# *Supplementary Information*

## Surveyed MCC Compacts

CBA spreadsheets of concluded MCC (Millennium Challenge Corporation) compact projects can be accessed publicity at <https://www.mcc.gov/our-impact/err>. These spreadsheets were downloaded and studied to understand the utilization of standard methods of uncertainty characterization (Sensitivity Analysis, Scenario Analysis and Monte Carlo Analysis) in economic analysis at a conventional development agency. Importantly, we paid attention to the summary and presentation of financial decision metrics like the economic rate of return (ERR), net present value (NPV) and present value (PV), as well as the types of uncertainties included in analysis. None of the compacts analyzed conducted uncertainty analysis on climate variables like precipitation and temperature, although about a third of the closed MCC compacts were water sector projects (including water supply, irrigated agriculture, sanitation, storm water drainage, etc.) likely to be affected by changing climate conditions. summarizes the 82 projects from closed MCC compacts surveyed (analysis period ranging from 2005 to 2014 *ex-ante*, and from 2008 to 2020 *ex-post*) for this study based on spreadsheets available as of September 1, 2023.

**Supplementary Table 1**: Summary of Surveyed MCC Compacts

|  |  |  |
| --- | --- | --- |
| **Compact Country** | **Total Projects** | **Water Sector** |
| Armenia | 3 | 2 |
| Benin | 3 | 0 |
| Burkina Faso | 5 | 2 |
| El Salvador | 8 | 1 |
| Georgia | 5 | 0 |
| Ghana | 6 | 3 |
| Honduras | 1 | 0 |
| Indonesia | 1 | 0 |
| Lesotho | 5 | 3 |
| Malawi | 1 | 0 |
| Moldova | 1 | 1 |
| Mongolia | 6 | 0 |
| Morocco | 12 | 2 |
| Mozambique | 8 | 5 |
| Namibia | 6 | 0 |
| Philippines | 2 | 0 |
| Senegal | 2 | 3 |
| Tanzania | 5 | 3 |
| Vanuatu | 1 | 0 |
| Zambia | 1 | 1 |
| **Total** | **82** | **26** |

## Input Data for Hydrologic Modelling using SWAT

**Supplementary Table 2** presents the input data used for hydrological modelling. The SWAT hydrologic model is a watershed to river basin-scale model useful in simulating the quality and quantity of surface and ground water, and predicting the environmental impact of land use, land management practices, and climate change. Overall, our model under-predicts the streamflow (percent bias is ≈ -12.4% in calibration and ≈ -21.8% in validation). However, the goodness of fit parameters were acceptable for the purpose of this analysis. Eleven years were specified for the model warm-up period.

**Supplementary Table 2**: Input Data for Hydrologic Modelling

|  |  |  |  |
| --- | --- | --- | --- |
| **Watershed / Land Characteristics Data** | | | |
| **Data** | **Source** | **Spatial Resolution** | |
| Digital Elevation Map (DEM) | US Geological Survey (USGS) | 30 m | |
| Land use / Landcover | Food and Agricultural Association (FAO) | 1 km | |
| Soil maps  Digital Soil Map of the World (DSMW) | Food and Agricultural Association (FAO) / UNESCO | Shape file | |
| **Climate Data** | | | |
| **Data** | **Source** | **Temporal Resolution** | **Coverage** |
| Precipitation | Princeton Global Forcings (PGF) | Daily | 1948 to 2016 |
| Temperature | Princeton Global Forcings (PGF) | Daily | 1948 to 2016 |
| Streamflow | Lesotho Department of Water Affairs (DWA, Gauge SG03) | Daily | 1972 to 2019 |

## SWAT Calibration Parameters

**Supplementary Table 3** presents the range and fitted values of the fractions (\*), and in some instances exact values, of parameters used for the SWAT hydrologic model calibration and validation.

