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An integrated PESERA/DESMICE model capable of simulating hydrological and economic impacts, including food and water security, of WH from field to regional scale.

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WAHARA DELIVERABLE 4.2

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Authors

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1. Introduction

The vast majority of African farmers rely on rainfall for food production: 95% of agricultural production in Africa comes from rainfed areas (UNEP, 2009). Productivity levels are low and grain yields oscillate typically around 1 ton per hectare, with strong inter-annual variability. There is an important yield gap between experimental results and farmers' reality (Rockström et al., 2010). The key to closing the gap lies in improved water management. African countries on average only store 4% of annual flow (WWDR3, 2009), and a low water buffer means high vulnerability to both droughts and floods. Risk of climatic anomalies in Africa will even increase as a result of climate change (Conway, 2009). By 2020, 75-250 million people may be exposed to increased water stress due to the combined effects of climate change and increased demand (IPCC, 2008).

Several management practices are available to improve soil water management, but what practices to recommend where depends on many factors. WAHARA studies water harvesting technologies (WHT), defined as "the collective term for a wide variety of low-cost interventions which are primarily or secondarily intended to collect natural water resources which otherwise would have escaped from human reach, and buffer them through storage and/or recharge on or below the soil surface. The effect is increased retention of water in the landscape, enabling management and use of water for multiple purposes. WHT can operate either as independent units, or require embedding in a larger system of environmental management interventions, or require specific natural conditions"

Although socio-economic and political conditions necessary for WH are qualitatively known, no quantification has been made yet to understand and support individual decisions by farmers (Vohland and Barry, 2009). Furthermore, those factors have not been combined with biophysical factors in models to evaluate feasibility of WH technologies. Furthermore, whereas it is generally accepted that WH technologies improve water buffering and consequently reduce vulnerability to climate anomalies (it is their raison d'être after all), little is known about their economic viability under climate change scenarios.

Although many authors identify upstream-downstream interactions as a potential effect of WH technologies, there is not much scientific evidence of the severity and extent of such impacts. One issue in this regard is that the only true loss of water from the watershed system is through evaporation and transpiration; reuse naturally occurs (Van Steenbergen et al., 2009). Despite the scientific debates over downstream impact, conflicts between upstream and downstream users are real, and unfortunately common (Ngigi, 2003; Oweis and Hachum, 2006). Models can provide insight in catchment water balance effects (Rockström et al., 2004) and economic impacts (Ward, 2009), and can moreover be used as tools for decision-making and conflict resolution.

Models of WH technologies at field scale have frequently been applied using soil water balance models (Panigrahi et al., 2001; Young et al., 2002; Fleskens et al., 2005; Raes et al., 2007; Makurira et al., 2009). Several authors have addressed suitability mapping of (ex situ) WH technologies (De Winnaar et al., 2007; Jasrotia et al, 2009; MwengeKahinda et al., 2008). RELMA (2005) has made an attempt to do this for Africa at a continental scale. Hut et al. (2008) present a model of the shallow groundwater effect of sub-surface sand-storage dams, including the impact of groundwater extraction. Interaction effects of cascades of sand-storage dams were modelled by Orient Quilis et al. (2009). Schiettecatte et al. (2002) applied a spatially explicit revised Morgan-Morgan-Finney model (Morgan, 2001) to a watershed in Morocco, but were unable to validate their model. Ouessar et al. (2009) modelled the effect of WH on the catchment water balance using SWAT for a watershed in southern Tunisia and validated the model with data from 38 runoff events. To assess impact on ecosystem services, models should include slow processes which are particularly important to secure long-term ecological resilience: the build-up of organic matter contents, soil structure, rooting depth, and microclimatic conditions (Rockström et al, 2004). Lebel et al. (2013) and Lebel (2015) conceptualised and modelled the performance of in situ water harvesting technologies in Burkina Faso highlighting the importance of additional manure and the value of soil pits in trapping seeds and organic matter.

