GLOBAL COMMISSION on the
ECONOMICS OF WATER

TECHNICAL REPORT

Water Consumption, Measurements and Sustainable Water Use

Chris J Perry[1], Richard Allen[2], Peter Droogers[3], Ayse Kilic[4] and
R. Quentin Grafton[5]

[1]Independent Consultant, London, UK

[2]Professor Emeritus, University of Idaho, USA

[3]Hydrologist at FutureWater, Netherlands

[4]University of Nebraska-Lincoln, USA

[5]Crawford School of Public Policy, The Australian National University, Canberra, Australia

Technical Report for the Global Commission on the Economics of Water. Convened by the Government of the Netherlands. Facilitated by the Organisation for Economic Co-operation and Development (OECD)

February 2023
watercommission.org

Acknowledgements

We give our deepest respects to their Elders, past and present, who have been and always will be the Traditional Custodians of Australia's waters including its aquifers, streams, and rivers. We acknowledge that Australia's Indigenous nations have long-standing cultural, social, environmental, spiritual, and economic values, rights and responsibilities with respect to their Country.

Maurice Nevile provided copy editing of two drafts of the manuscript and formatting assistance. Mai Nguyen greatly assisted with administrative support. Support with the final formatting, figures and proofing were provided by Cultivate Communications.

All errors and inconsistencies remain the responsibility of the authors alone.

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Executive summary

The pattern of water use in many countries is unsustainable: deterioration of the water-dependent environment, including both surface and groundwater systems, is ongoing and often accelerating. Understanding the drivers of this trend depends on sound water accounting, which is identifying the sources and uses of water at the appropriate scale. These accounts must distinguish clearly between *consumptive* and *non-consumptive* uses of water. Consumptive uses involve evaporation and/or transpiration of liquid water into water vapour in the atmosphere. Non-consumptive uses (domestic, hydropower and cooling for thermal generating plants) return the vast majority of water withdrawals back to the system.

Irrigated agriculture, by contrast, aims to maximise consumption of water, because transpiration is a primary determinant of yield. As farmers pursue this objective, typically through the adoption of “hi tech” irrigation technologies such as drip, local consumption increases at the expense of *return flows*, reducing aquifer recharge and downstream flows, which may already be productively utilised or support ecosystems. Quantifying withdrawals, consumption and return flows is thus fundamental to designing water governance programs that will result in sustainable and improved water use. Consumption of water, by transforming it from liquid to vapour, is globally by far the largest reducer of the freshwater resource.

Historically, consumption has been difficult to estimate, depending either on formulae embodying assumptions regarding climate, plant health, nutrient status, soil characteristics, etc., or on point measurements of actual consumption projected over large, heterogeneous areas. Since the mid-1990s, remotely measured data from satellites (and most recently from small drones) have offered the possibility to estimate water consumption over landscapes including irrigated areas, rainfed agriculture and natural vegetation, preferably ground-truthed by point data, and also capable of interpretation as productivity indices – ”crop per drop”.

These new technologies for measuring water consumption fundamentally enhance the basis for improved water governance. Internationally, an objective, uniformly derived set of data provides the basis for negotiation and the identification of potential common interests. Locally, the technologies can confirm that water rights are being observed (or at least can identify suspiciously high consumption rates); and at field scale, where the focus is less on water consumption and more on deriving maximum productive benefit from allocated water, when system management to maximise crop production can be improved.

Key findings

- In many water-short areas, demand and consumption are unsustainable, damaging ecosystems.
- Water accounting that identifies withdrawals, consumptive use and return flows, is essential to understand and address unsustainable demand.
- New technologies, using remotely sensed data, offer objective data on the temporal and spatial patterns of consumption at all levels and may provide a data bridge where on-the-ground metering and measurement are not possible.
- Such analyses, from basin to field, provide information for setting sustainable allocations, monitoring compliance and improving the productivity of allocations at the farm level.

Acronyms and abbreviations

API	application programming interfaces
eeMETRIC	Earth Engine Mapping EvapoTranspiration at High Resolution and Internalised Calibration
GSA	groundwater sustainability agencies
IWFM	integrated water flow model
IWRM	integrated water resources management
NBI	Nile Basin Initiative
RS	remote sensing
SGMA	California Sustainable Groundwater Management Act
TSS	technical support services
USGS	US Geological Survey

1 Background

In many countries, access to groundwater is effectively unregulated or unmeasured, even where licensing systems are nominally in place. Until the 1950s in developed countries, and the 1970s in developing countries, most private groundwater development was based on suction pumps that can only abstract water from depths of 10 metres or less, effectively ensuring "sustainable" groundwater use. Subsequently, the advent of inexpensive submersible pumps or submerged shaft-driven pumps removed that constraint, and aquifer depletion began in earnest, often supported by subsidised power. The problem with surface water is somewhat less severe due to the real physical constraints of streamflow, though many estuaries are at least seasonally water short, and fed by water of poor quality.

Consequently, the current pattern of water use in many countries is unsustainable. Demand and consumption exceed the renewable supply and are currently associated with the depletion of aquifers and general damage to the environment. Irrigation is critical to this story. More than 80% of freshwater use goes to irrigation, and irrigated agriculture contributes some 44% of agricultural production while accounting for only 16% of agricultural land (McLaughlin and Kinzelbach, 2015). Sustainable water use and food security are often pulling in opposite directions.

One well-researched example (Wada and Bierkens, 2014), which is far from being an outlier among the available studies, concludes that almost 20% of global water consumption by irrigation is sourced from aquifer depletion. Put another way, a reduction in the consumption of irrigation water of almost 20% is required to *stabilise* aquifers. More than half of this overdraft is generated in four countries: India, China, the United States and Pakistan. This figure does not account for the deteriorating status of many rivers, and thus understates the magnitude of the adjustment required to achieve sustainable water use. Climate change in many countries will exacerbate the demand for water as temperatures rise, crop water requirements increase, and yields fall. Elsewhere, conditions for agriculture may improve, but locally, and especially where irrigation is critical to agricultural production, problems will be severe and the countries listed above, plus almost the entire Middle East and North Africa, constitute an extensive "local" problem.

Meanwhile, the drivers of scarcity and competition for water remain strong – expanding populations and demand for food, fibre, hygiene and fuel. Yet access to water, especially groundwater, often remains uncontrolled.

1.1 Understanding water scarcity

Water scarcity, at its simplest, means we wish we had more. In the water sector, given that we can draw from aquifers that were formed over centuries and have rivers that often appear plentiful, scarcity has led to exploitation beyond the renewable supply. We are following the adage "Live now; pay later".

When we discuss water scarcity, we commonly use terms such as *demand*, *use*, *supply*, *withdrawal*, *abstraction* and *consumption*. Our usage is frequently casual, and this has led to genuine (and occasionally deliberate) confusion about the nature of the problem and the potential contribution of particular solutions (Perry, 2007).

Starting from first principles, the appropriate accounting framework for water is a river basin. The source of new water is precipitation (rainfall, snowfall). Precipitation (at basin scale) either evaporates from wet surfaces, is transpired by vegetation, contributes to a change in storage (lakes, aquifers), or runs to the sea. A basic and essential concept is that, at some depth, the earth's geology is dense enough to constitute a floor for an aquifer, thereby creating a closed system.

BOX 1 Water consumption

Evaporation and transpiration are effectively "consumption", meaning the transformation of liquid water to vapour that is then transported away to the atmosphere, removing liquid water from the local system. In this simple, but complete, framework, it is clear that if evaporation and transpiration *increase*, then either runoff to the sea, or storage in lakes and aquifers, must *decrease*. The law of conservation of mass applies.

Two factors commonly generate confusion in analysing water scarcity: first, accounting in terms of total withdrawals (rather than consumption of liquid water), and second, when local accounting ignores the context of the basin scale.

Suppose we have an undeveloped river with natural vegetation. The basin scale will, over time, become stable, with inflow, evaporation, transpiration, outflow and storage synchronised with one another and variations driven by the natural variation in the weather. All terms will sum to zero. Now we construct a diversion weir that *withdraws* water from the river, taking it to an area with limited rainfall and requiring irrigation to support agriculture. We can be sure that *consumption* increases as a result. Outflows from the basin system in consequence must *reduce*, and the reduction will correspond directly to the increased consumption. The quantity of water *withdrawn* is irrelevant to any induced scarcity to the *river* and *basin*: *consumption* is the driver.

A fundamental confusion between *withdrawals* and *consumption* is commonplace and damaging to policy setting (Kenny et al., 2009), planning and regulation. Data from the United States provide a simple example. A US Geological Survey (USGS) circular reports that thermal power stations account for 45% of water *withdrawals*, with irrigation accounting for a further 32%. A different USGS publication points out that thermal power stations only *consume* 1% of the water *withdrawn*, as very little liquid water is transformed to vapour (while irrigation in the US evaporates 70–90% of *withdrawals*). In *consumptive* terms, thermal power withdrawals are almost irrelevant, consuming a few percent of total water use, while irrigation dominates *consumption*.

Separately, while at the basin level, outflows to the sea are generally viewed as a clear loss to the system. For a local system (e.g. a town or an irrigation project), outflows from that local area may well be viewed as a loss to the local water utility or to local farmers. However, until we trace these flows to their ultimate destination, we cannot be sure that these local outflows – often termed return flows – are not already a valuable and productive source to other more downstream users. If so, an intervention becomes a zero-sum game, increasing beneficial water use in one location may be at the expense of another location.

In other sectors, confused terminology is also pervasive. Water utilities in the United Kingdom typically charge domestic users for water delivered to the household, based on meters. Households are then further charged for treatment of sewage on the assumption that 95% of the freshwater volume delivered to the premises returns to the system. For every thousand litres of water delivered to a household, 950 litres are, on average, returned via drains, are treated, and made available to other users in the system, who are normally downstream. Households are widely referred to as *consumers* of water. They are not; they are primarily *users* of water, returning the vast majority of the water supplied back to the environment. In these same systems, utilities are widely criticised for *losses* from leaky pipes, long showers or running toilets, which generally also return directly to any local aquifer or stream – albeit having incurred the financial costs of abstraction, treatment and distribution prior to leaking from the pipes (Clemmens et al., 2008).

Conversely, groups of farmers who manage irrigation collectively, generally described as “Water User Associations”, have the overall purpose of converting as much as possible of the water withdrawn into crop transpiration. Their primary objective is to *consume* water, and high *efficiency* in achieving high consumption percentages is often regarded by the public as good stewardship. Box 2 sets out terminology that can be applied to all categories of water use, to clarify these various issues.

None of this suggests that decreasing ratios of consumption to withdrawals is good, or that leaky pipes are an environmental asset. It merely highlights that discussions of scarcity and competition in the water sector must be carefully framed. The significance of return flows, in particular, makes it essential that water accounting, especially when addressing scarcity and competition, is comprehensive and unambiguous. When foresters, environmentalists, water utilities, fishers, irrigators and ferry operators debate scarcity, their conceptual frameworks must be coherent. This is illustrated in Figure 1 which combines the concepts of the consumed and not consumed water and the water flows, including return flows, with an overall zero sum.

