WaterPIP

Water Productivity Improvement in Practice

Compendium of Approaches to Improve Water Productivity

Version 3.0

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Acronyms

AETI	actual evapotranspiration and interception
CHIRPS	Climate Hazards Group InfraRed Precipitation with Station data
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DMP	dry matter production
ETa	Actual Evapotranspiration
ETref	reference evapotranspiration
FAO	Food and Agriculture Organization of the United Nations
GBWP	gross biomass water productivity
ha	hectare
kg	kilograms
km	kilometre
mm	millimetre
m^3	cubic metre
NPP	net primary production
PCP	precipitation
PHE	phenology
SDG	Sustainable Development Goals
T	transpiration
TBP	total biomass production
Ts	seasonal transpiration
WaPOR	FAO Water Productivity Open access Portal
WFD	wetting front detector
WP	water productivity
WP(AETI)	water productivity based on consumption through AETI
WP(T)	water productivity based on beneficial consumption though T
WP(WU)	water productivity based on water use
WU	water use
WUE	water use efficiency

1 Working on better water productivity

This *Compendium of Approaches to Improve Water Productivity* describes how the analysis of water productivity with the extensive database of the FAO portal to monitor WAter Productivity through Open access Remotely sensed derived data (WaPOR), can be used to identify practical measures to increase the crop production relative to the water which is consumed in specific land and water systems. This portal (https://wapor.apps.fao.org/home/WAPOR_2/1) is openly accessible and provides near real-time pixel information on biophysical water productivity, actual evapotranspiration, biomass production and reference evaporation on a 10-day basis as well as other datasets. This makes it possible to analyse trends and patterns in water productivity (WP) and identify where water productivity can be improved. Apart from detecting trends and patterns, the WaPOR database can be used for other applications as well.

There are several types of water productivity and within these types, the scale at which you look may lead to various different interpretations and terminology (see chapter 2.1). In this Compendium we are mainly focussing on biophysical water productivity – the amount of agricultural production per volume of water consumed - or in popular terms the 'crop per drop'. How this 'drop' is defined is also further discussed in chapter 2.1. As many solutions presented in this compendium do not (only) target water productivity improvements but also improvement of land productivity (LP) and water use efficiency (WUE) these concepts are also explained.

Globally, agriculture is the largest user of water, accounting for at least 70% of all water withdrawals (Gruère et al, 2020)[1]. Improving water productivity is important in agricultural water management, because the potential gains are tremendous. Livelihoods of people and national food securities depend on how effective crop production is, with water often being a limiting factor. Hence improving water productivity will not only contribute to water security, but also to food security and better farm returns. The need for better demand management is also explicitly reflected in the new Sustainable Development Goals. SDG 6.4 reads: *By 2030, substantially increase water-use efficiency across all sectors and ensure sustainable withdrawals and supply of freshwater to address water scarcity and substantially reduce the number of people suffering from water scarcity.*

The imperative is large, without improved water use efficiency the demand for water in agriculture will in 2050 be up by 70-90% over 2005 figures. This is triggered by a number of factors, namely:

- The demand for food is expected to rise by 60% by 2050 (FAO, 2011a). This is caused by rising population (40%) and by higher per capita calorie intake (11%). Additionally, there is an increase in consumption of lower calorie items (especially fruits and vegetables) (FAO, 2011b).
- This demand for food is matched by demand for non-food products. The demand for timber is to increase by 45% from 2005 to 2030; in the same period demand for roundwood will go up by 47% (FAO, 2009). Demand for cotton is to increase with 81% between 2010 and 2050.

However, in spite of this urge and in spite of all the attention to efficient water use in the last two decades, the overall trends in actual performance of the water systems in many countries has been negative rather than positive. From the tracking of a statistically significant set of robust pixels over the last ten years in each country, it is apparent that more rather than less water is used for instance in the existing irrigation systems and water productivity in many countries has gone down rather than up (Islamic Development Bank (forthcoming)). Similarly, in rainfed systems in a large number of countries water productivity has

[1] This statement refers to applied water rather than consumed water (ETa).

consistently gone down. This is quite revealing. In general, there is a huge need to focus much more on improving water management than on developing new water systems. It is time to make better use of the limited resource we have rather than inefficiently exploiting more of it.

Against these negative trends, some experts believe that improving water productivity in agriculture by 25 percent, in general, is feasible. Doing so will help keep up with increased demands and will free up water resources for other uses. This will reduce competition and conflicts and provide water for cities and industries to grow. It is important that rules are in place as to where to allocate the water to that is saved.

The improvements in water productivity apply to both irrigated and rainfed areas. In many irrigation systems, there is a tremendous scope for improvement by: optimizing water allocation rules, using appropriate water control structures, controlling leakages, promoting conjunctive management of surface and groundwater and introducing a wide array of precision techniques that enable better water management at field level. However, when looking at water productivity we want to improve the ratio of yield over water consumption. Thus, while increasing water efficiency is a good start, a focus should be on decreasing the non-beneficial consumption for the same yields, or for even higher yields preferably (for terminology see section 2.1). This leads to similarly, important improvements on the agricultural production side: improved crop agronomy, better selection of crops and varieties, adjusting crop calendars, better use of agri-inputs. The important argument in favour of such water productivity programs is that they often yield immediate results. They do not have the long gestation period, financial onus and social disruption that comes with the development of new irrigation systems for instance. It may be much more attractive to invest in better water management and higher water productivity than in additional water resource capture (see box 1). However, a thorough understanding should be obtained of the reasons *why* such investments may not have been made yet and combined with local knowledge on what types of investments are beneficial for both the WP and the farmers.

There is also considerable scope to improve water use efficiency in rainfed and flood-dependent agricultural water systems. There is a broad repertoire of measures that can help retain and store these more erratic rain dependent water resources, to use them more efficiently and to optimize cropping systems (Annex 4). It should be noted that this may not directly improve the Water Productivity. However, from a holistic perspective, less water is lost through evaporation, and the captured water can then be used in case of unexpected low rainfall amounts and thus preventing crop failure. This may then lead to a higher WP than if crops would have failed. A more detailed discussion on the different terminology and WP definitions can be found in section 2.1. The potential gains in increasing productivity in rainfed and flood-based farming are high. Several predictions are that the larger part of the increase in global food production will have to come from such rainfed and flood-based systems (Comprehensive Assessment of Water Management in Agriculture, 2007). Moreover, in Sub Saharan Africa for instance most farmers (84%) depend directly on rainfall or on flood events (ibid). Improved water productivity measures may lift them out of poverty and make them less vulnerable to normal or abnormal drought periods or shifting rainfall patterns. In fact, climate change and the effects it brings on agriculture and water use, is another compelling reason to revisit land and water management and cropping systems. Adjusting to climate change can go hand in hand with measures to improve water productivity.

Box 1: Increasing water productivity in Koga (Ethiopia)

It has been said many times that there is very little irrigation development in Africa, that there is little water storage per head of population, and that this adds up to high vulnerability to droughts. Several medium- and large-scale irrigation systems have been developed over the last 15 years. However, what they have in common is that water productivity has been disappointing.

The Koga Irrigation Scheme in Amhara in Ethiopia is one such example. It draws water from the Koga River, one of 50 tributary streams joining the Ethiopian Upper Blue Nile. The scheme was meant to irrigate 7,000 ha, but in reality, its service area is closer to 5000 ha. Also, it was meant to be used for water intensive crop cultivation but instead the main crop is wheat.

Figure 1-1 The Koga Irrigation Scheme in Amhara in Ethiopia

In a two-year field program under the project "Monitoring water productivity by Remote Sensing as a tool to assess possibilities to reduce water productivity gaps", implemented by the International Water Management Institute (IWMI), a large number of water users, water user group leaders and irrigation managers were introduced to technical innovations to enhance on-farm irrigation management decisions. This was done by providing soil moisture measuring devices to allow them to assess whether the land should be irrigated or has been irrigated too much. In particular the Wetting Front Detector (WFD) and Chameleon Soil Water Sensor were used. These two sensors were rolled out to six out of twelve blocks in the scheme, targeting 54 water user groups.

In the groups, farmers were taught how to use the devices, with some farmers actually operating the instruments on their farm. Special data collectors were deployed to help share the information between farmers. The results were spectacular. Within one or two seasons, farmers realized they applied too much water and this suppressed their wheat yield and reduced their field irrigation supplies. According to key farmers, they typically lengthened the irrigation cycle from the local storage reservoirs from 8 to 11 days, or 9 to 12-13 days – effectively a water use reduction of 35%, as everyone's irrigation turns became less frequent. Part of this high-water wastage earlier, related to the need to make ploughing easy. With reduced water applications the wheat crop yield went up: according to farmers' estimations with 10 to 20%. The gain in terms of water productivity or 'crop per drop of water supply' was an impressive 35-40%. Field research by Bahir Dar University confirmed this range of improvement. The farmers noted that improved water management resulted in a faster rotation among water users in the same group and resulted in a decline in water related conflicts. The saved water was used to extend the area under cultivation within the blocks, but also to reduce water deliveries from main scheme operations to the particular night storages. There was also a reduction in soil nutrient loss, as there was less leaching.

Figure 1-2 Farmers showing the Chameleon Sensor (handheld) and the Wetting Front Detector

2 How to use the compendium?

This compendium aims to systematically use the analysis of land and water systems with the WaPOR database to identify areas of improvement in water and land productivity and water use efficiency. It is meant to be a live document, hopefully going through a series of updates and improvements, as more experience develops in using WaPOR analyses and as more WP, LP and WUE improvement possibilities are documented.

2.1 Water productivities and definitions: focus on biophysical water productivity

There are various types of water productivities that provide important insights and can drive policies and influence water management on the ground (Figure 2-1). Economic water productivity for instance, measures the economic or financial value created with the volume of water consumed, or the number of jobs created per volume of water ('job per drop'). The latter is of much concern in the situation of high unemployment, when there is an urge to create gainful jobs. Another type of WP is social water productivity that analyses who benefits from the additional value created with water use. These are very important considerations in addition to the crop per drop argument. Take for instance the case where non-renewable groundwater is used for high value semi-mechanized export production of potatoes. This may be very impressive in terms of the yield per hectare or the financial revenues created, but the benefits may accrue to a few large producers only, with very few jobs created, no contribution to national food security and hidden subsidies in production (for instance in pumping).

Figure 2-1 Visualization of the different Water Productivity definitions. From left to right: Biophysical WP, Nutritional WP, Economic WP, and Social WP

The main WP perspective used in this compendium is biophysical WP based on water consumption or evapotranspiration and is referred to as WP(AETI). WaPOR is most suitable for computing the WP(AETI) at system level (e.g. irrigation system level (L1 – 250m and L2 – 100m resolution), or for large fields (Level 3 - 30m resolution). To clarify what this perspective on WP implies: this compendium considers both beneficial consumption of water and non-beneficial consumption. Beneficial consumption is considered water that is transpired by the plant, and non-beneficial water is considered water that is evaporated from soils in which plants are grown (see Figure 2-2).

Besides different definitions in identifying the denominator of WP, there are also two ways of identifying the numerator. If information on crop type is available and the analysis is conducted for an area of the same crop, the numerator is usually the yield in for example ton per hectare. In this case the term Crop Water Productivity (CWP) is used. When this crop information is not available the Total Biomass Production (TBP) is used as numeration, in which case the WP is called Gross Biomass Water Productivity (GBWP).

As disaggregating CWP into crop yield and AETI and comparing trends over time provides valuable insights into CWP performance, it is also valuable to look at land productivity (crop per area of land) separately. Within a given area there may be distinct differences in yields of the same crop, or when comparing outside similar agro-ecological boundaries or even internationally, yields may be considered very low. As such, comparing LP provides one of the (oldest and most used) performance indicators in agriculture.

Given the frequent confuse between water productivity and water use efficiency it is also necessary to provide a crisp distinction in this compendium. Water Use Efficiency as considered here is the ratio between water that is applied and the water that is being used. Neither yield nor biomass is being considered in this ratio, whereas in this compendium ET (ie. beneficially and non-beneficially consumed water) and water applied is (see also Figure 2-2). Some may consider water applied to be the water diverted from a source, others may consider it to be the amount that is applied in a plot or field. Important to consider is that WaPOR datasets do not provide data on water applied (irrigation and floods). However, if this application (or abstraction) data is available the AETI dataset can provide useful insights into efficiencies (at plot/irrigation unit/ scheme level).

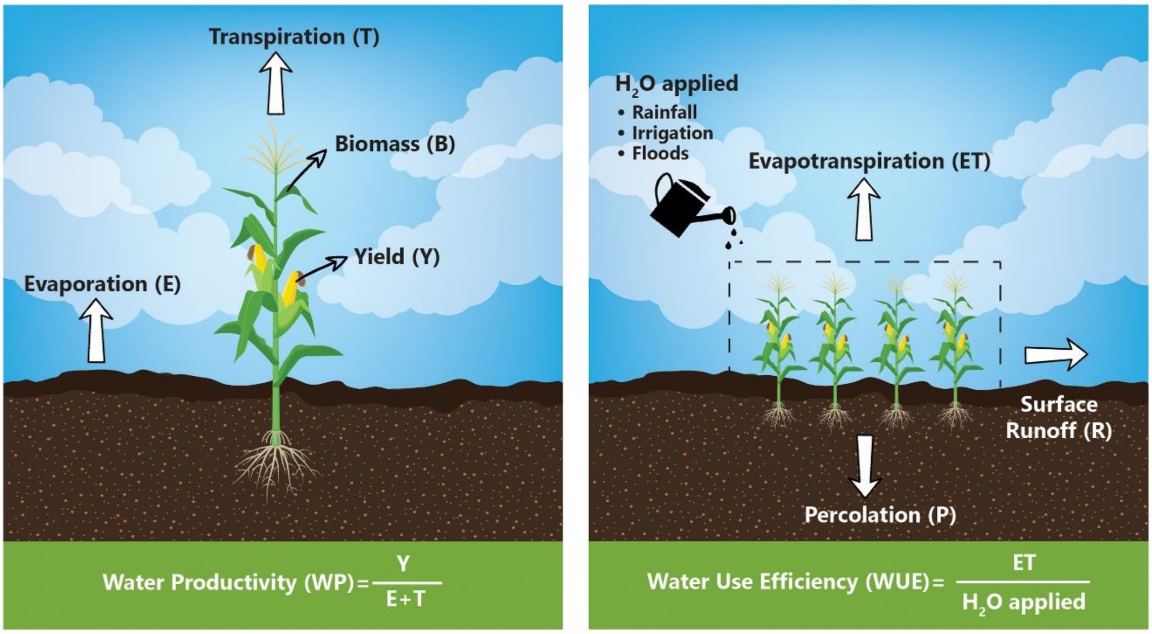


Figure 2-2: (Crop) Water Productivity (WP) and Water Use Efficiency (WUE) visualisation

When looking at WP, we always need to keep in mind that we are looking at a ratio. Therefore, the goal should not be to only increase WP but also pay attention to how the numerator and denominator develop. In many cases the emphasis will be on 'more crop per drop', as this will lead to more food production, and likely have economic and livelihood benefits too. However, in certain cases the emphasis may need to be on 'less drop per crop', for example in areas where the water resource is decreasing over time.

2.2 The WaPOR database

The source for the analysis of water productivity is the FAO portal to monitor WAter Productivity through Open access Remotely sensed derived data (WaPOR) (https://wapor.apps.fao.org/home/WAPOR_2). This is the first open access comprehensive dataset that combines water consumption (actual evapotranspiration, transpiration and interception), production (net primary production), land use (land cover classification), phenology, climate (precipitation and reference evapotranspiration) and water productivity layers (Table 2-2) covering sub-Saharan Africa and the Middle East and North African regions in near real-time for the period between 2009 to present day. The data is available at dekadal (10-day) timesteps, or for some datasets at a seasonal or annual timestep.

WaPOR data are publicly accessible and available at continental scale (Level 1 at 250 m), country and river basin level (Level 2 at 100 m) and project level (Level 3 at 30 m). The latest WaPOR portal (WaPOR v2.1), was improved from WaPOR v1.0 following the quality assessment by IHE Delft and ITC (FAO and IHE Delft, 2019). The methodology used for compiling the WaPOR database is provided by FAO (FAO, 2020). The data is available at three different levels, based on the spatial resolution of the data (Table 2-1).

On the WaPOR portal, maps of the datasets can be observed and the specific raster files can be downloaded. It is also possible to perform timeseries analysis for a point or area of interest. More information can be found on the website.

When working with the WaPOR data, it is highly recommended to consult the WaPOR catalogue for more detailed information on the specific datasets, as well as to compare the data with observations and knowledge from the ground. The datasets are constantly updated. There are also plans to expand WaPOR globally in the future.

Table 2-1 An overview of the different WaPOR data levels

Level 1 – Continental scale, with a ground resolution of 250m.	In this level, the data is (currently) available for the whole continent of Africa and for the Near East. The precipitation data (CHRIPS) and the Reference Evapotranspiration are only available in Level 1, as their spatial resolutions are much larger than that of the other datasets. Precipitation has a spatial resolution of 5km and the reference evapotranspiration has a spatial resolution of 20km. For this level NDVI and LST quality layers are available too.
Level 2 - Country scale, with a ground resolution of 100m	In this level, the data is available for a select set of countries and river basins. In this layer, also a phenology layer is included. This phenology data is used to determine seasonal values for certain datasets, such as the total biomass production and the gross biomass water productivity. For this level NDVI and LST quality layers are available too.
Level 3 – sub-national scale, with a 30 m ground resolution	Currently, for eight areas (irrigation schemes and sub-basins) the data is made available at the detailed resolution of 30m. In this level, the phenology layer is available, as well as a more detailed land cover classification map. This is the only level where crop specific maps are available. For this level NDVI and LCC quality layers are available too.

Table 2-2: Overview of WaPOR data used in this compendium

Data component	Abbreviation	Units	Description
Gross Biomass Water Productivity	GBWP	kg/m^3	The gross biomass water productivity of a season (m^3/ha) is the total biomass production (kg/ha) in relation to the total volume of consumed water AETI (mm) for that period (GBWP = TBP/AETI) (FAO, 2016). The indicator GBWP provides insights on how the biomass production, and thus vegetation development, relates to the total water consumed for a given area and time. Note that the GBWP in the WaPOR portal are provided annually (Level 1) and seasonally (level 2 and 3) using the phenology layer. If the seasonality is known for the study area, it is recommended to create an independent GBWP map for these alternative seasons.
Actual evapotranspiration and interception	AETI	mm/season (also available in 10-day, monthly and annual timesteps)	AETI is the sum of water transpired by a crop and evaporated from a cropping area surrounding it during the cropping season. The actual evapotranspiration is the total consumed water over the season. This is the sum of the soil evaporation (E), the canopy transpiration (T), and the evaporation of rainfall intercepted by the leaves (I). The AETI is expressed in depth (mm). The volume of water evaporated per pixel can be determined by first multiplying the value by a factor 10 to go from mm to m^3/ha, and then by the area of the pixel (e.g. for Level 2 (100m

			resolution) the pixel area is one hectare). There is no ready-made seasonal AETI layer available on the portal but this can be computed using the monthly or decadal data.
Transpiration	T	mm/season (also available in 10-day and annual timesteps)	T is the sum of water transpired by a crop during the cropping season. There is no ready-made seasonal T layer available on the portal but this can be computed using the monthly or decadal data.
Reference evapotranspiration	ETref	mm/season (also available in daily, 10-day, monthly and annual timesteps)	Reference evaporation is the estimation of the evapotranspiration from a hypothetical reference crop, reflecting the 'drying power' of the climate. Because of this reference crop, the reference ET does not relate to soil or crop conditions, but only the climatic conditions. There is no ready-made seasonal ETref layer available on the portal but this can be computed using the monthly, decadal or daily data. Note that the resolution of this layer is 20km.
Net Primary Production	NPP	gC/m^2 (10-day timestep)	The NPP expresses the conversion of carbon dioxide into biomass driven by photosynthesis. The NPP is only provided as decadal data.
Total Biomass Production	TBP	kg/ha (annual or seasonal)	TBP is the sum of the seasonal total biomass production (which is determined from the NPP). Similar as for the GBWP layer, the season is based on the phenology layer. Thus when using the TBP, it is important to check this phenology layer to see if the seasonality of WaPOR corresponds with the actual seasonality – if that ground information is available.
Land Cover Classification	LCC	Class	The annual LCC raster layers are created based on the Copernicus global land service map (100m) of the year 2015. Additionally, using decadal reflectance timeseries, the FAO Crop Calendar phenology information and applying a water deficit index, the irrigated and rainfed areas were derived for the years 2009-2019.
Phenology	PHE	Dekad	This phonology data component indicates the start, maximum and end of the growing season. The layer includes maximum two growing season and is comprised of one raster layer per date (SOS, max, EOS) so 6 raster files per year. The dates are expressed in decadal numbers.
Precipitation	P	mm/day (also available in 10-day, monthly and annual timestep)	Though this layer is based on CHIRPS data rather than WaPOR data, it is available on the WaPOR portal and valuable for rainfed and spate-irrigated agriculture analyses. This layer is only available at Level 1 and has a resolution of 5km.

Datasets are available on: https://wapor.apps.fao.org/home/WAPOR_2/1

2.3 Limitations of the WaPOR database

WAPOR is unique in making data available on biomass water productivity, and at 10-day (decadal) interval on net primary production and actual evaporation, for a large number of countries over a long period of time (from 2009 to now). The scans and diagnoses discussed in this Compendium (Chapter 3) use these datasets. At the same time the information contained in WAPOR has its limitations. It is important to understand these, because they define what applications are meaningful.

Table 2-3: Limitations of the WaPOR data

Limitation	Explanation
No crop specific data	WAPOR measures biomass in general and does not distinguish different crops, with the exception of a limited number of level 3 areas. This makes it hard to compare areas unless they have the same crop and are normalized for climate. Trends can be observed but may be distorted if cropping patterns change. Therefore, for area comparison, it is recommended to collect additional data from the field on crop type, location and seasonality before conducting crop-specific analyses using the WaPOR database. Trends are also harder to analyse if there are multiple or mixed cropping systems.
Spatial resolution	The WAPOR data comes at three levels – level 1 (250 meters resolution), level 2 (100 meters resolution) and level 3 (30 meters resolution). Level 2 and 3 data are available respectively only for selected countries and selected areas within a number of countries. The lower resolution in level 1 and 2 increases the chance of several land use or crop types being contained in a single pixel, making it more difficult to interpret its value. The possible distortion is more severe when relatively small areas are interpreted. Another potential issue regarding the spatial resolution is the downscaling of the LST (1km resolution) to the resolutions of level 1 and 2 (for level 3 Landsat LST data is used which has the same resolution as the level 3 output layers). This means that for agricultural areas the AETI and NPP data can be distorted with averaged water stress factors taken from 1 km^2 areas: in desert areas with large contrasts in bare soils and irrigated crops this leads to a gross underestimation of ET and NPP, whereas in large irrigated areas this leads to a smoothing out of spatial water stress differences, which may result in over- and under valuation of ET and NPP.
Accuracy	With WAPOR increasingly used, there is more and more feedback on the accuracy of data. Though with more validation data, in updated versions of WaPOR the quality is improving, the use of absolute values is still to be done with caution, and cross-referencing is strongly advised. This particularly applies to values on water productivity. These values are more sensitive as they are a composite of the two other data sets, which increases the likelihood of errors and potentially magnifies them. In general, to process the information of the WaPOR database in quality products it is recommended to use the data protocols developed under the Water-PIP project in particular the standardized protocol for land and water productivity analyses using WaPOR available at: https://github.com/wateraccounting/WAPORWP)
Land use classifications	In WAPOR, pixels are categorized according to several land use types based on Copernicus Global Land Service: Land Cover map of 100m resolution (Buchhorn et al., 2019). For agricultural land use, a distinction is made between irrigated and rainfed land using the water deficit index (FAO, 2020). Inevitably there are instances of misclassifications, and of non-agricultural land uses being classified as either irrigated or rainfed land. Additionally, a major constraint is that the Copernicus map used is from 2015 and only changes the separation between irrigated and rainfed agriculture each year, so on top of potential misclassification, the map does not include an annually varying land cover map.
Light use efficiency of crops	The WaPOR NPP layer is based on C3 crop. When studying C4 crops, such as maize, sorghum and sugarcane parameters are needed for an additional conversion of the data. C4 types use a different photosynthesis process, in particular a different C4 carbon fixation pathway to increase photosynthetic efficiency by reducing or suppressing photorespiration. To calculate the biomass or NPP for a C4 crop an adjustment is required, namely multiplying the biomass or NPP value by a crop factor (fc), which is the ratio of light use efficiency of C4 crops over light use efficiency of C3 crops.

Time series	For the level 2 data, the database is made up of data from two different satellites. Prior to 2014, the data is based on (resampled) MODIS (250m) data, from 2014 onward level 2 uses 100m Proba-V data. For analysing trends using the level 2 data, this should be taken into consideration as the data is inconsistent over a longer period.

2.4 Using trends, patterns and absolute values

In general, because of the limitations outlined above, caution is required in using absolute values from WAPOR although continuous improvements are made to the database to make the values closer to 'real' absolute values. However, in the meantime trends and patterns provide a lot of information already, including comparisons between different regions/areas.

Nevertheless, even when the absolute values improve, the local context should still be taken into account when comparing different areas with each other. Especially when decisions are made based on which area performs 'better', a thorough analysis is required on *why* these areas have higher WP and yield values. Are the values related to good practices which can be applied elsewhere, or is it simply because the environmental conditions are more favourable. For example, in the Rentang irrigation scheme in Java, Indonesia, part of the scheme borders salt farms. The WP(AETI) in these areas is much lower than other areas within the scheme (Hoogmoet *et al.* 2017). Rather than concluding that the farmers in this part of the scheme are 'bad' farmers, the potential causes of the lower land and water productivity (e.g. highly saline infiltration of water from bordering areas) should be taken into account. Then, suitable interventions regarding the salinity can be applied, rather than blaming the low WP on the farming practices.

It is therefore recommended to look at the trends and spatial patterns in analysing Water Productivity. Examples of trends and spatial patterns which can be analysed are the following:

- Trends over the years
- intra- and inter-seasonal/annual variability
- Spatial patterns in water productivity
- Spatial anomalies (extremely high or low scores).

The methodology proposed in this Compendium is to first make a scan of an area, followed by additional diagnoses so as to identify intervention areas. In the scan and diagnosis, the use of trends and spatial patterns is recommended through spatial and temporal analysis, whereas caution is required in using absolute values.

2.5 Getting the process right with stakeholders

Of paramount importance is to engage the stakeholders throughout the process. These stakeholders may be water managers, operational staff of irrigation systems, implementers of watershed campaigns and rainwater harvesting programmes, but also farmer organizations, cooperatives and main service providers. The process can also be used to design new Water Productivity programs with decision makers, investors and water users.