Several authors have made financial cost-benefit analyses of WH technologies from a land users' point of view (Panigrahi et al., 2001; Yuan et al., 2003; Machiwal et al., 2004; Fleskens et al., 2005; Fox et al., 2005; Ngigi et al., 2005; Sturm et al., 2009). Frequently, though not always, WH technologies have been assessed to be profitable. However, many WH systems still involve an element of risk. This is also acknowledged and various authors have included risk analysis in profitability assessments (Fleskens et al., 2005; Ngigi et al., 2005; Walker et al., 2005). In the context of adapting to climate change, an important factor is the land user's perception of risk in the without as compared to with situation. In determining the potential for adoption of WH technologies this attitude to risk should be taken into account. For example, Fox et al. (2005) calculated that water harvesting with water storage for bridging dry spells during crop cultivation in the rainy season in northern Burkina Faso is a cost-effective investment. Nevertheless, Barbier et al. (2009) found that the system had not been adopted at all, as areas to treat would be too large and farmers do not believe millet and maize grown during the rainy season will benefit from supplementary irrigation. However, they do grow irrigated maize in the dry season. Probably, farmers perceive a low risk of crop failure and are wary of large investments for little reward.

Scenario studies can be used in combination with models to assess the impact of WH technologies. We already discussed the importance of climate change and several socio-economic factors in this respect, but can add to this scenarios of technology diffusion (Samada and Okada, 2008), and land users attitudes to risk, collective action and equity. These can all be considered as strategies people use to adapt, learn and shape change in ways that build resilience. Methodologies to study these factors should be flexible and consider extremes, both in socio-economic conditions, and in natural variability of components of the hydrological cycle (Rockström et al., 2004).

The proposed generic modelling tool in the WAHARA project essentially combines the PESERA biophysical model (Kirkby et al., 2008) with the DESMICE economic model (Fleskens et al., 2009; 2014) to provide a spatially distributed forecast of appropriate water harvesting technologies across an area. This report presents the approach taken to partially integrate the PESERA and DESMICE models, and the improvements and extensions made to each model to better capture essential details for assessment of WHT.

2. Rationale for integrated assessment of WHT

Knowledge gained from stakeholders (their technologies, practice and attitude to risk) observed from different parts of Africa is conceptualised and incorporated in biophysical and economic models. The integrated biophysical and economic model driven by local and regional (e.g. climate, population growth and urbanisation) scenarios assesses the level of investment required for the production of a determined reference biomass across a range of scales considering both agricultural and domestic water. The model will consider how local and downstream effects interact and how WH investments may cause disparities or acceptance between stakeholder groups. Rainfall variability, described by long-term continental and local climate data allow practical climatic design criteria to be considered when running the integrated model. The integrated model then combines climatic risk, farmer risk perception and investment level/risk in the production of the reference biomass. Long-term continental records allow consideration of the transferability of observed and conceptualised technologies and practice.

3. An integrated PESERA-DESMICE model capable of simulating hydrological and economic impacts

For the WAHARA project, the pre-existing PESERA and DESMICE models have been partially integrated. The fundamental concept that underlies this integration is a calculation, performed for each cell and each plausible combination of crop and management strategies, of the expected net income from the land. This is calculated from the relationship:

Net present value (€/Ha) = Crop price (€/T) x Yield (T/Ha) – Management Costs (€/Ha)

Where:

- Crop price is a function of the chosen crop and the assumed market price for that crop
- Yield is the maximum expected yield for chosen crop x Physical suitability (%)/100
- Management costs are derived from:
    - Routine tillage and other agronomic operations
    - Construction cost of the WHT (averaged over its economic life)
    - Fertiliser/ manure additions
    - Sacrifice of land area for implementing WHT technology

A key strategy to deliver synergies between the two models is through generating suitability maps of PESERA output variables after a single base-line run of the PESERA model, using existing land use and management patterns. This minimizes the need for consecutive feeding in of outputs from PESERA and DESMICE components back to each other. After running PESERA in equilibrium mode to initialize, the model is run in time-series mode. The time series approach allows repeated realisations of the climate to be generated from the frequency distribution of observed data, thus generating suitability curves for the range of expected inter-annual variability. This approach has the potential to respond explicitly to future climate scenarios. The envelope of potential biomass growth is derived from the modelling of repeated realisations delivering suitability maps of e.g. biomass yield and runoff. DESMICE combines these physical suitabilities with estimated farm-gate prices and costs of modifying current management as the basis for assessing yields and net present value, taking account of the averaged risk of crop failure.

Integration between PESERA and DESMICE is implemented in two cycles (Figure 1). In the initial implementation cycle, PESERA and DESMICE are run without consideration of downstream effects of implementing a WHT option, so that it represents a cell-based assessment of WHT potential. In the second implementation cycle, analyses will aim at explicitly considering interactions between cells by accounting run-off flows, allowing estimation of trade-offs between up- and downstream areas to be assessed and a social cost-benefit analysis to be performed for the study area being simulated. Further consideration is to be given to scenarios in Task 4.5.