The importance of water consumption is nowhere more important than in the case of irrigated agriculture – the largest “consumer” of water in most countries. The purpose of irrigation is to ensure that crop growth is not constrained by shortage of water. It is important and useful to understand that transpiration and consumption is not something that plants *wish* to do. Rather, evapotranspiration (ET) is something that plants *have* to do. Transpiration from leaves pulls replacement water from soil that is laden with nutrients required for plant processes and biomass production. Transpiration also provides cooling of leaf temperature that promotes effective kinetic and chemical processes (Hatfield and Burke, 1991). Transpiration is mostly a “passive” process that depends on the dryness and temperature of the air surrounding leaves. Transpiration, in turn, allows CO_2 to enter the plant through the same

BOX 2 Terminology for water accounting

Water Use is the application of water from any source to any specific purpose (washing, cooking, generating power, irrigating, etc.). Water use goes to:

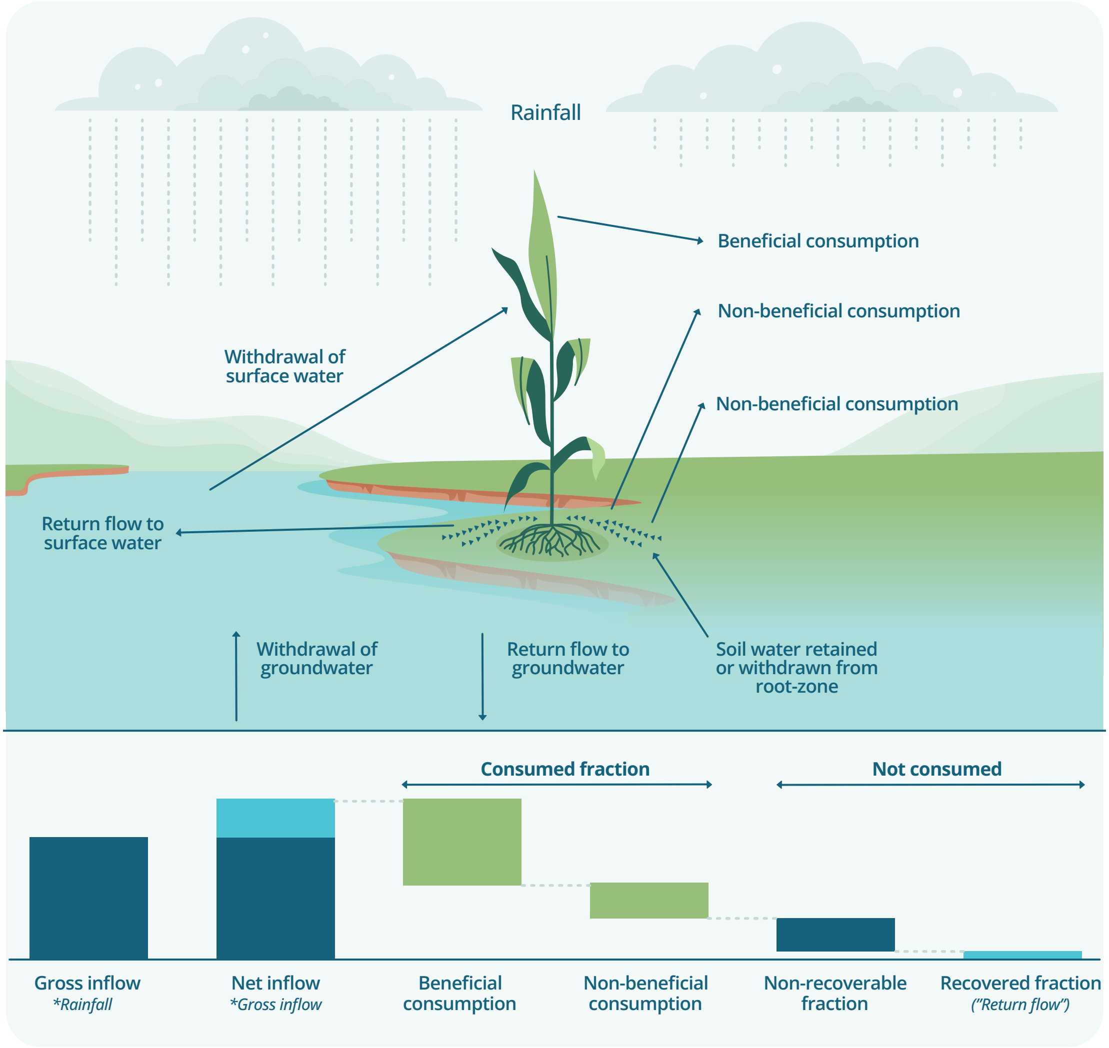
1. *Consumed Fraction* – the fraction of withdrawn water that is converted into vapour by evaporation and transpiration, comprising:
   a) beneficial consumption: evaporation or transpiration for the purpose of which water is withdrawn;
   b) non-beneficial consumption: evaporation or transpiration that does not contribute to the purpose.
2. *Non-consumed Fraction* – the proportion of water use that is not consumed (not converted to vapour) and returns to the environment as:
   a) recoverable return flows: water that reaches an aquifer or stream and is available for reuse at another time or place;
   b) non-recoverable return flows: water that reaches a saline sink, including the ocean, or is otherwise not economically recoverable.
3. *Changes in storage* (expressed as a fraction of the withdrawal)

Three points are critical in this categorisation. First, the sum of 1, 2 and 3 must equal 1.0, representing total 'water use'. If it does not, the water accounts are incomplete. Liquid water does not appear or disappear at a global scale, aside from its availability at a local scale as a result of water consumption, and the law of conservation of mass applies. Second, scarcity is addressed at basin scale by reducing total consumption and non-recoverable return flows. Third, in addressing scarcity, the priority is to minimize both non-beneficial consumption (e.g. weeds and waterlogged areas) and non-recoverable return flows.

leaf stomates and provide the building material for plant growth. The transpiration rate is governed by environmental energy, including solar radiation, which provides the energy consumed in the phase change from liquid to vapour. Because a primary goal of agriculture is to produce near-maximum amounts of plant biomass, it is generally in the interest of producers to maximise CO_2 in-flux to leaves, and therefore, as a consequence, to maximise out-flux of water vapour.

For historic reasons, discussion of water use in the irrigation sector is often dominated by a concept of "efficiency". What proportion of water withdrawn for irrigation supports transpiration (beneficial consumption divided by water use, in the terminology of Box 2)? This ratio can be as low as 50%; in flooded rice systems, the field efficiency may be even lower. In consequence, irrigation is widely seen as wasteful and inefficient due to our tendency to ignore the return flows within the hydrologic system. Until recently it was common to promote increased "efficiency" as the route to recovering and releasing more water to wetlands and

Figure 1. Illustrative overview of the consumed and not consumed water and water flows, including return flows



Source: FAO, 2012

downstream ecosystems (Davis, 2003), while a Google search on “inefficient irrigation” generates nearly six million hits.

An extreme example of understanding return flows and water consumption, rather than simply water withdrawals, is rice irrigation in northwest India. The irrigation field efficiency of irrigated rice in the monsoon season is typically in the order of 40%. Rainfall and irrigation water are captured in “bunded” fields, and much of the excess water recharges the underlying aquifer (a recoverable return flow), which is later exploited by wells during the dry season. Excess rainwater is, thus, transferred, via “inefficient” irrigation during the monsoon, to support groundwater use during the dry season. More “efficient” water management would not affect consumption during the monsoon season, since consumption is capped by potential ET rates and would reduce the transfer of water to the aquifer and would thereby lead to increased rates of aquifer depletion during the dry season. Since flooding is generally a problem during the monsoon, the increased infiltration from bunded fields, irrigating “inefficiently”, can also have the benefit of ameliorating excessive runoff.

2 The Irrigation Efficiency Paradox

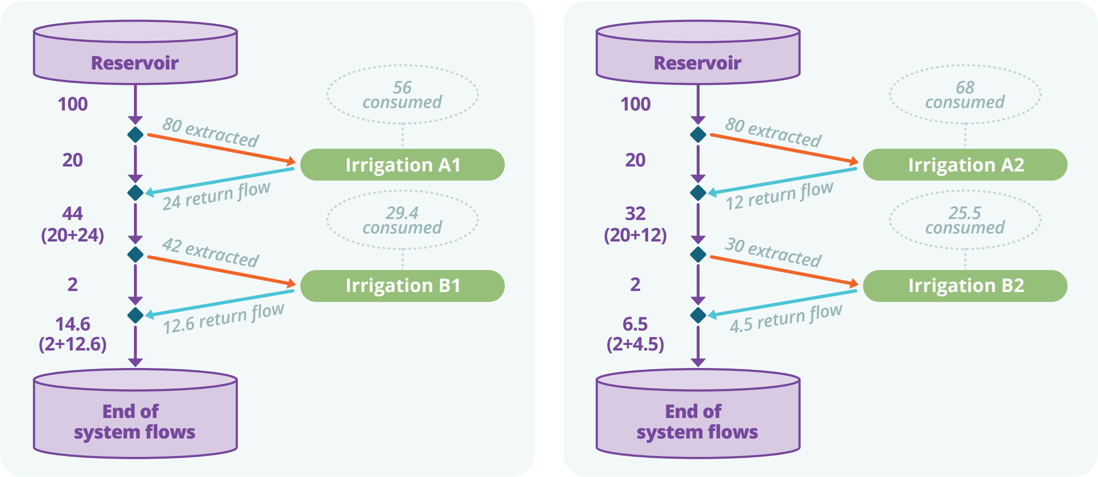
Figure 2 presents a highly simplified but conceptually accurate illustration of the potential effects of improving “efficiency” (the ratio of beneficial water consumption to water withdrawal) at the farm level. In a current situation (left diagram), all farmers (A1 and B1) have a 75% irrigation efficiency while with an increase in irrigation efficiency all farmers (A2 and B2) have an irrigation efficiency of 85%. In both cases, the total volume of water withdrawn from the reservoir is 80 units.

As irrigation efficiency increases (from 70% to 85%) the amount of water beneficially consumed by the irrigators in total increases (from 85.4 units with 70% irrigation efficiency to 93.5 units with 85% irrigation efficiency) due to more complete satisfaction of potential ET requirements by A1 and A2 and, thus, the volume of water returned back to the stream declines (from 24 units for A1 to 12 units for A2 and from 12.6 units for B1 to 4.5 units for B2). Thus, there is a reduction in, total, of return flows from 36.6 units (A1 and B1) at 70% irrigation efficiency to 16.5 units (A2 and B2) at 85% irrigation efficiency. In turn, this means the end of system flows decline from 14.6 units at 70% irrigation efficiency to 6.5 units at 85% irrigation efficiency. Increased efficiencies have enabled a more complete fulfilment of ET requirements by one user, increased total consumption of water and reduced end-of-system flows.

The paradox of irrigation efficiency highlights two effects:

1. the *physical* impact that increasing the fraction of water withdrawal that is *consumed*, with little or no change in the water withdrawals, must reduce the return flows that might otherwise be beneficially consumed elsewhere by irrigators or the environment; and

Figure 2. The Irrigation Efficiency Paradox



Irrigation Efficiency: 70%
Total (A1 + B1) Extractions = 80 + 42 = 122
Water Consumed (A1 + B1) = 56 + 29.4 = 85.4
Return Flows (A1 + B1) = 24 + 12.6 = 36.6
End of System Flows = 14.6

Irrigation Efficiency: 85%
Total (A2 + B2) Extractions = 80 + 30 = 110
Water Consumed (A2 + B2) = 68 + 25.5 = 93.5
Return Flows (A2 + B2) = 12 + 4.5 = 16.5
End of System Flows = 6.5

2. the *economic* demand for water *increases* because water delivered to the farm has become, locally, more productive.