As Figure 2-3 highlights, the engagement of stakeholders is throughout the process – in defining the initial scope of questions, in helping to understand the overall context, in validating the analysis – both the scan and the following diagnosis – and in discussing possible solutions and improvements. This increases the chance of the analysis leading to actual action.

What is preferred is to have the analysis done by and with the experts from the water or agricultural organizations concerned, training and coaching them to undertake the analyses themselves, and supplement it with field insights and field feedback.

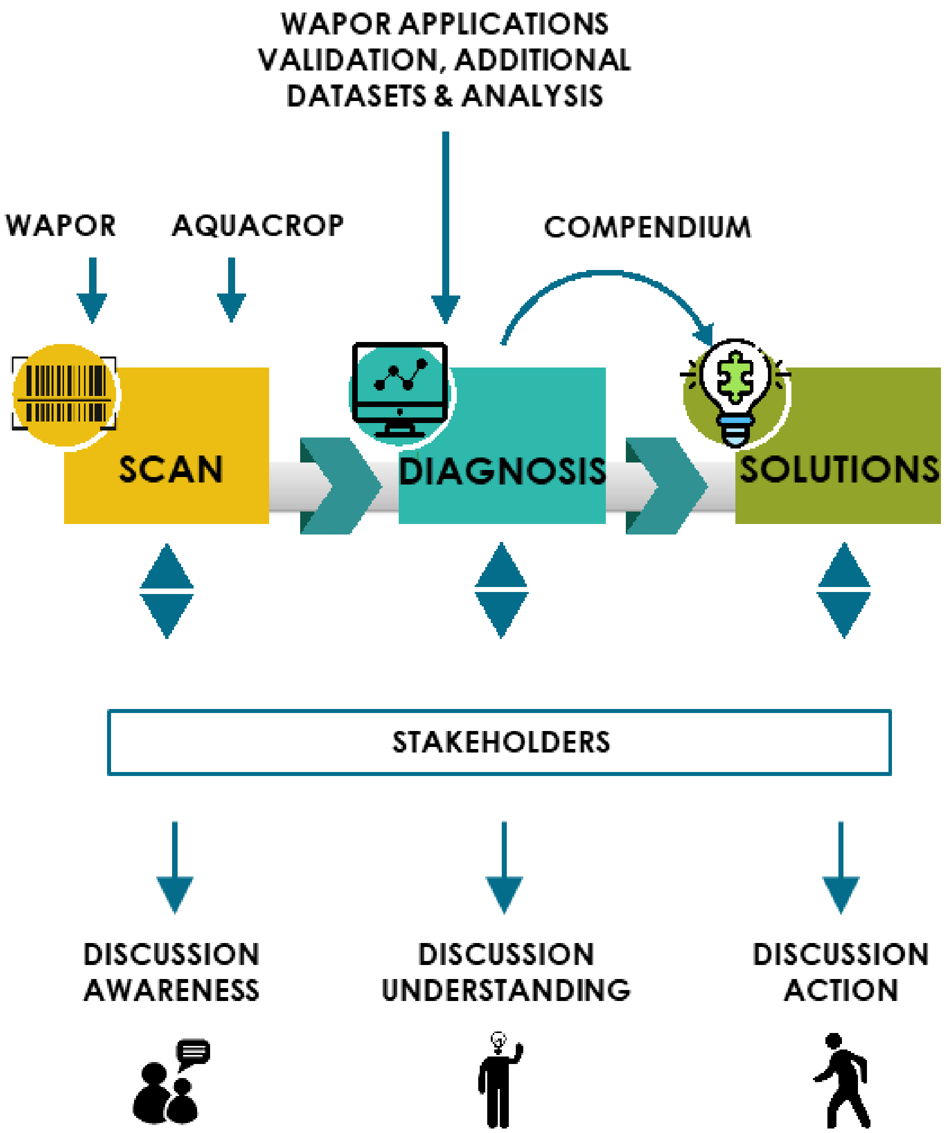


Figure 2-3 The Water Productivity Improvement Analysis Process

3 Identifying Water Productivity Improvements

In this chapter an approach is discussed for conducting water productivity analyses. This approach consists of three phases: The scan (section 3.2), the diagnose (section 3.3), and the identification of potential interventions (section 3.3.4 and chapter 4). These phases match with the following guiding questions: What is happening? (scan); Why is this happening? (diagnose); What can we do about that? (interventions). The method can be used to conduct analyses of various types of agricultural systems, namely irrigated agriculture, rainfed agriculture, and spate-irrigated agriculture. The majority of this method is the same for these three agricultural systems. However, especially in the interpretation of the analyses and in the identification of potential intervention areas, differences may arise. Therefore, the things to keep in mind when analysing each of these systems, including an example analysis, is provided in sections 3.4 (irrigated), 3.5 (rainfed) and 3.6 (spate-irrigated).

3.1 Introducing the analysis approach

Figure 3-1 provides an overview of the WP analysis approach. The three phases (scan, diagnose, interventions) of the analysis are structured according to three analysis types: 1) Spatial Analyses, 2) Temporal Analyses, and 3) Scatter plot Analyses. In the sections below this approach will be discussed in more detail. The analyses visuals can be created using open access sources such as the WaPOR portal combined with qGIS and the Jupyter scripts from IHE-Delft available on GitHub[2]. It should be noted that this method is used to conduct WP analyses using WaPOR data, but that other data sources may be valuable to include. Examples of such sources are soil maps (SoilGrids), Digital Elevation Models (DEM's), or discharge measurements. Additionally, it is recommended to continuously engage stakeholders in the phases of the analyses, to collectively assure for correct data interpretation, data verification, and the identification of potential errors. Though WaPOR can provide valuable insights, and this compendium can assist with providing linkages between the analysis and potential interventions, it remains essential to combine these analyses with local knowledge in order to identify the most suitable WP improvement interventions (section 2.5).

3.2 Scan

As the first step in the analysis, an assessment of the situation is needed. This is done by first making a scan of the current situation with respect to the Gross Biomass or Crop Water Productivity. It is required to collect basic data on the area of interest. This may entail a shapefile of the irrigation scheme or in case of rainfed or spate irrigation, a shapefile of the study area of this agricultural system. Additionally, it is valuable to collect information on the growing season, the management practices and the crop types. In the scan, the area concerned is analysed, with a focus on the spatial differences (section 3.2.1), the temporal changes or trends (section 3.2.2), and the pixel value distribution (section 3.2.3).

From the scan, some first observations may be identified. For example:

- Is WP increasing, declining or strongly fluctuating from year to year?
- Is WP relatively low compared to other systems with similar environmental conditions and crops?
- Are there large spatial differences?
- Are there unusual observations in the time lines (e.g. outliers) or in the maps (e.g. sharply defined areas with very different values than the rest of the scheme)?

[2] These Jupyter Notebooks are python language scripts and are made specifically for WaPOR analyses. They are structured according to several modules which can be used for the scan as well as the diagnostic analysis phase. The scripts and the corresponding documentation can be accessed at: https://github.com/wateraccounting/WAPORWP

These first observations can be discussed with relevant stakeholders and further explored in the diagnosis (see next section - 3.3).

3.2.1 Spatial analyses scan

For the spatial analysis, maps can be created of the various WaPOR database raster files. As water productivity refers to the amount of biomass or crop produced per unit of water consumed per season (Equation 3-1), it is recommended to start the spatial analysis with a seasonal map of the AETI and one of the NPP or biomass in addition to the Gross Biomass Water Productivity map. For more information on how to determine the season, see box 2.

$$GBWP = \frac{TBP_{season}}{AETI_{season}}$$

Equation 3-1

If crop information is available a crop specific yield map can be created too by converting the total biomass production of the season to the estimated yield using 1) the Light Use Efficiency (LUE) conversion faction (1 for C3 crops, 1.8 for C4 crops), 2) the harvest index (HI), 3) the above ground over total biomass ratio (AoT) and 4) the moisture content ratio (θ) (Equation 3-2). Default values of these 4 parameters are available on the WaPOR portal, but if site specific values are available, it is strongly recommended to use those instead. Once the yield map is created the Crop Water Productivity map can be created for that season (Equation 3-3).

$$Yield = TBP * LUE * HI * AoT/(1-\theta)$$

Equation 3-2

$$CWP = \frac{Yield}{AETI_{season}}$$

Equation 3-3

As rainfed agriculture is dependent on the amount and the spatial distribution of rainfall, it can be valuable to add a seasonal total rainfall map to rainfed-agricultural analyses, especially when the study area is very large and the rainfall distribution is known to be patchy.

Once the seasonal maps are created, it is important to check whether the values contain any large errors and whether they are consistent according to agronomic and hydraulic principles. This can be done by first comparing the values and units with those on the WaPOR portal, to ensure the appropriate conversion factor is applied (see the WaPOR catalogue) and that no other major calculation errors have occurred. Next, it is recommended to consult literature to check whether the values correspond to the literature values of the area, crop type and/or ecological zone. Furthermore, the quality layers of the NDVI and LST on the WaPOR portal can be consulted to see whether the study area contains pixels with very few observations. Finally, the scatter plot analysis should be conducted to check the WaPOR data on accuracy and agronomic consistency (section 3.2.3).When doing these analyses, always keep in mind the limitations of the WaPOR database and assess whether the analysis fits within the database applicability (section 2.3).

The final component of the spatial analysis scanning phase is to identify areas of interest to compute zonal statistics. For example, it may be valuable to 1) compute the mean values (incl. standard deviation) of upstream areas compared to downstream areas, 2) compare an old part of the irrigation scheme to a new part, or 3) compare the WP, AETI and biomass/crop values of a sloping area versus a flatter area (especially in rainfed). These kinds of additional scans will help with obtaining ideas about factors which may have a large influence on the WP of the study area. In the next phase, the diagnostic phase (section 3.3), these maps and zonal statistics will further be interpreted.

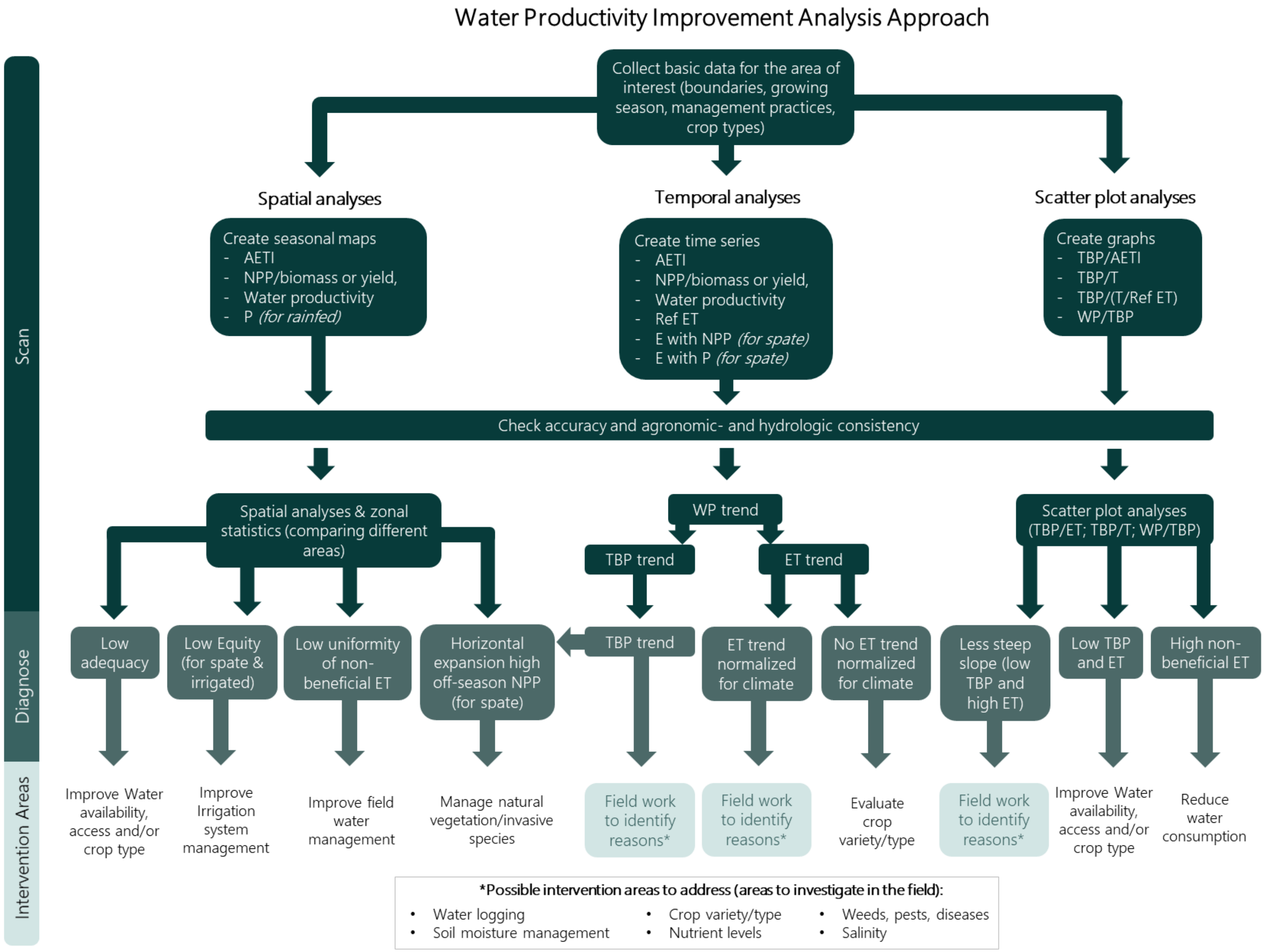


Figure 3-1 Overview chart of the Water Productivity Analysis Approach

Box 2 – A note on Seasonality

The start of season (SOS) and end of season (EOS) are important parameters in WP analyses. When conducting and analysis with incorrect SOS and EOS values, incorrect maps and graphs will be generated, potentially resulting in ineffective or even harmful interventions. A common situation in which seasonality errors can arise when creating one WP map for an area which contains multiple crops with different SOS and EOS. To estimate the most suitable SOS and EOS it is first and foremost recommended to obtain these values from field data. If this is not available, the phenology layer from the WaPOR portal can be used for Level 2 and Level 3 analyses. For Level 1, such a phenology layer is not available. In this case the dekadal timeseries can be plotted of the Transpiration or NPP, and the SOS and EOS can be estimated based on the dates at which the T or NPP are the lowest (or by determining a threshold), however, this should be done with caution (see Figure 3-2).

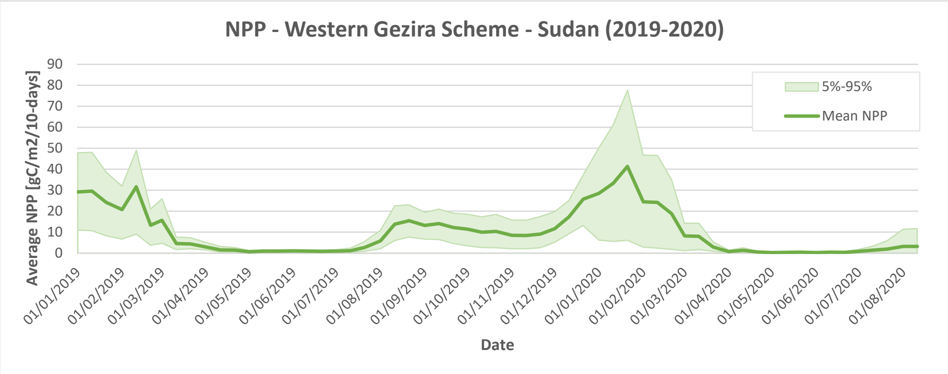


Figure 3-2 Dekadal NPP timeseries for the western part of the Gezira Scheme in Sudan for the 2019-2020 season based on WaPOR Level 2 data. The area is known to have a large wheat production which is sown in October-November and which grows between November-April. From the timeseries a clear wheat peak can be distinguished, but also some increased NPP values between August-November. This could be an indication of other crops growing in this area too such as pigeon peas.

For spate irrigation, seasonality is estimated in a different way compared to rainfed and irrigated systems. It is therefore not recommended to use the phenology layer of the WaPOR portal for spate analyses. The seasonal AETI (specifically the evaporation component) needs to be computed starting from the arrival of the spate floods on the fields. This may be weeks or even months, prior to sowing and the amount of evaporation depends greatly on when these floods arrive and what land management practices the farmer applies (van Steenbergen *et al.*, 2010). Figure 3-3 provides an example of a typical spate irrigation AETI and NPP pattern, including the estimated SOS's and EOS's.

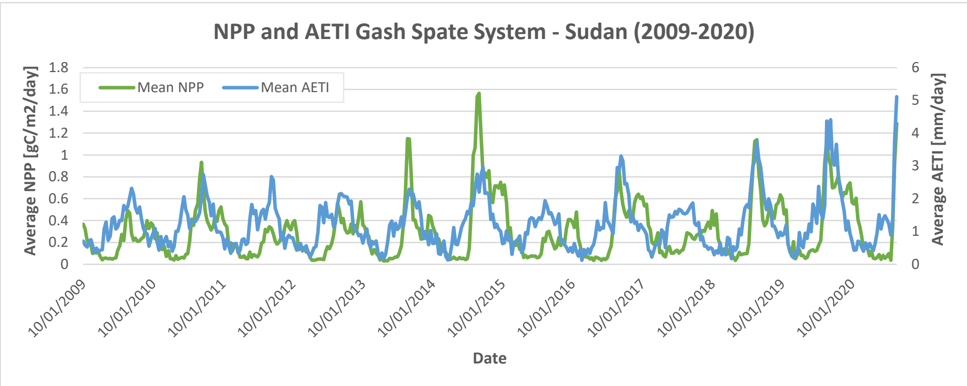


Figure 3-3 The mean NPP and AETI timeseries over The Gash spate irrigation scheme in Sudan for 2009-2020 using WaPOR Level 2 data. This pattern is common for spate irrigation as the season starts (SOS) with an increased AETI (when the fields are flooded), followed by an increase in NPP once the crops grow. The EOS can be identified when both the NPP and the AETI have reached a low point.

3.2.2 Temporal analyses scan

In addition to assessing the seasonal spatial distribution of the WP, biomass, AETI (and P), it is powerful to look at how the values change over time. Such temporal analyses are the second branch of the scanning phase. Through the WaPOR portal or other tools such as python scripts, timeseries can be created for each of the WaPOR data layers. For the WP analyses, it is particularly valuable to create time series of the following variables:

- AETI
- NPP, biomass or yield,
- Water productivity
- Reference ET
- E with NPP (for spate)
- E with P (for spate)

These timeseries will help to identify patterns, trends, and anomalies. For example, a WP timeseries may, in a given area, indicate a decreasing trend following a major change but show that the WP was stable before that change. The seasonal AETI and biomass timeseries may then show that the biomass remained relatively stable, but that the decreasing trend is due to increasing AETI. In the diagnostic phase, further research can then be conducted on whether this observation is recognized by the stakeholders and why this phenomenon is taking place (e.g. climatic changes, management changes etc.), after which suitable interventions can be explored.

Sometimes it may be valuable to look at the dekadal timeseries rather than the seasonal ones. This is particularly the case when identifying the SOS and EOS (box 2) but may also be useful to detect changes within or between seasons such as the length of the season, or shifts in rainfall patterns, flood arrival times or sowing dates. For spate irrigation systems, besides comparing the dekadal E timeseries with the NPP for SOS and EOS estimation, it may also provide insights in management changes. A continuous high NPP for example with a sinusoid E patter may indicate that the floods are distributed over fields with high natural vegetation or presence of invasive species (e.g. trees, shrubs and/or weeds). Evidently this has to be verified with fieldwork and interviews in the diagnostic phase.

Timeseries are also powerful tools for contributing to assessing the impact of climate and/or weather fluctuations. Reference evapotranspiration for example, calculated using climatic parameters, may provide a reason for seasonal differences in AETI. Seasonal ETref may indicate whether a decrease in AETI is (partially) caused by a decrease in ETref or whether the ETref has actually increased at the same time, indicating that the decline in AETI is even greater than previously thought. Such insights are essential when looking at changes over time, differences in patterns on a large scale and when identifying the cause behind the patterns to identify suitable interventions. Therefore, it is recommended to use ETref not only as a comparison to analyze temporal patterns but also to normalize for climate in general (see section 3.2.3).

All these timeseries analyses can be combined with spatial analyses (zonal statistics) to identify changes over both time and space. For example, when trying to understand the cause behind large spatial differences between upstream and downstream areas, it may be important to see when these differences emerged.

With all timeseries, the standard deviation should be taken into account, especially when computing the mean over a large area and when using zonal statistics. Such standard deviations can indicate whether trends are significant or lay within the margin of error. Additionally, like the spatial analyses, it is essential to always check whether the graph values are consistent with agronomy and hydrology (by comparing it to the WaPOR portal values and literature values).

3.2.3 Scatter plot analyses scan

The final component of the scanning phase is the scatter plot analysis. This analysis can be conducted by creating scatter plots of the study area pixel values from the seasonal maps which were created as part of the spatial analysis component. The scatter plots are firstly used to check the accuracy and agronomic consistency of the WaPOR data. When the data is found to be accurate and confirm the agronomic expectations, the data and resulting scatter plots can be used for further analyses.

The relationship between biomass production and transpiration is known to be linear for a given crop in a specific climate, and with similar nutrient conditions (Steduto *et al.,* 2007). Scatter plots can be created to assess whether the data is in accordance with several physical principles and agronomic properties. In Perry *et al.* (2009) these relationships are described in more detail and below an overview is provided. The scatter plots used for this show the relation between the total biomass production and three seasonal water consumption variables: biomass versus actual evapotranspiration, biomass versus transpiration, and biomass versus normalized transpiration. Where the normalized transpiration ($\sum T_a/ET_{ref}$) is the seasonal accumulation of the dekadal transpiration divided by the dekadal reference evapotranspiration.

As part of the accuracy and agronomic consistency check of WaPOR data, first of all outlier pixels can be identified in scatterplots. When point are observed that have a value for the total biomass production, but show no seasonal transpiration, or the other way around, these points should be cleared from the data before further analysis is conducted. When the data is cleared, the point in the scatter plot are expected to show a linear relationship. The correlation between the biomass and the water consumption variable can be assessed by plotting the linear regression line, forced through the origin. The slope of this linear regression line is the water productivity (e.g. TBP/AETI). An example is shown in Figure 3-4 . The coefficient of determination (R^2) shows statistical correlation between the biomass and the water consumption, the closer the value gets to 1, the stronger the correlation. Since the linear regression lines are forced through the origin, the slope of the B/AETI regression line will be lower than that of B/T. In the case of the WaPOR analysis for sugarcane in Wonji (Figure 3-4) and sugarcane in Xinavane (Chukalla *et al.,* 2020) the low ET values drop below the regression line, indicating a high E in the initial growth stages of the crop.

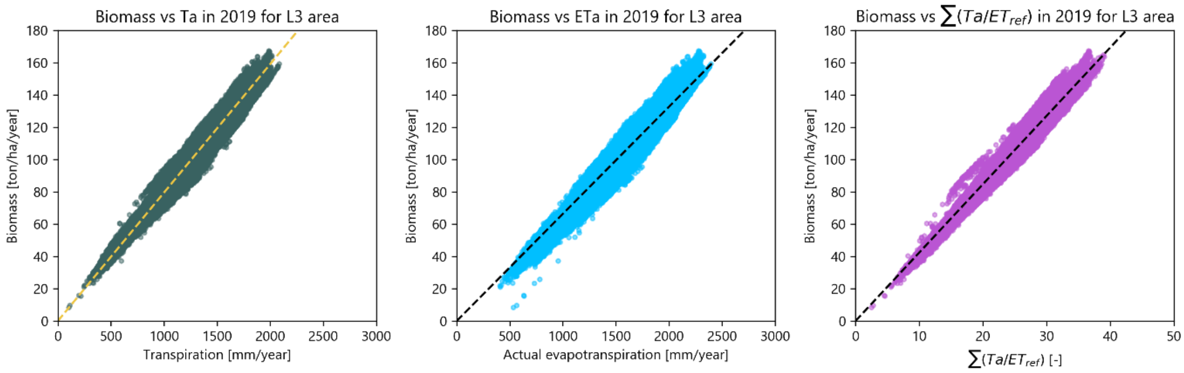


Figure 3-4: Example of scatter plot analyses for the relationship between biomass production and (a) transpiration, (b) actual evapotranspiration, and (c) normalized transpiration for the case study of sugarcane in Wonji.

Additionally, with the scatter plots it can be assessed whether the data is in accordance with several physical principles and agronomic properties. In Perry *et al.* (2009) these relationships are described in more detail and below an overview is provided.

If the data follows the expected patterns, additional information can be obtained from the plots, which can be used in the diagnostic analysis phase, for example:

- If the study area shows linear relationships between biomass and transpiration but there are multiple lines which go through the origin with different slopes (see graph (a) below), this may indicate (1) there are areas with higher or lower nutrient availability, (2) there are different crop types, (3) there are genetically modified and non-genetically modified crops of the same type.
- In the WaPOR analyses, the regression line for biomass versus ET is forced through the origin, meaning there will be no offset, in contrast to Figure 3-5b. However, the attribution of E and T can follow from the difference in slope of the regression line between TBP/ET and TBP/T. When the slope for biomass versus ET is equal to that for biomass versus T, it should mean that all the ET can be attributed to the T (beneficial consumption). Contrarily, if the slope for biomass versus ET is much lower, a large part of the ET can be attributed to non-beneficial consumption. This would then be worth exploring further in the diagnosis to see if for example soil moisture conservation techniques such as mulching would be appropriate.
- For large areas, the difference in slope from the first example (graph (a)) can also be attributed to a difference in climate conditions. To resolve this, the transpiration can be normalized for climate by dividing it by the reference ET (for more information see Steduto *et al.* (2007)). The second graph can also be normalized for climate by dividing the ET by the reference ET.