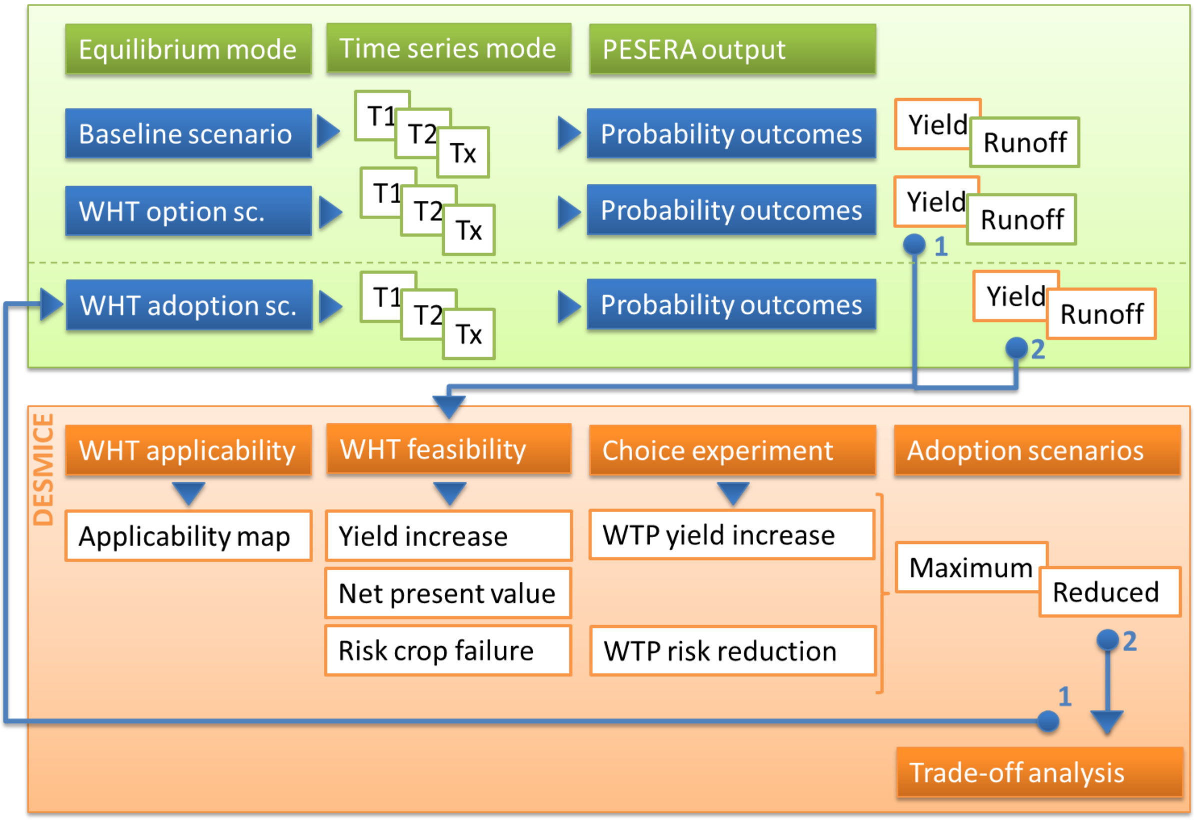

Figure 1. Conceptual diagram of PESERA-DESMICE integration for assessment of WHT technologies.

4. PESERA model improvements

Two types of modification are being implemented in the PESERA model, in order to achieve better integration with the conceptual approach of the DESMICE model. The first of these is to incorporate a series of physical suitability estimates, which will be incorporated into the combined model to assess the best combination of land use and management choices in terms of their net present value, taking account of physical suitability, market value of the crop and costs in implementing any change in management practices. The second series of changes is to make some estimate of how changes in one cell will impact on downstream sites, principally by making greater or lesser demands on available water for agriculture. This involves routing of flood waters from cell to cell through the network.

Incorporation of physical suitability functions will allow suitability for a wide range of crops and management practices to be made after a single baseline run of PESERA. Each suitability function will express the percentage suitability (relative to optimum conditions) as relative yield in sub-optimal conditions. The major factors for which suitability is assessed are as follows:

- Gradient/relief & management (e.g. terracing)
- Growing season actual E-T (for annual crops)
- Year-round actual E-T (for tree/shrub crops)
- Degree days > 10°C (for irrigated agriculture)
- Minimum monthly temp (for tree/shrub crops)
- Inter-annual variability

Figure 2 below provides illustrations of the form of these functions for two examples.