**Supplementary Table 3**: SWAT Calibration and Validation Parameters

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **SWAT Calibration Parameters** | **Description** | **Minimum** | **Maximum** | **Fitted Value for Calibration** | **Fitted Value for Validation** |
| \*CN2.mgt | Curve Number | -0.0402 | 0.0064 | -0.0333 | -0.0038 |
| \*ALPHA\_BF.gw | Baseflow alpha factor (1/days) | 0.5195 | 0.7286 | 0.7265 | 0.5454 |
| GW\_DELAY.gw | Groundwater delay (days) | 561.2191 | 680.8492 | 606.4094 | 658.2690 |
| GWQMN.gw | Threshold depth of water in the shallow aquifer required for return flow to occur (mm H2O) | 1764.8728 | 2157.1023 | 2005.9959 | 2135.2354 |
| SHALLST.gw | Initial depth of water in the shallow aquifer (mm H2O) | 4954.0195 | 6570.3613 | 6155.3657 | 5796.5376 |
| \*RCHRG\_DP.gw | Deep aquifer percolation fraction | -0.1364 | 0.0914 | -0.0478 | 0.0847 |
| \*ESCO.hru | Soil evaporation compensation factor | 0.6834 | 0.8257 | 0.7239 | 0.7568 |
| \*EPCO.hru | Plant uptake compensation factor | -0.1017 | 0.2816 | -0.0966 | 0.0795 |
| CNCOEF.bsn | Plant ET curve number coefficient | 1.5115 | 1.8836 | 1.8524 | 1.8608 |
| \*HRU\_SLP.hru | Average slope steepness (m/m) | 0.7000 | 1.1112 | 1.0348 | 1.0722 |
| SLSUBBSN.hru | Average slope length (m) | -26.8633 | 12.0898 | 9.0612 | 11.6126 |
| SOL\_AWC(..).sol | Available water capacity of the soil layer (mm H2O/mm soil) | 1.2489 | 1.8833 | 1.5881 | 1.2503 |
| EVRCH.bsn | Reach evaporation adjustment factor | 0.7113 | 0.7516 | 0.7114 | 0.7385 |
| REVAPMN.gw | Threshold depth of water in the shallow aquifer for percolation to the deep aquifer to occur (mm H2O) | 302.4072 | 338.5049 | 318.9850 | 334.3266 |
| \*BFLO\_DIST.bsn | Baseflow distribution | 0.0330 | 0.3018 | 0.1059 | 0.0961 |
| USLE\_K(..).sol | USLE equation soil erodibility factor (m3-metric ton cm) | 0.5651 | 0.7886 | 0.6854 | 0.6638 |

## Modelling ICM measures in the SWAT hydrologic model

The check dams were modelled as filtration ponds in SWAT filter sediments using the threshold size of the median particle diameter, *d50*as in eq. 1. Sediments smaller than *d50* are retained in the filtration ponds, while larger sediments remain suspended in the runoff (Arnold et al., 2013).

eq. (1)

where,

*mclay* – percent clay in the surface soil layer (μm)

*msilt* – percent silt in the surface soil layer (μm)

*msand* – percent sand in the surface soil layer (μm)

The runoff volume from the pond is simulated by the SWAT model based on the beginning (IFLOD1) and end (IFLOD2) of the non-flood season according to eq. 2 to eq. 4. For the study area in Lesotho, based on the summer months, IFLOD1 is May while IFLOD2 is September.

eq. (2)

and, eq. (3)

when monfld,beg < mon < monfld,end

Or,  eq. (4)

when mon ≤ monfld,beg  or mon ≥ monfld,end

where,

*Vtarg* – target pond volume for a given day (m3H2O)

*Vem*– volume of water held in the pond when filled to the emergency spillway (m3H2O)

*Vpr* – volume of water held in the pond when filled to the principal spillway (m3H2O)

*V* – volume of water stored in the pond (m3H2O)

*Vtarget* – target pond volume for a given day (m3H2O)

*NDtarget* – number of days required for the pond to reach target storage

*SW* – average soil water content in the subbasin (mm.H2O)

*FC* – water content of the subbasin soil at field capacity (mm.H2O)

*mon* – month of the year

*monfld,beg*– beginning month of the flood (rainy) season

*monfld,end* – ending month of the flood (rainy) season

*Vflowout*– volume of water flowing out of the water body during the day (m3H2O)

The main parameter that drives runoff and infiltration in the contours is the curve number (Boughton, 1989) which was set to the SWAT default of 60 (lower than the calculated average sub-basin curve number of 73) to reduce the rate of runoff and encourage infiltration (Arnold et al., 2013). The length, depth and width of the grassed waterways was adopted from ICM recommendations in the concluded project feasibility studies (AECOM, 2022a). To model revegetation in fenced off areas, a minimum residue land cover of 1000 kg / ha was specified from a possible range of 0 to 5000 kg / ha. Unavailability of data on specific vegetation target for livestock feeding prevented the adoption of more accurate values, and higher values were avoided to prevent excessive evapotranspiration losses (Zölch et al., 2017).

