority of rice farmers (84%), most sugarcane growers (87 and 100 % in the South and West canal sectors, respectively), and all the fodder crop growers surveyed reported field leveling works (Figure 3.6).

Despite the high percentage of field leveling in rice, we found that 24% of farmers, mostly concentrated in the West canal sector, reported waterlogging problems that could negatively affect yields (Samson et al., 2004; Tsubo et al., 2006; Borgia et al., 2012). The predominance of soils with a high clay content in the West canal sector (Tables 3.1 and 3.3) probably predisposes them to waterlogging problems, which explains the high percentage of field leveling work in this sector (Figure 3.6).

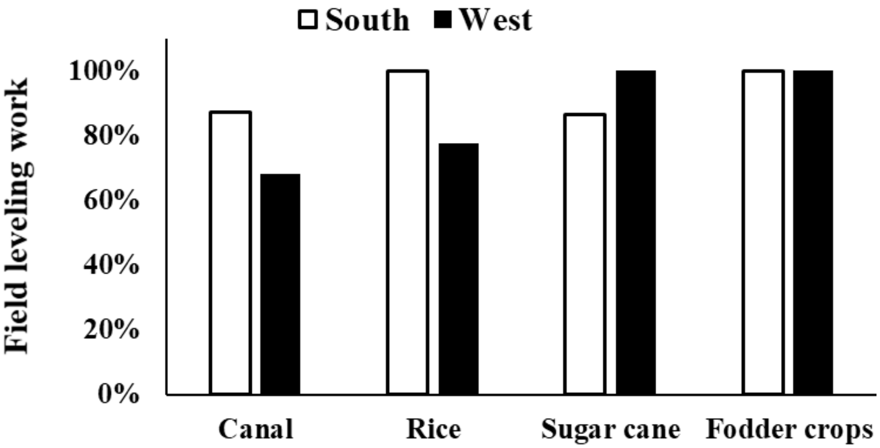


Figure 3. 6 Field leveling work reported by users in main irrigation canals and each crop in DRAT

3.3.4 Problem perception

Figure 3.7 summarizes the survey results regarding the main irrigation issues and some problems caused by the rainy season. Flow rate limitations was the irrigation problem mentioned the most, and reported more frequently by farmers in the West than in the South canal sector (Figure 3.7). This problem affected the most to the users at the tail end of the canals. According to the farmers interviewed, the factors that contributed to the low flow rate at the farm outlets were: i) water level fluctuations in the canal, due to changes in inflow at the head of the system caused by variations in the regime of the upstream hydroelectric power plant; ii) poor coordination of the control of farmoutlet and check gates, that are operated manually only by the water-guards, reducing supply reliability, particularly in periods of high water demand; and iii) poor state of some hydraulic structures.

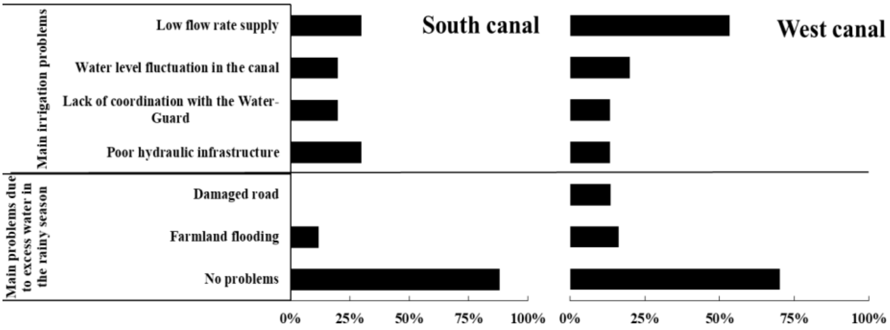


Figure 3. 7 Description of the main problems encountered in the rainy season and in irrigation problems. Grouped by irrigation sector (South and West Canals).