As rainfall variability and the occurrence of drought are key issues to be addressed by water harvesting, a time series analysis considers the probability of achieving a defined yield under baseline conditions (without WHT) and with WHT. After an initial baseline run of PESERA to equilibrium, a simulated time series generated from historical climate statistics is run repeatedly for the model of each treatment to produce a probability distribution of yield, overland run-off, sub-surface run-off and erosion. This is used to provide a suitability functions to show the response to inter-annual climatic variability, and has the potential to respond to prospective climate change scenarios.

Further adjustments are also being informed by conceptual models of the functioning of water harvesting technologies selected for field implementation in WP3 based on WOCAT technology descriptions (WP2). Further calibration of these adjustments will be made when final field measurement datasets from WP3 become available, so that the model can be validated with field measurements once these become available (as part of Task 4.5). In situ water harvesting measures are predominantly agronomical measures associated with the maintenance of plant litter cover and the addition of soil organic matter and mulch. These measure where prominent within the DESIRE project. Additional in situ water harvesting technologies include demi-lune and zai. The zai soil pits have been considered by Lebel (2015), highlighting that soil pits alone have little benefit unless combined with manure. Additional benefits of pits are not readily modelled such as trapping efficiency reducing the removal of seed and biomass. Ex situ/Spate solutions require the routing of runoff and the distribution of runoff into surface and subsurface storage.