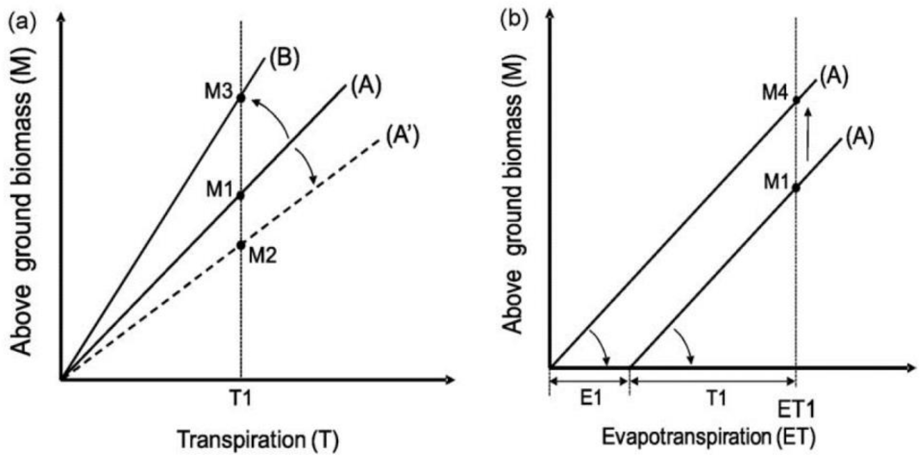


Figure 3-5 The theoretical linear relationships between T and biomass and between ET and biomass from Perry et al (2009)

Another valuable scatter plot for the water productivity analysis, is that of water productivity versus biomass. As WP represents the ratio between biomass production and water consumption, in some cases WP can increase while the biomass or yield may decrease. This is evidently not an ideal outcome, particularly not for farmers and for land productivity. Therefore, when identifying areas of interest regarding a high WP, it is valuable to combine this with an assessment of areas with a high yield or biomass production. This can be done by creating a scatter plot with the WP on the y-axis and the biomass/yield on the x-axis. After assuring that only one crop type is taken into account, checking that the analysis falls within the WaPOR database capabilities (section 2.3), and checking for agronomic- and hydrologic consistency, a careful estimate can be made of the productivity target using such a scatter plot (Figure 3-6). The pixel values can then be transferred to biomass gaps and WP gaps after which two maps can be created with these values to assess the spatial distribution.

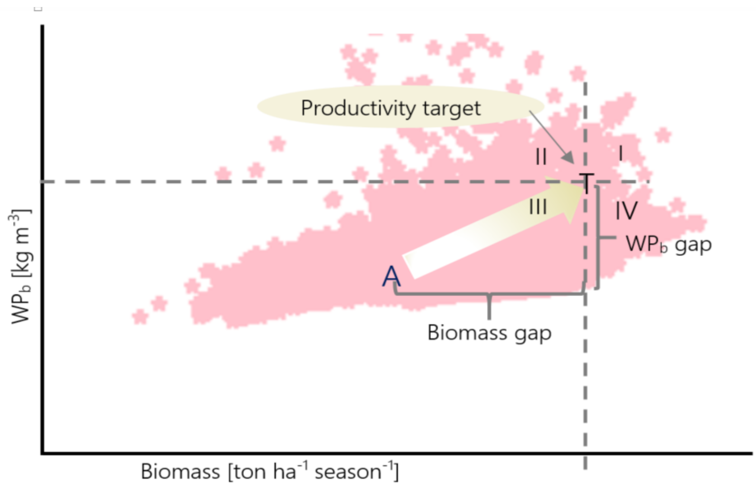


Figure 3-6 Example schematic of WP and Biomass scatter plot for identifying the productivity target and the biomass and WP gaps. The arrow indicates the path to be followed in closing the productivity gaps at plot A, it links productivities at a plot A to the target productivities at plot T. The grey vertical and horizontal dashed lines represent the 95 percentile of B and WPb, respectively, dividing the plot in four quadrants. (Chukalla *et al.,* 2020)

3.3 Diagnose

In the scanning phase, observations have been made to identify 'what is happening', for example: the WP is declining over time; the WP is much lower in one area compared to another area in the same system; or there is a sudden shift to a low biomass production and a low WP in a specific season after which they both stay low. To identify suitable interventions to improve the WP in an area, it is essential to find the causes behind these 'symptoms': Why is this happening?

To explore these causes it is worth starting with a short contextual analysis. Here questions are asked that may explain some of the changes, scores and the variations in water productivity. This can for instance be the introduction of new crops that changes the water productivity in an area or a difference in soil type that explains spatial differences in WP values. This contextual analysis will put the results of the scan in perspective and should be conducted preferably with main stakeholders (see also 2.5). Examples of the types of questions which can be asked in a contextual analysis are given below.

- In case of spatial variability,
    - Are there misclassifications in crop type or differences in cultivar and irrigation systems over the area?
    - Is there much variety in for instance soil types in the area?
- In case of temporal changes,
    - Has there been major variability in climate? (If not done yet in the scan, make sure to normalize for climate – see 3.2.3)
    - Are the temporal changes location, irrigation system, or soil type specific? (zonal statistics)
    - Have there been changes in the crops/ varieties grown?
    - Have there been changes in the access to inputs, forms of inputs (liquid/solid, organic/chemical), mode of application of inputs, or their pricing?
    - Have there been major changes in the way the water systems are managed (watershed campaigns, irrigation investment, field water management (Box 1), rehabilitation)
    - Have there been major crises that explain the patterns and trends that are seen?

Though the ultimate identification of the causes behind the scan observations requires ground information and local knowledge, the WaPOR database can be used to construct several hypotheses and to identify the corresponding interventions (section 3.3.4), which can then further be explored with the stakeholders. Additionally, similar as in the scan, it is important to determine which variation can be considered realistic and is attributable to differences in agronomic practices with statistical certainty, and which variation can be attributed to the data and methodological noise. These hypotheses and additional tests may be explored using similar categories as in the scan: spatial (section 3.3.1), temporal (section 3.3.2), and scatter plots (section 3.3.3).

3.3.1 Spatial analyses diagnose

A common way to diagnose phenomena in agricultural systems is using performance indicators. Examples of such indicators related to spatial analyses are adequacy, equity (irrigation- and spate systems), and beneficial fraction. For spate irrigation another spatial diagnose is important which is related to the change in spatial extent of natural vegetation or invasive species. Each of these topics will be discussed below.

Adequacy

The adequacy (A) indicator is "the measure of the degree of agreement between available water and crop water requirements in an irrigation system" (Chukalla *et al.*, 2020, p. 12). It is the ratio between the AETI and the potential evaporation. However, when using the WaPOR database the ETref (Equation 3-4) is used instead of the potential evaporation, which means the adequacy represents the amount of water which is consumed compared to the amount of water which could have been consumed for the specific climate conditions under unlimited water conditions and for a reference crop. Therefore, this value is very rarely equal to 1. Identifying which adequacy value is considered 'good' and which 'poor' is crop and context specific. Karimi *et al.* (2019) based this determination on the adequacy which correlates to the *critical* yield which is required for a farmer to recover the investment costs. Based on this an adequacy value for sugarcane between 0.8 and 1 was considered to be 'good' performance, $0.68 < A \leq 0.8$ acceptable and $0.68 \geq$ poor (Karimi *et al.*, 2019).

$$A = \frac{ET_a}{ET_{ref}}$$

Equation 3-4

If an area has a poor adequacy, the next step is to find out why this is the case. Additionally, it is valuable to identify how long this has been the case and whether a decreasing trend or a sudden event can be identified. In case of irrigated agriculture, there may be a general water shortage in the system, or much water may be lost within the irrigation infrastructure, causing water stress for the plants. However, in terms of water productivity, it depends on the timing of this water stress in the growing season and the duration of the stressed period, on whether the WP will actually decrease. If water stress occurs during the initial growing stage for example, this may reduce the biomass production initially, but it may result in efficient water use in a later phase, resulting in a low water consumption for a relatively high production. Therefore, adequacy should still be compared to the WP and the yield values. If there is indeed a poor adequacy and low AETI and yield, it is worth considering interventions related to water availability (e.g. water harvesting in rainfed or spate agriculture, or restoring degraded infrastructure in irrigated agriculture). If it is not possible to improve the water availability, it could be worth reconsidering the crop types and looking into crops which may do well under limited water conditions.

Equity

When the scan output shows large spatial differences in the WP due to large spatial differences in AETI, this can be quantified using the equity indicator. Equity stands for the spatial uniformity of water distribution or water consumption. To quantify this, the coefficient of variation (CV) of the seasonal AETI in the study area is determined, by dividing the standard deviation of the seasonal AETI by the mean

(Equation 3-5). When this value is between 0 and 10% it is considered 'good', while 10-25% is 'fair' and more than 25% 'poor' (Chukalla *et al.*, 2020).

$$CV_{ET_a} = \frac{\sigma_{ET_a}}{\mu_{ET_a}}$$

Equation 3-5

However, even though such an indicator may make it easier to compare the study area with other study areas or over time (under similar conditions), it does not explain the cause behind this inequity. It would be valuable to discuss such outcomes with the stakeholders to identify which interventions may be useful to increase the equity. For example, in case of inequity in spate irrigation systems it may be worth revisiting water distribution rights and regulations, especially when the same spatial pattern can be identified each year. For inequity in irrigated agriculture, it may be related to malfunctioning of parts of the irrigation system. Thus, an intervention could include assessing these parts of the system and restoring it. In rainfed agriculture not much can be done about large-scale inequity, especially if each year shows a different spatial pattern. Therefore, this indicator is not used for rainfed analyses.

Beneficial fraction

The beneficial fraction is the transpiration (T) divided by the AETI (Equation 3-6). If the beneficial fraction is low, it means there is a lot of non-beneficial consumption (e.g. soil evaporation). This can be an indication of water ponding for which field water management interventions could be suitable such as leveling or increasing field discharge. It should be noted that flooding the fields is common in spate irrigation and that this subcomponent is therefore not applied to spate analyses. From the scatter plot analyses (section 3.2.3) should follow if the separation of AETI into E and T makes agronomically sense. Only when this is the case, the beneficial fraction should be used as an indicator.

$$BF = \frac{T}{ET_a}$$

Equation 3-6

As a subcomponent of equity, the spatial uniformity can be assessed based on the beneficial fraction (BF). This is determined by dividing the standard deviation of the seasonal BF by the mean (Equation 3-5).

Horizontal expansion high off-season NPP

In spate irrigation a common challenge is high water consumption of natural vegetation. This may at times be beneficial for certain ecosystems, however, it can decrease the water availability for farmers. This phenomenon is particularly challenging when an invasive species has taken over large parts of a wadi and spreads rapidly through the spate irrigation system. A sign of such invasive vegetation may already be visible in the scanning phase, if large areas with high year-round natural vegetation occur. Naturally, such areas have to be verified with field data to identify if it indeed involves an invasive species with a large negative impact on the water supply, and what potential adverse impacts are of removing such vegetation (e.g. increased erosion). If the high year-round biomass values indeed concern an invasive species, an analysis can be conducted on whether this area is expanding over time and thus contributes to a decreasing WP(WU) in the system. This type of analysis could entail the creating of maps in which the spatial extent is recorded of this vegetation based on biomass threshold values. An example of such an analysis is provided in section 3.6.2. In such a situation a potential intervention may be to remove the invasive species (in the expanded areas)

3.3.2 Temporal analyses diagnose

Once (significant) trends have been identified in the scan, the causes behind these observations should be explored. Some of these causes may have already emerged during the contextual analysis (first part of the diagnose), but in addition to that it would be valuable to conduct a few extra checks. The first one relates the observation of a TBP trend and the second to an AETI trend. These two will be discussed below. Besides trends, sudden changes or events may occur in the timeseries. If these sudden shifts are not due to data issues (transition from MODIS to Proba-V of Level 2 data in 2014 – see section 2.3), the causes behind such shifts can be explored through interviews with local experts.

TBP trend

An increasing trend in TBP may not necessarily mean an increase in WP(WU) in an area, especially when it occurs in a spate irrigation system. Such an increase may point towards an expansion of invasive species for example. Therefore, if an increasing TBP trend is visible for a spate irrigation system, it is recommended to assess whether such high biomass production values are high year-round and whether the area in which these values occur is increasing over time. This can be done according to the approach described in section 3.3.1 above (see also the example analysis in section 3.6.2).

In case a TBP trend is visible in rainfed agriculture, irrigated agriculture, or spate irrigation where no invasive species occur, it is valuable to compare this trend to the AETI timeseries and normalize for climate to see whether weather fluctuations or climatic shifts may be the drivers behind such a trend (see next section *ET trend*). If there is no trend visible in AETI and only in TBP it is worth to conduct additional fieldwork to identify the causes behind this phenomenon, for example: have the crop varieties changed over time; has the soil turned more saline or is it contaminated; has there been a major increase of weeds or the occurrence of pests or diseases; etc (see Figure 3-1).

ET trend

To investigate the potential causes behind an AETI trend, it is essential to normalize for climate first. Such a normalization can be conducted by dividing the AETI by the ETref for each timestep (e.g. per season, or per dekade). In addition, it may be worth to divide the AETI by precipitation, especially for rainfed analysis (precipitation in the study area) and spate irrigation analysis (precipitation in the catchment). In the case of normalizing the AETI for precipitation in spate irrigation, it is discouraged to look at a decadal scale as delays may occur between the rainfall event in the catchment and the arrival of a spate flow. In this case it is recommended to only look at the seasonal AETI and P ratio. If no trend can be identified after normalizing for climate and/or precipitation, an intervention may concern evaluating the crop types and considering a variety or crop type which may be more suitable for the respective climatic conditions. If a trend can still be identified even after climate normalization, it is recommended to conduct further field analysis and stakeholder discussions to further explore the causes (see Figure 3-1).

3.3.3 Scatter plot analyses diagnose

The scatter plot analysis observations from the scan can be followed up with some additional analyses in the diagnostic phase to identify potential causes behind such observations, which can then be followed up with field verification. For example, the point cloud can be split into colours based on different categories (see example analysis 3.4.2). Such categories can be based on for instance irrigation management type (irrigated agriculture) or upstream and downstream classification (spate and irrigated), soil type, land holding and type of farm management (see also Karimi et al., 2019). When splitting the data into categories, the scatter plots of each category should be analysed to access the consistency of the data and whether the results of the scatter plots make agronomically sense (section 3.2.3).

In the case of comparing different irrigation methods for the same crop in the same area, the scatter plots for TBP/ET are expected to vary. These variations are expected to be less for the TBP/T scatterplots, as only the crop transpiration is taken into account and no evaporation from the soil, and to decrease even more for the TBP/normalized transpiration scatter plots, where the differences in climate are taken into account. Furthermore, some general observations can be drawn from the scatter plot. For example, a less steep slope may be visible (low TBP and high AETI) for the TBP/ET scatter plot, a low TBP and AETI may be identified, or a high non-beneficial fraction. These three scenarios are discussed below. Additionally, from the WP/TBP scatter plot, areas may be identified with both high WP and TBP from which lessons may be learned, or a low WP and/or TBP for which the causes may be further explored. Thus, this WP/TBP scatter plot can be used as tool to identify areas of interest for other diagnostic analyses (e.g. spatial and/or temporal).

Less steep slope (low TBP and high ET)

If there is a relatively low TBP and high ET it is worth understanding the high ET component further by determining the beneficial fraction (see section *High non-beneficial ET* below). If the high ET and low biomass cannot be explained by a high beneficial fraction, it is recommended to explore this phenomenon with additional fieldwork (see Figure 3-1).

Low TBP and ET

If there is both a low TBP and a low AETI, this may be related to a low adequacy of water. In this case the cause behind this shortage should be further explored through fieldwork. In the case of rainfed and spate irrigated systems, the precipitation values could be observed and compared to literature values and local knowledge on whether this is sufficient for the type of crop. For irrigated areas a follow up study to assess causes behind the water shortage may relate to whether major leakage occurs in canals for instance. In all cases an intervention may entail improving water availability and/or access. However, if that is not possible, it may be worth to evaluate the crop varieties or types and see whether there is a more suitable option for the amount of water which is available.

High non-beneficial ET

As described in section 3.3.1, the beneficial fraction gives an indication on what fraction of the AETI consumption is used for crop development (transpiration) and which part is non-beneficial for the crop (e.g. soil evaporation). If a high non-beneficial ET is identified and intervention in terms of reducing water consumption is likely most appropriate. In case of water ponding for example, improved field drainage may contribute to reduced water consumption (assuming the trained water will be used later on in the system or for another purpose evidently). The beneficial fraction can also vary between irrigation methods applied, a system with drip irrigation has a higher beneficial fraction compared to a system with furrow irrigation. Changing the irrigation system may contribute to reducing the non-beneficial ET.

3.3.4 From diagnose to solutions

In the following three sections, section 3.4 to 3.6, an example analysis is provided for respectively irrigated, rainfed and spate irrigation systems. These sections in addition to Figure 3-1, the diagnostic explanations of 3.3.1-3.3.3, and the overview table (Table 3-1), share how these analyses may be linked with potential intervention areas. However, it is essential to treat the analyses as an indication and not as the definite truth. Discussions with stakeholders during the process and when identifying potential interventions are essential. This is a continuous process and may need several cycles based on feedback from the stakeholders and ground verification, before coming to the most suitable intervention. Examples of key questions which may be discussed with the stakeholders are the following:

- According to you, which areas are likely to have a high WP, a medium WP and a low WP?
    - Why?
- Our analysis shows X, Y, Z. Do you recognize this?
    - Why (not)?
    - Do you have any ideas about what may cause this?
- Together we have identified X as an issue in this area. Interventions which may contribute to improving this issue are A, B and C. Do you think any of these are suitable to apply in this area?
    - Why (not)?
    - Do you have any other suggestions for suitable interventions according to your experience?

In addition to these questions, field data may be collected in the form of surveys and/or field sampling. Such data collection could include soil moisture sampling (box 1), crop validation or surveys on land- and crop management with farmers. For validation and surveys, mobile phone apps may be valuable such as the open access app named Kobo Toolbox (https://www.kobotoolbox.org/).

Though the focus of this compendium is on identifying interventions for areas where WP can be improved, it may sometimes be valuable to look at areas where the WP is high, to see what lessons can be obtained from this. Likewise, it may sometimes be worth investing into interventions in medium WP areas where there still may be much to gain with little extra input, rather than areas where the WP is very low and much input is required to inly increase the WP slightly. Evidently decisions such as which area and aspect to focus on are site dependent and should be made together with relevant stakeholders.

Table 3-1: Overview of examples from scan to intervention

	scan observation	diagnostic observation	follow up diagnostics	Intervention areas	agricultural system applicability
Spatial analysis	relatively low biomass and AETI values	low adequacy	canal leakage	rehabilitate water infrastructure	irrigated
			general water shortage	water harvesting	irrigated/spate/rainfed
				crop type	irrigated/spate/rainfed
	large spatial differences in WP and AETI	low equity	large differences up- and downstream	water distribution rights reassessment	spate
			malfunctioning section of irrigation system	restore malfunctioning parts of irrigation system	irrigated/spate
	large spatial difference in WP and relatively high AETI in some areas	low uniformity beneficial ET	occurrence of ponding	improve field discharge	irrigated/rainfed
				improve field levelling	irrigated/rainfed
	areas with high year-round biomass values	increase extent year-round biomass production	expansion of invasive species	remove the invasive species (from the expanded areas)	spate
temporal analysis	TBP trend	increase extent year-round biomass production	expansion of invasive species	remove the invasive species (from the expanded areas)	spate
		no increase extent year-round biomass production	explore causes through further field studies (e.g. weeds, pests, diseases, crop variety/type, etc)	based on findings field work	irrigated/spate/rainfed
	AETI trend	AETI trend after climate normalization	explore causes through further field studies	based on findings field work	irrigated/spate/rainfed
		no AETI trend after climate normalization	Evaluate crop variety/type	find suitable crop variety/type for climate conditions	irrigated/spate/rainfed
Scatter plot analysis	Less steep slope (low TBP and high ET)	high non-beneficial ET	occurrence of ponding	improve field drainage	irrigated/rainfed
				improve field levelling	irrigated/rainfed
		low non-beneficial ET	explore causes through further field studies	based on findings field work	irrigated/spate/rainfed

Low TBP and ET	low adequacy	general water shortage	water harvesting	irrigated/spate/rainfed
			crop type	irrigated/spate/rainfed
		canal leakage	rehabilitate water infrastructure	irrigated

3.4 Applying the approach to Irrigated Agriculture

Unlike for rainfed (section 3.5) and spate irrigated agriculture (section 3.6), irrigated agriculture often is based on a more consistent water source such as a perennial river, a dam or ground water. There are several types of irrigation technologies, noted down by FAO (2002) as the following:

- Surface – usually includes a form of flooding e.g., furrows or complete submersion
- Sprinkler – imitating rainfall e.g., in the form of pivots
- Drip – small amounts of water applied to soil only above the root zone of the plant
- Underground irrigation – through porous pots or pipes which are placed under the surface at the root zone
- Sub-irrigation – raising the ground water level to moisturize the root zone

A mayor advantage of irrigated agriculture is that often much higher yields can be obtained (especially when enough water is available – see Figure 3-7). Additionally, irrigated agriculture is generally much less vulnerable for climate change. Usually, the timing of the irrigation is set to a predesigned scheme and schedule and water can be managed carefully to decrease non-beneficial consumption, such as through drip irrigation or root-zone irrigation techniques.

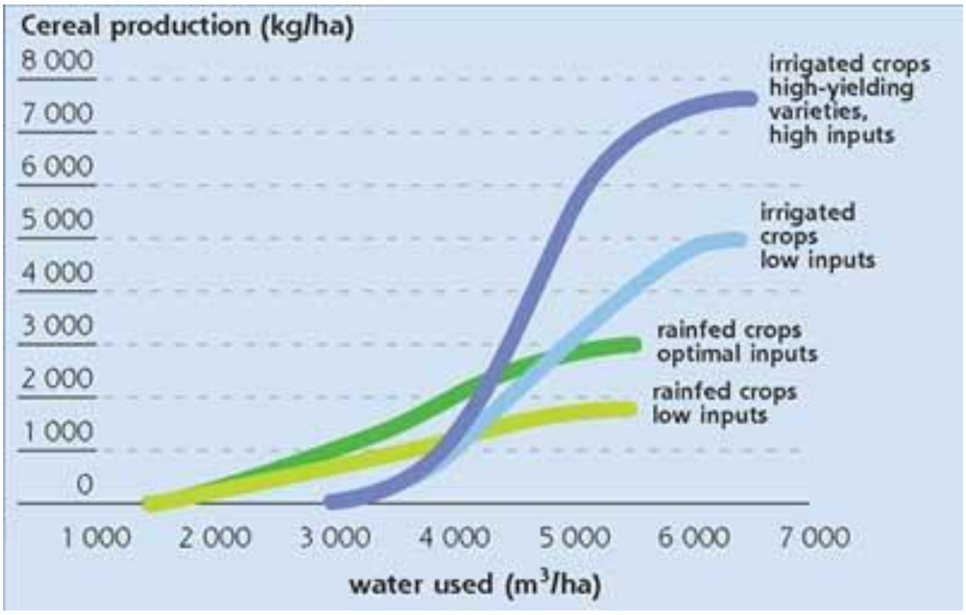


Figure 3-7 Comparison cereal production yields and water requirements of irrigated and rainfed agriculture. This graph indicates that for cereal production irrigated agriculture has a high potential to generate high yields compared to rainfed agriculture. However, this is only the case if enough water is available. For smaller water resources rainfed agriculture may generate more yields. However, note that the source does not provide information on the irrigation technique, nor the methodology, so cautious interpretation is required. (source: FAO, 2002)

Disadvantages of irrigated agriculture are that it is often expensive and requires intensive management and maintenance making it economically unfeasible or unattractive in many areas in the world (FAO, 2002). In high-intensity irrigation, waterlogging and/or salinization occur at times, which may negatively affect the useability of the land. According to the FAO (2002) due to this "about 30 percent of irrigated land is now severely or moderately affected" and "the salinization of irrigated areas is reducing the existing area under irrigation by 1-2 percent a year."

3.4.1 Things to keep in mind for irrigated agriculture analyses

Several things should be kept in mind when analysing irrigated agricultural systems. With the exception of rice paddies, generally the season which is used for the WP(AETI) analysis starts when the transpiration (and NPP) increases. The season for rice paddy cultivation which is based on full field flooding starts, like for spate irrigation, once the AETI (specifically E) begins to increase.

As WP(AETI) is heavily impacted by the type of irrigation technique, it is valuable to disaggregate the irrigation techniques during the analysis. Drip- , underground-, and sub-irrigation will likely have higher WP(AETI) values and especially a higher beneficial fraction, compared to sprinkler and surface irrigation, where surface irrigation will likely show the lowest WP values and highest non-beneficial consumption. An example of such disaggregation is provided in the next section (3.4.2).

3.4.2 Example analysis Irrigated Agriculture

Example case Wonji will be added.

3.5 Applying the approach to Rainfed Agriculture

Rainfed systems (including spate irrigation) are responsible for 60% of global food production (FAO, 2003) and account "for more than 95% of farmed land in sub-Saharan Africa [and] 75% in the Near East and North Africa" (IWMI, 2021). Several scenarios predict that the larger part of increased food production may come from rainfed and flood-based agriculture, as the scope to develop new irrigation systems is limited (IWMI, 2021). Moreover, the large majority of small-holder farmers – especially in Sub Saharan Africa depend on rainfed farming. It is not uncommon that an agricultural livelihood of rainfed farming is combined with pastoralism. In such cases livestock feeds on crop residues and form a natural fertilizer for the land. This livelihood is often referred to as agropastoralism and usually occur in areas where the rainfall is between 400 and 600mm (Otte & Chilonda, 2002).

Several scientists have advocated for increase in investment in rainfed agriculture (IWMI, 2021; Molden *et al.*, 2011; Ramirez-Vallejo, 2011; Rockstöm *et al.* 2010; Wani *et al.,* 2009). They argue that relatively low investments can already increase yields, that rainfed agriculture as in cases proved to be better for the environment than irrigated agriculture, and that investing in rainfed agriculture has shown to decrease poverty. However, one of the major disadvantages of rainfed agriculture is that it is more likely to be directly affected by climate change compared to irrigated agriculture, as it is highly vulnerable to climate and weather fluctuations including droughts.

Unlike for irrigated agriculture, the main water source for rainfed agriculture is direct rainfall on the fields or runoff from closely surrounding areas. Therefore, the timing of the water supply is often unknown or it is roughly estimated through local knowledge on the weather and/or national weather forecasts if available and if considered to be at high enough quality according to the farmers. The seasonality of the crop production is often hand in hand with the rain season for which the sowing often occurs when the first rains have started to fall (FAO, 2014).

3.5.1 Things to keep in mind for rainfed agriculture analyses

There are several things to keep in mind when conducting rainfed system WP analyses and when interpreting the resulting data. Firstly, compared to irrigated areas, water productivity (TBP/AETI) has a different connotation in rain-dependent systems. This is mainly the case because the volume of water cannot be regulated to the same degree. In rainfed systems, water can be better retained and distributed, but it cannot be controlled at the source. The water available is more of a given, not an input that can be administered.

Secondly, unlike spate systems and similar to irrigated systems, the growing season generally starts when transpiration and NPP begin to increase (an exception may be rice paddies if a ponding technique is applied).

Finally, similar as for the other systems, WP values can be normalized for climate by dividing by the Etref. However, in the case of rainfed systems it may also be valuable to normalize for rainfall to identify whether changes over time in rainfed systems are due to precipitation changes or due to other factors. For such analysis the rainfall which falls over the study area fields can be used (unlike for spate where the rainfall over the catchment is used).