Most writers combine these two impacts under the heading of Jevons' Paradox, a reference to the economist who predicted that the demand for coal would increase as the efficiency of steam engines improved in the 1800s. Because less coal was needed to produce a given amount of mechanical energy, many economists expected the demand for coal would fall. Jevons' insight was that mechanical energy would become cheaper and hence demand would increase. He was right: coal consumption in the United Kingdom increased more than one hundred-fold during the century.

Jevons' insight was related only to the second, "economic" effect of increased irrigation efficiency. The improvements to steam engines involved capturing heat energy that was otherwise lost, unproductively into the atmosphere (non-beneficial consumption in the terminology of Box 2), and thus had no possible "recoverable" component, and no potential third party impacts to offset against efficiency gains. In irrigation, this is turned on its head, where the water "losses" remain as liquid, generally recoverable and reusable water, whereas it is the productive portion, transpiration, that is lost to the system as vapour.

BOX 3 A convenient misunderstanding

A 2017 submission by Netafim (Australia) to the Government's Standing Committee on Agriculture and Water Resources quoted an independent report by the Sustainable Agriculture Initiative: "Drip irrigation remains without any doubt the most efficient irrigation technique and most powerful solution towards improving water productivity and ensuring food security". The rest of the sentence was omitted. It reads "but due to the popular confusion in water accounting terminology, reports on efficiency gains have to be looked at carefully. It is thus important to always carefully assess what potential impacts the introduction of drip irrigation and planned increase of local crop production have on the overall water availability at watershed scale and the water flows left to other water users in the basin."

The distinction between, and separate consideration of, the physical and economic impacts on water consumption is important for governance. For example, when water is abstracted from a very deep aquifer, to which there are no return flows capable of partial recovery for the aquifer within any useful timescale, it makes complete sense to maximise the proportion of deliveries that are consumed, but only if this reduces the aquifer withdrawals. But in doing so, the original economic dimension of Jevons' Paradox remains, and the incentive to pump will be enhanced by the increased value of water that is delivered. So just as in the case where useful return flows are impacted, it is still necessary to account fully for water consumption, and the impacts of changed technology both physically and economically.

These two, separate, impacts on water consumption that may result from technology changes were recently confirmed in a detailed statistical analysis of data from China (Xu and

Yang, 2022). This showed that the technological measures intended to "save" water in various districts in China, compared over time to control areas without such interventions, resulted in *increased* abstraction from aquifers, and *increased water consumption*. The data were sufficiently detailed to allow differentiation between the physical effect of increased irrigation efficiency (~30% of overall impact) and the economic response to the increased value of water as an input (~70%). These figures are location specific but confirm that the physical and the economic impacts are separable and significant.

3 Governance for sustainable water use: From strategy to management

Governance is now commonly referenced as important and problematic in the management of water resources. Governance is not a single entity activity, but attempts to separate and identify the components and their interdependences are rare. The responsibilities of a ministry of water resources and the managers of a water users association are different, though the sequence of activities required to perform their separate tasks are logically similar. The ministry is concerned with strategic choice – setting priorities for allocation of existing resources among competing sectors of the economy; investigating and evaluating options to expand or limit access to water; setting policies on funding infrastructure construction and maintenance; monitoring trends in aquifer levels, river flows and water quality; and assessing likely implications of climate change, etc. These activities are long term. Plans and policies are likely to be in place for years before substantial updating and revisions are required. Irrigation managers, on the other hand, make day-to-day decisions based on information about water availability and the pattern of demand they are facing, and (as elaborated later) they manage allocations, not consumption. Farmers, once provided with their allocation of scarce water, will legitimately seek to maximise the return they derive from it, which in turn means maximising consumption. As they strive towards this end, revisions to allocations may be necessary to ensure their sustainability target is met.

Strategically, water resources management must be grounded in a system of sound accounting, especially in terms of *consumption*. This is not a simple task, as availability (precipitation) varies sharply over time and space, aquifers are complex structures, often with poorly understood characteristics and linkages (both vertically and horizontally), climate change is progressively affecting consumption, and so on. Added to these complexities, consumption may be difficult to measure. What can be assembled is a "best estimate" of availability, distribution and consumption, perhaps projected for average, wet and dry scenarios, for a distinct area. This best estimate will point to the most important uncertainties and hence priorities for more detailed research.

Water accounts (see Box 4) are the essential basis for the first element of strategic governance: the *political debate and decisions* regarding appropriate allocations of the renewable resource. If demand exceeds supply and negative environmental trends persist, decisions are needed, such as a process for setting priorities, defining minimum allocations in times of severe scarcity and establishing criteria for intervention. There are no right or wrong decisions here, just an acceptable political consensus (though many participants and external observers will have opinions).

The political process is translated into *legislation,* or *rules* that reflect the political decisions in more precise and actionable detail: defined minimum streamflow rates or sequences for curtailing supply, proportions of water to be assigned to different users, etc. The politically self-evident priority that drinking water should have priority over golf courses is easily stated, but the actual rules that result in that outcome are more difficult to draft.

With the rules defined, *institutional arrangements* are then needed for implementation, monitoring and enforcement.

These three components of governance (political, legal, institutional) occur at multiple levels for a basin and may often involve different actors. For example, basin authorities may be established to implement national policies, which in turn will assign allocations to entities such as urban water utilities: these may be private companies, who in turn will set rules governing water allocation within their supply areas, including rules that limit watering of gardens in times of scarcity, or charging schedules that favour certain classes of user. Water assigned to an irrigation project may be managed by an elected management board, or by water user associations. At each level, physical water allocation from the higher management level sets boundaries within which the local agency again goes through the process of setting

BOX 4 Water accounting and hydrology

The science that addresses the disposition of water in a landscape is hydrology (from the Greek words for "water" and "study of"). Essentially, it is the application of the law of conservation of mass to the multiple natural components of a water system – precipitation, evaporation, transpiration, infiltration, runoff, streamflow, aquifer storage – and associated human interventions of changing land use, storage, diversion and pumping.

Water accounting has gained momentum in recent years because scarcity has drawn attention to the integrated nature of a river basin – "integrated" in the sense that water availability at any location is the cumulative impact of all that happened upstream of that point. Thus, Integrated Water Resources Management (IWRM) became a central theme of debate about water scarcity, culminating in the Dublin Declaration in 1992. Hydrology describes outcomes without judgment as to their merit. The Dublin Declaration assigned very clear preferences (on participation, gender and valuation), and by now IWRM embraces as many perspectives as there are pressure groups.

Water accounting sits between these extremes. The labels described in Box 2 include the words "beneficial" and "non-beneficial", which appear to be normative but only reflect the purpose of the use. No judgment is made as to whether consumption by a crop is "good", but rather that the objective of the use was to enhance crop consumption. This line item measures the extent to which that objective is achieved, and hydrologically recognises that this outcome has wider implications in terms of, for example, return flows.

priorities, rules and guidelines *within* its area of responsibility – for example, giving priority in times of drought to perennial crops. Progressively, moving down the hierarchy, water users lose interest in the distinction between withdrawals, consumption and return flows. Ultimately, farmers treat their water allocation as an entitlement to consume and will legitimately pursue success in achieving that end without regard to the impact at wider scales. Yet, as we will discuss later, the technologies that assist in strategic water resources governance can help improve management and maximise returns to scarce water at the farm level.

4 Governance, consumption and remote sensing

Understanding the role of consumption in managing scarcity is essential, and managing consumption is fundamental to achieving sustainable patterns of water allocation and use.

Physical measurements of flows, diversions and deliveries, will always have a basic role in water resources management. These are, relatively, the easiest parts of the hydrological system to measure – accurately, publicly and continuously. Consumption – identified above as the critical variable in understanding and managing scarcity – is unfortunately much harder to measure and is complicated by whether the water consumed is from blue water (streams, rivers, aquifers and water storages) or green water (precipitation and soil moisture), as shown in Box 5.

In agriculture, *potential* consumption by a fully watered, healthy crop is governed primarily by the weather – temperature, humidity, sunshine and windspeed that provide the energy to transform liquid to vapour – and the nature of the plant – tall, short, leafy, rough, smooth. The *actual* consumption is usually somewhat less, depending on moisture availability to the plant, and nutrient status. In short, there are many variables at play, and the variables themselves vary spatially over quite short distances. Potential consumption can be extrapolated based on point information from weather station data or an evaporation pan and crop description, projected over the surrounding areas. “Point” measurements of actual consumption include lysimeters, sap-flow meters, soil water depletion measurement, eddy-covariance, and Bowen ratio systems (Allen et al., 2011a). Scintillometers measure consumption over a linear path that may be hundreds of meters long.

Furthermore, as consumption is constrained, either by intervention of governments seeking to achieve sustainability targets, or simply as aquifers dry up, attention turns to productivity – how much crop can be produced with the limited water availability, the “crop per drop” indicator? This parameter is of interest to both strategic governance (where can water consumption be reduced at minimum economic cost?) and to the system manager and farmer seeking maximum returns to a limited allocation of water.

While these technologies are highly developed and accurate in the context they are used, a point measurement system can only provide consumption information for one field. When the concern is scarcity at the basin scale, and the domain of interest may be thousands of hectares (in the case of an irrigation scheme) or millions of hectares (for a basin landscape), such approaches are hopelessly inadequate due to costs for equipment, management and maintenance.

Remote Sensing (RS) has been developed to help resolve the constraints and costs of point measurement and offers novel insights on both consumption and productivity issues. Remote sensing offers the possibility to collect and interpret data from the global to the sub-10 metre level, providing indicators of both consumption and productivity, depending on the types of sensors used. In the following brief summaries, examples of such analyses are presented. The examples are organised in terms of scale, from basin to field.

Global Scale Remote Sensing (RS)

Over the last 25 years, satellite-based RS has offered the prospect of direct estimation of actual water consumption in the most important sector – irrigated agriculture – and over large areas. Most analyses use the fact that when the consumptive demand of vegetation is met, the surface temperature at that location is lowered due to evaporative cooling. Under-

BOX 5 Assigning colour to water

Water has historically been defined as a colourless, odourless fluid, but the advent of "water footprints" (Hoekstra et al., 2011) and associated attempts to classify water have assigned specific colours to different categories of water. In the context of agriculture in general, and irrigation in particular, *green* and *blue* water are of interest (*grey* and *black* water are hues or sub-categories of blue water that refer to water quality and whether the water should be reused for certain purposes with treatment (black water) or without treatment (grey water).