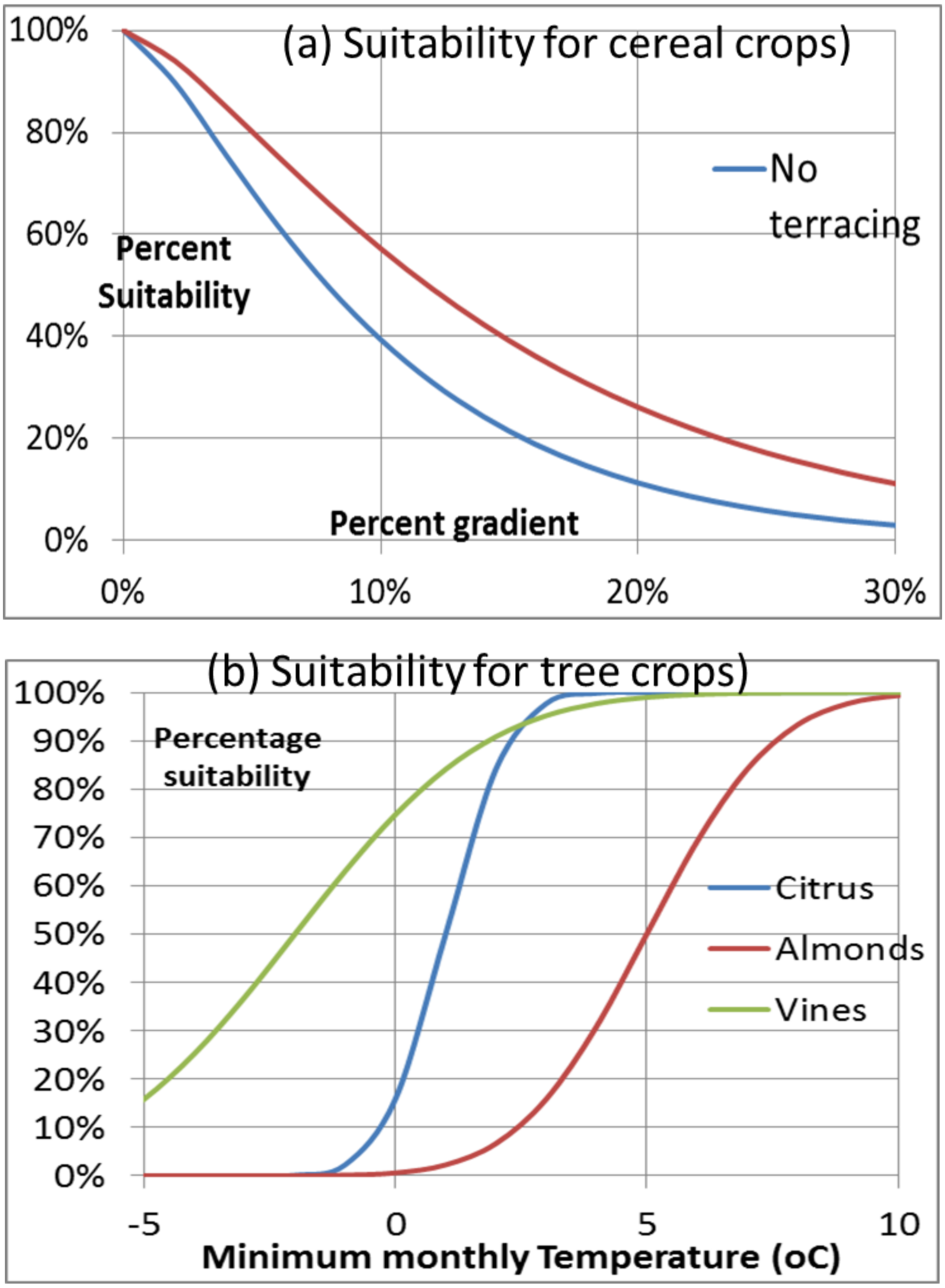

Figure 2. (a) Dependence of cereal yields in terms of local gradient or relief. With terracing, higher yields can be maintained. (b) Response of tree crops to minimum monthly temperatures which may prevent satisfactory setting of fruit at the blossom stage.

For the second component in updating the PESERA model to better accommodate the effects of water harvesting technologies, it is important to follow the impact of water harvesting management in one cell on water availability downstream. This has been achieved by modelling flow duration curves for each cell, based on a 50-year realisation of monthly climate variations. The runoff threshold model in PESERA and QUICK-SCAN is used to partition run-off into two fractions, rapid overland flow run-off, and slower sub-surface run-off, each with its characteristic flow duration curve. As contributions from each cell are accumulated downstream through the network, the low-flow component is almost unchanged, whereas the quick-flow degrades progressively towards the average, due to the normal differences in rainstorm timing. The observed degradation is slow in humid areas, but more rapid, over a ca. 50km range, for semi-arid areas. Figure 3 illustrates the two components for a semi-arid catchment, and how the contribution of the upstream cell to the combined duration curve progressively degrades over ten successive 15km reaches downstream.