3.6 Applying the approach to Spate-Irrigated Agriculture

Spate irrigation is based on diverting flash floods to agricultural fields. Though it is often classified under rainfed systems, for WP analyses it shows many characteristics of both rainfed and irrigated systems and is therefore treated separately in the compendium. Spate irrigation occurs in North Africa, West Africa, South-West Asia, Central Asia and Latin America. The flood-based irrigation systems range in area between several hectares to 30 000 ha, under a single wadi (van Steenbergen *et al.* 2010).

Unlike for rainfed agriculture, the main source of water for these systems does not originate from precipitation which falls directly over the fields, rather from rainfall over the upstream catchment. The timing of when exactly the floods will arrive is unknown and the distribution goes according to predetermined water rights. These rights are agreed upon by the community members and include who's turn it is to receive the flood water. After a field is flooded, the water infiltrates and the soil is usually 'sealed', for instance through mulching, to avoid further soil evaporation. Crops are cultivated after the irrigation and infiltration period and use the residual moisture to grow (van Steenbergen *et al.,* 2010). Similar as for rainfed agriculture, spate irrigated agriculture is often combined with pastoralism in which the livestock feeds on the crop residue.

A common issue in spate irrigation systems is the high abundance of natural vegetation which grows from the residual soil moisture in and around canals. As part of soil erosion and land degradation programs, *prosopis juliflora* was brought from Central and South America across the world (Africa, Asia, Australia, Middle East, North America) (Kool *et al.*, 2014; Muturi & Goudzwaard, n.d.). However, this shrub was very successful and is now often classified as an invasive species, spreading rapidly and competing with crops for water resources. Besides decreasing erosion, rehabilitating degraded lands and competing for water resources, when Prosopis occurs in large amounts it can deteriorate the canal structures, shift drainage patters severely and decrease the amount of floodwater which actually reaches the fields. Therefore, effectively managing this species is high on the agenda for a large amount of spate irrigation systems (Kool *et al.*, 2014).

Due to the high dependence on rainfall and the expected increase of unpredictability of rainfall events, spate irrigation systems are likely to be impacted by climate change. Through ingenious diversion systems, farmers manage to divert the short floods and keep out destructive floods (van Steenbergen *et al.,* 2010). However, land preparation may be done months in advance for fields which do not end up receiving any floods or other way around, some land may not have been prepared, while floods do arrive.

3.6.1 Things to keep in mind for spate-irrigated agriculture analyses

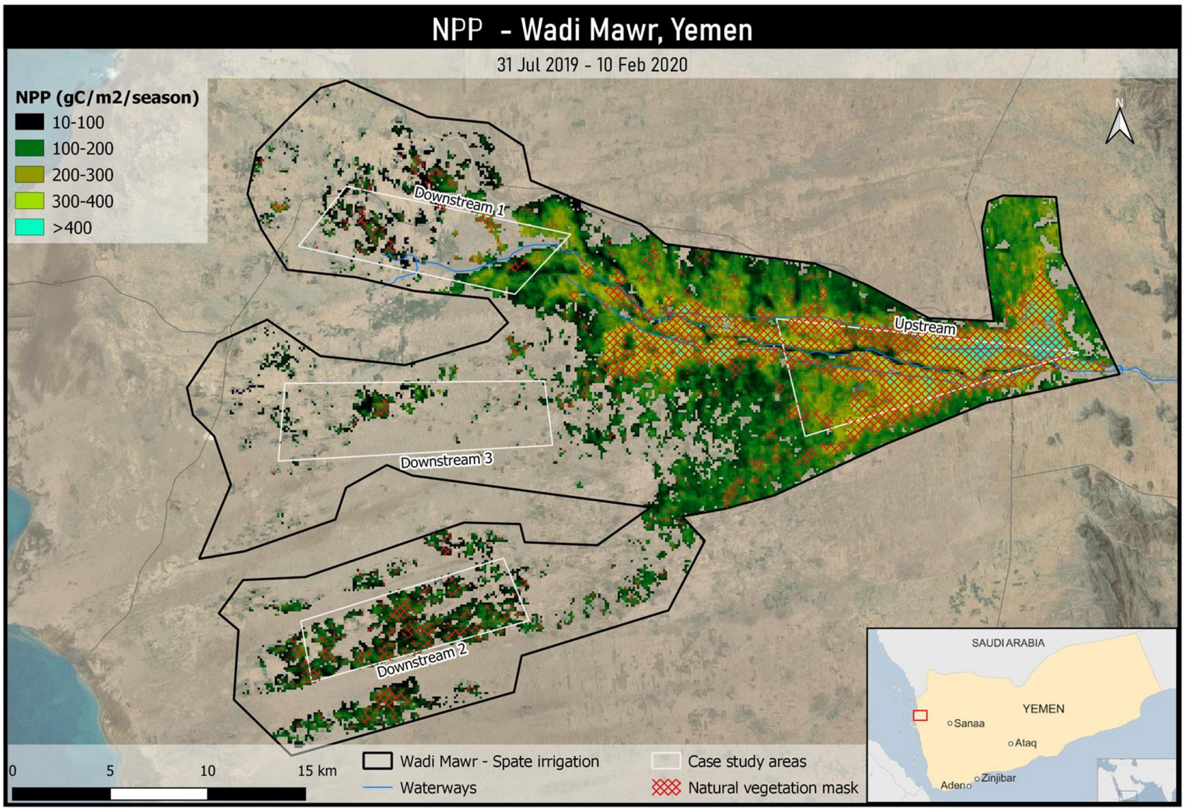
The most significant difference between spate irrigation WP (TBP/AETI) analyses and rainfed and irrigated WP analyses is the determination of the seasonality. While rainfed and irrigated agriculture usually start the season with an increase in NPP and T, spate irrigation starts with an increase of AETI (E specifically due to the flooding of the fields) and no T or NPP. Box XAX provides further information on how to identify the SOS and EOS.

When evaluating the AETI pattern and formulating a suitable diagnose and potential interventions, it is valuable to take the water distribution agreement into account. This will determine when which field receives water and how many times. To understand whether major changes in the agricultural production and WP are related to changes in climate and weather patterns it is recommended to normalize for climate (Etref) and Precipitation. In contrast to rainfed agricultural analysis, for spate irrigation the precipitation over the entire upstream catchment should be used rather than the precipitation which falls directly on the fields.

A final component to keep in mind when conducting spate irrigation WP analysis is that water ponding is part of the spate irrigation practice. Therefore, calculating the beneficial fraction (especially in the flooding phase) will likely not provide any useful insights.

3.6.2 Example analysis spate-irrigated agriculture

In this compendium it becomes evident that several diagnostic analyses can follow from the initial scan, very much depending on the main issues at hand in the specific problems in the area studied. In this section an example is provided for a spate irrigation system Wadi Mawr, in the Red Sea Coast area of Yemen (Figure 3-8). In this area there is a high abundance of invasive vegetation, *prosopis juliflora* (Figure 3-9), which in some parts of the system heavily affect the efficiency of water distribution. *Prosopis juliflora* was originally introduced as a sand dune stabilizer and to combat erosion, but spread rapidly and is now considered a severe problem in many flood and rain dependent areas.



Credits: Made in qGIS, shapefile Wadi Mawr by eLEAF. Sources: NPP based on WaPOR; Waterways, OpenStreetMap contributors; Background, ESRI World Hillshade/Topo/Satellite; Overview map, BBC news.

Figure 3-8: Wadi Mawr Spate irrigation system in Yemen. The map shows the seasonal Net Primary Production (NPP) values of 31 July 2019 till 10 February 2020. Additionally, the natural vegetation mask is shown. From this map a high abundance of natural vegetation is visible in the upstream area, corresponding to high seasonal NPP values of 300-400 gC/m2/season and more than 400 gC/m2/season.

Figure 3-9: Prosopis in the spate irrigation system, Tihama area, Yemen (source: spate-irrigation.org)

To get an understanding on where this vegetation is located and whether it is expanding or decreasing in extent, the invasive vegetation was masked out for each season. Filtering out the incidence of the perennial *prosopis juliflora* additionally helps to better estimate the biomass generated from seasonal crops.

The threshold of this invasive vegetation presence was determined using transpiration (T) and NPP data of the period when the T and NPP values were the lowest (10 March till 10 April). The resulting NPP graphs are provided in Figure 3-10. From these graphs, several conclusions can be drawn:

- invasive vegetation contributes to on average 40% of the biomass production in the area, ranging between 22% (2010-2011) and 63% (2012-2013) depending on the season.
- In Wadi Mawr the biomass production of the invasive vegetation is increasing relative to the overall biomass production, which is mainly due to the increase upstream rather than downstream.
- The biomass production upstream is on average 4 times higher than downstream.
- The biomass production of the invasive vegetation is relatively low downstream and high upstream.
- The biomass production of invasive vegetation is decreasing downstream relative to the overall biomass production and increasing upstream.

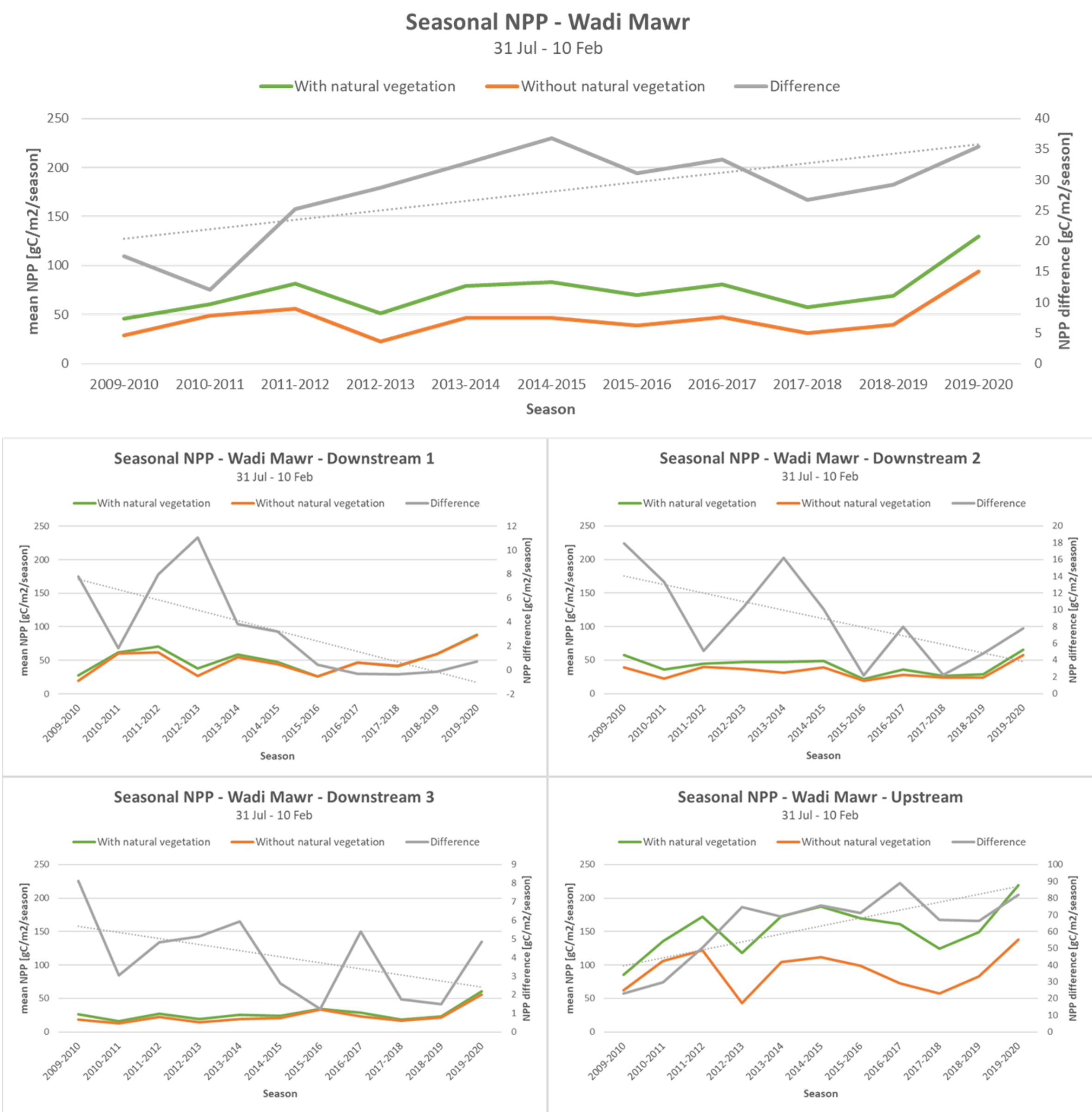
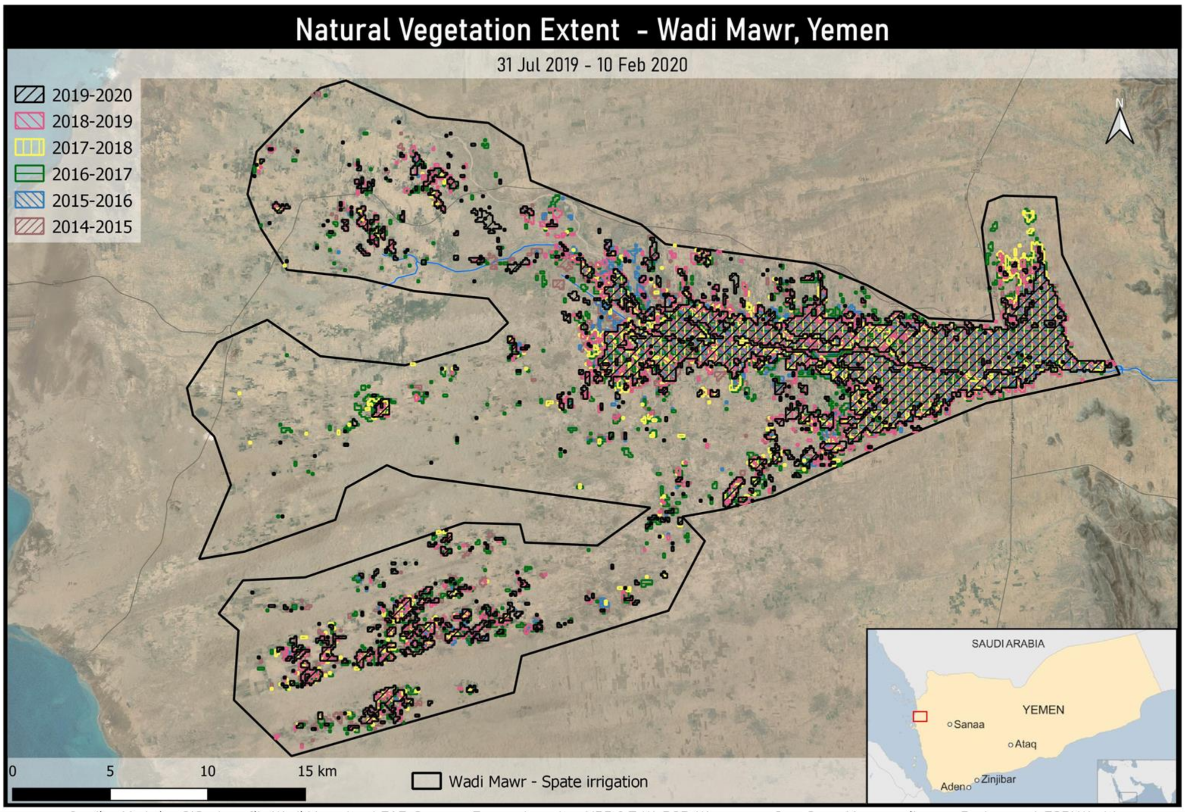


Figure 3-10: Seasonal Net Primary Production (NPP) graphs of the whole Wadi Mawr area, and 4 case study areas (which are shown in Figure 3-8). The mean seasonal NPP values are provided for: (1) natural vegetation included (green); (2) natural vegetation excluded (orange); and (3) the difference between 1 and 2 (grey). The highest mean biomass production values are upstream. Additionally, there is a higher abundance of natural vegetation upstream compared to downstream. Overall, the natural vegetation is increasing in the area, which is due to the increase in natural vegetation upstream, rather than downstream.

In addition to obtaining an understanding of the biomass production of the invasive vegetation, it can be valuable to get an impression of the extent of the invasive vegetation over time. The results are provided in Figure 3-11. From the graph in the figure, it becomes evident that even though the biomass production is increasing, the extent of the invasive vegetation does not seem to be increasing. Thus, the invasive vegetation is increasing in density, rather than extent. The corresponding map of the seasonal invasive vegetation extent since 2014, shows that a large part of the vegetation is located in the same area each year. However, the occurrence of invasive vegetation on the outskirts of this larger area fluctuates over time.



Credits: Made in qGIS; shapefile Wadi Mawr by eLEAF. Sources: Extents based on NPP & T, WaPOR; Waterways, OpenStreetMap contributors; Background, ESRI World Hillshade/Topo/Satellite; overview map, BBC News.

Figure 3-11: The invasive vegetation coverage in hectares in Wadi Mawr, Yemen. There seems to be a declining trend since 2009, though it can also be argued that it has remain relatively stable since the war (2014).

In summary, this analysis makes it possible to understand the invasive vegetation dynamics in the Wadi Mawr spate irrigation system. These findings are valuable for improving the WP(WU) in the area as *prosopis* (the main occurring invasive vegetation) limits the amount of water which reaches the fields as it obstructs the fields and also is a large water consumer itself. Therefore, to improve the "crop per drop", it is an effective start to control and eradicate the invasive *prosopis juliflora* vegetation. From this analysis, it can be concluded that targeting the upstream invasive vegetation areas will likely be more beneficial than the downstream areas. However, even though this analysis provides valuable support for decision making, it should still be combined with fieldwork and stakeholder engagement, to both verify the results and gain additional information of the ground situation.

4 Intervention areas

The WaPOR scans and diagnoses ultimately lead to identification of intervention areas. In dialogue with the land and water users and managers, promising interventions specific to the analysed areas may be developed and implemented. With this dialogue it is hoped that a tangible contribution to increased water productivity can be made.

In annex 1 to this compendium a description of fifty plus of the most common interventions that may (beneficially) impact water productivity, water use efficiency and production (yield). The interventions are organized in the following categories:

1. Water resources enhancement
2. Irrigation system management
3. Irrigation field water management
4. Water management in rainfed and flood dependent conditions
5. Soil moisture management in rainfed and flood dependent conditions
6. Cropping system management
7. Crop input management
8. Control of pests

The above categories cover the interventions areas as identified in Table 3-1, of section 3.3.4, in annex 1 however the full list provides a more comprehensive overview of all possible interventions. It is hoped to extend the analysis in the near future to include the management of rangeland areas and provide specific interventions for these as well.

As mentioned in the introduction, the Compendium of Approaches to Improve Water Productivity is to be seen as a living document, that will progress through several versions. With more applications, also the diagnostic analyses will be further refined. Similarly, as the quality of data of WaPOR improves, new applications may emerge and potentially powerful combinations with other data sets will arise. In the current compendium the focus is on using WaPOR data only, but more elaborate analysis is possible. It is hoped that also the list of water productivity interventions in Annex 1 is expanded and fine-tuned and that the linkage between the diagnosis and the identification of the intervention areas is further strengthened as the Compendium is used.

5 Glossary

Actual evapotranspiration and interception	This is the sum of the actual canopy transpiration, the actual soil evaporation, and the evaporation of rainfall intercepted by the leaves.
Beneficial water consumption	The amount of consumed water that is beneficial for the crop production, which is the transpiration.
Biophysical water productivity	Biophysical water productivity is the ration between the biomass, or yield, produced and the volume of water applied. This is also called 'crop per drop'.
Gross biomass water productivity	The gross biomass water productivity is the total biomass production of a season or year in relation to the total volume of water consumed in that period (actual evapotranspiration and interception).
Net Primary Production	The Net Primary Production expresses the conversion of carbon dioxide into biomass driven by photosynthesis.
Reference evapotranspiration	Reference evaporation is the estimation of the evapotranspiration from a hypothetical reference crop, derived from the Penman-Monteith equation; it simulates the behaviour of a well-watered grass surface.
Water consumption	The water consumption in this document is defined as the total amount of water evaporated through direct soil evaporation, plant transpiration and evaporation from rainfall intercepted by leaves.
Water productivity	Water productivity is an indicator used in agriculture to measure production given a certain amount of water. Production commonly relates to the amount of crop that is produced, but can also relate to value of the crop, or the amount of jobs that are sustained in the production which is then called the economic or social water productivity.

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Annex 1: Water Productivity Interventions

Interventions list summarised

The interventions listed in this compendium do not comprise an exhaustive overview of all the possibilities (it is a living document), nor does it solely refrain to those that might only impact water productivity. Also it is important to consider that the expectations associated with crop water productivity are not only restricted crop performance (the bio-physical) but may also include economic, social, ecological and technical (as referred to in chapter 2.1). Crop water productivity measures also do not only take place at plant level, but also at field, scheme and policy level.

Summarised are the (potential) impact the solutions may have when applied. These impacts are qualified by the following three (categories of) indicators, being: water productivity (WP); water use efficiency (WUE); and land productivity (or Yield). These categories of indicators follow the definitions as described in paragraph 2.1 and depicted in Figure 2-2, the visualisation of the definitions.

WP - Water productivity for the purpose of qualifying the impacts of the interventions is considered as dividing the yield by the evapotranspiration (Y/ET). This is also called CWP and referred to in this compendium as WP(AETI)(also referred to in paragraph 2-1).

> T – transpiration may increase or decrease. An increase may imply either an increase in biomass (and potentially yield) and a decrease may imply a decrease in biomass (and potential yield). It is important to consider this indicator together with the Yield (Y), and Transpiration (T) over Evapotranspiration (ET) ratio to ascertain any positive or negative impacts with regards to consumptive water use are achieved.
>
> Y/B – the Yield (Y) Biomass (B) ratio provides a specific indication of the potential stresses a crop may have endured. It is also known as the harvest index. If this ratio is below the attainable (ie. the standard harvest index for that crop) it can be assumed that the crop has endured stresses during its growing season.
>
> T/ET - Transpiration (T) over Evapotranspiration (ET) ratio is an indicator of the fraction of water that is consumed beneficially (T) over total consumptive use (ET), including non-beneficially consumed water (E).

Water Use Efficiency (WUE) –as considered in this compendium is the ratio between water that is applied and the water that is being used. Yield (nor biomass) is not being considered in this ratio, whereas in this compendium ET (ie. beneficially and non-beneficially consumed water) and water applied is (see also Figure 2-2). The water applied may simply be the amount of rainfall or depth of flooding, such as in spate irrigation systems, or it could be the amount of water that is abstracted from a source such as a river, lake or (tube)well. In case of rainfed agriculture this efficiency may also be referred to as Precipitation Use Efficiency (PUE) in which the denominator is then the amount of precipitation (mm) as snow or rain received during the cropping season. In case of irrigated agriculture the denominator is the amount of irrigation water applied plus rainfall.

Land productivity (or Yield) - Yield is considered to include all or any part of the crop that is usable for consumption (both human and animal) or processing purposes (oils, cottons, fuels, etc.). If an intervention is believed to contribute to an increase in yield this is indicated in underneath table with a +.

What is important to consider that the indicators suggest an impact, which implies a (significant or measurable) change over time for a specific place and for some indicators also for same crops. The following considerations are provided when browsing through the solutions list and write-up:

- most if not all solutions are not stand-alone solutions if intending to improve water productivity;
- besides introducing solutions, improving water productivity comes with: adequately being able to measure to do so (as this compendium suggests); performing the right comparison; having a clearly identified objective; and keeping the intended impact in mind;
- keep in mind the potential trade-offs a solution may have in a given context, with regards to water resources management (within a basin or hydrogeological unit); the environment; the societal and economic impact. These trade-offs are mentioned in the descriptions of the solutions.

Where the fields are left open, ie. no significant impact is expected.

	WP	WUE	Y
Control of pests			
I 1- 1: Integrated pest management (IPM)	+		+
I 1- 2: Nanotech pesticides	+		+
I 1- 3: Ecologically based rodent management	+		+
I 1- 4: Eradication of invasive species	+		+
Irrigation field water management			
I 2- 1: Root zone irrigation (or sub-irrigation)	+		+
I 2- 2: Greenhouses and polytunnels	+		+
I 2- 3: Land levelling	+		+
I 2- 4: Mulching	+		+
I 2- 5: Furrows and field basin irrigation		+	+
I 2- 6: Command area irrigation scheduling		+	+
I 2- 7: Pressured irrigation systems		+	+
Irrigation system management			
I 3- 1: Deficit irrigation	+		
I 3- 2: Conjunctive use of ground and surface water		+	+
I 3- 3: Storm water drainage			+
I 3- 4: Rootzone drainage		+	+
I 3- 5: Rationalise irrigation duties		+	+
I 3- 6: Supplemental irrigation			+
I 3- 7: Alternate wetting and drying (AWD)		+	
I 3- 8: Canal and watercourse lining		+	
Crop input management			
I 4- 1: Efficient fertilizer use	+		+
I 4- 2: Integrated nutrient management	+		+
I 4- 3: Smart fertilizers			+
I 4- 4: Bio-fertilizers			+
I 4- 5: Rock dust soil amendments			+
I 4- 6: Chemigation			+
I 4- 7: Bio-stimulants and micro-nutrients			+
I 4- 8: Reel gardening			+
I 4- 9: Farm mechanization			+
Water resources enhancement			
I 5 1: Surface water storage			+

I 5- 2: Improved shallow groundwater storage		+	+
I 5- 3: Reuse of stored water		+	+
I 5 4: Water harvesting: using roads			+
I 5- 5: Water harvesting: using rock outcrops			+
Water management in rainfed and flood dependent conditions			
I 6- 1: Improving flood water distribution		+	
I 6- 2: Field bunding and water guiding		+	
I 6- 3: Controlled field water management		+	
Soil moisture management in rainfed and flood dependent conditions			
I 7- 1: Planting pits		+	
I 7- 2: Double dug beds			+
I 7- 3: Demi lunes/ half-moons		+	
I 7- 4: Bench terracing		+	+
I 7- 5: Gully plugging		+	+
I 7- 6: Grass strips		+	+
I 7- 7: Tied ridge		+	+
I 7- 8: Bunds (contour, stone and trapezoidal)		+	+
I 7- 9: Minimum and zero tillage		+	
I 7- 10: Deep tillage and mulching		+	+
I 7- 11: Deep ploughing and planking title		+	
I 7- 12: Direct seeding			+
I 7- 13: Making use of invertebrates		+	+
Cropping system management			
I 8- 1: Adjusting crop sowing dates			+
I 8- 2: Crop rotation			+
I 8- 3: Crop varieties selection			+
I 8- 4: Multiple cropping systems			+
I 8- 5: Agroforestry/shelter belts		+	
I 8- 6: Promoting promising minor crops in spate irrigation			+

1 Pest control

Pest control directly improves water productivity. As pest affect maturing or harvested plants, they reduce biomass and yields whilst the water to produce this biomass or crop yield has already been consumed. So by reducing the effect of pests and increasing the amount of harvestable and usable crop the WP ratio (yield/ET) is increased.