The rainy season also affects both sectors differently. Farmers in the West canal sector reported farmland flooding and damaged roads, while in the South canal sector only 5% of users reported damage due to farmland flooding (Figure 3.7). These problems directly affect crop yields, due to crop damage and limited access to harvest. The differentiated content of clay in the soils in the two sectors, mentioned above, may explain the different severity of the problems caused by rain in the rainy season in the South and West canal sectors.

3.3.5 Service perception

Figure 3.8 shows the satisfaction and quality of the service based on the perception of users of the sufficiency of the amount of water delivered by DRAT, the price of the irrigation water, and the procedure to arrive at it. The amount of water delivered was considered sufficient by most farmers in both sectors (Figure 3.8a), despite their awareness of unreliable flow rates (Figure 3.7). The percentage of users who reported insufficient amounts of water was 22% of those in the West canal sector and only 13% in the South canal sector (Figure 3.8a). However, most DRAT users did not know how they could use less water for irrigation, and only a small fraction (13 and 8 % of users in the South and West canal sectors, respectively) thought that it might be possible (data not shown).

Overall, 50% of users considered that the price of the water was adequate, and 14% said that it was cheap (Figure 3.8a). Users of the South canal found it between expensive and acceptable, while users of the West canal were inclined to define it as acceptable and/or cheap. The majority (57%) of users agreed with the methodology used to calculate the price of water, which was accepted best by users of the West canal (Figure 3.8a).

This perception of water payment also varied according to the main crop grown by the farmer interviewed (Figure 3.8b). Most rice and sugarcane growers thought that the price of water was adequate, while farmers of fodder crops considered it to be expensive. Many sugarcane producers (45%) disagreed with the methodology for calculating the payment for water, while most rice and fodder crops farmers agreed with it (Figure 3.8b).