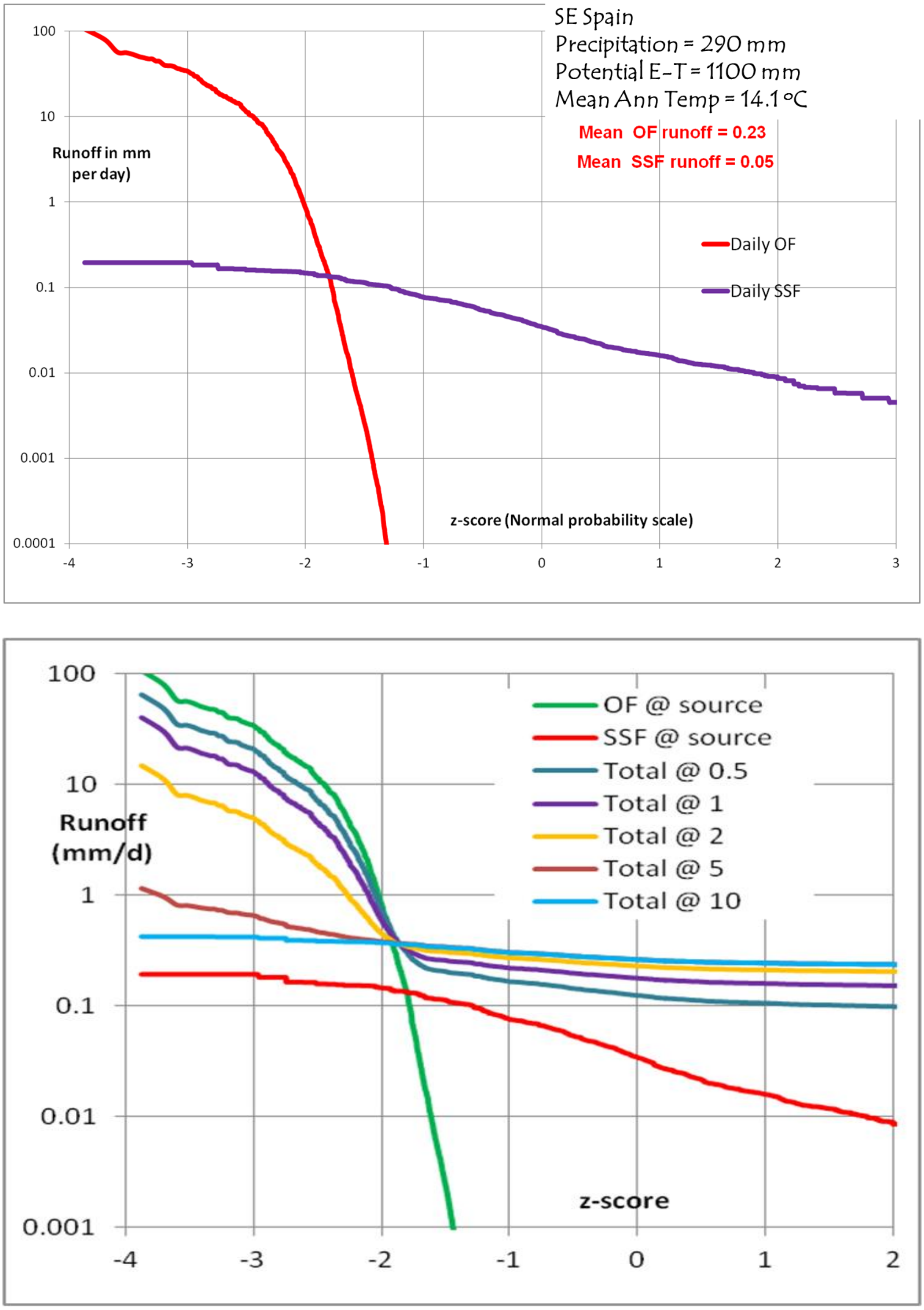

Figure 3. (a) Illustration of overland flow and sub-surface (base-)flows as two components of the flow duration curve, for a semi-arid site in SE Spain. (b) Contribution of an upstream cell to successive cells downstream, at distances of up to 10 steps (150 km) from the origin cell. It can be seen that the quick-flow portion is progressively attenuated towards its average, whereas the base-flow components is transmitted without change. The complete flow duration curve for a downstream cell is formed from the combination of such contributions from all up-stream cells, offset by losses due to channel evaporation and groundwater recharge.

5. DESMICE Economic model extension

The existing DESMICE model has been extended to take into account other factors influencing decision-making, informed by the results of the choice experiment (Task 2.5). The choice experiment undertaken in all four study sites tested farmer's preferences for investing time and money in WHT to reduce risk of crop failure and/or increase level of crop production. Preferences for different possible levels of crop failure and yield improvement relating to dry, average or wet years were tested in combination to different levels of investment cost (Dave and Fleskens, 2015). Respondents of the choice experiments needed to consider trade-offs between investment cost, yield level and risk of crop failure. This reflects real-world trade-offs, where investments in WHT might not improve yields during normal-wet years, but on the other hand might reduce risk of (total) crop failure in dry years.

Whereas a WHT may lead to a higher level of crop production in years of sufficient rainfall, a land user may only be interested in investing in the technology if the technology also reduces crop failure in less favourable years. A land user may even be interested in investing in WHT with no expected yield increase if a reduction in risk is achieved. Financial cost-benefit analysis as undertaken in the existing DESMICE model is based on average yield and therefore does not take risk reduction into account. PESERA-DESMICE can be run for different conditions, including for dry years and without WHT, to define risk as the chance that yield is below a certain level. However, the preference for reducing risk of crop failure cannot be determined by the model. Therefore data from the choice experiment is used to construct willingness to pay (WTP) graphs for reduced risk of crop failure (Figure 4).

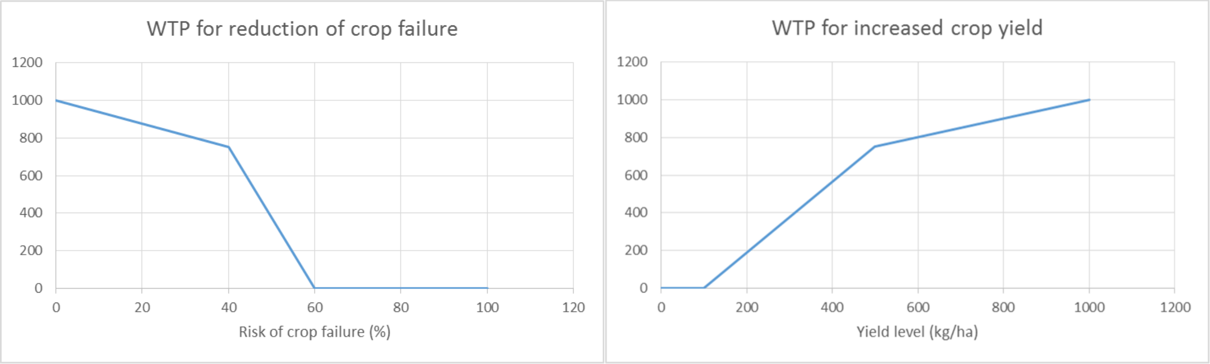

Figure 4. Land user's willingness to pay (WTP) for reduced risk of crop failure and increased crop yield.