I 1- 1: Integrated pest management (IPM)

Intervention:	Integrated pest management (IPM)
Application	• Irrigated areas • Rainfed areas • Spate irrigated areas • Rangelands/ catchments
Contributes to:	• Improving water productivity (Y/ET) • Improved water use efficiency (from source to rootzone availability) • Improved crop production (crop/biomass)
Description:	Integrated pest management (IPM) as opposed to single pest control methods is a strategy that combines a larger range of cultural, biological, mechanical and chemical tools and practices. It relies on a deep understanding of pathogen life cycles and plant-pathogen interactions. By rationalizing chemical interventions and doses, IPM aims to use resources more efficiently, reducing costs and environmental and health externalities. IPM includes four steps: 1) setting an action threshold; 2) monitoring and identification of pests; 3) prevention; and 4) control. Prevention methods encompass several practices using pest-resistant crops, including rotations, intercropping and using certified and pest-free planting material. These methods can be highly effective and cost-efficient while preserving the environment and human health. Similarly, any method for early monitoring and pest detection is crucial in preventing the outbreak of devastating diseases and avoiding cost-intensive measures. Once the threshold for action has been reached, various control methods are available, starting with the least risky pest control methods, such as pheromones for pest mating or mechanical control. If these are not working, then, targeted pesticides may be applied. Broadcasting and nonspecific pesticides are the last resort (US EPA n.d). Several studies confirm the potential and profitability of this approach (Dasgupta et al. 2007; Pretty et al. 2011). IPM has found wide application in Asia and Africa, often promoted in farmer field schools as part of programs aimed at social and human development. Rice yields in Mali have been reported to rise from 5.2 to 7.2 t/ha and in Senegal from 5.19 to 6.84 t/ha, with up to 90% reductions in pesticide use (Pretty et al. 2011).
Remarks:	Documents: Co-optimizing Solutions | Water and energy for food, feed and fiber (https://metameta.nl/wp-content/uploads/2014/09/WBCSD-Co-op-Main-Report-DEF.pdf)(Borgia et al., 2014) US EPA n.d / Dasgupta et al. 2007 / Pretty et al. 2011

I 1- 2: Nanotech pesticides

Intervention:	Nanotech pesticides
Application	• Irrigated areas • Rainfed areas • Spate irrigated areas • Rangelands/ catchments
Contributes to:	• Improving water productivity (Y/ET) • Improved water use efficiency (from source to rootzone availability) • Improved crop production (crop/biomass)
Description:	Despite global pesticide use of 2.5 million tonnes every year, production losses as a consequence of plant pests remain in the order of 20-40% (FAO 2011a). Oerke (2006) estimates

	total losses* of 28% for wheat, 37% for rice and 31% for maize. Conventional pesticides are strongly associated with environmental degradation and health hazards. This is due to pesticide toxicity, non-biodegradability, the impreciseness of some formulations, and leaching and other losses during application. This combination of side effects and low efficiency is the imperative for rethinking conventional pesticide use, the aim being to halve current losses. Breakthroughs in pesticide control are expected in the field of nanotechnology. Nanotechnology refers to a range of techniques for manipulating materials, organisms and systems at a scale of 100 nano meters or less. Nano pesticides contain nanoscale chemical substances. The theoretical advantages are: 1) increased efficacy, stability or dissolvability in water as compared to larger-scale molecules of the same chemical substances and 2) controlled release of pesticides due to the nanoencapsulation of pesticide substances. Some smart pesticides can release their active ingredient only when inhaled by insects (Kuzma and VerHage, 2006). Nano pesticides are also better combined with genetically engineered insecticide-producing crops and genetically engineered herbicide tolerant crops. Nano pesticides are still in the experimental stage: one issue to be resolved is precautionary concerns on the release of the particles in a larger environment.
Remarks:	https://metameta.nl/wp-content/uploads/2014/09/WBCSD-Co-op-Main-Report-DEF.pdf FAO 2011a / Oerke (2006) /Kuzma and VerHage (2006)

** Globally, cereal crops losses from weeds are estimated at 8-11%; from animal pests 8-15%; from pathogens 9-11% and from virus strains 1-3%*

I 1- 3: Ecologically based rodent management

Intervention:	Ecologically based rodent management
Application	• Irrigated areas • Rainfed areas • Spate irrigated areas • Rangelands/ catchments
Contributes to:	• Improving water productivity (Y/ET) • Improved water use efficiency (from source to rootzone availability) • Improved crop production (crop/biomass)
Description:	To safeguard local food supplies an immediate priority is to control the loss of the current harvest by drastically reducing rodent damage. Both in the field and in storage. At the same time, it is essential to combat rodent vectored diseases, which amount to over 60 different diseases. For example, the Lassa-and Hanta viruses are brought by rodents. Chemical control is currently the primary driver of "Integrated Pest Management" (IPM) for rodents. This generally provides effective control in the short term, regardless of the rodent species. However, governments are concerned about the use of chemicals, especially when they are striving to provide clean and green food products for their domestic and export markets. In developing countries, the challenge is first to develop a good understanding of the ecology of the pest species and then assess the efficacy of using traditional and new methods of rodent control. This will enable adoption of management actions that are more environmentally sound and sustainable (environmentally and culturally). Therefore, Ecologically Based Rodent Management (EBRM) which promotes integrated control mechanisms could greatly improve agricultural production standards in quantity and quality, and improves healthy living conditions.

I 1- 4: Eradication of invasive species

Intervention:	Eradication of invasive species
Application	• Irrigated areas • Rainfed areas • Spate irrigated areas • Rangelands/ catchments

Contributes to:	• Improving water productivity (Y/ET) • Improved water use efficiency (from source to rootzone availability) • Improved crop production (crop/biomass)
Description:	An 'invasive species" is defined as a species that is non-native to the ecosystem under consideration and whose introduction causes or likely to cause economic or environmental harm or harm to human life. Invasive species are a major cause of crop loss and can adversely affect food security (Cook et al., 2011). With good planning, adequate techniques and sustained effort, it is now possible to eradicate many types of invasive species, especially in the early stages of an invasion, or where a population is confined to an island or limited habitat. The eradication of invasive species can yield major economic benefits, by permanently removing the cause of damage to crops, livestock or native biodiversity, and obviating the need for costly perpetual control. The difference between eradication and control is only one of grade; these two strategies are part of a gradient of interventions and both share the purpose of annulling or (if not feasible) decreasing the impact exerted by invasive species. The methods used to control or eradicate invasive species are: (a) mechanical removal of invasive species from an area; (b) construction of barriers to prevent their spread; (c) reduction of their population size by using biological means; or (d) by using biocides; or (e) by having recourse to autocidal approaches; and (f) habitat management (Gherardi & Angiolini, 2009). Eradication, that is the removal of every potentially reproducing individual of a species from an area where this behaves as invasive or the reduction of its population density below sustainable levels, is the best management option, since it removes the need for further control and ongoing financial and environmental costs. Low-cost tools such as the 'Tree puller' can be very useful. However, eradication is likely to be successful only in the earliest stages of an invasion, or in "island" systems of manageable size. Eradication is often difficult, particular in extensive land use such as in rainfed cultivation or rangelands. In intensive cultivation the re-emergence and reinfestation can be controlled. Before starting any eradication program, managers should be fully aware that (a) adequate funds and commitment exist to complete the eradication, (b) monitoring of the population size is feasible, and (c) eradication will be followed by the restoration or management of the community or ecosystem resulting from the removal of a "keystone" target species.
Remarks:	Video: The Tree puller (https://thewaterchannel.tv/videos/the-tree-puller/) Web resources: https://www.invasivespeciesinfo.gov/what-are-invasive-species https://portals.iucn.org/library/sites/library/files/documents/SSC-OP-028.pdf https://portals.iucn.org/library/sites/library/files/documents/2018-030-En.pdf http://issg.org

2 Irrigation field water management

In irrigation and drainage at field level a lot can be improved with regards to the amount of water that is consumed beneficially (T) versus the amount that is consumed non-beneficially (E) and not consumed at all (including the recoverable and non-recoverable fraction). Water productivity improvements however can only be mentioned as such where the beneficial fraction (or fraction of T/ET) is increased.

I 2- 1: Root zone irrigation (or sub-irrigation)

Intervention:	Root zone irrigation (or Sub-irrigation)
Application	• Irrigated areas • Rainfed areas • Spate irrigated areas • Rangelands/ catchments
Contributes to:	• Improving water productivity (Y/ET) • Improved water use efficiency (from source to rootzone availability) • Improved crop production (crop/biomass)
Description:	Rootzone irrigation is an irrigation system buried below the soils surface. systems can consist of (low-pressure) drip tubes, buried diffusers or clay pots (pitcher method). It can be installed for the purposes of growing tree crops and orchards as well as in permanent high-production (high-value) crop growing setups such as for horticulture or fruit crops. Rootzone or sub-irrigation considerably reduces the amount of evaporation from the soils and with that (particularly in arid climates or in open-soil greenhouses) also the accumulation of salts at the surface. It also reduces weed growth (as soil surfaces are not continuously wetted) and keeps infrastructure in the field out of the way and out of sight, which reduces the damages as a cause of field activities or theft. Comparing with surface irrigation systems and their common effects such as crusting, saturated conditions of ponding water, and potential surface runoff (including soil erosion) are eliminated when using subsurface irrigation (D. Reich, R. Godin, J.L. Chávez, n.d.). This type of irrigation system does come with a high-labour and often high-capital investment to start of with, however there are also low-cost developments. One of these low-cost systems is the System of Water for Agriculture Rejuvenation (SWAR), whereby low cost drip systems are combined with unglazed clay plots that have diffusers which provides for a combination of wetting and sweating at the rootzone of the crops. This has an advantage over conventional drip systems as water efficiency is even higher and by providing precision water to the tree roots water is reduce water application with 30-70%, and as literature suggests 'as much as 10 times' higher plant root efficiency 'than conventional surface irrigation' (Bainbridge, 2001). SWAR also encourages deeper root development which makes plants more resilient to drought events. (Gebru et al., 2018) describe how bar-shaped clay pots performed in comparison with furrow irrigation on tomato, pepper and Swiss chard, with yields increasing up to 32, 30 and 51% respectively and water savings for all by 41%.
Remarks:	Video: SWAR: Irrigation at the Roots (https://thewaterchannel.tv/videos/swar-irrigation-at-the-roots/) Documents: Subsurface Drip Irrigation (https://extension.colostate.edu/docs/pubs/crops/04716.pdf) More to add on rootzone irrigation technologies

I 2- 2: Greenhouses and polytunnels

Intervention:	Greenhouse and polytunnels
Application	• Irrigated areas • Rainfed areas • Spate irrigated areas

	• Rangelands/ catchments
Contributes to:	• Improving water productivity (Y/ET) • Improved water use efficiency (from source to rootzone availability) • Improved crop production (crop/biomass)
Description:	Greenhouses and polytunnels are structures with walls and roof made chiefly of transparent material, such as glass, in which plants requiring regulated climatic conditions are grown. These structures range in size from small sheds to industrial-sized buildings. The interior of a greenhouse exposed to sunlight becomes significantly warmer than the external temperature, protecting its contents in cold weather. Greenhouses and polytunnels provide a variety of advantages such as: (1) Longer growing season (even in cold climates) (2) Create an optimum growing environment (3) Suitable for a wide variety of plants (4) Protection of pests and diseases (5) Increased crop yield compared to conventional farming
Remarks:	

I 2- 3: Land levelling

Intervention:	Land levelling
Application	• Irrigated areas • Rainfed areas • Spate irrigated areas • Rangelands/ catchments
Contributes to:	• Improving water productivity (Y/ET) • Improved water use efficiency (from source to rootzone availability) • Improved crop production (crop/biomass)
Description:	Levelling, smoothing and shaping the field surface is very important. It is a process for ensuring that the depths and discharge variations over the field are relatively uniform and, as a result, that water distributions in the root zone are also uniform. These field operations are required nearly every cropping season, particularly where substantial cultivation following harvest disrupts the field surface. The preparation of the field surface for conveyance and distribution of irrigation water is as important to efficient surface irrigation as any other single management practice the farmer employs. There are two main land levelling philosophies: (1) to provide a slope which fits a water supply; and (2) to level the field to its best condition with minimal earth movement and then vary the water supply for the field condition. The second philosophy is generally the most feasible. Because land levelling is expensive and large earth movements may leave significant areas of the field without fertile topsoil, this second philosophy is also generally the most economic approach. Land levelling always improves the efficiency of water which leads to improved agricultural production.
Remarks:	

I 2- 4: Mulching

Intervention:	Mulching
Application	• Irrigated areas • Rainfed areas • Spate irrigated areas • Rangelands/ catchments
Contributes to:	• Improving water productivity (Y/ET) • Improved water use efficiency (from source to rootzone availability) • Improved crop production (crop/biomass)
Description:	Plastic mulching is a technique by which polyethylene (mainly low-density polyethylene (LDPE) films) are applied as a thin foil over the soil surface. This creates a microclimate allowing better

control of crop growth factors. Plastic mulching reduces evaporation, controls weeds, protects the soil against erosion and stimulates nitrogen fixing microbial activity. It also protects the crop from soil contamination. Most importantly, it helps retain nutrients in the root zone, allowing for more efficient nutrient use. Moreover, in temperate areas, the control over temperature makes it possible to start cultivation earlier. In some very dry areas, the control over soil moisture evaporation allows for crop growth where it was impossible before. Plastic films are applied in horticulture but can also be applied to field crops, such as maize, sorghum and sugar. A variety of plastics – size, thickness and colour – mean the grower can select the right plastic for the right crop and conditions. Plastic mulching is widely applied in the U.S., Australia and China but far less elsewhere. The area under plastic mulch in China was estimated at 12 million ha in 1999 – a figure that must have at least doubled by today. Water savings from plastic mulch are substantial – up to 26-50% compared with furrow irrigation – or even more if combined with drip irrigation. Crop yields are significantly higher, up 50%, but in exceptional cases a factor of four or five is possible. Presented below are the benefits of biodegradable mulch compared to non-biodegradable LDPE plastics.

Energy	Water	Productivity	Climate	Costs
Bio-mulch requires 70 GJ/t less than LDPE plastics	-50% water use at plot level	+10 to 50% increase in yield	reduces fossil fuel use over 50%	Bio-mulch costs are 15% higher than LDPE plastics

The current challenge is to develop commercially attractive photodegradable and biodegradable plastic mulches, ones that do not disintegrate too fast or too slow and are not too "flaky". Farmers may even add plant nutrients or seeds to the thin films. When biodegradable plastics are made from bio-based material, it is important to consider possible competition with food and feed for land and resources. This is especially true for first-generation feedstock. Second-generation feedstock and by-products from agriculture and forestry to produce bio based plastics do not compete with food and feed.

Organic polymers, such as hydrogels (polyacrylic acids), are a related synthetic product. Added to the soil, these polymers improve the moisture-holding capacity. The niche for polymers is now in specialized uses: tree nurseries, turf grass and gardening. The challenge is to adapt these polymers to large-scale vegetable and field crop uses. Field trials have shown that depending on crop, soil type and water availability, yield increases of 5-30% are achievable. For irrigated crops, the choice would be to reduce irrigation water deliveries while maintaining similar yields by using soil modifiers.

Examples are the systematic use of mulch (from banana or mango leaves) that reduces evaporation and increases the organic matter in the soil or the use of (low cost),

I 2- 5: Furrows and field basin irrigation

Intervention:	Furrows and field basin irrigation
Application	• Irrigated areas • Rainfed areas • Spate irrigated areas • Rangelands/ catchments
Contributes to:	• Improving water productivity (Y/ET) • Improved water use efficiency (from source to rootzone availability) • Improved crop production (crop/biomass)

Description:	Basin irrigation is the most common form of surface irrigation, particularly in regions with layouts of small fields. If a field is level in all directions, is encompassed by a dyke to prevent runoff, and provides an undirected flow of water onto the field, it is herein called a basin. A basin is typically square in shape but exists in all sorts of irregular and rectangular configurations. It may be furrowed or corrugated, have raised beds for the benefit of certain crops, but as long as the inflow is undirected and uncontrolled into these field modifications, it remains a basin. There are few crops and soils not amenable to basin irrigation, but it is generally favoured by moderate to slow intake soils, deep-rooted and closely spaced crops. Crops which are sensitive to flooding and soils which form a hard crust following an irrigation can be basin irrigated by adding furrowing or using raised bed planting. Reclamation of salt-affected soils is easily accomplished with basin irrigation and provision for drainage of surface runoff is unnecessary. Of course it is always possible to encounter a heavy rainfall or mistake the cut-off time thereby having too much water in the basin. Consequently, some means of emergency surface drainage is good design practice. Basins can be served with less command area and field watercourses than can border and furrow systems because their level nature allows water applications from anywhere along the basin perimeter. Furrow irrigation avoids flooding the entire field surface by channelling the flow along the primary direction of the field using 'furrows,' 'creases,' or 'corrugations'. Water infiltrates through the wetted perimeter and spreads vertically and horizontally to refill the soil reservoir. Furrows are often employed in basins and borders to reduce the effects of topographical variation and crusting. The distinctive feature of furrow irrigation is that the flow into each furrow is independently set and controlled as opposed to furrowed borders and basins where the flow is set and controlled on a border by border or basin by basin basis. Furrows provide better on-farm water management flexibility under many surface irrigation conditions. The discharge per unit width of the field is substantially reduced and topographical variations can be more severe. A smaller wetted area reduces evaporation losses. Furrows provide the irrigator more opportunity to manage irrigations toward higher efficiencies as field conditions change for each irrigation throughout a season.
Remarks:	Documents: Guidelines for designing and evaluating surface irrigation systems (http://www.fao.org/3/t0231e/t0231e04.htm#2.2.3%20furrow%20irrigation)(Walker, 1989)

I 2- 6: Pressured irrigation systems

Intervention:	Pressurized irrigation system
Application	• Irrigated areas • Rainfed areas • Spate irrigated areas • Rangelands/ catchments
Contributes to:	• Improving water productivity (Y/ET) • Improved water use efficiency (from source to rootzone availability) • Improved crop production (crop/biomass)
Description:	Reducing evaporation while increasing productive transpiration can enhance water productivity at the field level. Evaporation varies with agricultural practices (C. Burt et al., 2005) and ranges from 4% to 25% in sprinkler irrigation systems (C. Burt et al., 2001), and up to 40% and more in rainfed systems (Rockström et al., 2007). Conventional irrigation systems often have low water application efficiencies; usually between 40-50% because of in efficient local practices. However, by switching to pressurized irrigation systems this water use application can be increased to 70-90% (Borgia et al., 2014). Pressurized systems have minimal runoff and evaporation losses and hence can have better field application efficiencies. There are several pressurized systems in use and a service industry has developed that produces and installs the systems. In some cases packages are offered whereby for instance drip systems are combined with soil moisture sensors and advise whether to irrigate or not is generated.

	The most common pressurized systems are: (1) Drip (or trickle) irrigation systems (2) Sprinkler systems (3) Centre-pivot systems (4) Bubbler systems Studies have shown that up to 40% water savings without compromising yield capacity can be attained through subsurface drip irrigation. In addition, systems such as micro irrigation allow for optimal root zone management of water, fertilizer and pesticides, reducing the leaching and runoff and reducing the subsequent pollution from these substances. . The benefits of precision irrigation are not only limited to water savings. Studies have shown that 10-54% increase in yield is possible, especially in the horticulture field if more precise water applications could be implemented. Benefits such as reduced incidence of fungi in fruit and vegetable farms are also related benefits. However, care should be taken in the use of precision irrigation as drip irrigation can lead to accumulation of salt in the root zone of plants and hamper development of crops in salt affected areas or in areas where saline water is used for irrigation. The major trade-off between surface and pressurized methods lies in the relative costs of land levelling for effective gravity distribution and energy for pressurization (Walker, 1989). In tree crops, for example, the E reductions by localized irrigation can be substantial (Bonachela et al., 2001), especially when the canopy cover is sparse. Subsurface trickle systems eliminate most if not all of the E loss (Hsiao et al., 2007). Although this 'gain' must be off-set against the investments costs for such systems. There is considerable difference as to the ease of use and longevity of the systems. In drip irrigation the emitters for instance are often weak link, as they make clog easily and are difficult to clean. There are also a low cost versions suitable for small farmers. . Mini-sprinklers for instance are widely available at low costs in Kenya for instance. There is also the mini-pivot system (developed by Practica) and several version of simple tubes being used as low cost drip systems.
Remarks:	Though pressurized systems require little water to grow a crop and hence are highly 'water productive', there are a number of cautions as to their usage. First is that they make it possible to expand the area under cultivation. Therefore if the concern is to avoid overuse of water, they may achieve the opposite. Secondly. the beneficial fraction of pressurized system, if used well, is high. Yet almost all the water that is not used by the plant ends up in the atmosphere, In particular with sprinkler and centre pivot systems. From there it cannot be recovered or reused, so all loss is a real loss. Thirdly, because of their automated nature in some countries pressurized systems are used carelessly – still leading to high water wastage.

3 Irrigation system management

I 3- 1: Deficit irrigation

Intervention:	Deficit irrigation
Application	• Irrigated areas • Rainfed areas • Spate irrigated areas • Rangelands/ catchments
Contributes to:	• Improving water productivity (Y/ET) • Improved water use efficiency (from source to rootzone availability) • Improved crop production (crop/biomass)
Description:	Deficit irrigation is an optimization strategy whereby net returns are maximized by reducing the amount of irrigation water; crops are deliberately allowed to sustain some degree of water deficit and yield reduction. Deficit irrigation takes place where farmers have less access to water than the maximum ET needs, which could be as a cause of: deficient irrigation supplies. The timing (during the plant stages) and the volumes and frequency then applied are important for farmers to be aware of. The application of irrigation needs to be below the full crop ET. The reasons to implement deficit irrigation can be summarised to be: • most or all of the applied water remains in the rootzone; • plants are forced to extract more water from the soil, rather than it being evaporated from it; • yield biomass ratio (or) harvest index may be enhanced as full irrigation may lead to excessive vegetative growth

Crop	Plant stages during which deficit irrigation could take place
Crop	Appropriate growth stages
Cotton	Flowering, boll formation
Sunflower	Vegetative, yielding
Sugar beet	Vegetative, yielding
Soybean	Vegetative growth
Wheat	Flowering, grain filling
Groundnut	Early season (once crop is established), 20-25 days
Chickpea	Progressive (terminal)

	References: (Vinay Nangia, Theib Oweis & Schnetzer, 2018)(Gowda et al., 2009)(FAO, 2000)
Remarks:	

I 3- 2: Conjunctive use of ground and surface water

Intervention:	Conjunctive use of ground and surface water
Application	• Irrigated areas • Rainfed areas • Spate irrigated areas • Rangelands/ catchments
Contributes to:	• Improving water productivity (Y/ET) • Improved water use efficiency (from source to rootzone availability) • Improved crop production (crop/biomass)
Description:	Conjunctive use of surface and groundwater consists of harmoniously combining the use of both sources of water in order to minimize the undesirable physical, environmental

and economic effects of each Intervention and to optimize the water demand/supply balance (FAO, 1995). In many cases conjunctive use systems are not planned for, but conjunctive management plans evolve within irrigation schemes where water deliveries are falling short in timing and quantity and where drainage is failing or not present.

In Pakistan, less than 50% of water applied in various large-scale irrigation commands comes from the canal system, and most of the rest comes from water wells. Groundwater irrigation has developed widely in numerous irrigation-canal commands, usually on a spontaneous basis but sometimes encouraged by government subsidy. In part these measures were taken to overcome drainage challenges but also considering the strained surface water deliveries and dilapidated systems (reusing canal seepage).

The following benefits have been the driving force for spontaneous conjunctive use of shallow aquifers in irrigation-canal commands worldwide (Foster & van Steenbergen, 2011):

(1) much greater water-supply security—by taking advantage of natural aquifer storage
(2) larger net water-supply yield than would generally be possible using one source alone
(3) better timing of irrigation-water delivery—since groundwater can be rapidly deployed to compensate for any shortfall in canal-water availability at critical times for crop growth,
(4) reduced environmental impact—by counteracting land water-logging and salinisation, and excessive river-flow depletion or aquifer overexploitation.

Important to consider is that the institutional dimension of conjunctive use management is significantly more complex than where surface water or groundwater alone is the predominant water-supply source. Therefore it is important for surface water managers and groundwater managers (hydrogeologists) to consider facilitating these systems institutionally besides also supporting local initiatives that showcase the potential. This spontaneous conjunctive use usually arises in situations where canal-based irrigation commands are:

(1) tied to rigid canal-water delivery schedules and unable to respond to crop needs;
(2) over-stretched with respect to surface-water availability for dry season diversion
(3) inadequately maintained and unable to sustain design flows throughout the system, and
(4) poorly administered, allowing unauthorized or excessive off-takes

Whereas conjunctive water use in existing crop lands can distinctly improve crop performance and sustainability of cropping areas (water buffering and soils improvement); the systems may lead to cater expansion of agricultural land as farmers in the Rio Dulce irrigation system in Argentina did resort to. Due to rigid water delivery schedules and the underperformance of the canal systems farmers in reacted by developing a new source 'groundwater form a (tube)well', thereby gaining independence of the system to expand to high-value drip irrigated agriculture (Borghuis, 2017).