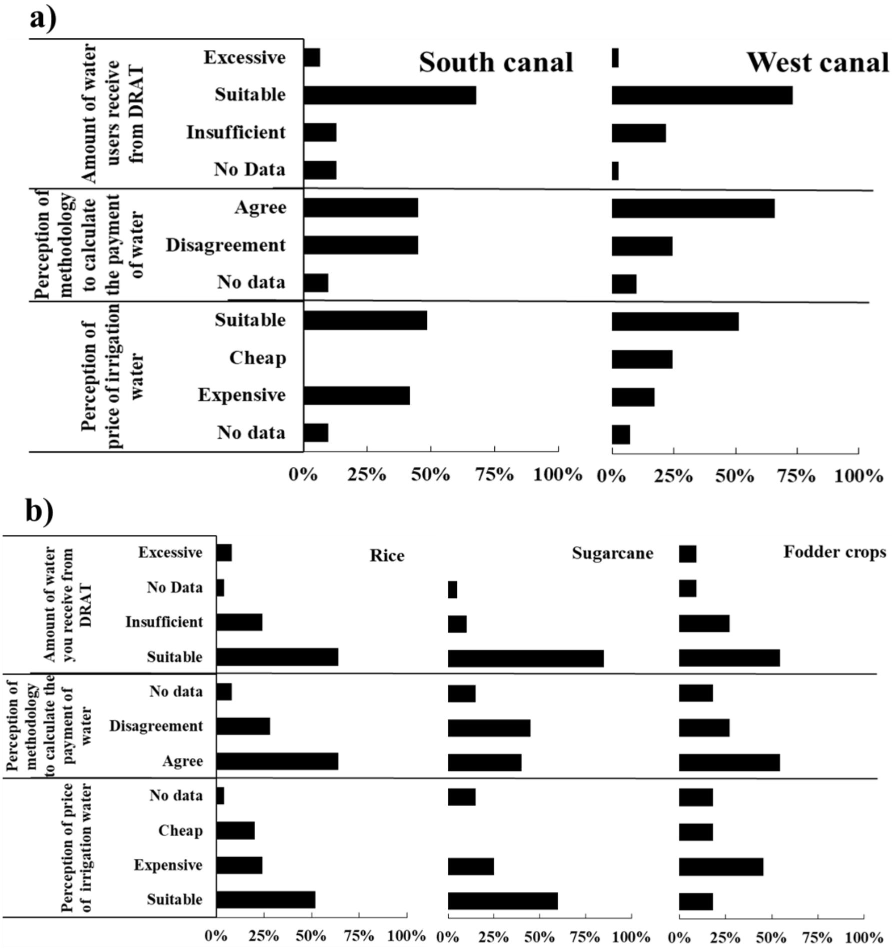


Figure 3. 8 The satisfaction and quality of the service, based on users´ perception of the price of irrigation water, the methodology to calculate the payment of water for irrigation, and the amount of water received from DRAT. Figure 8a presents results grouped per irrigation sector (South and West Canals), and Figure 8b presents the results by crops).

3.4 Discussion

The NIR for the five years calculated with the AquaCrop and CROPWAT models represented only 32% of the water delivered by the DRAT in the main canals (in the dry season it reached 48%, and in the rainy season only 17%). The corresponding high RIS values should be attributed not only to a low on-farm irrigation efficiency, but also to other reasons related to canal operation and maintenance and hydroelectricity production. First, DRAT assumes a low application, distribution and conveyance efficiency when estimating water requirements (36% for rice and 52% for other crops), which results in high operational losses. Second, additional water is diverted during the rainy season to keep the canal full to prevent damage due to uplift pressure when the groundwater table is high. Third, unexpected inflow fluctuations at the canal head are due to an uncoordinated operation of the hydroelectric power plants upstream.

Nevertheless, the average value of RIS in the DRAT (3.2) was lower than other values observed in tropical or subtropical irrigation schemes, as reported by Burt and Styles (1998) in Coello, Colombia (RIS of 4.4), in Muda, Malaysia (4.1), or in Lam Pao, Thailand (4.1). Kloezen and Garcés-Restrepo (1998) also reported a RIS as high as 4.8 in Salva Tierra, Mexico. All of these irrigation schemes had cropping patterns (mainly rice), irrigation systems, distribution networks, climate and delivery schedules similar to those of DRAT. The RIS in DRAT was similar to the ones reported by Molden et al., (1998) in Gorgo, Burkina Faso (3.5), and by Burt and Styles (1998) in the Yaque river basin, Dominican Republic (3.2). When compared to semi-arid and temperate areas, the RIS of DRAT was higher than those reported by García-Vila et al. (2008) in Spain (0.64); by Lozano and Mateos (2008) also in Spain (RIS close to 1 during the peak demand period); by Molden et al (1998) in Chishtian, Pakistan (1.2) and in the Nile Delta, Egypt (1.6); by Ntantos and Karpouzos (2010) in Thessaloniki, Greece (2.09); and by Burt and Styles (1998) in Seyhan, Turkey (2.4). In all those temperate areas, the rainfall is considerably lower than that in DRAT. Benavides et al. (2021) have shown that irrigation schemes in regions with acute water shortages (e.g., the Middle East and North Africa) or regions with substantial investments in modernization (e.g., Europe) have RIS values close to unity, while regions with limited access to irrigation technologies (e.g., Sub-Saharan Africa, Latin America or Southeast Asia) show a higher RIS. Furthermore, these authors found that the RIS tends to increase with precipitation and has a negative relationship with latitude. Therefore, although the RIS value of DRAT is quite high, it is similar to or even lower than those observed in comparable tropics or subtropics schemes.