PESERA model calculations deliver average yield and probabilities of reaching yield levels under conditions with and without a WHT under scrutiny, whereby the probabilities are calculated by running PESERA in time-series mode with different climate realizations (see Section 4). Based on yield level and probability of not reaching a certain yield level threshold, suitability for growing different crops can be determined. DESMICE can then assume that the most suitable crop is grown, which in a situation with WHT might be a different, higher return crop than without WHT. Investment costs for implementing WHT are considered in function of environmental conditions and distance to markets (Fleskens et al., 2014). For financial CBA, the benefit derived from the net difference in average yields multiplied with crop price (and annual maintenance and production costs, where these change as a result of implementing WHT) is considered and discounting applied over the economic life of the technology.

The following sequence of tests are performed when assessing a certain WHT for a given location with DESMICE:

1. What is the most profitable crop that can be grown without WHT?
2. Is the most profitable crop changing when implementing WHT?
3. What is the investment cost for the WHT?
4. What is the NPV for the WHT?
5. What is the yield improvement reached in with vs. without WHT situation? (Note yield level is used if the same crop is grown, yield times price if different crops are grown)
6. What is the risk of crop failure in with vs. without WHT situation?
7. Is NPV for the WHT positive?
8. Is the WHT investment associated with simulated yield improvement below the WTP threshold for yield improvement elicited from the choice experiment?
9. Is the WHT investment associated with simulated reduction in risk of crop failure below the WTP threshold for reduced risk of crop failure elicited from the choice experiment?
10. What combination of NPV and yield increase and risk reduction vs. WTP emerges, and what outcome regarding feasibility should be attributed to each cell considered?

Table 1 gives an overview of the situations that can occur with proposed implications of the outcome of the analysis in terms of recommendation of WHT options. WTP for yield increase is considered as a check for NPV calculations, but is assumed not to substitute the NPV calculation. The reasoning behind this approach is that eliciting WTP assumes a direct triggering of yield increase from investment, whereas NPV calculations explicitly take time into account. An outcome where the yield increase associated with an investment in WHT is below the WTP threshold for yield increase while NPV is negative suggests that the temporal distribution of benefits or the opportunity cost of capital (captured in the discount rate applied) are issues to be overcome. In contrast, the WTP for risk reduction criterion is assumed to dominate the NPV criterion. The reasoning behind this is that investment in WHT is for many farmers primarily a risk reduction strategy, and could thus be a rational strategy even if no yield increase is obtained (without yield increase, NPV will generally be negative, except in instances where WHT leads to cost savings in annual operations).

Proposed outcomes will be cross-checked with the importance local stakeholders attached to each of the three criteria. This can however only be done in workshops where model results are presented (e.g. Stringer et al., 2014).

Table 1. Feasibility assessment of WHT options based on three criteria: NPV and WTP for yield increase and risk reduction.

NPV	Yield increase	Risk reduction	Outcome
<0	<WTP	<WTP	Not feasible
<0	>WTP	<WTP	Not feasible
<0	<WTP	>WTP	Feasible
<0	>WTP	>WTP	Feasible
>0	<WTP	<WTP	Not feasible
>0	>WTP	<WTP	Not feasible
>0	<WTP	>WTP	Feasible
>0	>WTP	>WTP	Feasible

The updated model will also be capable of assessing the social effects of upstream-downstream interactions within a watershed area. The approach to this will take as a starting point a potential for investment scenario based on cell-based assessment of the potential for field-based WHT and an algorithm for spatial allocation based on catchment-to-cropped area ratio for ex-situ WHT (Figure 5). This algorithm allocates WHT starting from the watershed boundaries downwards on the basis of flow accumulation criteria.

Randomised and targeted reduced uptake of WHT scenarios will subsequently explore whether reduced density of investment in WHT leads a) to higher on-site returns; and b) to different down-stream impacts. Downstream impacts will only consider water availability effects, and no other aspects such as flood risk and sedimentation.