Remarks:	Video: Conjunctive win win (https://thewaterchannel.tv/videos/conjunctive-win-win/)

I 3- 3: Storm water drainage

Intervention:	Storm water drainage
Application	• Irrigated areas • Rainfed areas • Spate irrigated areas • Rangelands/ catchments
Contributes to:	• Improving water productivity (Y/ET) • Improved water use efficiency (from source to rootzone availability)

	• Improved crop production (crop/biomass)
Description:	The timely removal of excess water following heavy rainfall or local floods is important to avoid crop damage and build-up of water logging. The inability to remove excess rainfall runoff can be problematic in low lying areas or areas with a flat gradient in particular. In storm water drainage, before constructing dedicated storm water drainage systems a number of • Priority should be given to unblocking natural drains closed by roads and residential areas and make adequate cross drainage on new and old infrastructure compulsory • Retaining runoff at source or diverting excess water where the gradient allows to recharge areas will have a double benefits: the runoff will be used beneficially and no downstream drainage problems will occur In some cases local dugouts may also serve to lower groundwater tables and as local freshwater storage
Remarks:	

I 3- 4: Rootzone drainage

Intervention:	Rootzone drainage
Application	• Irrigated areas • Rainfed areas • Spate irrigated areas • Rangelands/ catchments
Contributes to:	• Improving water productivity (Y/ET) • Improved water use efficiency (from source to rootzone availability) • Improved crop production (crop/biomass)
Description:	Drainage problems should be tackled at the root – i.e. by avoiding over irrigation. Applying more water than necessary is common in many large irrigation systems. It is often the results from inappropriate irrigation duties, i.e. allowing too much water into a command area. It is not unusual for such irrigation duties to be defined at one point in time but never to be updated and adjusted to real requirements. Overirrigation is also often due to bad management practice – diverting water beyond the original entitlements. Water theft is very common in irrigation systems and can take many shapes: illegal diversions, uncontrolled direct outlets from canals; tampered intakes; unsanctioned openings of intakes. Water theft happens throughout – at main canal level up to farmer level. It will lead to water logging and salinity. Herein, it is important to make a clear distinction between drainage for storm water removal and root zone drainage. Root zone drainage will remove excess water from the soil in canal command areas. This can be done by subsurface drains or by open drains. These drains will be placed in the command areas – the distance and depth depending on the drainage co-efficient, i.e. the volume of water to be removed. A special version are interceptor drains – located alongside the main source of seepage, i.e. the irrigation canals. Drainage can also be done by direct pumping. Due to the energy costs, this is often a more expensive option. A particular version of the drainage tube well is the scavenger well, that removes the thin layers of fresh water on top of the saline groundwater for reuse and for controlling water tables. In developing rootzone drainage, the general principles are: • The main aim is to create enough storage space in the upper soil layers to ensure adequate soil aeration for crop growth. In addition, this root zone aeration would help to avoid rainfall flooding • Unless overirrigation is controlled, investment in drainage should be refrained from.

	• There is usually no reason at all to develop or maintain public drainage facilities in fresh groundwater zones, as normally most of the drainage requirement would be taken care off by private pumping in such areas. Such private pumping may be further stimulated by the curtailing and rationalization of surface supplies, as described above. This may also create enough space to accommodate excess rainfall or floods. • Ideally, where root zone drainage is provided there should be the possibility of flexibility in water levels and no uniformity. • Finally, biological drainage – in particular the promotion of eucalyptus tree stands – can be considered. What is important here is to select the appropriate varieties, in terms of biomass growth and effect of the trees/ leaves on the soil fertility. This requires also the promotion of local concentrated eucalyptus forest rather than isolated stands.
Remarks:	

I 3- 5: Rationalise irrigation duties

Intervention:	Rationalise irrigation duties
Application	• Irrigated areas • Rainfed areas • Spate irrigated areas • Rangelands/ catchments
Contributes to:	• Improving water productivity (Y/ET) • Improved water use efficiency (from source to rootzone availability) • Improved crop production (crop/biomass)
Description:	In many irrigation schemes all over the world designs may not meet practices anymore as farmers have changed cropping patterns (low farm-gate prices), soils have become logged or salinized (failing drainage), or lack of proper operation and maintenance with attempts at devolving roles and responsibilities bringing about even more confusion. Scheme managers and farmers may simply also be confronted with less water due to competing usages or changing climates. An enormous challenge or potential lies in reiterating the 'services' that irrigation schemes can or better said are desired to provide. As modern irrigation management is essentially concerned with responding to the needs of current users with the best use of the available resources and technologies as well as a sense of anticipating the future needs of the scheme (Renault, 2007). This is, however easier said than done, as for most large-scale open-channel water conveyance and distribution systems, chaos often dominates, having a direct and negative impact on productivity. This low productivity of irrigation projects is seldom the result of poor performance by individuals at any level, but reflects systematic flaws in the overall management approach. A change in management philosophy is required, which includes both (re)iteration of administrative and physical controls as well as the adequate measurement and accounting of water at intermediate points within the distribution network (Clemmens, 2005). Focussing on canal operation techniques the FAO published a methodology called MASCOTTE, which embeds a service-oriented approach. This approach focusses on the conveyance and delivery of irrigation water to users according to an agreed level of service that is well adapted to their requirements for water use and cropping systems. The irrigation scheme services, however can in many cases not be seen separate from other challenges within irrigated areas and often conjunctive measures are required to improve irrigated agriculture. In most areas it has become important to consider groundwater availability and quality when allocating surface water. In the canals where fresh useable groundwater is available, duties

	may be adjusted so as to encourage supplementary groundwater use. This will reduce the risk of water logging and will introduce demand-control in the irrigation systems, as shallow groundwater can be used when needed. The irrigation duties should be set so to develop an optimum balance between surface water supplies and groundwater availability. What is needed is that surface water seepage recharge is equivalent to groundwater use and that surface water supplies are set at an optimum scarcity so that they encourage groundwater pumping as a complementary source. Where groundwater is of marginal quality the mixing of surface water and pumped groundwater should be done so as to result in useable water quality. This leads to the second main advantage – which is that better buffer management in the canal commands among others by revisiting the irrigation duties will save enough water to be able to consider other users and usages. The better use of shallow groundwater will also make it possible to intensify and extend the cropped areas through more groundwater irrigation by shallow wells or in case of fresh water overlaying saline water through skimming wells. In areas that have heavy soils drainage water can be collected for reuse.
Remarks:	Documents: Modernising irrigation management – the MASSCOTE approach. (http://www.fao.org/3/a1114e/a1114e.pdf)

I 3- 6: Supplemental irrigation

Intervention:	Supplemental irrigation
Application	• Irrigated areas • Rainfed areas • Spate irrigated areas • Rangelands/ catchments
Contributes to:	• Improving water productivity (Y/ET) • Improved water use efficiency (from source to rootzone availability) • Improved crop production (crop/biomass)
Description:	Supplemental Irrigation (SI) is a key strategy, still underused, for unlocking rainfed yield potential and water productivity (Rockström et al., 2007). SI is the addition of limited amounts of water to essentially rainfed crops to improve and stabilize yields when rainfall fails to provide sufficient moisture for normal plant growth. SI can take place in areas with unreliable rainfall or with periods of extreme heat. The timing of SI is again irrigation scheme and weather dependant. Either before planting (or 'onset rainfall'), allowing farmers to plant their crop early or optimally scheduling it during the critical stages of crop growth (flowering and grain filling). SI is an effective response to alleviating the adverse effects of soil moisture stress on the yield of rainfed crops during dry spells. This in particular during critical crop growth stages, can improve crop yield and water productivity.
Remarks:	

I 3- 7: Alternate wetting and drying (AWD)

Intervention:	Alternate wetting and drying (AWD)
Application	• Irrigated areas • Rainfed areas • Spate irrigated areas • Rangelands/ catchments
Contributes to:	• Improving water productivity (Y/ET) • Improved water use efficiency (from source to rootzone availability) • Improved crop production (crop/biomass)
Description:	Alternate wetting and drying (AWD) is a water-saving technology that lowland (paddy) rice farmers can apply to reduce their water use in irrigated fields. In AWD, irrigation water

	is applied to flood the field a certain number of days after the disappearance of ponded water. Hence, the field is alternately flooded and non-flooded. The number of days of non-flooded soil in AWD between irrigations can vary from 1 day to more than 10 days depending on the soil type. AWD has also been used for other crops, such as sugarcane. Water savings may be up to 15 to 25 percent with no yield penalty. AWD promotes good root anchorage, thus reduction in plant lodging problems. In pump irrigation systems, it reduces pumping costs and fuel consumption and an increased income of USD 67 to 97 per hectare. It reduces 30 to 70 percent of methane emissions depending on the combination of water usage and management of rice stubble. It also promotes higher zinc availability in soil and grains by enabling periodic aeration of the soil, which releases zinc from insoluble forms and makes it available for plant uptake. AWD is a water saving technology for lowland (paddy) rice production under irrigation. A special form of AWD is the System of Rice Intensification (SRI), whereby rice is broadcast – so that a large root system develops and the rice is not all the time inundated. The challenge with the AWD and SRI methods is that more weeds develop, because the land is not all the time covered with water.

Remarks:	Document: Rice farming: saving water through Alternate Wetting Drying (AWD) method, Indonesia (http://www.fao.org/3/ca4023en/ca4023en.pdf) Video: Alternate wetting and drying (AWD)--using less water to grow rice (https://www.youtube.com/watch?v=tfKWKfagfFs)

I 3- 8: Canal and watercourse lining

Intervention:	Canal and water course lining
Application	• Irrigated areas • Rainfed areas • Spate irrigated areas • Rangelands/ catchments
Contributes to:	• Improving water productivity (Y/ET) • Improved water use efficiency (from source to rootzone availability) • Improved crop production (crop/biomass)
Description:	The lining of existing canals and water courses is a continuous debate from farmers to scheme managers and policy makers. Considering all the different opinions and perspective on the matter it is important that when considering lining the objective and the interdependency with the management, operation and maintenance of the scheme is considered. The objective of lining canals or water courses can be (a combination) the following: - to conserve both quantity and quality of water, water losses in unlined canals can be very high due to seepage and water consumed by weeds; as well as that any water lost as seepage will to a varying degree reduce in quality (particularly in populated areas or saline environments); - avoiding of seepage to adjacent land or roads, severe seepage of canals can cause very wet or waterlogged conditions, making adjacent land unsuitable for productive agriculture - increasing the reliability of water deliveries; as flow velocity increases in lined canals, the timeliness and reach of irrigation water can be improved as well as reducing the siltation in canals - reducing the maintenance as concrete, brick or plastic, on the canal prevents the growth of plants and discourages hole-making by rats or termites, and so the maintenance of a lined canal can be easier and quicker than that of an unlined canals

	The most common used types of lining include: concrete, concrete blocks, bricks or stone masonry, sand cement, plastic and compacted clay. Considering, however these objectives the following however needs to be considered: - lining is not a substitute for robust scheme management (effective canal operational and maintenance) particularly if increasing irrigation reliability is the objective or equally when considering reducing delivery amounts (accommodating water productivity improvement in the field) - Maintenance of lined canals may become less cumbersome as appose to unlined canals, however research has shown that desilting of canals (annual practice in Pakistan by farmers), even for unlined canals, results in higher distribution reliability and reach than (only) lining (Murray-Rust & Vander Velde, 1994) - except in cases where underlying groundwater is saline or very high seepage rates, the lining of canals would in most cases need to be considered as a subsidy. As lining comes at incredible costs, in most irrigation schemes this means that the positive rate of return (ie. the investment costs versus the increase in cropping intensity and hence increase in farmer irrigation duties) is difficult to achieve if not impossible. - - farmers may have become dependent on seepage losses from canals (by means of directly capturing seepage or pumping from shallow aquifers), this gives to question the objective of conserving water and for whom.

Remarks:	Document: Canals. Irrigation Water Management - Training Manual no. 7. (http://www.fao.org/3/ai585e/ai585e.pdf) (FAO and ILRI, 1992)

4 Crop input management

What a plant has readily at its disposable at the right moment in its crop stages determines how it grows and what it yield it may produce. A good understanding of soil and soil biota (micro organisms), micro nutrients, water, oxygen and plant requirements is needed to know what external inputs are required. If plant stresses can be avoided, then plants can flourish and optimal water use is possible. Crop input management will not only increase yield but may also improve the beneficial fraction, ie. the ratio beneficially consumed water versus the non-beneficial consumed water.

I 4- 1: Efficient fertilizer use

Intervention:	Efficient fertilizer use
Application	• Irrigated areas • Rainfed areas • Spate irrigated areas • Rangelands/ catchments
Contributes to:	• Improving water productivity (Y/ET) • Improved water use efficiency (from source to rootzone availability) • Improved crop production (crop/biomass)
Description:	Fertilizer use is important to crop yields, energy use in agriculture and effects, such as pollution. Most (89%) of the increased agricultural production over the coming decades is expected to come from agricultural intensification, bringing along more intensive use of fertilizer. In several regions, nutrient limitations set the major ceiling on yields (Bindraban et al. 1999; Breman et al. 2001). Fertilizer use is particularly low in many parts of Africa and this constrains land and water productivity (in sub-Saharan Africa, only 9 kg/ha of external nutrients are used as compared to 73 kg/ha used in Latin America, 100 kg/ ha in South Asia and 135 kg/ha in East and Southeast Asia) (Kelly 2006). Therefore, particularly in sub-Saharan Africa, the world's major agricultural frontier, a system of sustainable intensification is advocated (Pretty et al. 2006; Pretty et al. 2011; Tilman et al. 2011). With current rainfall patterns, improved soil fertility could double productivity in Africa (Molden et al. 2010), particularly if the appropriate dose and right type of fertilizer (responding to soil deficiencies, as can be evaluated by soil testing) are used. It is important is that fertilizers are used efficiently, as overuse contributes to influxes of nitrogen and phosphorus. These are negatively affecting many Earth systems in the form of groundwater pollution, eutrophication, reduced or depleted oxygen in water bodies causing extinction of species and land degradation (Rockström et al. 2009). Bio-based fertilizers and other nutrient sources, if properly used, are often a credible alternative to chemical fertilizers. Bio-based fertilizers more over help to improve the soil structure - a very important advantage. They also have the advantage of being produced locally – generating job opportunities. There are several types of bio-based fertilizer: - Organic manure - Compost - Vermicompost - Green manuring - Bio-fertilizer (see S.3.7)
Remarks:	Documents: Co-optimizing Solutions | Water and energy for food, feed and fiber (https://metameta.nl/wp-content/uploads/2014/09/WBCSD-Co-op-Main-Report-DEF.pdf)(Borgia et al., 2014) Bindraban et al. 1999 / Breman et al. 2001 / Kelly 2006 / Molden et al. 2010 / Pretty et al. 2006 / Pretty et al. 2011 / Tilman et al. 2011 / Rockström et al. 2009

I 4- 2: Integrated nutrient management

Intervention:	Integrated nutrient management
Application	• Irrigated areas • Rainfed areas • Spate irrigated areas • Rangelands/ catchments
Contributes to:	• Improving water productivity (Y/ET) • Improved water use efficiency (from source to rootzone availability) • Improved crop production (crop/biomass)
Description:	In many instances, integrated nutrient management (INM) appears to be a viable way forward. INM uses complementary measures – both natural and man-made sources of soil nutrients and mechanical measures – while considerable attention is paid to timing, crop requirements and agro-climatic considerations (Gruhn et al. 2002). Real-time crop sensors for site-specific application of nitrogen are a breakthrough in precision agriculture (Singh et al. 2006) and allow for significant improvements in nitrogen use efficiency. The combination of mineral and organic fertilizers shows sustained yields in the long run compared to just mineral fertilization, as well as increased crop production per unit of synthetic fertilizer applied (Gruhn et al. 2000). Inorganic fertilizer combined with green manure leads to increased yields in rice-groundnut cropping (Prasad et al. 2002). They registered yield increases of 1.6 t/ha and 0.25 t/ha for rice and groundnut respectively.
Remarks:	Documents: Co-optimizing Solutions | Water and energy for food, feed and fiber (https://metameta.nl/wp-content/uploads/2014/09/WBCSD-Co-op-Main-Report-DEF.pdf)(Borgia et al., 2014) Gruhn et al. 2002 / Gruhn et al. 2000 /Singh et al. 2006

I 4- 3: Smart fertilizers

Intervention:	Smart fertilizers
Application	• Irrigated areas • Rainfed areas • Spate irrigated areas • Rangelands/ catchments
Contributes to:	• Improving water productivity (Y/ET) • Improved water use efficiency (from source to rootzone availability) • Improved crop production (crop/biomass)
Description:	A smart nitrogen fertilizer incorporates a mechanism controlling nitrogen release based on crop requirements. This reduces unproductive losses, such as leaching and atmospheric emissions, while increasing nutrient-use efficiency and crop yields. The major mechanisms used are: 1) slow and control mechanisms; 2) nitrification inhibitors; and 3) urease inhibitors. Based on these mechanisms, a wide variety of smart fertilizers have been developed.
Remarks:	Documents: Co-optimizing Solutions | Water and energy for food, feed and fiber (https://metameta.nl/wp-content/uploads/2014/09/WBCSD-Co-op-Main-Report-DEF.pdf)(Borgia et al., 2014)

I 4- 4: Bio-fertilizers

Intervention:	Biofertilizers
Application	• Irrigated areas • Rainfed areas • Spate irrigated areas • Rangelands/ catchments
Contributes to:	• Improving water productivity (Y/ET) • Improved water use efficiency (from source to rootzone availability) • Improved crop production (crop/biomass)

Description:	Biofertilizers are a fermented product made from cow dung, milk, sugars, ashes, and rock dust mixed with water. After a month of fermentation, the solution contains numerous minerals and compounds that feed and protect plants from insects and pathogens. Biofertilizers are a good alternative to chemical fertilizers for several reasons. Chemical fertilizers need to be bought, which means they depend on timely distribution and availability, and are a significant expense. Since biofertilizers are produced at home or on the farm, they are always available when needed and can be produced with locally available materials at minimal cost. Additionally, chemical fertilizers, while offering a short-term nutritional boost to the soil, leave the soil depleted of nutrients and soil life by the end of the growing season; these leaves the farmer dependent on buying and using more fertilizer every season! In contrast, biofertilizers nourish, regenerate, and reactivate the soil's life as the benefits build up with successive applications.
Remarks:	GFF biofertilizer manual

I 4- 5: Rock dust soil amendments

Intervention:	Rock dust soil amendments
Application	• Irrigated areas • Rainfed areas • Spate irrigated areas • Rangelands/ catchments
Contributes to:	• Improving water productivity (Y/ET) • Improved water use efficiency (from source to rootzone availability) • Improved crop production (crop/biomass)
Description:	Soil fertility directly impacts the yield and nutrient density of the plants grown within it. Plants remove water and nutrients from the soil as they are used. Conventional fertilizers applied to replace these nutrients often contain only a handful of elements that are the most used in plant growth. With time, this results in deficits of the nutrients that are not replenished in some way, which translates into less nutritious food. Use of ground rock dust blends as a soil amendment may provide a more complete source of many plant-available elements and minerals, allowing for more wholesome plant growth and the production of higher quality, more nutrient-dense foods. The mechanism by which the rock dust is broken down also provides long-term improvements to soil fertility, reducing the resources needed to apply the amendment, thereby improving the overall sustainability of the growing operation.
Remarks:	Web resources: Improving Soil Fertility with Rock Dust Blends and Biochar (https://ag.umass.edu/sites/ag.umass.edu/files/research-reports/Improving%20Soil%20Fertility%20with%20Rock%20Dust%20Blends%20and%20Biochar.pdf)

I 4- 6: Chemigation

Intervention:	Chemigation
Application	• Irrigated areas • Rainfed areas • Spate irrigated areas • Rangelands/ catchments
Contributes to:	• Improving water productivity (Y/ET) • Improved water use efficiency (from source to rootzone availability) • Improved crop production (crop/biomass)
Description:	Chemigation is a technique developed over the last three decades that consists of incorporating any chemical (e.g., fungicide, insecticide, herbicide, fertilizer, soil and water amendments) into the irrigation water. Chemigation allows for a more precise application of agro-chemicals, thus reducing energy use (fewer chemicals, less tractor movements) and increasing yields (C. M. Burt, 2003). A chemigation system

	typically includes an irrigation pumping station, a chemical injection pump, a reservoir for the chemical, metering and monitoring devices, a backflow prevention system and safety equipment. Progress in equipment technology leads to increased precision and effectiveness. The latest chemigation systems are designed to work with different chemicals simultaneously. The chemical's distribution uniformity is related to irrigation uniformity, which is dependent on a number of factors (i.e., wind, pressure differences in the emitting lines, clogging of emitters, unlevelled soils and soil infiltration rate). With fertigation, fertilizers can be applied with irrigation water on demand during periods of peak crop demand at or near the roots and in smaller doses, which ultimately reduces losses while increasing yields and quality of product (Tilman et al. 2002). If properly designed and scheduled and also taking into consideration soil properties (Gärdenäs et al. 2005), fertigation systems allow for the more efficient application and use of nitrogen (Singandhupe et al. 2003; Hou et al. 2007) thereby reducing its leaching and runoff.
Remarks:	Documents: Co-optimizing Solutions | Water and energy for food, feed and fiber (https://metameta.nl/wp-content/uploads/2014/09/WBCSD-Co-op-Main-Report-DEF.pdf)(Borgia et al., 2014) Tilman et al. 2002 / Gärdenäs et al. 2005 /Singandhupe et al. 2003 /Hou et al. 2007

I 4- 7: Bio-stimulants and micro-nutrients

Intervention:	Bio-stimulants and micro-nutrients
Application	• Irrigated areas • Rainfed areas • Spate irrigated areas • Rangelands/ catchments
Contributes to:	• Improving water productivity (Y/ET) • Improved water use efficiency (from source to rootzone availability) • Improved crop production (crop/biomass)
Description:	There is a range of elements that stimulate plant growth if applied in the right doses. The positive stimulation of plant stress resilience has been reported for a number of fungi-based compounds, particularly the class of strobilurines produced by the fungus Strobilurus that have a suppressive effect on other fungi. Such products are already marketed in several areas but are unknown and untested elsewhere. They contribute to higher resistance to drought-induced stress. Yield increases of up to 10% under water-stressed conditions can be achieved according to field trials (Beck et al. 2002). Another bio-stimulant is the use of micronutrients, such as boron (B), copper (Cu), chlorine (Cl), iron (Fe), zinc (Zn), manganese (Mn), molybdenum (Mo). Micro-nutrients are required in minute amounts by plants but the play a particularly important role in plant growth and development. This method is considered a major winner leading to more vigorous growth and higher quality, more resistant crops. Plant metabolism, nutrient regulation, reproductive growth, chlorophyll synthesis, production of carbohydrates, fruit and seed development, etc., are such effective functions performed by micronutrients (Tripathi et al., 2015). Micro-nutrients in adequate supplies increase the growth and yield of plants, thereby protecting the plants from adverse effects of various biotic and abiotic stresses (see figure below).Prevalence of micronutrient deficiency has become more common in recent years and the rate of their reduction has further been increased by the perpetual demands of modern crop cultivars, high soil erosion, etc. The most common practice to maintain adequate amounts of micronutrients in the soil and thus enhance their uptake by the crops, is the application of either chemical or organic fertilizers. Although the direct application of micronutrients to soils is the most common method, it could decrease the availability as they react with soil minerals and organic matter. Unlike chemical fertilizer, the adoption of organic amendment techniques has been fostered as the most feasible and sustainable approach to restore soil fertility (Masunaga & Fong, 2018).

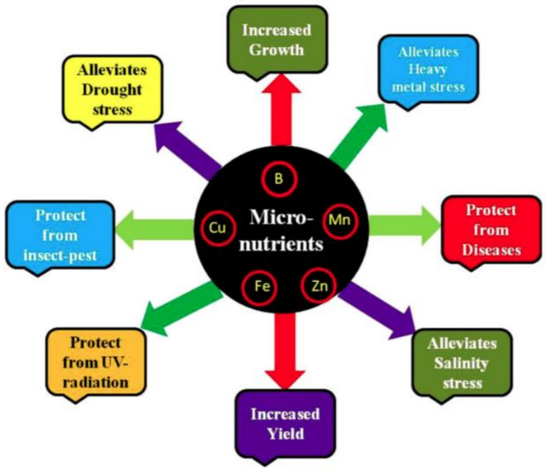


Figure: Response of micronutrients in different abiotic and biotic stresses (by Tripathi et al (2015)).

Remarks:	Documents: Co-optimizing Solutions | Water and energy for food, feed and fiber (https://metameta.nl/wp-content/uploads/2014/09/WBCSD-Co-op-Main-Report-DEF.pdf)(Borgia et al., 2014) Beck et al. 2002

I 4- 8: Reel gardening

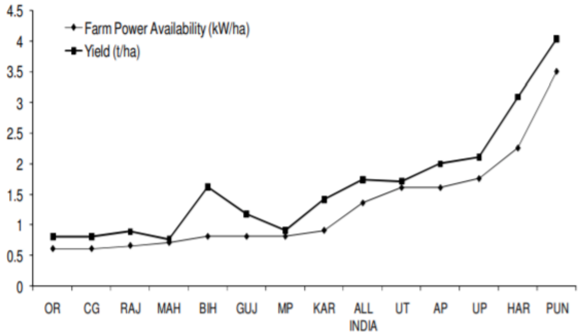
Intervention:	Reel gardening
Application	• Irrigated areas • Rainfed areas • Spate irrigated areas • Rangelands/ catchments
Contributes to:	• Improving water productivity (Y/ET) • Improved water use efficiency (from source to rootzone availability) • Improved crop production (crop/biomass)
Description:	Reed Gardening is a biodegradable seed tape that can be planted straight into the ground. The tape contains high quality, non-chemically treated seeds. The seeds are held within the tape at the correct depth and distance apart for the plant to grow. The illustrations on the seed tape provide easy to follow instructions. The tape also provides information on where the plant is germinating and growing. This makes it easy for the users to irrigate only the spots where plants are grown and not the entire surface, which reduces irrigation water up to 80%.
Remarks:	Web resources: Reel gardening (https://reelgardening.co.za/how-it-works-2/)

I 4- 9: Farm mechanization

Intervention:	Improved seeds
Application	• Irrigated areas • Rainfed areas • Spate irrigated areas • Rangelands/ catchments
Contributes to:	• Improving water productivity (Y/ET) • Improved water use efficiency (from source to rootzone availability) • Improved crop production (crop/biomass)
Description:	Mechanized agriculture is the process of using agricultural machinery to mechanize the work of agriculture, greatly increasing farm productivity. Mechanization covers all levels of farming and processing technologies, from simple and basic hand tools to more sophisticated and motorized equipment. It eases and reduces hard labour, relieves labour shortages, improves productivity and timeliness of agricultural operations, improves the efficient use of resources, enhances market access and contributes to mitigating climate related hazards.

Without mechanized agriculture, farm operations are either partially done or sometimes completely neglected, resulting in low yield due to poor growth or untimely harvesting or both. There is a positive correlation between application of improved technologies and the land productivity (figure below).

Impact of mechanization on productivity



Source: Indiaagristat.com

Remarks:	Web resources: Sustainable Agricultural Mechanisation, FAO (http://www.fao.org/sustainable-agricultural-mechanization/en/)

5 Water resource enhancement

There are several techniques to ensure that a larger portion of the run-off is captured and stored and made available for reuse. This will help the availability of water, effectively enhancing the water that can be used for crop production. Enhancing the availability of surface water – also called water harvesting – is common in rain fed and flood dependent systems, where the strategy is to capture a larger part of the run-off and the floods. It can also be applied in irrigated areas – creating more buffer capacity within the irrigated areas – through more storage, either in surface ponds or in the shallow groundwater.