The high RIS found in DRAT, its year-to year variation, and the fact that in 2014 the RIS in the South canal was notably higher than that in the West canal (Figure 3.4) suggest the possibility of reducing water use without limiting the irrigation supply below the crop water requirements. For instance, our analysis showed that 84% of rice producers continue to apply irrigation during the last stage of grain ripening, despite the fact that water is not required at that stage (Carrijo et al., 2017; Song et al., 2015). In another direction, inadequate management of drains affected a quarter of rice farmers, who reported negative waterlogging problems in the West canal sector. These issues reveal that rice production experienced inadequate irrigation strategies. Moreover, Figure 3.7 shows that there was an important fraction of farmers who complained about low flow rate supply. Therefore, to improve the RIS, the irrigation scheme must also reduce water losses occurring in the collective open channel distribution system. Plusquellec, (2009) stated that one of the main actions towards improving irrigation management is upgrading the hydraulic infrastructure, for instance, replacing open channel networks by pressurized pipes. However, this requires important capital investments, which is not always economically viable. Alternatives to the rationalization of water use in open channel irrigation schemes include the training of irrigators (Skogerboe and Merkley, 1996), automatic canal control (Lozano et al., 2010b), implementation of decision support systems (Lozano and Mateos, 2009; Mateos et al., 2002) and/or dissemination of new irrigation technologies to be used at farm level (Hsiao et al., 2007). Technology for measuring the actual amount of water supplied to secondary canals and farms is becoming more common (Lozano and Mateos, 2008), helping to reduce non consumptive use and allowing better adjusted water delivery schedules (Clemmens and Bos, 1990). In addition, at farm level, promoting the use of pressurized irrigation systems, where viable, should reduce some of the losses that occur under surface irrigation

(Gonçalves et al., 2015). This kind of improvements could facilitate the adjustment of the water supply to the evapotranspiration plus the leaching requirements and, indirectly, to close the crop yield gaps. The means to close the current yield gaps in DRAT would depend on the crop. Next, we discuss yield gaps issues in DRAT for the two main crops, rice and sugarcane.

The actual yield of rice obtained in DRAT did not show any dependence on the farm's size, although in the South canal sector (6.38 t ha^{-1}) it was higher than in the West canal sector, where it varied from the wet season (4.27 t ha^{-1}) to the dry season (5.45 t ha^{-1}). However, the wide rice yield gaps and the corresponding low yields observed in DRAT were similar to those reported by other authors in similar environments. For instance, Guilpart et al. (2017) reported yields of between 5 and 6.5 t ha^{-1} in Bangladesh; Borgia et al. (2013) reported an average yield of 4.75 t ha^{-1} in Mauritania; and Silva et al. (2017) reported rice yields in Philippines of 3.5 and 4.8 t ha^{-1} in the rainy and dry seasons, respectively. The yield gaps found by Silva et al. (2017) (3.2 and 4.8 t ha^{-1} in the rainy and dry seasons, respectively) were similar to those reported in DRAT, although, contrary to what we observed, the smallest yield gap was recorded in the dry season. The causes identified by researchers of the large rice yield gaps observed in tropical environments include: suboptimal timing of weeds removal (Poussin et al., 2003), inadequate use of fertilizers (Alam et al., 2013; Haefele et al., 2004; Poussin et al., 2003), poor quality of the water supply service (García-Bolaños et al., 2011), and inadequate irrigation schedules and drainage (Borgia et al., 2013; García-Bolaños et al., 2011; Song et al., 2015). Of these, a third of the DRAT rice producers interviewed reported the poor quality of the water supply service as a reason for insufficient irrigation water.