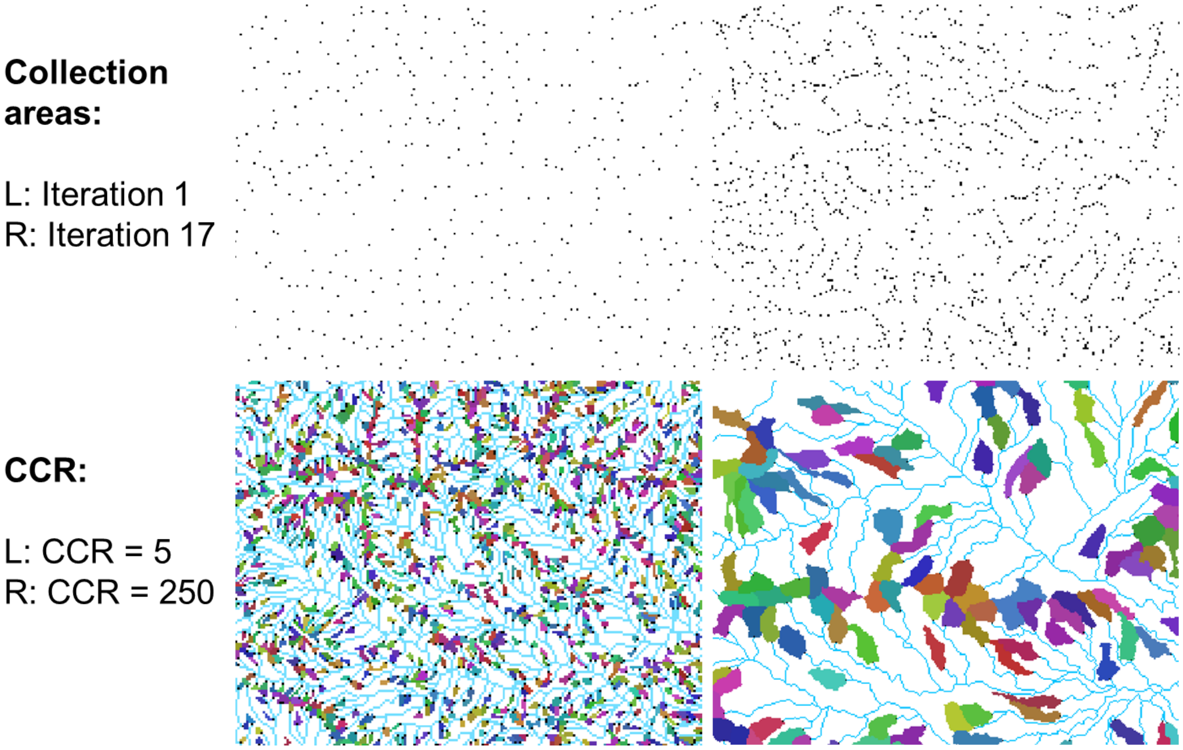

Figure 5. Example outputs of spatial allocation of collection areas and catchments based on different catchment-to-cropped area ratios for ex-situ WHT technologies.

6. Conclusion

This report has highlighted how the PESERA and DESMICE models have been modified and partially integrated in order to assess the impact of WHT. Compared to existing versions of both models, assessing the impact of WHT required attention to be paid to suitability assessment for crops under variable environmental and climatic conditions and the attenuation of downstream impacts of run-off capturing (PESERA), and considering preferences for risk reduction and yield improvement in addition to financial investment criteria (i.e. NPV) as well as enabling catchment scale analysis of up-stream – downstream interactions regarding water availability (DESMICE). For ex-situ WHT, furthermore a methodology was required that respects the design catchment-to-cropped-area ratio when generating applicability maps. The report has also indicated how these modifications, which lead to significant additional complexity of the models, can be integrated in an assessment of WHT that uses the PESERA and DESMICE models in a streamlined way.

The approach to integrated assessment of WHT using PESERA-DESMICE has now been established, and test applications have been implemented to assess the newly developed features and functionalities of the respective models. When experimental data collection is finalized and made available (WP3 reporting), this gives a good basis for the integrated model assessment across all 4 WAHARA study sites. The integrated PESERA-DESMICE model has been tested for a Cabo Verde application which aimed to appraise the applicability of the PESERA-DESMICE modelling approach to extend biophysical and economic benefits of a promising SLM technology across typical field conditions in the Ribeira Seca catchment and Santiago Island under variable climatic conditions. Rainfall time series for modelling were generated from the distribution of historical data and provided the opportunity to explore a full range of climate variability. Promising results were obtained, offering a basis to now apply the approach more extensively across the WAHARA study sites.

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