I 5- 1: Surface water storage

Intervention:	Surface water storage
Application	• Irrigated areas • Rainfed areas • Spate irrigated areas • Rangelands/ catchments
Contributes to:	• Improving water productivity (Y/ET) • Improved water use efficiency (from source to rootzone availability) • Improved crop production (crop/biomass)
Description:	More water can be stored within land and water systems. Construction of ponds and mini-dams can make water available during dry spells in the rainy season, and for a few months after the rains cease. In irrigated areas storage ponds can create a buffer capacity and avoid night irrigation. There are many different designs with varying shapes, materials and dimensions. The water concentrated in the ponds originates from the surrounding naturally sloping surfaces, or conveyed from paved surfaces (roads, paths) and channels (cut-off drains). The water is used to irrigate crops and thus increase the agricultural production, to water the livestock, and for domestic use. As water storage ponds can be designed in many different ways, their impacts may also vary. When they are successful in collecting rain and runoff water, the ponds have many favourable water regulating services. Most ponds however, have open water. Especially when the sides have a gentle slope, habitat for mosquitoes may be created. The ponds may become convenient sources of water for domestic purposes, but when the water is stored for several weeks or more, the quality may deteriorate and become insufficient for drinking purposes but also for bathing and watering animals. Circular and trapezoidal ponds are the most common design, though circular ponds such as charco-dams, are considered to have the best excavation to storage ratio. In many cases ponds can be built on pre-existing depressions or for instance they can consist of a converted borrow pit or even elephant pond. Being open surface water bodies, water is lost through evaporation. To reduce evaporation, in very arid areas it is recommended using a roof/cover or planting a shelterbelt in the prevailing wind direction. Also, a substantial portion water can be lost to seepage. To prevent this, the pond should be lined or compressed. There is wide range of material for this – plastic liners, geotextile, clay/ termite soil, ferro-cement.
Remarks:	Documents: Securing Water and Land in the Tana Basin: a resource book for water managers and practitioners. (https://metameta.nl/wp-content/uploads/2010/05/FINAL_tana_manual_digital_LQ.pdf) (Knoop et al., 2012) Web resources: Global Database on Sustainable Land Management (https://www.wocat.net/en/global-slm-database/)

I 5- 2: Improved shallow groundwater storage

Intervention:	Improved shallow groundwater storage
Application	• Irrigated areas • Rainfed areas • Spate irrigated areas • Rangelands/ catchments
Contributes to:	• Improving water productivity (Y/ET) • Improved water use efficiency (from source to rootzone availability) • Improved crop production (crop/biomass)
Description:	There are many techniques to intercept run-off and floods and store it as shallow groundwater. There is a wide variety of techniques that can be used to recharge shallow groundwater such as percolation ponds and contour trenches, tube recharge, subsurface dams, sand dams and sand dune water infiltration.. The best storage is in shallow sandy or sandy loamy aquifers. In canal irrigated areas conjunctive management can contribute to improved shallow groundwater storage with excess canal flows recharging the aquifer underneath the canal system and in some places creating fresh water lenses - A controlled shallow groundwater table can moreover contribute to crop production through the phenomena of sub-irrigation. Capillary rise from shallow groundwater may be considered as an important contribution to secure soil moisture and hence agricultural productivity (Beltrão et al., 1996). Under dry climate water table contribution to crop evapotranspiration may reduce or even completely eliminate irrigation requirements without compromising on crop yields (Prathapar & Qureshi, 1999)(Nosetto et al., 2009). On the other hand, when groundwater becomes too shallow, such as during flooding, it limits oxygen availability to roots and the resulting water logging harms crop productivity. Targeted management of shallow groundwater at the landscape scale and active tile drainage at the field scale could help close the "yield gap" - between maximum potential crop production and actual production - thus improving efficiency in agriculture.
Remarks:	http://www.cropj.com/luo_5_13_2011_1692_1697.pdf Web resources: www.bebuffered.com

I 5- 3: Reuse of stored water

Intervention:	Reuse of stored water
Application	• Irrigated areas • Rainfed areas • Spate irrigated areas • Rangelands/ catchments
Contributes to:	• Improving water productivity (Y/ET) • Improved water use efficiency (from source to rootzone availability) • Improved crop production (crop/biomass)
Description:	Scarcity is not resolved simply by managing demand by reducing usage, or the promoting more efficient use, it also requires actions to keep water in active circulation. Three processes are important in managing reuse: controlled (non-beneficial) evaporation, management of water quality and the ensuring of availability and accessibility over time. Controlled evaporation may be achieved by efficient irrigation. This type of irrigation reduces the evaporation loss in the irrigation process and makes sure that the majority of the water used directly benefits the crops. It is important to strike a fine balance between keeping good soil moisture and avoiding loss of water through evaporation. The second process of managing the water quality is largely dependent on the required quality for the intended purpose, as different purposes demand different qualities. It is important therefore that high-quality water is not mixed with a lower quality grade of water. Special emphasis and effort must therefore be placed on keeping the water quality within safety thresholds when reusing water, or in the circulation of water. To thoroughly ensure water availability and accessibility requires water not be allowed to migrate to an area from which it is hard to retrieve

	or reuse. Recharged water in a dry unsaturated buffer, although not lost, is hard to retrieve and difficult to bring back into circulation.
Remarks:	Documents: SMART 3R Interventions (http://www.rainfoundation.org/wp-content/uploads/Smart-solutions-3R-2-web-1.pdf)

I 5- 4: Water harvesting: using roads

Intervention:	Harvesting water from roads
Application	• Irrigated areas • Rainfed areas • Spate irrigated areas • Rangelands/ catchments
Contributes to:	• Improving water productivity (Y/ET) • Improved water use efficiency (from source to rootzone availability) • Improved crop production (crop/biomass)
Description:	One of the most promising water harvesting techniques is the capture of run-off with road bodies. Rainwater runoff during rainy seasons is often considered undesirable for roads as it can damage the road and by creating gullies and water logging in the landscape. However, with simple measures this runoff can be harvested and utilized. During a 30 mm rain shower, a 1 km-long, 4 m-wide road catches 96,000 l of water. Harvesting runoff from roads enables farmers to use water that previously would cause flood damage, by intercepting the water and guiding it through channels or culverts to recharge areas, surface storage structures or distributing it over the farmland. There is a wide variety of available techniques to harvest water from roads depending on the geography, climatic conditions, and local needs of each examined area. Some examples include earth dams, tanks, underground cisterns, subsurface dams, water ponds, runoff farming, etc. The tools and materials needed depend on the chosen technique. The most common requirements include: sand, cement, stones, bricks, PVC pipes, water, lime, barbed wire, chicken mesh, transport and labour. In arid and semi-arid regions, where crop production is critically limited by soil moisture, the agricultural production can be significantly increased by the additional water supply from road runoff. This helps farmers to overcome rainfall variability and dry-spells by increasing water availability for agriculture. Also, by harvesting water from roads and guiding it for productive uses, not only the road infrastructure is protected from water damage allowing the access of people to markets and services but also the landscape around the roads which in turn can be used for agricultural production. This intervention can be done at different levels community level, district level or national level. Besides roads can be used to control water levels in adjacent low-lying fields, control erosion and influence micro-climate and reduce wind erosion
Remarks:	Web resources: www.roadsforwater.org

I 5- 5: Water harvesting: using rock outcrops

Intervention:	Harvesting water from rock outcrops
Application	• Irrigated areas • Rainfed areas • Spate irrigated areas • Rangelands/ catchments
Contributes to:	• Improving water productivity (Y/ET) • Improved water use efficiency (from source to rootzone availability) • Improved crop production (crop/biomass)
Description:	Harvesting water from rock outcrops is widely used in the. A wide variety of techniques is currently in practice, ranging from harvesting from natural depressions such as rock pools and gorges to

	harvesting from complete rock catchments with dam walls. The largest rock catchment in Kenya can store up to 8 million litres of water (Nissen-petersen, 2006). The amount of water generated by rock catchments is significant: a rock surface of 1 ha can harvest 1 million l of water from 100 mm rain (Nissen-petersen, 2006). Harvesting water from rock outcrops increase water supply for people, livestock and drinking water. When water is used for irrigation purposes, the agricultural production is increased due to the increased water availability. Regarding the construction of such structures, after identifying a suitable rock outcrop (most rock surfaces in arid and semi-arid regions are suitable) and the development of a design, all loose parts need to be removed from the rock surface. Removed stones can be crushed to be used in constructing the dam wall. Rainwater is diverted through garlands or gutters towards the reservoir. Stone gutters must have a minimum gradient of 30% to avoid overflow.
Remarks:	Documents: Securing water and land in the Tana Basin – A resource book for water managers and practitioners. (https://metameta.nl/wp-content/uploads/2010/05/FINAL_tana_manual_digital_LQ.pdf) (Knoop et al., 2012) Video: Water from Rocks (https://thewaterchannel.tv/videos/water-from-rocks/)

6 Water management in rainfed and flood dependent systems

I 6- 1: Field bunding and water guiding

Intervention:	Field bunding and water guiding
Application	• Irrigated areas • Rainfed areas • Spate irrigated areas • Rangelands/ catchments
Contributes to:	• Improving water productivity (Y/ET) • Improved water use efficiency (from source to rootzone availability) • Improved crop production (crop/biomass)
Description:	While some spate schemes have a recognizable canal system serving each field, field-to-field irrigation is usually practised. To practice filed-to-field irrigation, field bunding is a common technique that slows down water flow, encourages infiltration (groundwater recharge) and soil moisture. The bunds are usually constructer by the farmers. Under field-to-field irrigation, the uppermost field receives the water first and it is allowed to pond to a pre-determined depth. When that depth is reached, the field bund is breached, and the ponded water is released to the next field. Meanwhile, any incoming flow passes through the first field to the next one. This process is progressively repeated. The main advantage of this system is that water is applied quickly at high flow rates, during the short time that spate flows occur. There is also no investment in, or land lost to, a separate canal system. Crops in upstream fields may be damaged if there is a flood when the downstream land is still entitled to water. Further, the lack of separate channels means that more water will percolate and less water will reach the downstream areas (an advantage for the upstream fields). The normal upstream-first hierarchy for spate irrigation means that the flow capacity of field offtakes has to be sufficient to take the full incoming canal flow. Properly engineered large capacity offtakes are expensive. Open channel offtakes are less expensive than gated culverts. Whether offtakes need gates or other means of closing them will depend on the canal water level when any check structures on the canal are open. In more conventional water distribution systems, where water is supplied to a number of field offtakes at the same time, there is still a requirement to provide large offtake capacities. Very substantial irrigation duties are required in spate schemes to supply water at the flow rates wanted by the farmers. The importance of such field-to-field systems should not be underestimated since they represent a major improvement in water productivity. The reduction of downstream erosion avoids in-field gullying, which could lead to a dramatic depletion of soil moisture apart from the loss of irrigation to the downstream fields, since water moves without control from field to field.
Remarks:	Web resources: www.spate-irrigation.org Document: Guidelines on spate irrigation (http://www.fao.org/3/i1680e/i1680e.pdf) (van Steenbergen et al., 2010)

I 6- 2: Controlled field water management

Intervention:	Controlled field water management
Application	• Irrigated areas • Rainfed areas • Spate irrigated areas • Rangelands/ catchments
Contributes to:	• Improving water productivity (Y/ET) • Improved water use efficiency (from source to rootzone availability)

	• Improved crop production (crop/biomass)
Description:	Field water management and soil moisture conservation is crucial to maximize productivity in spate irrigation systems. As the floods arrive before the cropping season, the moisture is stored to be available for use later in the season. Rutting and gullying of fields is to be avoided. There are several techniques to conserve moisture and improved field water management: deep ploughing, planking and mulching, controlled overflow structure, bund spill overs, gated field intakes and drop structures. All these can result in higher water productivity.
Remarks:	Web resources: www.spate-irrigation.org

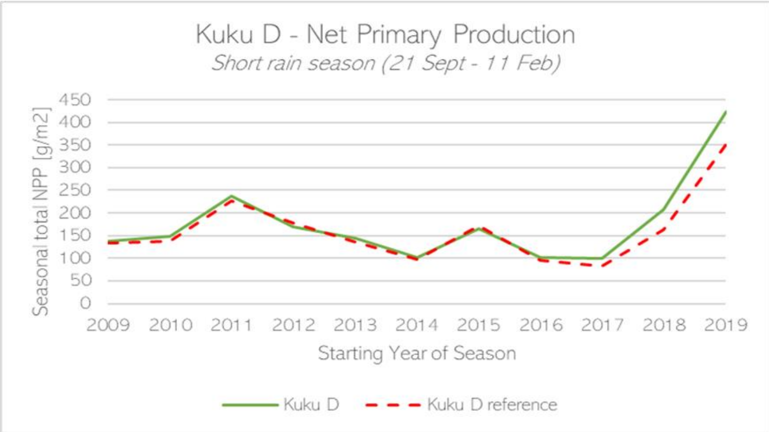
7 Soil moisture improvements in rainfed agriculture

Water harvesting is the collection of runoff for productive purposes. Instead of runoff being left to cause erosion, it is harvested and utilized. Water harvesting (WH) can be considered as a rudimentary low-cost alternative form of irrigation. The difference is that with WH the farmer has no control over timing. Runoff can only be harvested when it rains. In regions where crops are entirely rainfed, a reduction of 50% in the seasonal rainfall, for example, may result in a total crop failure. If, however, the available rain can be concentrated on a smaller area, reasonable yields will still be received. Of course in a year of severe drought there may be no runoff to collect, but an efficient water harvesting system will improve plant growth in the majority of years (Critchley et al., 1991). In arid environments, where 90% of rainfall evaporates back into the atmosphere, water harvesting can increase the beneficial rainwater available for transpiration from 20% to 50% (Oweis et al., 1999). Water harvesting as such increases the soil moisture available for the plants to grow, and hence contributes to water productivity improvement reducing E, raising T hence increasing biomass (or yields).

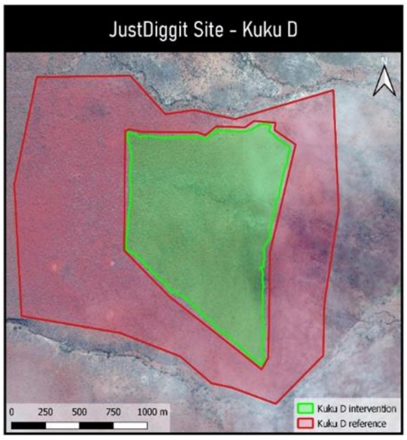
Water harvesting can take place in almost any given part of the world, from arid regions receiving less than 250 millimetres rainfall per year to harvesting water in the tropics. Techniques can be categorised into three basic categories: Microcatchments (sometimes referred to as "Within-Field Catchment System"); External catchment systems (Long Slope Catchment Technique); and Floodwater farming (floodwater harvesting, often referred to as "Water Spreading" and sometimes "Spate Irrigation") (Critchley et al., 1991).

An example of an 'external catchment system' would be the Jessour in the arid environment (<200mm rainfall) of Tunisia in which catchments are combined with the construction of terraces and dykes to capture and direct water for the production of fruit trees (e.g. olive, fig, almond, and date palm), legumes (e.g. pea, chickpeas, lentil, and faba bean), barley and wheat.

An example of micro-catchments is the semi-circular bunds which are typically used for rangeland rehabilitation or fodder production. In Kenya (Amboseli) semi-circular bunds were dug at scale (JustDiggit) to restore rangelands for pastoralist. By means of using WaPOR data and google earth engine (GEE) an assessment could be made to ascertain whether or not the intervention area is actually regreening. To assure observations in change are not due to climatic changes, the intervention site was compared to a buffer area around it (the reference site). As the graph (Figure 7-1) shows the NPP (or net primary production, an indication of biomass) in the intervention area increased as compared to the reference are starting from 2016 when the semi-circular bunds were developed. The percentage difference (in NPP) in 2019 already amounted to more than 20%. To verify whether the regreened area is indeed pasture restoration and no other unpalatable vegetation, this WaPOR assessment can be combined with ground observations.



(a)



(b)

Figure 7-1 A comparison of the Net Primary Production (NPP) between the Kuku Intervention site (Kenya) where semi-circular bunds where constructed, and the reference site. Figure (a) shows the timeseries of the NPP in which a positive difference between the intervention and reference site are visible from 2016 onward (when the bunds where constructed). The intervention site (green) and the reference site (red) are shown in figure (b).

I 7- 1: Planting pits

Intervention:	Planting pits (zai)
Application	• Irrigated areas • Rainfed areas • Spate irrigated areas • Rangelands/ catchments
Contributes to:	• Improving water productivity (Y/ET) • Improved water use efficiency (from source to rootzone availability) • Improved crop production (crop/biomass)
Description:	Planting pits collect rainfall and concentrate soil moisture for food and fodder production. Plants are grown inside pits, benefitting from the higher moisture content. Often manure and/or compost is added. This adds nutrients and also attracts termites that loosen up the soil around the planting pits, thus increasing the capacity of the soil to absorb runoff water. Planting pits contribute to a significant increase in yields. Thy are used to grow trees but recently they have started to be used also for crop production (Mati, 2006). Planting pits vary in dimensions, shape and husbandry system (see table below). The best-known system is the western African "zai". Zai pits are circular holes dug by hand on gently sloping land in order to catch and retain runoff water. They are scattered on the surface and approximately follow the contour lines. The pit size and depth varies but a general lesson has been not to make the pits too small (Reij et al. 2009). If pits are under-sized, the amount of water trapped will not satisfy the plants requirements. Zai pits require a considerable amount of mainly manual labour. To make the process easier, it is suggested to perform the excavation in the dry season - right after the rain period - when the soil is easier to work with (Desta, Carucci, & Wendem-Agenehu, 2005). Thereafter, one full spade of compost or manure is applied to each pit in order to improve soil quality and water retention. After the first rains, sorghum or millet can be sown. Following the harvest, the plant stalks should be left in the pits to increase the organic matter content. In the second year, new zais can be dug in between the first year's lines and sown with Sorghum or Millet. Also, legumes can be planted in the one-year old pits. In order to decrease the runoff speed, stone lines are laid on the contour every 20-30 lines.

Name	Crop	Shape	Depth (cm)	Width (cm)	Inter-row dist. (cm)	In-row dist. (cm)	Country

Zai	Sorghum	Circular	15 - 50	30 - 50	60 - 75	30 - 50	Burkina Faso
Katumani	Fodder	Crescent	15 - 20	Not available	Not available	Conti-nuous	Kenya
Chololo pits	Millet	Circular	20 - 25	20 - 25	100	0.5	Tanzania
Banana pits	Banana	Square	60	60	300	300	Kenya, Tana
Sugar cane	Sugar cane	Square	60 - 75	100	60	60	Kenya, Mwingi
Five by nine pits	Maize	Square	60	60	Not available	Not available	Kenya
Tumbukiza	Napier	Various	Various	Various	Various	Various	Western Kenya

Remarks:	Documents: Securing water and land in the Tana Basin – A resource book for water managers and practitioners. (https://metameta.nl/wp-content/uploads/2010/05/FINAL_tana_manual_digital_LQ.pdf) (Knoop et al., 2012) (Mati, 2006) / (Reij et al. 2009) / (Desta, Carucci, & Wendem-Agenehu, 2005)

I 7- 2: Double dug beds

Intervention:	Double dug beds
Application	• Irrigated areas • Rainfed areas • Spate irrigated areas • Rangelands/ catchments
Contributes to:	• Improving water productivity (Y/ET) • Improved water use efficiency (from source to rootzone availability) • Improved crop production (crop/biomass)
Description:	With the double dug bed technique, it is possible to create small productive vegetable gardens. This is done by double-digging the soil and incorporating adequate amounts of manure. This alternative digging process allows the farmer to work the soil deeper and to spread compost evenly along the whole excavation profile. The hard pan that is often formed on tropical soils is broken by the process. This allows aeration and improved nutrient adsorption in the soil. The deep incorporation of compost favours the breakdown of humic components, and reduced loss of nutrients via runoff and decomposing gaseous emissions. The deep cultivation creates a soft medium that allows roots to grow longer and stronger, retains more water and it is likely to increase yields. Double dug gardens are created in an elongated shape with a width of around 1.5 m. The length can vary, but 7 m is often suggested as ideal (Nandwa, Onduru, & Gachimbi, 2000). The double dug bed should be narrow enough to be conveniently farmed in every section by standing on its edges. Its establishment entails the cultivation of the designated garden in a stepwise manner by applying one layer of compost or manure and then digging small, adjacent trenches until the whole area is double dug. In the end, the double dug bed will look elevated due to the increased volume of the air voids and the incorporated organic matter. The same procedure must be followed in the following years. After some time the soil will be softer, darker and easier to work (Stein, 2000).
Remarks:	Documents: Securing water and land in the Tana Basin – A resource book for water managers and practitioners. (https://metameta.nl/wp-content/uploads/2010/05/FINAL_tana_manual_digital_LQ.pdf) (Knoop et al., 2012) (Nandwa, Onduru, & Gachimbi, 2000) (Stein, 2000).

I 7- 3: Demi lunes/ half-moons

Intervention:	Demi lunes
Application	• Irrigated areas • Rainfed areas • Spate irrigated areas • Rangelands/ catchments
Contributes to:	• Improving water productivity (Y/ET) • Improved water use efficiency (from source to rootzone availability) • Improved crop production (crop/biomass)
Description:	Demi lunes - also known as semi-circular bunds or 'eyebrows' - require the creation of small bunds in the shape of a half-moon with their tips on the contour. The ponding area inside the demi lune retains water flowing down the slope from above the bund. Demi lunes capture runoff and are used to improve rangeland and increase grass, tree, and crop production. Demi lunes are more efficient than trapezoidal bunds in terms of the ratio between the bund volume and the ponded area. The design varies according to topography, climatic conditions and plant requirements. In dry conditions, the bunds are bigger and equipped with spillways. In wetter conditions, more bunds of smaller radius are constructed per hectare. They are rarely used on slopes steeper than 5%. When used for rangeland improvement, local grasses can be grown, but the introduction of more productive trees and shrubs is recommended. When used to grow crops, drought resistant species such as sorghum, pearl millet and certain pulses must be chosen. To satisfy the plant's water requirements, farmers tend to reduce the catchment area of the semi-circular bunds to increase the cultivated land.
Remarks:	Documents: Securing water and land in the Tana Basin – A resource book for water managers and practitioners. (https://metameta.nl/wp-content/uploads/2010/05/FINAL_tana_manual_digital_LQ.pdf) (Knoop et al., 2012)

I 7- 4: Bench terracing

Intervention:	Bench terracing
Application	• Irrigated areas • Rainfed areas • Spate irrigated areas • Rangelands/ catchments
Contributes to:	• Improving water productivity (Y/ET) • Improved water use efficiency (from source to rootzone availability) • Improved crop production (crop/biomass)
Description:	Alternating series of 'shelves' and 'risers' characterize bench terraces. They are usually developed on relatively steep slopes (15-55%) with deep soils that allow this type of landscaping. Bench terraces help to store water and by reducing runoff and taping sediment they also prevent soil erosion. Therefore, by using this technique more water can be available for the plants which, in turn, increases the agricultural production. In bench terraces the riser is often reinforced with stones and/or vegetation cover. When the shelf is made slightly inward sloping, water storage increases and soil protection is improved. In arid areas, conservation bench terraces are preferred. In such cases, the distance between terraces is increased and a portion of the sloping land is left to act as catchment area. The runoff generated by the catchment area will nourish the plants placed immediately above the riser wall.. The construction of bench terraces is labour or equipment intensive. The bench terraces have to be laid carefully on the contours – so that the hydraulic pressure is evenly spread. The design starts with a careful survey and pegging of the contour lines. This process can be carried out with an A-frame level or a water tube level. Consequently, the cut and fill areas are defined and the excavation is performed. Care is taken to preserve the upper layer of the soil that holds most of the nutrients. The construction must start from the

	lower level of the field and then proceed upwards. Thereafter the newly created riser can be reinforced with locally available stones. When required, ditches and drains must be dug to dispose excess water. Conservation bench terraces should be considered as water harvesting techniques, as they allow the generation of additional runoff. They should be planned according to plant requirements and climatic features of the area.
Remarks:	Documents: Securing water and land in the Tana Basin – A resource book for water managers and practitioners. (https://metameta.nl/wp-content/uploads/2010/05/FINAL_tana_manual_digital_LQ.pdf) (Knoop et al., 2012)

I 7- 5: Gully plugging

Intervention:	Gully plugging
Application	• Irrigated areas • Rainfed areas • Spate irrigated areas • Rangelands/ catchments
Contributes to:	• Improving water productivity (Y/ET) • Improved water use efficiency (from source to rootzone availability) • Improved crop production (crop/biomass)
Description:	Temporary and permanent gully plugs are used to rehabilitate gullies and retain sediments that would be otherwise washed away. Gully plugs are structural barriers that obstruct the concentrated runoff inside gullies and ravines. They are often temporary structures built to favour the establishment of a permanent soil cover to effectively conserve soil and water. In some cases, they are used to create new farmland using the harvested and intercepted sediments. They are often built in series to progressively decrease the runoff speed and trap sediments through the whole length of the gully. Gully plugs can have an enormous beneficial effect on the soil moisture in adjacent lands as well as shallow groundwater tables which leads to improved agricultural production. Gully plugging is essential in both arid and humid areas. In non-humid regions earth plugs can be used to restore gullied areas. The gully should preferably not be steeper than 10% or deeper than 2 m. In more humid areas diversion channels may be added to decrease the burden on the gully plug structure (Geyik, 1986). When stones are readily available stone check dams can be constructed to restore small gullies. The trapped sediments can be used as arable land, which can provide additional income to the farmers (Desta, Carucci, & WendemAgenehu, 2005). Preferably flat stones are used as they add more strength. Brushwood check dams are constructed across gullies with width less than 3 m and slope length less than 100 m. Plant materials are stacked behind a series of wooden posts that are driven deep into the soil. Brushwood from species that propagate vegetatively from cuttings is ideal to use as the roots encourage consolidation of the structure and the soil (Desta et al., 2005). After few years the established stems-plants can be pruned providing fodder and fuel (Liniger & Critchley, 2007). Once the check dam structure is in place, gully reshaping is required to ease plant establishment. In case of big gullies, a sediment storage and overflow dam can be used. The overflow dam is a stone-faced earthen dam that traps sediments and creates new farming land. It also acts as a rainwater collector, improving water availability for crops. It can potentially create new land and restore eroded landscapes (Desta et al., 2005).
Remarks:	Documents: Securing water and land in the Tana Basin – A resource book for water managers and practitioners. (https://metameta.nl/wp-content/uploads/2010/05/FINAL_tana_manual_digital_LQ.pdf) (Knoop et al., 2012) (Geyik, 1986) / (Desta, Carucci, & WendemAgenehu, 2005) / (Desta et al., 2005) /(Liniger & Critchley, 2007) / (Desta et al., 2005)

I 7- 6: Grass strips

Intervention:	Grass strips
Application	• Irrigated areas • Rainfed areas • Spate irrigated areas • Rangelands/ catchments
Contributes to:	• Improving water productivity (Y/ET) • Improved water use efficiency (from source to rootzone availability) • Improved crop production (crop/biomass)
Description:	Grass strips are widely used as vegetative barriers to reduce soil loss and to increase infiltration and soil moisture. Due to increased soil moisture, there is more water available for the crops which leads to increased agricultural production. Grass is grown in alternating strips following contour lines. Depending on the grass used, the strips may provide fodder for livestock as well. Compared to other interventions grass strips can be easily crossed by oxen and ploughs. Grass strips can filter sediment, evacuate excess runoff and can also withstand inundation. They may ultimately form into bench terraces. Grass strips work best in areas with a good amount of rainfall. The technique can be applied on gentle slopes as well as on steep slopes. Preparing grass strips involves relatively modest-labour inputs and basic equipment (e.g. hoes, wires and tree branches.) The grass type chosen should not be too aggressive: it should not expand into adjacent crop land. The width of grass strips ranges from 0.5 to 1.5 m (Desta et al, 2005). Permanent vegetation strips (used on steep slopes) range from 2 to 4 m (Morgan, 2010). The interval between the strips depends on the slope: 33 m is common over 3% slopes while a 7 m distance is used over 15% slopes. Since grass strips are usually laid along the contours, the distance between them is dictated by the slope of the land. Preferably, perennial grasses are planted on the strips. Grass types should be persistent and be able to withstand drought and flood. Suitable species include Napier grass (Pennisetum purpureum), Guatemala grass (*Tripsacum laxum*), Makarikari grass (*Panicum coloratum*), Canary grass (*Phalaris canariensis*), Oat grass (*Hyparrhenia spp.*), Wheat grass (*Agropyron spp.*), and Lyme grass (*Elymus spp.*) (Morgan et al, 2010). Seedbed preparation is necessary in the case of direct sowing. A depth of 0.5 to 1.5 cm is optimum for most species. The grass seeds should be covered with a thin layer of soil. (Desta, 2005). If grass splittings are used to establish the strips, they should be planted in a staggered way using double or triple rows.
Remarks:	Documents: Securing water and land in the Tana Basin – A resource book for water managers and practitioners. (https://metameta.nl/wp-content/uploads/2010/05/FINAL_tana_manual_digital_LQ.pdf) (Knoop et al., 2012) (Morgan et al, 2010 / (Desta, 2005)

I 7- 7: Tied ridge

Intervention:	Tied ridge
Application	• Irrigated areas • Rainfed areas • Spate irrigated areas • Rangelands/ catchments
Contributes to:	• Improving water productivity (Y/ET) • Improved water use efficiency (from source to rootzone availability) • Improved crop production (crop/biomass)

Description:	Small earthen tied contour ridges break the slope, slow down erosive runoff and store water in the soil. They enable water to infiltrate the soil more efficiently and add soil moisture storage which contributes to increased crop production. They usually have a height of 15 to 20 cm and have an up slope furrow. These upslope furrows accommodate runoff from an uncultivated catchment strip. The catchment strips between the ridges can be used for small-scale production. Tied ridges can be used in arid and semi-arid areas with annual average precipitations between 200-750 mm per year. The soil should be at least 1.5 m deep to ensure adequate tree root development and to store sufficient water. The topography must be even without too many gullies and slopes can be up to 5% (Critchley, Siegert, & Chapman, 1991).
Remarks:	Documents: Securing water and land in the Tana Basin – A resource book for water managers and practitioners. (https://metameta.nl/wp-content/uploads/2010/05/FINAL_tana_manual_digital_LQ.pdf) (Knoop et al., 2012) (Critchley, Siegert, & Chapman, 1991).