Green water is that proportion of crop consumption that is supplied from *in situ* rainfall. *Blue* water is water that is pumped from an aquifer, diverted from a stream, or delivered from a storage – and as such can be "managed". These distinctions rapidly lose clarity when examined closely: if a field is simply planted with a rainfed crop, then clearly all the consumed water is *green.* If the field is "bunded" to capture rainfall and enhance crop consumption, is the incremental consumption *green* or *blue* water? If we now add irrigation to the same field, complexities multiply: clearly the extra water applied is *blue*, but if it is added to an already flooded field (as is frequent in rice systems), or if the irrigation is followed by rainfall, we have less of an idea how to assign consumption between the *blue* and *green* water. Moreover, the early application of *blue* water to establish a crop will increase the ability of that crop to capture *green* water from subsequent rainfall (deeper rooting depth; increased leaf area that reduces non-beneficial evaporation from wetted soil). Thus, that application of *blue* water can increase the nominal consumption of *green* water, which in turn will reduce infiltration and runoff, thus reducing *blue* water availability elsewhere.

The concepts of *green* and *blue* water are, therefore, a helpful indicative shorthand for describing water sources, but are insufficient: detailed water measurement and water budgets are required when considering water management options and trade-offs.

lying data for this work at global scale are available freely from NASA[1], generated from the LANDSAT series of satellites. Accuracy of consumption estimation can often be within 10 to 15% (Allen et al., 2011a,b; Melton et al., 2022).

Most recently, the Google Earth Engine[2] allows any user to download and interpret spatial data on estimated water consumption and from large areas of the world, including historic data over several decades.

Requirements for using remote sensing of evapotranspiration

The advent of freely available RS of ET data for a number of areas of the globe provides an important future gateway to improved water resource management. The production of time series of ET data by automated expert platforms is reducing the technical expertise required to utilise this type of spatial information. Technical requirements become only those required for the formulation and operation of GIS systems and informing the GIS regarding local land use, ownership, cropping data, ET data and spatial precipitation. Information regarding the extraction and consumption of water can be derived from the RS of ET data. This substantially reduces the burden of obtaining continuous on-the-ground measurement of extractions or consumption. In addition, RS of ET data tend to provide a level playing field amongst all users.

A remaining challenge is the transformation of total ET as estimated by satellite into the consumption of extracted water only. This requires the subtraction of ET supplied by within-year precipitation. Several methods can be employed for estimating effective precipitation. These include the use of daily balances of soil water where precipitation inputs and simulated irrigation events are added to soil and the extraction of water for ET is estimated. Examples include the ETDemands model[3] of the United States Bureau of Reclamation and Desert Research Institute and Github[4] and the WaPOR model[5] of FAO. Other approaches to estimating effective precipitation are through sampling of non-irrigated areas surrounding an irrigated area from RS of ET results. This has the advantage of eliminating the need for accurate spatial precipitation information. However, it has the disadvantage of potentially poor temporal sampling of ET during clouded periods and whether non-irrigated areas have the vegetation density to actively extract infiltrated precipitation and therefore to produce full ET from effective precipitation to be observed by satellite.

One consideration in management is that water consumption is a largely “invisible” process, whereas, ground-based measurement of irrigation withdrawals can be made visible to all. In addition, RS of ET that produces estimates of consumption is mostly a reactive process that may require days to months to produce, whereas, measurement of withdrawals can be a proactive, instantaneous and forward-looking process. Therefore, in many situations, it is necessary for an agency to use a combination of RS of ET to establish consumption and ground-based measurement of withdrawals in the form of diversions, water pumped from groundwater or deliveries in order to regulate and manage day-to-day withdrawals. Regulation and management of withdrawals, in turn, will control the resulting consumption.

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[1] https://OpenETData.org

[2] https://eeflux-level1.appspot.com

[3] https://www.usbr.gov/watersmart/baseline/docs/irrigationdemand/irrigationdemands.pdf

[4] https://github.com/usbr/et-demands

[5] https://wapor.apps.fao.org/home/WAPOR_2/1

The correspondence of withdrawal measurements and the associated consumption can be established by co-measurement over a several year period where ratios of one to the other are established. As has been discussed, estimation of consumption of withdrawn water generally requires the subtraction of consumed precipitation from the bulk RS of ET estimates. Ratios of withdrawal to consumption include an additional non-consumptive components that account for excess application required for complete field coverage by irrigation and for any runoff of irrigation water. Ratios of withdrawals to consumption can in many cases be grouped by crop, phenology and irrigation system type, in situations where consumption is measured by ground-based systems so that fewer measurements of consumption may be needed, with all withdrawals to field or distributary measured instead by flow meters.

Regional: WaPOR

In 2016 FAO initiated the WaPOR project, with the support of the Ministry of Foreign Affairs of the Netherlands. WaPOR is FAO's portal to monitor "Water Productivity through Open Access of Remotely Sensed Derived Data", providing access to the water productivity data and its thousands of underlying map layers, including satellite-based evapotranspiration.

The WaPOR project started by acknowledging that for the agriculture sector, being a key water user, careful monitoring of water productivity, and exploring opportunities to increase it, are imperative to counter the increased pressure that agriculture puts on water resources. The current WaPOR database contains data related to biomass production, evapotranspiration and agricultural land and water productivity in Africa and the Near East at various resolutions (up to 30 metres).

The database has 26 parameters, including actual evapotranspiration at 10-day aggregation level. The portal's services are directly accessible through dedicated FAO WaPOR application programming interfaces (APIs), or directly via Google Earth Engine, or by FAO's own portal[6]. Data access is designed to be simple through this FAO portal, and is used by many (Javadian et al., 2019; Blatchford et al., 2020; Geshnigani, Mirabbasi and Golabi, 2021). Data are available in near-real time.

Gradually, WaPOR can enter the domain of governance to support decision-making processes. The expectations are that WaPOR will play a key role in decision-making to support sustainable water management and agricultural production.

International: Nile Basin Initiative

The Nile Basin Initiative (NBI) is an intergovernmental partnership of 10 Nile Basin countries. The objectives of the NBI are "to develop the Nile Basin water resources in a sustainable and equitable way and to ensure efficient water management and the optimal use of the resources". To achieve this, NBI states that "reliable estimates of regional evapotranspiration are necessary to improve water resources management and planning".[7]

There are many studies undertaken to assess evapotranspiration of the entire Nile Basin, or regions within the Nile Basin. Over 14,000 publications can be found in Google Scholar using

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[6] https://wapor.apps.fao.org/home/WAPOR_2/1

[7] https://dspace.mit.edu/handle/1721.1/110307

"Nile basin satellite evaporation" as search terms. To what extent this evapotranspiration information is actually used to support governance in improving water resources management and planning remains unclear. For example, the well-known Nile Basin Water Resources Atlas includes actual ET maps (based on MOD16ET) and the main advice to governance was: "from the maps, it can be observed that the equatorial lakes region and the Ethiopian highlands as well as the open water bodies have very high values of actual evapotranspiration compared to the downstream parts of the basin."[8]

A more recent study to support decision-making governance in the Nile Basin is FAO and IHA Delft (2020). That study concluded, based on open access of remotely sensed derived data (WaPOR v2.0), that:

- the potential for agricultural expansion in the basin is limited from a water resources perspective, even though the irrigated land accounts for only 2% of the total area;
- the largest proportion of the water in the basin is consumed by natural land covers;
- the beneficial water consumption is low compared to non-beneficial consumption;
- agricultural expansion in the basin could theoretically be implemented if non-consumptive use of water by natural land cover is minimised through improvement of landscape strategies; and
- such expansion should take into account the hydrological response of the basin, environmental flow requirements, potentially revised sharing of the water resources among the riparian countries, and the effect of climate variability on seasonal and periodic availability of water resources.

The World Bank, in collaboration with the International Water Management Institute, identified the Mara River Basin in Kenya for "piloting the satellite-based hydrological model to assess the current status of water resources in the Mara Sub-Basin" (IWMI, 2020). A thorough analysis and comparison of satellite-based evapotranspiration products was undertaken. Based on the best available data, the following governance and investment advice was given:

- the use of the water allocation plan and issuance of water use permits should be accompanied with consistent monitoring to ensure resource availability;
- water should be stored during the wet season and made available during the dry season; and
- agricultural best management practices should be implemented to target a reduction in evaporation across the basin.

Basin: Indus

Various initiatives to monitor water consumption by irrigated crops in the Indus Basin, using satellite information, have been undertaken. Many of those initiatives are published in the scientific literature and attempts to use this knowledge to support governance have been initiated. One such study (Simons et al., 2020), using satellite-based ET data, revealed that return flow reuse is an essential component of the Indus Basin dynamics, leading to the result that "water saving and efficiency enhancement measures should therefore be imple-

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[8] https://atlas.nilebasin.org/treatise/evaporation-and-evapotranspiration/

mented with great caution", recognising the principles covered earlier that increases in efficiency may increase local water consumption and thereby reduce availability of water downstream. The overall conclusion was that relying on globally available satellite-based ET data and limited additional data to determine consumed fractions and non-consumed flows can support policy makers in determining how to make irrigation systems more efficient without detriment to downstream users.

Based on those analyses, the Punjab Irrigation Department is currently setting up an ET group to support decision making. FAO and Asian Development Bank are supporting those initiatives where satellite-based ET information is considered as an important instrument to manage water sustainably. The FAO project is financially supported by Green Climate Fund and has the objective of transforming the Indus basin with climate resilient agriculture and water management. The ADB-supported initiative emphasises that irrigation should be considered from a basin perspective, and the title of the initiative makes this clear: "Transformation of Punjab Irrigation Department to Water Resources Department". Satellite-based ET is put forward as key information for sustainable water management.

Basin: The Upper Colorado River Basin

The Upper Colorado River Basin presents an example of using RS of ET data to manage conservation and reductions in total depletions to a large surface water resource – the Colorado River. The 2,330 km long Colorado River drains an expansive watershed that encompasses parts of seven U.S. states and two Mexican states (Figure 3). The river is a vital source of water for 40 million people. An extensive system of dams, reservoirs and aqueducts divert most of its flow for agricultural irrigation and urban water supply. The river's large flow and steep gradient are used to generate hydroelectricity, meeting peaking power demands in much of the Intermountain West of the United States. Intensive water consumption has dried up the lower 160 km of the river, which has rarely reached the Pacific Ocean since the 1960s.

The US federal government constructed most of the major dams and aqueducts on the river between 1910 and 1970; the largest, Hoover Dam, was completed in 1935. Numerous water projects have involved state and local governments. With all of its water fully allocated, the Colorado is now considered among the most controlled and litigated rivers in the world.

The Colorado River is managed and operated under numerous compacts, federal laws, an international treaty, court decisions and decrees, contracts, and regulatory guidelines collectively known as the "Law of the River." The Colorado River Compact is a 1922 agreement among the seven U.S. states that fall within the Colorado River drainage basin. The pact governs the allocation of the river's water rights and divides the river basin into two areas, the Upper Division comprising the US states of Colorado, New Mexico, Utah and Wyoming and the Lower Division comprising the US states of Nevada, Arizona and California and mandates that the basin's water be shared equally among the upper and lower basins. The states within each basin are required to divide their allotment among themselves. In addition, 59 cubic metres per second (1.9 km^3 per year) of Colorado River water is allocated to Mexico.

Each state has authority to manage water rights and consumption internal to their boundaries. This is done using a generally well designed and managed system of water rights and permissions for individuals or groups of individuals to divert or extract water from streams

Figure 3. The Colorado River basin of the United States showing the lower basin in orange colour and the upper basin in dark tan colour. The main stem of the Colorado River is outlined in blue.