The potential sugarcane yields simulated for the DRAT were similar to those reported by other authors in Brazil (Maule et al., 2001; Monteiro and Sentelhas, 2014; Dalri et al., 2008) and Costa Rica (Rodriguez et al., 2015). The actual yields reported herein were also in the range from other authors. Monteiro and Sentelhas (2013) gave yields that varied from 50 to 120 t ha^{-1} in Sao Pablo, Brazil, while Zu et al.(2018) found actual yields from 56 to 115 t ha^{-1} in Guangdong, China, both ranges being comparable with the range observed in DRAT. These authors attributed the wide yield gaps to differences in management, namely the application of water and nitrogen. The average potential yield simulated in DRAT (245 t ha^{-1}) would require about 390 kg ha^{-1} of nitrogen (Leite et al., 2016; Thorburn et al., 2011). Such levels are way above the amount of N fertilizers applied in DRAT; thus, to close the yield gap of sugarcane in DRAT, the current fertilizer amounts should be increased. Moreover, the higher actual yields observed in the South as compared to the West canal sector could be explained by differences in the soil characteristics. Soils with medium (loam) textures are more suitable for sugarcane than clay soils in this province (Angulo and Rodríguez, 2017). The higher yields in the South canal could therefore be associated with the dominance of well-drained soils of a loamy texture where sugarcane is planted, while vertisols with a slow drainage rate dominate the area served by the West canal. In addition, the soil orders that predominate in the South canal have a higher soil organic matter and cation exchange capacity (characteristics that favor the sugarcane yield; Sanches et al., 2019) than the soils in the West canal sector (Tables 3.1 and 3.3).

3.5 Conclusion

The high RIS found in DRAT was attributed to an overestimation of crop water demand, to poor gate control, to the significant amounts of water supplied for canal maintenance, and to an excess of water entering the system due to fluctuations generated by the operations of hydroelectric power plants. Nevertheless, high RISs seem to be common in tropical irrigation schemes since the values obtained in DRAT were in the lower part of the range of RIS published in the literature for schemes in similar environments and with similar technology. Farmers' and managers' interviews uncovered factors leading to the high RIS and helped to define measures for improving irrigation management in DRAT, thus providing indications for future developments. We concluded that the RIS performance indicator is very useful if complemented by another type of analysis that provides further internal insight such as farmers' and managers' surveys.

This study also provided an overview of the actual yield gaps in DRAT, and pointed to actions that could reduce them, such as upgrading the drainage system in the sector where the high clay content of the soils slows down drainage and causes waterlogging. Another measure that could contribute to closing the yield gap in DRAT would be to modernize the control of canal checking and turnout gates to improve the water delivery schedule that causes eventual water shortages, particularly in the tail of the canals. The optimization of fertilizer application on sugarcane would be another practice identified for its potential to reduce the yield gap. Although the diagnosis and recommendations concerning the yield gaps were case specific, a comparison with similar evaluations of yield gaps in other schemes in tropical environments highlighted common constraints. Future irrigation plans should pay attention to irrigation scheme performance assessment studies to improve target upgrading and modernization projects.