I 7- 8: Bunds (contour, stone and trapezoidal)

Intervention:	Bunds (contour, stone and trapezoidal)
Application	• Irrigated areas • Rainfed areas • Spate irrigated areas • Rangelands/ catchments
Contributes to:	• Improving water productivity (Y/ET) • Improved water use efficiency (from source to rootzone availability) • Improved crop production (crop/biomass)
Description:	Contour bunds are small barriers to runoff coming from external catchments and possibly to a field where crops are to be grown. Bunds slow down water flow on the ground surface, reduce erosion, encourage infiltration and soil moisture and increase yields. Contour bunds exist in many different designs and have been globally used as a mean of water buffering and soil conservation. Stone bunds is one example of how the basic principles of contour bunds can be applied. On gentle slopes, stone bunds are also used for harvesting water for the crops in between the lines and increase crop production (HP Liniger, Studer, & Hauert, 2011). Stone bunds are suitable for arid and semi-arid areas, but when the soils are well drained, they can also be applied in wetter zones. Stone bunds are used on sandy, sandy/loamy crusty soils and on slopes less than 5% (Hanspeter Liniger & Critchley, 2007). Small stone ties can be constructed every 5 m along the upslope face of the bund for an even distribution of the impounding water (Desta et al., 2005). The width and, consequently, the height of the bund vary considerably with slope and availability of construction material. Sometimes the structure can be just one stone high (Hanspeter Liniger & Critchley, 2007). When enough sediments have been trapped behind the structure, the stone bunds can be upgraded to stone-walled level terraces by carefully raising their height (Desta et al., 2005). Trapezoidal bunds are a type of non-enclosed bunds which upstream side is left open to collect water from the slopes and its downstream side is enclosed on three sides by a trapezoidal shaped bund with 45° angles (Critchley & Reij 1992). They enclose large areas (up to 1 ha) and they are usually made out of soil. The wings of the side bunds are preferably reinforced with stones. Trapezoidal bunds are not suitable for steep slopes because the construction would involve prohibitive amounts of earthwork and they should not be built on cracking clay soils that will not be able to hold the water. The most common uses of trapezoidal bunds is cereal cultivation within the enclosed area and livestock watering. The spacing of the trapezoidal bunds can vary depending on the ration between catchment and cultivated area and the climate (for example in arid areas there is less water to go around and the spacing may be larger).

Remarks:	Documents: Securing water and land in the Tana Basin – A resource book for water managers and practitioners. (https://metameta.nl/wp-content/uploads/2010/05/FINAL_tana_manual_digital_LQ.pdf) (Knoop et al., 2012) (HP Liniger, Studer, & Hauert, 2011) / (Hanspeter Liniger & Critchley, 2007) / (Desta et al., 2005). / (Critchley & Reij 1992).

I 7- 9: Minimum and zero tillage

Intervention:	Minimum tillage and zero tillage
Application	• Irrigated areas • Rainfed areas • Spate irrigated areas • Rangelands/ catchments
Contributes to:	• Improving water productivity (Y/ET) • Improved water use efficiency (from source to rootzone availability) • Improved crop production (crop/biomass)
Description:	Tillage is the agricultural preparation of soil by hand held, or ox or tractor drawn agitation. This agitation can be described as shovelling, hoeing and raking or as ploughing , disking and cultivating. Minimum (or reduced) and zero tillage systems aim to reduce the amount and frequency of soil agitation taking place. Commonly minimum tillage includes the practice of cultivating the soil, followed by planting the crop followed by cultivation again. In no-till systems only planting takes place. Minimum and zero tillage systems are very similar in that the ground is worked very little or not at all before the seed is sown. This approach has increased in use over recent years with, for example, 8 million hectares in Brazil and a major swing towards the technology in Asia. The most important advantage of minimum tillage is that crops can be sown almost immediately the previous crop has been harvested and commonly approaching the optimum sowing time This is not possible with conventional tillage as that is time consuming. So it is highly suited to areas where two or more crops are rotated on the same land within the year. In much of south Asia yield in wheat reduces rapidly as sowing time is delayed beyond the optimum date for the area, see (Hobbs & Giri, 1997) for details. So delay costs yield. Minimum tillage in addition to shortening turn-around time between crops can be much cheaper than conventional tillage.
Remarks:	Document: Irrigated wheat (http://www.fao.org/3/X8234E/x8234e0a.htm)(Rawson & Macpherson, 2000)

I 7- 10: Deep tillage and mulching

Intervention:	Deep tillage and mulching
Application	• Irrigated areas • Rainfed areas • Spate irrigated areas • Rangelands/ catchments
Contributes to:	• Improving water productivity (Y/ET) • Improved water use efficiency (from source to rootzone availability) • Improved crop production (crop/biomass)
Description:	A three year field study (Arora et al., 2011) on the effects of irrigation, tillage and mulching on soybean yield and water productivity on sandy loam and loamy sand trials (Indian Punjab), show that: deep tillage (chiselling up to a depth of 0.35m) and use of straw mulch (6t/ha) enhanced water productivity from 1.39 to 1.97 kg/ha/mm in a partial irrigation regime (withholding irrigations during pod-filling) and from 1.87 to 2.33 kg/ha/mm in full irrigation regime. Yield and WP gains are ascribed to deeper and denser rooting due to moderation of soil temperature; and to water conservation with straw mulching and tillage-induced reduction in soil mechanical resistance. Comparable yield responses to deep tillage or mulching in the loamy

	sand soil suggest that either deep tillage or mulching, depending on cost and availability considerations, can be employed for improving soybean yield and water productivity.
Remarks:	

I 7- 11: Deep ploughing and planking title

Intervention:	Deep ploughing and planking
Application	• Irrigated areas • Rainfed areas • Spate irrigated areas • Rangelands/ catchments
Contributes to:	• Improving water productivity (Y/ET) • Improved water use efficiency (from source to rootzone availability) • Improved crop production (crop/biomass)
Description:	In spate irrigated areas of Pakistan (Balochistan), the ploughing of fields before irrigation and ploughing and planking of fields after pre-sowing irrigation is very much important to store and conserve soil moisture. The preservation of soil moisture is essential to secure a higher productivity. The ploughing ensures that soils are sufficiently wetted and the planking ensures soil moisture is retained in the soil. Both ensuring proper germination (soil contact) and crop maturation.
Remarks:	

I 7- 12: Direct seeding

Intervention:	Direct seeding
Application	• Irrigated areas • Rainfed areas • Spate irrigated areas • Rangelands/ catchments
Contributes to:	• Improving water productivity (Y/ET) • Improved water use efficiency (from source to rootzone availability) • Improved crop production (crop/biomass)
Description:	Direct seeding refers to farming systems that fertilize and plant directly into undisturbed soil in one field operation, or two separate operations of fertilizing and planting. Only narrow strips of soil are disturbed by the equipment openers used to place fertilizer and seed in the soil without full width tillage. Much of the residue from the previous crop is retained on the soil surface. The reduced soil disturbance and retention of surface crop residues with direct seed systems provide improved environmental protection while maintaining or increasing soil productivity, and reducing production costs for farmers. At the same time, this technique improves the effective use of rainfall, reduces irrigation needs and methane emissions (since it does not require standing water at the base of the crop). Inundated rice not only uses more water than physiologically required, it also accounts for 15-20% of human-induced methane emissions, amounting to approximately 50-100 million tonnes of methane emissions per year. The warm, waterlogged soil of rice paddies provides the conditions for methanogenesis, and although some of the methane produced is oxidized in the shallow overlying water, the vast majority is released into the atmosphere. Dry rice cultivation and the use of aluminium sulphate may reverse the process of methane emissions.
Remarks:	

I 7- 13: Making use of invertebrates

Intervention:	Making use of invertebrates
Application	• Irrigated areas • Rainfed areas • Spate irrigated areas • Rangelands/ catchments
Contributes to:	• Improving water productivity (Y/ET) • Improved water use efficiency (from source to rootzone availability) • Improved crop production (crop/biomass)
Description:	Many useful invertebrate species live under our feet and pass unnoticed until the soil is exposed and they are brought to the surface. Termites, earthworms and sowbugs are some of the best-known examples. What is less known is the positive effect that they have on the soil and the capacity to store moisture. This beneficial effect comes from loosening up and mixing of the soil structure creating more aeration and stimulating plant root development. Many invertebrates, also through their constant burrowing activities, improve and maintain the infiltration capacity of the soil and ensure that runoff continues to be absorbed, soil is not 'clogged' and crop production is increased. Termites: Termites build mound-shaped nests that are a common sight in arid and semi-arid regions of East Africa. There are many kinds of termites, and although only a few of them are plant pests, farmers often consider all of them to be a plague. Nevertheless, the termite's activity is a positive influence on soil's physical properties, with their tunnelling enhancing porosity and lowering soil bulk density. This leads to improved water infiltration. Additionally, mound nests are constructed with fine soil particles brought to the surface by termite activity. These fine particles often have a high nutrient concentration thanks to termites' feeding habits. The mounds can be used as soil amendment. They are destroyed and the resulting material ploughed into the soil (Okwakol & Sekamatte, 2007). The main constraint to the utility of termites is the slow growth of the nest and the large amount of termite soil needed to fertilize land. A sustainable way of managing this involves using only a portion of the termite nest to allow for its regeneration (Miyagawa et al., 2011). Earthworms: Earthworms ingest organic matter and transform it into nutrient-rich material. Vermi-composting is the practice of using earthworms to produce high quality compost in controlled conditions. By constructing a simple worm-box it is possible to transform 1000 tons of wet organic material in 300 kg of good compost (Butterworth, Adolph, & Reddy, 2003). Compost can be harvested from a typical box every 3 to 4 months (Liniger & Critchley, 2007). This vermi-compost greatly improves soil water retention capacity – besides improving soil fertility.
Remarks:	Documents: Securing water and land in the Tana Basin – A resource book for water managers and practitioners. (https://metameta.nl/wp-content/uploads/2010/05/FINAL_tana_manual_digital_LQ.pdf) (Knoop et al., 2012) (Okwakol & Sekamatte, 2007) / (Miyagawa et al., 2011) / (Butterworth, Adolph, & Reddy, 2003) / (Liniger & Critchley, 2007)

8 Cropping system management

I 8- 1: Adjusting crop sowing dates

Intervention:	Adjusting crop sowing dates
Application	• Irrigated areas • Rainfed areas • Spate irrigated areas • Rangelands/ catchments
Contributes to:	• Improving water productivity (Y/ET) • Improved water use efficiency (from source to rootzone availability) • Improved crop production (crop/biomass)
Description:	Sowing dates depend on market dates, as well as geographical location. Because of great variations in plant growth and bloom dates due to natural environmental conditions, sowing schedules cannot be determined on a national scale. Conditions vary from year to year even in one location with early springs and rainy spells upsetting schedules. At best, a schedule can only estimate the time and events between sowing and marketing. The sowing schedule also depends on whether plants are to be sold green or in bloom. If the market will tolerate green plants, considerable greenhouse time can be saved in producing them. Temperature is one factor that can be controlled that will influence scheduling. Each species has an ideal medium temperature for germination and early seedling growth. Variations in temperature will delay germination, which in turn delays flowering. Note that by temperature, we mean temperature in the medium, not the air in the greenhouse. A thermostat placed at eye level will be easy to read but will not be an accurate indicator of temperature in the flat. Soil thermometers are needed to monitor temperatures and to maximize germination percentages.
Remarks	

I 8- 2: Crop rotation

Intervention	Crop rotation
Application	• Irrigated areas • Rainfed areas • Spate irrigated areas Rangelands/ catchments
Contributes to:	• Improving water productivity (Y/ET) • Improved water use efficiency (from source to rootzone availability) • Improved crop production (crop/biomass)
Description	The crop rotation definition can be put like changing different kinds of crops year by year in the same field. A cycle may include a different number of years, from 3 up to 7+ planting various crops in turns and/or leaving the land fallow to recover. In this case, areas may be either unused or used as green leys for livestock. The matter is that certain plants devastate the land of one type of nutrients while releasing the others. In their turn, the produced nutrients are required for the development of the other species. There is no standard crop rotation chart though, even though certain regularities could be traced. There are multiple benefits of implementing the crop rotations approach such as (a) saturation of nitrogen, (b) optimization of expenses saving on chemicals, (c) nature protection, (d) water retention, (e) reduced usage of pesticides, (f) protection from erosion, (g) increased yields.
Remarks:	

I 8- 3: Crop varieties selection

Intervention:	Crop varieties selection
Application	• Irrigated areas • Rainfed areas • Spate irrigated areas • Rangelands/ catchments
Contributes to:	• Improving water productivity (Y/ET) • Improved water use efficiency (from source to rootzone availability) • Improved crop production (crop/biomass)
Description:	Starting with 'the green revolution' plant breeders have been continuously worked on breeding varieties that would yield more, in terms of consumable (seed/fruit/pod/boll, etc.) per plant or plants per area. For breeders the challenge was to create varieties that could still stand straight but would also have largest portion of harvestable produce. This meant searching for the right biomass versus produce ratio, also known as the harvest index, ie. the ratio of grain yield to the total above ground biomass. This breeding and searching for higher harvest indexes has for the most common crops reached its limits, however in many areas of the world the potential yields of these varieties are often not achieved. In areas where this actual yield is 50% below the varieties potential, there sufficient scope to improve its yield and at the same time improve water productivity[3]. Plant breeders have, ever since the green revolution also worked on developing crops that are more resilient to non-optimal conditions, be it as a cause of biotic stresses (pests and diseases) or abiotic stresses (nutrients, water, temperature, salinity) (Borgia et al., 2014). This kind of 'smart breeding' would allow crops to grow in new agricultural areas, be adapted to altered agricultural calendars (production outside traditional cropping periods), as well as make them more resilient in places where climates are changing. So, as global seed markets can offer a great diversity of crops and crop varieties with a wide range of characteristics in terms of adaptation to environmental conditions, production systems and properties of the end-products, small-scale farmers in many developing countries have very limited access to those varieties and to the knowledge and required inputs associated with them. In many cases local seed are normally well adapted to the natural and cultural environment in which they are grown (drought, pest, disease tolerance). They may also offer the best bargain considering seed reusability and limited inputs required. If the local markets and or farmers have appropriate means (dry and cool) for storing seed these varieties should be preferred. For crops such as maize or vegetables for which local varieties do not exist, the general rule for selecting the right variety is to choose the 'open-pollinated varieties' (OPVs), because rather than hybrids, OPVs maintain the properties of the variety for several seasons (hence seed reusability) (Fajardo Vizcayno et al., 2014). • High yielding varieties can in contexts where their yields are not meeting their potential offer tremendous increase, consider: raising yields from 1 to 2 tons per hectare (ha) will lead to much more gains in water productivity than doubling the yield from 4 to 8 tons per ha. (Molden et al., 2010). • Smart varieties, example • Drought tolerant (see Intervention 9-4) • Local varieties, considering their suitability to the local (biotic and abiotic) context and most importantly accessibility and affordability for farmers
Remarks:	

I 8- 4: Multiple cropping systems

Intervention:	Multiple cropping systems
Application	• Irrigated areas • Rainfed areas

[3] When yields are above 40–50% of their potential, however, yield gains come at a near proportionate increase in the amount of ET, thus incremental gains in water productivity become smaller as yields become higher.

	• Spate irrigated areas • Rangelands/ catchments
Contributes to:	• Improving water productivity (Y/ET) • Improved water use efficiency (from source to rootzone availability) • Improved crop production (crop/biomass)
Description:	Multiple cropping systems build diversification within a field, with the purpose of optimizing ecological synergy between crops. Diversification can be done either in time (i.e., rotations) or in space (i.e., intercropping). When properly designed, this leads to improved nutrient uptake and nitrogen use, increased soil fertility, increased water-use efficiency and reduced incidence of pests. Ecological approaches to pest reduction become important in view of the vulnerability of monocultured crops to pest and diseases (Waddington et al. 2010; Hartman et al. 2011; Ratnadass et al. 2012). For instance, the simultaneous use of different rice varieties (glutinous and hybrid rice) was tested in China with promising results. Yields of glutinous rice were 89% greater and pest incidence was 94% lower than in monoculture systems. Hybrid (non-glutinous) rice yields were nearly equal to those of monocultures (Zhu et al. 2000) Another successful example of mixed cropping comes from mechanized wheat farming in the U.S. By using multiple wheat cultivars and wheat and barley intercropping, disease reduction was larger than with the application of fungicides (Vilich-Meller 1992; Kaut et al. 2008). Biological nitrogen fixation by leguminous crops is of great importance. Intercropping of cereal and legumes makes it possible to use significantly less fertilizer without having an impact on yields. In India, nitrogen fertilizer savings of 35-44 kg/ha were registered when a leguminous crop preceded rice or wheat. Intercropping of soybean with maize saved 40-60 kg of nitrogen per hectare (Venkatesh and Ali 2007). Crops with different nutritional requirements, timing of peak needs and diverse and deeper root structures are grown on the same land simultaneously (Gliessman et al. 1985), thus optimizing nutrient and water use.
Remarks:	Documents: Co-optimizing Solutions | Water and energy for food, feed and fiber (https://metameta.nl/wp-content/uploads/2014/09/WBCSD-Co-op-Main-Report-DEF.pdf)(Borgia et al., 2014) (5Waddington et al. 2010 \ Hartman et al. 2011 \ Ratnadass et al. 2012) \ Zhu et al. 2000 \ Morris and Garrity 1993 \ Gliessman et al. 1985 \ Vilich-Meller 1992 \ Kaut et al. 2008 \ Venkatesh and Ali 2007

I 8- 5: Agroforestry/shelter belts

Intervention:	Agroforestry/shelter belts
Application	• Irrigated areas • Rainfed areas • Spate irrigated areas • Rangelands/ catchments
Contributes to:	• Improving water productivity (Y/ET) • Improved water use efficiency (from source to rootzone availability) • Improved crop production (crop/biomass)
Description:	Agroforestry: Agroforestry systems, if well managed, produce food, feed and fibre in proper balance. In agroforestry, trees are included in the cropping system or combined with livestock production in agro-silvo-pastoral systems. Benefits include biodiversity conservation, water and soil quality enhancement and carbon storage. By supporting a variety of complementary products (i.e., food, feed, fuel wood, timber and energy), agroforestry is an important means to increase smallholder incomes. Most importantly, agroforestry systems are modelled to maximize eco-efficiency – reducing the need for external inputs while enhancing nutrient cycling. The observed competition effect between trees and crops for radiation, topsoil water and nutrients, which might translate into lower crop yields, is outpaced by positive effects on soil moisture and nutrient improvement and the

	reduction of pest pressures. Recent studies on the productivity of temperate silvo-arable agroforestry systems show 20-60% higher productivity relative to the respective monocultures (van der Werf et al. 2007; Smith 2010; Dupraz and Talbot 2012). Productivity in multiple cropping systems is expressed by land equivalent ratios (LER), which is the ratio of the area under sole cropping to the area under intercropping needed to give equal amounts of yield at the same management level. It is the sum of the fractions of the intercropped yields divided by the sole-crop yields. Shelter belts: Together with temperature and humidity, wind speed is one of the strongest drivers of evaporative losses from soil, plants, and surface water/moisture. As the air passes over surface, leaves, and water bodies or morning dew, it draws water along with it. Wind speed can however be drastically reduced by placing barriers in the way of oncoming air currents to serve as windbreaks, some of the most effective windbreaks are trees. Trees planted as windbreaks disrupt and lift incoming air currents, significantly reducing the wind force for a distance up to 10 times the height of the trees. This an important consideration for long-term planning, as the sheltered area of the field will expand horizontally as the windbreak trees grow vertically over the years. The effective height of young trees can be boosted by planting them on earth banks or bunds to add some height in the initial growth stages. The reduced wind speed, in turn, reduces evaporation but many other benefits are gained such as microclimate amelioration, timber and non-timber products (forage, fruit, etc.), ecological corridors and habitat, crop protection (reduced damage and blossom loss), reduced soil erosion, and of course carbon sequestration and cycling. Considerations: Gaps, both horizontal and vertical, in wind-break lines should be avoided as they will serve to funnel wind directly onto the field. Therefore, parallel rows of tree planting are recommended, with the tallest-growing species in the middle, and shorter-growing trees or shrubs on either side to close the gap between the trunks of the central trees, creating a homogenous barrier against the wind. Selection of tree species also warrants careful consideration, to be an effective and long-lasting wind breaker, trees should be deep rooting to offer stability against the force of oncoming winds. They should also have narrow canopies with small crowns to avoid being damaged by the wind themselves. When possible, trees should also be selected for their multifunctionality, such as the ability to produce fruit, fodder, of fix nitrogen in the soil. To avoid competition with crops for water, a shallow trench, or impermeable barrier can be placed between the windbreak and cropping areas, keeping root systems separated.
Remarks:	Documents: Co-optimizing Solutions | Water and energy for food, feed and fiber (https://metameta.nl/wp-content/uploads/2014/09/WBCSD-Co-op-Main-Report-DEF.pdf)(Borgia et al., 2014) van der Werf et al. 2007 / Smith 2010 / Dupraz and Talbot 2012

I 8- 6: Promoting promising minor crops in spate irrigation

Intervention:	Promoting promising minor crops in spate irrigation
Application	• Irrigated areas • Rainfed areas • Spate irrigated areas • Rangelands/ catchments
Contributes to:	• Improving water productivity (Y/ET) • Improved water use efficiency (from source to rootzone availability) • Improved crop production (crop/biomass)
Description:	Wild crops: Several minor crops crow wild and have valuable benefits. The seeds are left in the soil and germinate usually after the area has been irrigated by the spate flow. Sanwak, cheena and smookha

	are examples. Bread and porridge are made with their seeds, their leaves and stems are used as roofing material and the whole plant serves as animal feed, especially in times of drought. Isagbol is a wild medicinal plant. Multipurposed trees: The use of multipurpose trees is the backbone of spate agricultural farming systems and are used for shading, timber, fodder, fencing, fire wood, edible fruits, sand dune stabilization, honey, medicinal, charcoal, handicrafts (like from the Mazri plant), spate diversion, bird nesting and root use. In Pakistan, the most common multipurpose trees are Selam, Sedr, Ber, Arack, Jaal, Haleg, Date Palm, Dome, Athel, Daber, Jand, Karita, Kikar and Mesquite. The outputs of these trees provide income on top of the income of farming and can serve as a reserve fund. In case of drought and other harsh climate conditions, their crops might die but the trees will survive. Multipurposed shrubs: The use of multipurpose shrubs is the backbone of spate agricultural farming systems and are used for timber, fodder, fencing, fire wood, edible fruits, , medicinal, charcoal, handicrafts, spate diversion, bird nesting and root-use. Most common multipurpose shrubs are Paneer, Boi, Lana, Phag, Sinwaar, Ak, Plantain, Wanza, Sisal, Poinsettia, Mangrove and Mutundu. Similarly to the multipurposed trees, outputs of these shrubs provide income on top of the income of farming and can serve as a reserve fund.
Remarks:	Web resources: Improved Livelihood Opportunities in Spate Irrigation (http://spate-irrigation.org/wp-content/uploads/2020/05/Livelihood-opportunities-brochure-FINAL-1.pdf)