Source: adapted from Adams, 2020

and groundwater. Management of water rights is done independent of other states. Surface water and groundwater are generally managed separately, but conjunctively, so that impacts of groundwater pumping on surface water depletions are monitored and mitigated. In the western United States, a seniority system is usually employed where historically older (more senior) water rights have protection against negative impacts by junior water users. Junior water users are curtailed before any curtailment of more senior water users. This has been a somewhat harsh and rigid system, historically, but one that is transparent and predictable and where the economic value of individual water rights is readily established. Some trading, sale or leasing of water rights is common, and provides for evolution of water rights and depletions toward economically optimal and predictable levels.

Prolonged drought and low runoff conditions accelerated by climate change have led to historically low water levels in Lakes Powell and Mead over the last two decades. As a result, U.S. Department of Interior leaders have engaged Colorado River Basin partners to enact elevated drought response operations and reduced water consumption.[9]

A version of the METRIC remote sensing method named "Earth Engine Mapping EvapoTranspiration at High Resolution and Internalised Calibration" (eeMETRIC) was adopted by the Upper Colorado River Commission (UCRC) (U.S. states of Colorado, Wyoming, Utah and New Mexico) in June of 2022 for quantifying water consumption (ET) of irrigation water in the upper basin. This adoption is in line with recommendations made by the Upper Colorado

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[9] https://www.doi.gov/pressreleases/interior-department-announces-actions-protect-colorado-river-system-sets-2023

River Basin Assessment for Agricultural Consumptive Use Study – Phase III Report.[10] The eeMETRIC-based ET estimates are used for monitoring and planning decisions among the states and between the upper basin and the lower basin.[11]

The adoption of eeMETRIC was based on comparative study results and efficiency and speed of applications.[12] Comparisons included on-the-ground measurements of ET by eddy covariance and with other RS of ET methods on the Google Earth-based OpenET system.[13] The use of eeMETRIC replaces the traditional use of the SCS-Blaney-Criddle and ASCE Penman-Monteith methods that use a climate-based reference ET and crop coefficient to estimate potential ET for crops. The traditional methods were judged to be more uncertain than the RS of ET methods due to their inability to estimate actual ET that may be constrained by water limitations and scarcity. The eeMETRIC RS of ET method is able to quantify reductions in ET occurring during the fallowing of irrigated land where a residual ET from stored soil water and precipitation occurs.

Irrigation identification and classifications are made using a vegetation index-based Harmonized Landsat Sentinel-2 Mapper (publication pending) to identify irrigated areas for assignment of consumed water volumes. UCRB study reports may be accessed on the UCRC webpage.[14] Identified irrigated parcels are outlined in Geographic Information Systems (GIS) along with monthly and growing season ET estimated by eeMETRIC, enabling parcel-by-parcel ET to be sampled. The gross actual ET is adjusted downward using estimated effective precipitation (precipitation that is used to support ET of the parcel). The end product represents ET of irrigation water.

ET estimates from eeMETRIC are made freely available on the Environmental Defense Fund / NASA OpenET platform for the period 2016–2022 for the western half of the United States. The six-year time series enables the evaluation of current trends in water consumption and to quantify and verify reductions in water consumption stemming from water conservation measures such as fallowing, conversion to low-water-use crops or deficit irrigation. Management of water rights and water conservation is accomplished within each state on a parcel-by-parcel (field-by-field) basis, with RS of ET information used for scoping and planning water consumption reduction efforts and to monitor impacts. Ultimately, ET data will be made freely available on OpenET as far back as 1984 representing the advent of the thermally equipped Landsat 5 satellite.

Subregion: California

The historic passage of the California Sustainable Groundwater Management Act (SGMA) by the State of California in the United States in 2014 created a state-wide framework to protect groundwater resources over the long term.[15] In signing SGMA, California Governor

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[10] http://www.ucrcommission.com/wp-content/uploads/2022/11/Assessing-Agricultural-Consumptive-Use-in-the-UCRB-Phase-III-Report-November-2022.pdf

[11] http://www.ucrcommission.com/wp-content/uploads/2022/12/UCRC-DM-Investigation-Summary-Report-Dec-13-2022.pdf

[12] http://www.ucrcommission.com/consistent-consumptive-water-use-measurement-for-agricultural-irrigation-in-the-upper-colorado-river-basin/

[13] https://openetdata.org/

[14] http://www.ucrcommission.com/reports-studies/

[15] https://water.ca.gov/programs/groundwater-management/sgma-groundwater-management

Jerry Brown emphasised that “groundwater management in California is best accomplished locally”. SGMA requires local agencies to form groundwater sustainability agencies (GSAs) for identified high and medium priority basins. GSAs are to develop and implement groundwater sustainability plans (GSPs) to avoid and mitigate undesirable overdraft of groundwater within 20 years. Overdraft is defined when total depletion of groundwater exceeds total recharge.

The State of California serves two roles to support local SGMA implementation. These are: 1) Regulatory oversight through the evaluation and assessment of GSPs and 2) Providing ongoing assistance to locals through the development of a) best management practices and guidance; b) planning assistance; c) technical assistance; and d) financial assistance. SGMA Technical Support Services (TSS) support GSAs as they develop their GSPs. TSSs provide education, spatial data and GIS tools to build the capacity needed to achieve sustainability.

ET in SGMA GSPs can be estimated using the Integrated Water Flow Model Demand Calculator (IDC) of the California Department of Water Resources (DWR), where agricultural water demand is calculated based on climate data, crop type, crop acreages, soil properties and irrigation methods using a traditional crop coefficient x reference ET approach embedded in a spatial GIS-type of system. Urban demand is calculated based on population and per-capita water usage. IDC is a stand-alone root zone component of the Integrated Water Flow Model (IWFM).

An acceptable alternative to the use of the traditional crop coefficient x reference ET approach is the use of RS of ET. The California DWR suggests that ET information can be developed or obtained from satellite-based estimates of ET rates (e.g. METRIC calculations).[16] Many GSAs have used a range of RS of ET systems including those by Irriwatch (SEBAL) and Land IQ (METRIC). These systems have been used by more than two dozen GSAs.[17] It is noted, however, that some media articles do voice scepticism by some GSA users regarding accuracy and dependability of RS of ET estimates.[18] Scepticism to new technology is normal and expected. One purpose of the OpenET platform is to reduce scepticism and to promote its use in formulating the groundwater sustainability plans and implementation of the plans to reduce groundwater pumping and to increase groundwater recharge. A second purpose is use of RS of ET by the State of California to monitor progress towards long-term sustainability.

An example of ET estimation by a GSA is the Merced Water Resources Management area (MercedWRM) that surrounds Merced, CA (Figure 4), where agricultural demand is dynamically calculated every month using METRIC to verify the consumptive use demand estimated by the IDC model. The estimation of water demand by the two methods offers distinct but parallel results.[19] In the MercedWRM application, potential ET from the crop coefficient-based IDC model is adjusted (calibrated) using actual ET produced by METRIC. Adjustments account for any needed reductions in estimated potential ET caused by water shortage or less than optimal planting density or health of crops. The adjustments can also account for underestimation of potential or actual ET by the IDC method due to the employment of non-representative crop coefficients. An example of a comparison of IDC monthly ET estimates and those from the METRIC model is shown in Figure 5.

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[16] https://water.ca.gov/-/media/DWR-Website/Web-Pages/Programs/Groundwater-Management/Sustainable-Groundwater-Management/Best-Management-Practices-and-Guidance-Documents/Files/Climate-Change-Guidance_Final_ay_19.pdf

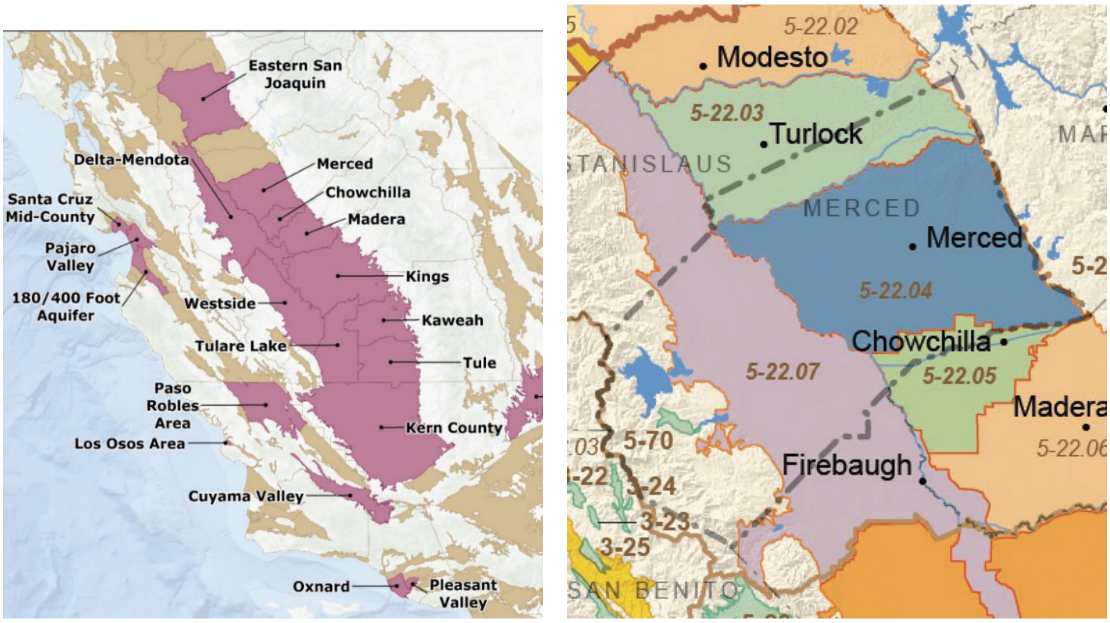
[17] https://andthewest.stanford.edu/2022/a-simmering-revolt-against-groundwater-cutbacks-in-california/

[18] Distrust of satellite monitoring delays Madera County’s plan to penalize growers for over pumping - SJV Water

[19] http://mercedsgma.org/assets/pdf/gsp-sections/Merced-Subbasin-GSP-Appx-D-MercedWRM-Model.pdf