Acknowledgement in chapter 3

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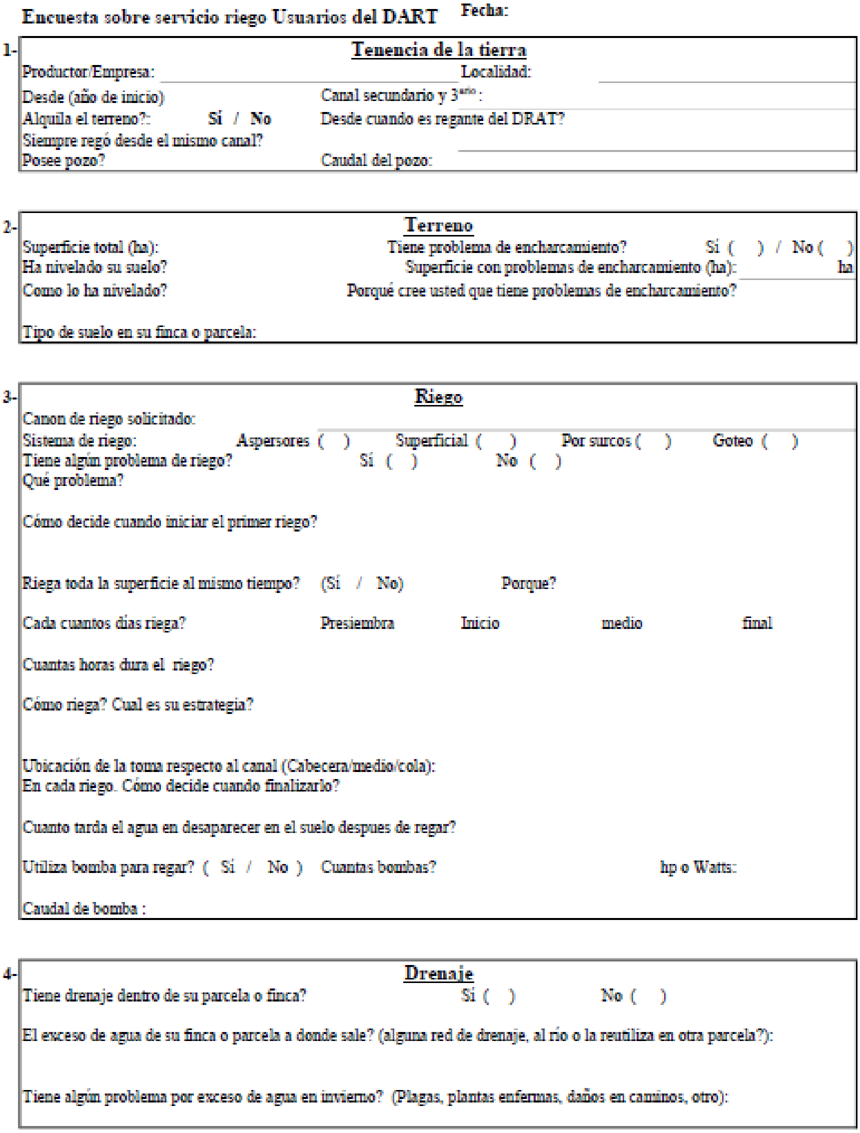
3.6 Material suplementario del Capítulo 3

Figure B 1 Encuesta de riego a los usuarios del DRAT



Encuesta sobre servicio riego Usuarios del DART **Fecha:**

1- **Tenencia de la tierra**

Productor/Empresa: Localidad:
Desde (año de inicio) Canal secundario y 3^{ario} :
Alquila el terreno?: **Sí / No** Desde cuando es regante del DRAT?
Siempre regó desde el mismo canal?
Posee pozo? Caudal del pozo:

2- **Terreno**

Superficie total (ha): Tiene problema de encharcamiento? Sí ( ) / No ( )
Ha nivelado su suelo? Superficie con problemas de encharcamiento (ha): ha
Como lo ha nivelado? Porqué cree usted que tiene problemas de encharcamiento?
Tipo de suelo en su finca o parcela:

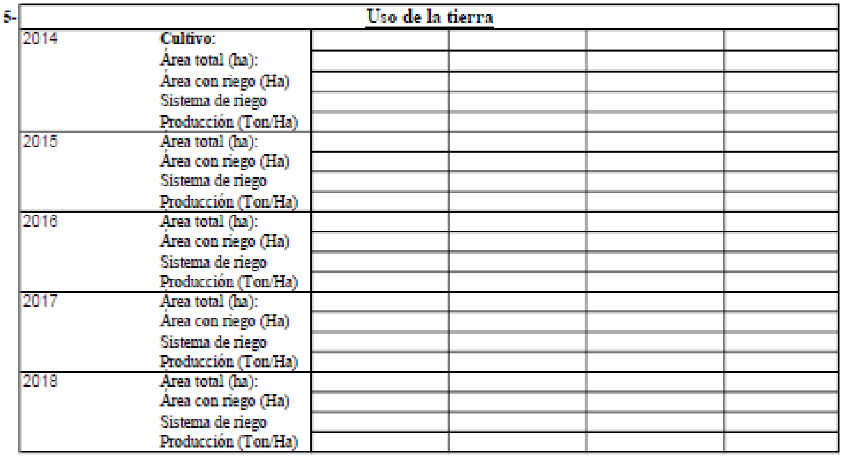
3- **Riego**

Canon de riego solicitado:
Sistema de riego: Aspersores ( ) Superficial ( ) Por surcos ( ) Goteo ( )
Tiene algún problema de riego? Sí ( ) No ( )
Qué problema?
Cómo decide cuando iniciar el primer riego?
Riega toda la superficie al mismo tiempo? (Sí / No) Porque?
Cada cuantos días riega? Presiembra Inicio medio final
Cuantas horas dura el riego?
Cómo riega? Cual es su estrategia?
Ubicación de la toma respecto al canal (Cabecera/medio/cola):
En cada riego. Cómo decide cuando finalizarlo?
Cuanto tarda el agua en desaparecer en el suelo despues de regar?
Utiliza bomba para regar? (Sí / No) Cuantas bombas? hp o Watts:
Caudal de bomba :

4- **Drenaje**

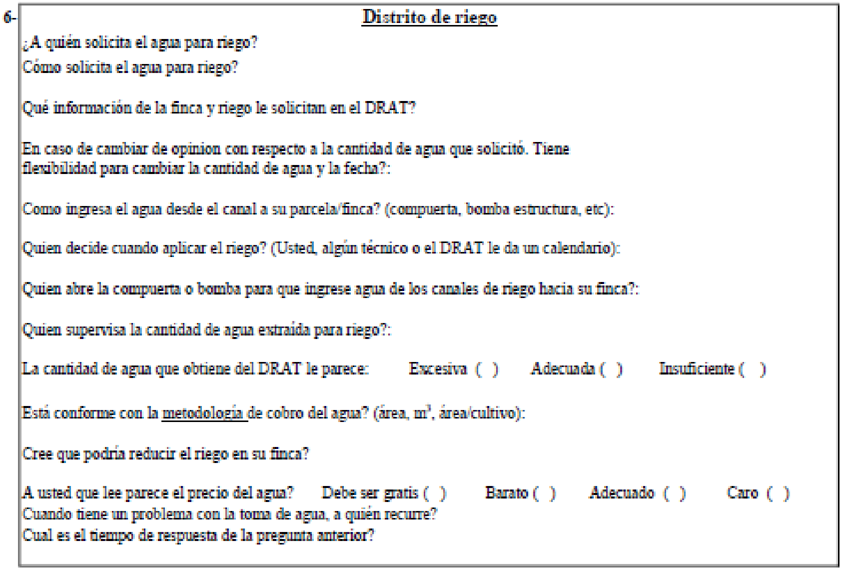
Tiene drenaje dentro de su parcela o finca? Sí ( ) No ( )
El exceso de agua de su finca o parcela a donde sale? (alguna red de drenaje, al río o la reutiliza en otra parcela?):
Tiene algún problema por exceso de agua en invierno? (Plagas, plantas enfermas, daños en caminos, otro):

Table B. 1 Encuesta de riego a los usuarios del DRAT



5- **Uso de la tierra**

2014	**Cultivo:**				
	Área total (ha):				
	Área con riego (Ha)				
	Sistema de riego				
	Producción (Ton/Ha)				
2015	Área total (ha):				
	Área con riego (Ha)				
	Sistema de riego				
	Producción (Ton/Ha)				
2016	Área total (ha):				
	Área con riego (Ha)				
	Sistema de riego				
	Producción (Ton/Ha)				
2017	Área total (ha):				
	Área con riego (Ha)				
	Sistema de riego				
	Producción (Ton/Ha)				
2018	Área total (ha):				
	Área con riego (Ha)				
	Sistema de riego				
	Producción (Ton/Ha)				



6- **Distrito de riego**

¿A quién solicita el agua para riego?

Cómo solicita el agua para riego?

Qué información de la finca y riego le solicitan en el DRAT?