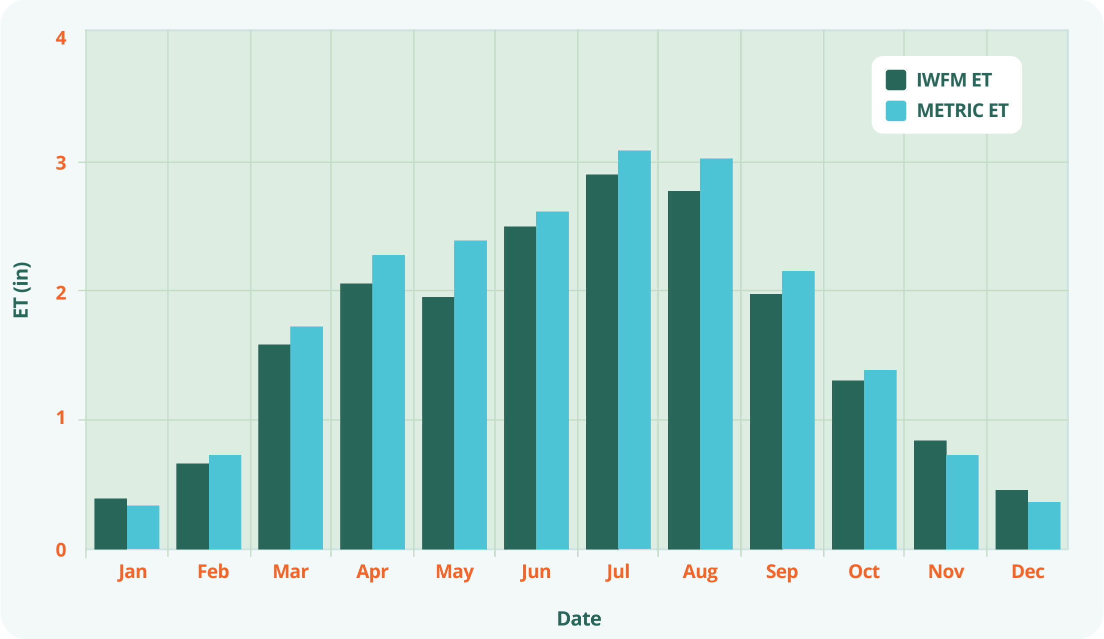
In summary, the Merced groundwater sustainability plan and its context in the State of California's mandate for sustainable depletion of groundwater resources by year 2040 provides a useful example on how a large governing entity (California) can provide both the mandate and the technical and financial resources for reducing groundwater depletion. The SGMA of California demonstrates how the groundwater resource can be parsed into local groundwater districts and sustainability areas for manageable modelling, monitoring and regulation. Each

Figure 4. Merced Water Resources Management area located in the Central Valley of California, left, and closeup (right) in blue



Source: (left) https://www.linkedin.com/pulse/today-day-gsps-critically-overdrafted-high-basins-due-sean-hood and (right) https://www.countyofmerced.com/3140/Sustainable-Groundwater---SGMA

Figure 5. Comparison of monthly ET estimated by the crop-coefficient-based IWFM (IDC) model and by the METRIC model for the Merced Water Resources Management area



Source: Woodard and Curran, 2019

GSA holds responsibility for organising and managing water users within the GSA. The GSA develops the forward-looking plan and means for plan implementation, be it by purchasing and retiring irrigation wells, by reduced pumping of all wells, by implementing a seniority system for curtailment, or by group-funded plans for increasing groundwater recharge. Spatial information on ET provides transparency on where and when water is consumed. Further, it provides detail during monitoring of reductions or shifts in depletions into the future.

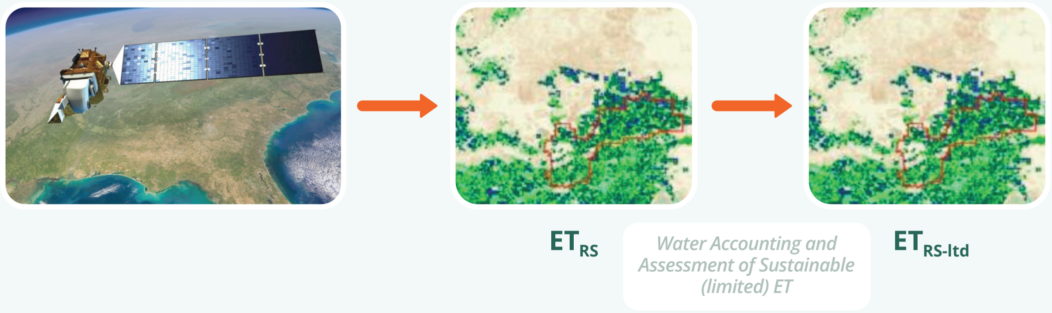
In other areas of California, perennial vineyards and orchards are replacing non-permanent field crops and pastures, effectively “hardening demand” for water use. Addressing increasing competition in year-to-year water demand will require significant reductions in water consumption. A recent study (Anderson et al., 2018), combining data from various satellites with ground data from flux towers, provides policy makers with detailed information on the pattern of water consumption, disaggregated by crop.

An insight from these data, which contradicts the common assumption that rice requires 2–4 times more water than other grain crops, is that the *consumption* by rice is only about 12% more than that of maize (900 mm versus 1020 mm).

Project: “ET Management” in China

The People's Republic of China has considerable scientific capacity (satellites and research expertise) to collect and analyse relevant data to compute water balances at various scales (Figure 6). In the North China Plain – the main wheat-growing area – analysis demonstrates that current water consumption exceeds the renewable supply by about 20% (Wu et al., 2014), and that even under full implementation of “water saving” measures, there would still be a substantial shortfall in supply (Yan et al., 2015). A series of World Bank/Global Environmental Facility projects focused on the concept of “ET Management”, realising that the only way to stabilise and restore aquifers is to reduce water consumption. These projects defined allowable consumption starting from the basin level, with successive allocations to sector, project and farm level defined – in consumption terms – to reflect in total the calculated equi-

Figure 6. Translation of ET from RS into on-the-ground limitation on withdrawals



$$\text{Withdrawal}_{ltd} = \frac{ET_{RS-ltd} - P_{eff}}{Eff}$$

$$\text{Hours per week} = \frac{\text{Withdrawal}_{ltd}}{\text{Withdrawal Rate}}$$

librium consumption (World Bank, n.d.). Types of mitigation include constraints on growing more than one crop per year.

An important lesson from this process was that while the consumption-based water balance (as distinct from a withdrawal-based analysis) was essential to setting a sustainable framework for water management at basin scale, at a farm level the only effective *management* variable was volume of water delivered, rather than water consumption by the individual farmer. Hence, water allocations to the farm are computed by adjusting the consumption target upwards into a delivered quantity based on assumed irrigation efficiency – effectively reversing the conventional sequence of estimating the volume of water available to the crop by adjusting the delivered quantity by irrigation efficiency. Within that delivered quantity, the farmer is expected to maximise consumption and, hence, water productivity. The result is the establishment of an on-the-ground measurable quantity (delivery) that can be accessed and monitored, as previously discussed.

Farm Level: Drones, flying sensors

Development in remotely sensed data to support management of water has probably made its biggest step forward in drone services, often referred to as Flying Sensors. Flying Sensors are not restricted by clouds, offer unprecedented high spatial resolution, and allow user-determined timing of data acquisition.

A typical example of the application of Flying Sensors is the Apsan Vale project in Zambezi Valley in Mozambique (Figure 7).[20] The Apsan Vale project aims at increasing smallholders' productivity through a combination of improvements in water, irrigation and agronomical management practices. The specific role of the Flying Sensors is, on the one hand, to monitor the water productivity of farmers' fields and determine spots with high or low water productivity. On the other hand, the Flying Sensor information is used to compare water productivity of target areas to other areas where no interventions take place. A key component of the project is that by combining the Flying Sensor information with satellite-based data, monitoring extends over spatial scales from field to basin.

Given the relatively low costs and easy operation of modern drones, applying Flying Sensors for local water management and governance is available to all. A typical example is the "ThirdEye" initiative in Africa[21], which started as an investment program in the context of the Securing Water for Food[22] initiative in 2014. Currently, real businesses have emerged in Mozambique (six employees) and Kenya (five employees) where Flying Sensor operators provide services to farmers, water managers and development partners. One of the key strengths of the Flying Sensors is that they collect information outside the visible light (near and thermal infrared), so that crop stress can be determined about 10 days earlier than with the human eye. Moreover, actual ET can be detected so that real water consumption and crop water productivity can be monitored. Challenges exist with the accurate retrieval of ET information that may require expert oversight and sensor calibration.

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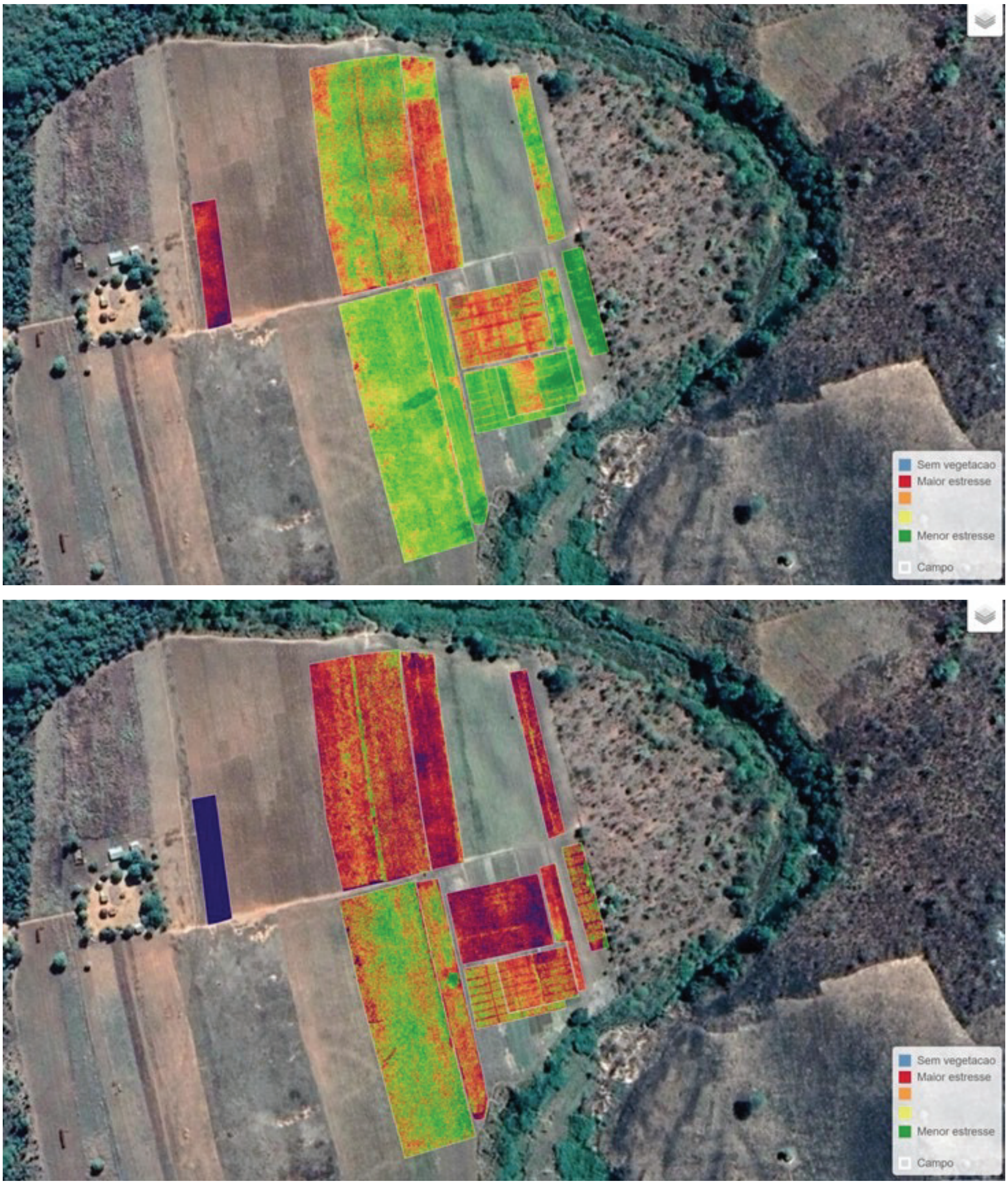
[20] https://www.futurewater.nl/projects/apsan-vale-nl/

[21] https://www.futurewater.eu/projects/third-eye/

[22] https://securingwaterforfood.org/

Figure 7. Ultra-high resolution data from Flying Sensors showing fields in the Zambezi Valley for 14-Jul-2021 (top) and 5-Aug-2021 (bottom).