En caso de cambiar de opinion con respecto a la cantidad de agua que solicitó. Tiene flexibilidad para cambiar la cantidad de agua y la fecha?:

Como ingresa el agua desde el canal a su parcela/finca? (compuerta, bomba estructura, etc):

Quien decide cuando aplicar el riego? (Usted, algún técnico o el DRAT le da un calendario):

Quien abre la compuerta o bomba para que ingrese agua de los canales de riego hacia su finca?:

Quien supervisa la cantidad de agua extraída para riego?:

La cantidad de agua que obtiene del DRAT le parece: Excesiva ( ) Adecuada ( ) Insuficiente ( )

Está conforme con la metodología de cobro del agua? (área, m^3, área/cultivo):

Cree que podría reducir el riego en su finca?

A usted que lee parece el precio del agua? Debe ser gratis ( ) Barato ( ) Adecuado ( ) Caro ( )
Cuando tiene un problema con la toma de agua, a quién recurre?
Cual es el tiempo de respuesta de la pregunta anterior?

Capítulo 4. Conclusiones Generales

Capítulo 4 Conclusiones generales

1. El indicador suministro relativo del riego (RIS) permitió discriminar el desempeño de múltiples distritos de riego con características muy distintas en seis regiones bien definidas (Europa, América latina, Medio Oriente y norte de África, África subsahariana, Indostán y Sudeste asiático), así como determinar los atributos clave del riego que influyen en este indicador. Un análisis de regresión de mínimos cuadrados parciales y un análisis de conglomerados de k-medias demostraron que los valores bajos de RIS son característicos de los distritos de riego más avanzados tecnológicamente. Un análisis de la covarianza demostró que los sistemas de riego presurizado y los sistemas de distribución a la demanda mejoran significativamente el RIS. Los atributos clave del riego que influyen en este indicador fueron: la precipitación, la latitud, el método de entregas de agua (a demanda, acordado y rotación fija), el sistema de riego en parcela (localizado, aspersión, superficie, localizado combinado con aspersión; y aspersión combinado con riego por superficie) y la red de distribución de agua (canal abierto, tubería presurizada y combinada con canal abierto).

2. El modelo lineal general de ANCOVA que predice el desempeño del RIS en distritos de riego colectivos con diferentes características en cualquiera de las seis regiones del mundo tuvo buena

capacidad predictiva, con un coeficiente de determinación de $R^2 = 0,83$.

3. El RIS del distrito de riego tropical en el norte de Costa Rica que se evaluó por un periodo de cinco años osciló entre 2,48 y 3,78. Los factores internos que influyeron en el alto RIS se atribuyeron a: i) una sobreestimación de la demanda de agua de los cultivos, ii) un control deficiente de las compuertas, iii) las importantes cantidades de agua suministradas para el mantenimiento de los canales, y iv) un exceso de agua que ingresa al sistema debido a las fluctuaciones generadas por las operaciones hidroeléctricas de las plantas de energía existentes aguas arriba. No obstante, los altos valores de RIS obtenidos se encuentran en el intervalo inferior de los valores encontrados en distritos de riego de otras partes del mundo con características ambientales y de manejo similares.

4. Las brechas del rendimiento productivo de los tres cultivos principales en el distrito de riego evaluado en Costa Rica difirieron entre los dos sectores (Oeste y Sur) que lo componen: en el cultivo de arroz, 4,84 (43%) y 3,34 (26%) t ha^{-1}; en la caña de azúcar ,170 (69%) y 148 (64%) t ha^{-1}; y en cultivos forrajeros, 11.2 (30%) y 18.4 (40%) t ha^{-1}; respectivamente.

5. La comparación de las brechas de rendimiento y de RIS con las obtenidas en otros distritos de riego en ambientes tropicales similares mostraron que los puntos clave comunes que pueden mejorar la productividad de los cultivos en esta región son: i) la mejora del sistema de drenaje, priorizando en sectores con problemas de encharcamiento, ii) la modernización del control de los canales y tomas de fincas, para mejorar el programa de entrega de agua, y iii) la optimización de la fertilización.

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