Source: https://futurewater.nl/apsanvaleportal/

5 Description of remote sensing of evapotranspiration approaches

Remote sensing can provide spatial coverage of the consumptive (evapotranspiration) component of water, which is valuable because consumption can be highly variable from field to field and over time. In comparison, ground-based ET measuring systems such as eddy covariance, Bowen ratio, lysimeters, scintillometers and soil water meters and balance are often expensive and difficult to manage to provide complete spatial information on ET. On a field scale, costs for accurate ground-based measurement can average as high as USD 5000 per field per year. In some cases, fields that have similar crop type and planting date may be grouped into one class to facilitate using fewer measurement locations. However, if regulation and protests occur on a field-by-field basis, then the consumptive measurement should be local and directed. Even so, it is difficult for ground-based systems to keep up with ever-changing crop species and timings, and, as with most human-derived systems, the systems and programs are apt to deteriorate over time. In addition, there is opportunity, over years, to derive clever ways for cheating or bribing consumption measurements.

Remote sensing of ET therefore provides a bridge and effective combination with ground-based ET measurement for extrapolation and extension of local measurement. This combination allows ground-based ET measurement to be conducted only at well-managed research and other controlled sites and over a limited time period of a few years. The ground systems, when distributed over a sufficient area and variation in crop type, provide absolute ET measurements to calibrate and confirm remote sensing models. This has been the approach of the American OpenET program (OpenETdata.org) that now provides routine ET information for most of the US. More than two hundred eddy covariance stations have been compared against OpenET models with some stations used for model improvement and others reserved, blind to model groups, for independent assessment and confirmation (Melton et al., 2022).

Satellite-based remote sensing of ET (RSET) can provide a level playing field to all irrigation users in a basin regarding equity and commonality in ET estimates. The same satellite and algorithms are used for all areas and usually the same entity produces the ET data. Therefore, any biases in estimates impact all users in all areas.

Background on satellite-based remote sensing of ET

The following focuses on the production of high-resolution maps of ET, meaning at the approximately 30-metre scale. Evapotranspiration is defined here as the aggregate sum of evaporation I direct from the soil surface and the surfaces of plant canopies and transpiration (T), where T is the evaporation of water from the plant system via the plant leaf, stem and root-soil system. RS of ET produces the “bulk” ET that includes ET from both irrigation and precipitation. In general, no distinction between ET of irrigation water and ET of precipitation can be made by the satellite.

Vapour flux from vegetation is invisible to current-day satellites. Instead, satellites are good at viewing the short-wave (solar) radiation reflected from Earth’s surface back to space.

Thermal-imager equipped satellites additionally view the thermal radiation emitted from the surface. That radiation is transformed during processing into a temperature of the surface.

Field-scale determination of ET requires the use of satellites such as the US Landsat and European Sentinel 2 that have 30x30 m pixel size or smaller. The 30 m pixel size of Landsat allows the identification of ET from fields larger than about 1 hectare in size if ET estimates are based mostly on short wave reflectance. For strictly short-wave based estimation the 10 m Sentinel 2 satellite system can enable estimates for fields as small as 0.1 hectare. The minimum size increases to about 8 hectares if ET estimates are based on thermal imagery. This is because Landsat, which is the only operational field-scale satellite equipped with thermal imagers, has thermal pixel size that varies from 60 to 120 m. These field sizes are based on the requirement that at least one full pixel is located completely within the boundaries of a field so that a representative pixel or area can be identified for sampling. It also considers registration error (spatial accuracy) of pixels themselves. This generally requires a field size that is larger than three pixels on a side.

Traditional ET estimation. Prior to the use of satellites, and used even now for planning and water management, the crop coefficient – reference ET approach has been widely depended upon for ET estimation. The two-part procedure utilises a reference ET to represent the near maximum ET expected from an extensive, well-watered surface of clipped grass – the reference ET (ET_{ref}) varies with weather conditions of solar radiation, air temperature, humidity and wind speed. The ET_{ref}, which is utilised for all crop types, is then adjusted using a crop coefficient (K_c) that considers characteristics of the crop that cause it to deviate from the grass reference. These include the amount of ground covered by vegetation, the height and leafiness of the vegetation, the vegetation type, the stage of development and the wetness of the underlying soil surface. The ET_{ref} defined by FAO (Allen et al., 1998) is a "virtual" and hypothetical grassed reference vegetation surface having full ground cover and extensive, well-watered surface that describes how that surface will respond to climatic demands.

The crop coefficient can be expressed as $K_c = ET_T/ET_{ref}$ where ET_T is total ET that includes both transpiration and evaporation from the soil surface. A typical K_c curve is shown in Figure 8 where values begin at low ratios following planting and during an initial period. The value increases as vegetation develops and reaches a maximum during the middle of the growing period, after which it reduces due to plant aging and dying.

The solid curve in the figure is a "basal" (K_{cb}) curve that follows the relative evolution of transpiration over the crop development periods. That curve represents the K_c of a crop when the underlying soil surface is dry and nearly all ET is via transpiration. The K_{cb} is generally related to the amount of vegetation that shades the soil. The dashed "spikes" in the figure represent temporary increases in the relative ET rate following wetting of soil by precipitation or irrigation. These spikes are labelled "K_e". When the K_{cb} and K_e values are added and then smoothed over time, the result is the smoothed single K_c curve (K_{cm}), shown as the dotted line.

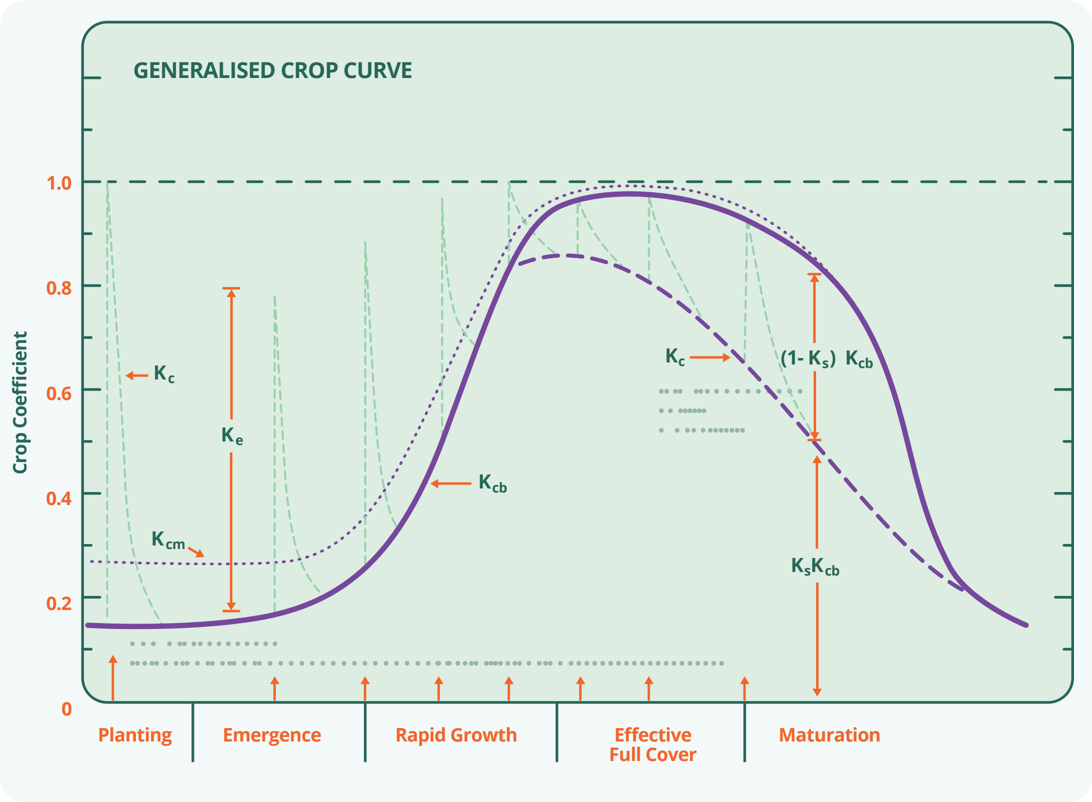
A limitation of the traditional Kc approach is that its application often assumes a single, average curve that is applied over large numbers of fields having the same crop type. This avoids having to monitor or estimate the crop growth stage conditions for each individual field when there are large numbers of crops and fields. In addition, there may be some question whether actual vegetative and growing conditions for an individual field are achieving the conditions represented by idealised Kc curves and values. This can occur in water scarce areas where actual ET is less than potential ET as defined by the Kcb curve due to low water availability.

Classes of Satellite-based ET Techniques. Satellite based models can be separated into the following classes, building on Kalma et al. (2008):

- Surface Energy Balance based on the satellite image: $\lambda E = R_n - G - H$ (terms are defined below) (these include the SEBAL, METRIC, SSEB, ALEXI, ETWatch models)
- Simplified correlations or relationships between surface temperature extremes in an image and endpoints of anticipated ET (these include the SSEBoP, PT-JPL models)
- Vegetation-based relative ET (i.e. K_c or ET_rF) that is multiplied by a weather-based reference ET to produce ET or that use the Penman-Monteith directly (these include the SIMS, ETLook, ETMonitor models)

Energy balance models. ET results from the conversion of liquid water into vapour. That process requires substantial quantities of energy that must come from radiation energy from the sun or atmosphere or must come from extracting sensible heat from the air or ground. Approximately 2.4 million Joules (megajoules) of energy are required to evaporate one kilogram of water at room temperature. Because satellites cannot directly measure ET, models calculate ET using an energy balance of the inputs required to drive the evaporation. In energy balance models, λE represents latent heat flux density that is the energy required for the conversion of liquid water into vapour. R_n is net radiation at the evaporating surface

Figure 8. Generalised crop coefficient curves showing their characteristic behaviour over time (x-axis).



and is comprised of short-wave (solar) and long-wave (thermal) components, G is heat flux into or out of the ground, and H is sensible heat flux to or from the air. G and H are positive when sensible heat flows away from the surface. They are negative when sensible heat flows toward the surface.

The general equation for the surface energy balance is:

$$\lambda E = R_n — G — H \tag{1}$$

λE is converted from units of energy into ET having units of millimetres by dividing by the latent heat of vapourisation, λ. Λ is approximately 2.4 megajoules per kilogram as previously cited.

An advantage to determining ET by energy balance is that it determines the actual ET from a unit of land rather than the potential ET determined by the crop coefficient approach. Actual ET can be less than potential due to effects of water shortage, low irrigation uniformity, salinity of soil and water, sparse vegetation, waterlogging and disease.

Surface energy balance-based ET is valuable in that it includes all forms and components of ET including evaporation I of water from a wet soil surface. Another advantage of ET by energy balance is that a specific classification and identification of crop type by field is usually not required, as it might with a vegetation index (VI) based approach. Crop-specific classifications can significantly increase costs for ET mapping and may take months to complete.

Mitigation for biases in remotely sensed ET. Most polar-orbiting satellites such as Landsat and Sentinel 2 orbit about 700 km above the Earth's surface and record only radiative fluxes from the surface. However, the transport of vapour and sensible heat from land surfaces is strongly impacted by aerodynamic processes including wind speed, turbulence and buoyancy, all of which are essentially invisible to satellites. In addition, the precise estimation of albedo, net radiation and soil heat flux from satellites can be uncertain and potentially impacted by biases in measurements and estimation. Therefore, even though the best efforts are made to estimate each of these parameters as accurately and as unbiased as possible, some biases do. Essentially all satellite-based surface energy balance models can be impacted by biases in components and measurements.

The METRIC model tends to stand out in its mitigation for biases In that the calibration of the estimated vertical air temperature gradient used to estimate sensible heat utilises weather-based reference ET to set endpoints on ET during model calibration for a specific satellite image. This helps to automatically correct the surface energy balance for systematic computational biases associated with empirical functions and uncertainties. The end result is that biases inherent to R_n, G, and subcomponents of H are cancelled by the subtraction of a bias-cancelling estimate for H.

Several publications describe the estimation accuracy of the methods as well as for other methods. Comparisons include the OpenET publication by Melton et al., (2021), which estimated accuracies for six well-established Landsat-based ET models. Melton found mean model estimation of total growing seasonal ET to be within 8% mean total ET calculated from flux tower data for all but one of the six models. The comparison for agriculture used 15 sites and 40 total growing seasons.

The Vegetation Index (VI) approach. An alternative to the use of surface energy balance and thermal satellite imagery is to base the ET estimate on short-wave radiation alone. An advantage of this is that additional non-thermal-imaging satellites, for example, Sentinel 2, can be utilised in addition to Landsat. In the VI approach, reflectance of short-wave solar radiation is used to estimate a vegetation index, normally varying from 0 to 1, that represents the amount of vegetation covering the surface. The VI is then converted into a crop coefficient, K_c, that can be multiplied by reference ET derived from weather station data. The estimation of K_c from VI is possible because of the generally close correspondence between vegetation amount and transpiration. As vegetation cover increases, leaf area increases and transpiration increases.

Disadvantages with VI-based methods include estimating evaporation from bare soil following precipitation and irrigation events, because wetness of soil is not readily visible to the short-wave bands. Another important disadvantage of VI-based methods is that their estimation of K_c represents the K_c that is associated with potential ET from crops that are not short of water. This is caused by the multipliers used to convert the VI into K_c and lack of knowledge of any water stress that may be occurring. As a result, VI-based methods tend to overestimate transpiration and understate evaporation from soil. VI-based methods are often best used to estimate potential ET under adequate water supplies.

Advantages of VI-based estimation of ET are their relative quickness and relative universality. They have a physical foundation in that ET is estimated to vary in proportion to the estimated amount of vegetation present. Weaknesses or vulnerabilities of the method are for crops that have some degree of water stress caused by water shortage. Under those conditions, ET will be lower than estimated by the standard equations. Because of these disadvantages of VI-approaches, surface energy balance methods are generally recommended for estimating actually occurring ET from irrigated fields, especially in areas facing water shortage or irrigation curtailment.

Interpolation of ET in between satellite overpass dates. None of the remote sensing methods, in and of themselves, go beyond the creation of a series of “snapshots” of ET occurring for a series of satellite image dates. Large periods of time can exist between snapshots of ET, especially in areas plagued by clouds.

The procedures employed to estimate ET for periods in between satellite image dates generally employ linear or spline-based interpolation of ET expressed as a fraction of reference ET (ET_oF) (Allen et al., 2007). The idea is that ET, expressed as a fraction of ET_o, evolves slowly because the fraction is primarily related to the amount of vegetation and transpiration present, much like the similar K_c. ET_oF is expected to evolve slowly from day to day as vegetation develops or as water stress deepens. The primary day-to-day change in ET is caused by weather variation and is captured by multiplying the daily interpolated ET_oF values by a calculated ET_o determined from local or gridded weather data. Accuracy of final ET estimates may vary with accuracy of the reference ET estimates. Accuracy of reference ET estimates depends on the quality of measured weather parameters and the acquisition of weather data from irrigated environments as described in FAO56 (Allen et al., 1998). Stringent quality control is required and highly recommended.

Contending with cloudiness. As described, ET from RS requires some type of interpolation of ET_oF between satellite image dates. As cloudiness of an area increases, the successful acquisition of clear, cloud-free imagery decreases. Accuracy of the interpolation of ET_oF (and therefore ET) between image dates degrades as the time between clear images increases. In general, one should hope to acquire at least one clear look at a location every four to six weeks in order to follow progression of ET_oF during plant development. RS-based ET estimation in persistently clouded areas may need to involve aggregating data from several types of satellites (or UAV) that are likely to have different overpass schedules and differing resolutions (30 m, 250 m, 1 km, etc.). As more coarse resolution imagery from other satellites are used to fill time gaps, the poorer will be the determination of ET for individual parcels.

6 Conclusions

Remotely sensing data provide an entirely new perspective (in temporal and spatial scale) on the pattern of water consumption across the world, which in turn is fundamental to sustainable water resources management. Clearly, these technologies are a powerful new asset in building the "best estimate" of *consumption* in the water accounts for a region, including variability, extreme events and trends. We highlight that such data are a complement to, not a substitute for, the on-the-ground measurement of water flows.

Better estimates of the relative consumption in natural forests, irrigated and rainfed agriculture, and downstream environmental assets assist in identifying the more, and less, important drivers of scarcity. Evaluation of interventions will also be much improved by RS of ET in two ways: first, the physical implications of an intervention in one location for availability elsewhere are identified; second, since RS data allow evaluation of productivity, and the *economic* choices implicit in allocation decisions are clarified.

Legal aspects of governance can be better targeted when consumption patterns are more fully understood, but as elaborated below, there are limitations to incorporating "consumption" into allocation management and priority setting.

Institutional aspects of governance that are facilitated by consumption data from RS are primarily at larger scales – national and basin levels – monitoring of consumption to ensure consistency with sustainability targets. More locally, remote-sensing is a powerful tool for identifying potential illegal wells or unauthorised diversion of surface water, and project and farm level remote-sensing – especially by drones – offers scheme managers and farmers information that can enhance productivity.

The central challenge to controlling water consumption is political. The choices that are needed to be made can be unpopular and may include reallocating water away from relatively poor rural citizens; placing greater pressure on food security; and complicating water management. Unsurprisingly, examples of success are rare (Molle, 2017). Decision makers, typically, prefer easier challenges. The implications of allowing persistent excessive water consumption, especially locally, will be severe as the most valuable uses of water, for domestic and commercial use, are progressively curtailing and curtailed by agricultural consumption.

One useful outcome – in areas where politicians take up the challenge of constraining water access – is that *reliable* access, with water supplies constrained for all farmers, promotes "farmer-researchers". That is, farmers in a water-constrained environment will be incentivised to find ways to increase the benefits of the limited volume of water allocated to them, provided they are as fully informed as possible about the quantity and timing of that water allocation. It is in this context that the accurate measurement of water use and water consumption is an important priority if the world is to deliver "water for all".

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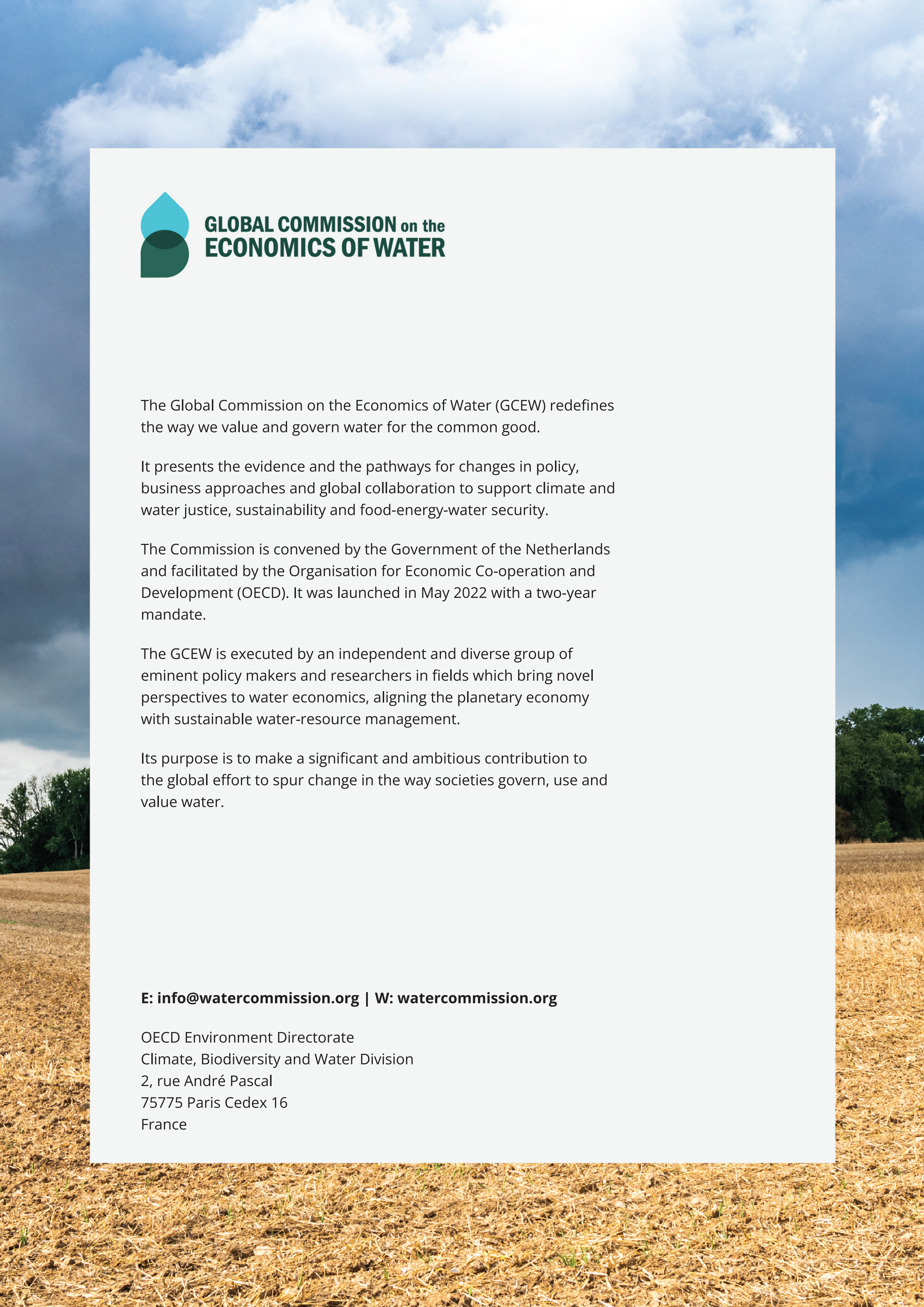

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OECD Environment Directorate
Climate, Biodiversity and Water Division
2, rue André Pascal
75775 Paris Cedex 16
France