## Stochastic Weather Generator

illustrates the performance of the ten 69-year precipitation traces developed by the stochastic weather generator, with the red dots indicating historical monthly averages (1949 to 2016). Weather generator performance was acceptable for the two Princeton precipitation gages, PGF 1 and PGF 2, and the monthly mean precipitation in both observed and simulated timeseries are presented in Supplementary Figure 1.

A comparison of a graph

Description automatically generated with medium confidence

**Supplementary Figure 1**: Weather Generator precipitation traces

**Supplementary Table 4**: Mean of monthly precipitation in Observed (PGF gages) and Simulated timeseries.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Month** | **PGF 1 Observed** | **PGF 1 Simulated** | **PGF 2 Observed** | **PGF 2 Simulated** |
| Jan | 111.9 | 113.4 | 114.3 | 115.1 |
| Feb | 91.3 | 90.6 | 92.2 | 91.5 |
| Mar | 97.1 | 95.0 | 99.0 | 97.3 |
| Apr | 57.9 | 54.9 | 58.7 | 55.0 |
| May | 27.1 | 27.2 | 27.3 | 27.5 |
| Jun | 18.9 | 18.3 | 18.6 | 17.7 |
| Jul | 15.1 | 14.5 | 15.1 | 14.4 |
| Aug | 19.2 | 18.2 | 20.4 | 18.9 |
| Sep | 30.6 | 29.7 | 30.4 | 29.3 |
| Oct | 66.2 | 63.4 | 68.0 | 65.6 |
| Nov | 84.2 | 85.4 | 85.5 | 87.0 |
| Dec | 101.1 | 104.1 | 100.1 | 104.2 |

Supplementary Figure 2 also presents the Fourier plot showing periods of climate variability in the historical time series. The stochastic weather generator identified 11 significant periods of variability in historical precipitation at 90% confidence interval, and this was used to inform the 10 traces simulated for the climate stress test.

A comparison of different types of heat waves

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**Supplementary Figure 2**: Fourier Plot showing 11 significant periods in historical time series (1949 to 2016)

## Irrigation Water Requirements

Irrigation water requirement (IWR) was calculated according to eq. 5 to eq. 8, and SAPWAT calculated change in soil water content using eq. 9.

eq. (5)

eq. (6)

eq. (8)

where,

*ETc* – crop evapotranspiration

*ET0* – reference evapotranspiration (the evapotranspiration of short grass).

*Kc* – crop coefficients

*Kcb*– transpiration

*Ke* –soil evaporation

*Re* – Effective rainfall (the component of rainfall that contributes to crop transpiration)

eq. (9)

where,

*ΔD* – change in soil water content

*I* – irrigation

*P* – precipitation

*RO* – runoff

*E* – soil surface evaporation

*T* – crop transpiration

*CR* – capillary rise

*DP* – deep percolation

*SF* – sub-surface flow

A mix of drip and sprinkler irrigation systems with combined irrigation efficiency of 0.95 have been proposed for the MDIH scheme and the gross irrigation requirement (GIR) was calculated according to eq. 10.

eq.(10)

where,

*Ieff* – efficiency of irrigation system

*IWR* – irrigation water requirement

From a total scheme area of 70 ha marked out for irrigation by the Phamong dam according to the project design, Supplementary Table 5 presents the number of hectares to be irrigated monthly, and their corresponding IWR and GIR (AECOM, 2021). In each climate scenario, the actual number of hectares irrigated monthly is calculated using eq. 11.

eq. ()

where,

*A* – amount of water allocated to crops in a given month

*Hactual,mon* – actual hectares of crops irrigated in a given month

**Supplementary Table 5**: Monthly Target Hectares and corresponding Volumetric Irrigation Demand

|  |  |  |  |
| --- | --- | --- | --- |
| **Month** | **Irrigation Water Requirement**  **(m3/month)** | **Gross Irrigation Requirement**  **(m3/month)** | **Target Hectares** |
| Jan | 45978 | 48398 | 40 |
| Feb | 29703 | 31266 | 50 |
| Mar | 15196 | 15996 | 27 |
| Apr | 15305 | 16111 | 27 |
| May | 14841 | 15622 | 33 |
| Jun | 9782 | 10297 | 26 |
| Jul | 10357 | 10902 | 16 |
| Aug | 8757 | 9218 | 21 |
| Sep | 11594 | 12204 | 12 |
| Oct | 23921 | 25180 | 41 |
| Nov | 33089 | 34831 | 45 |
| Dec | 50500 | 53158 | 44 |
| **Total** | **269022** | **283182** | **381** |

## Proposed Cropping Patterns

The three alternative crop patterns shown in Supplementary Figure 3 to Supplementary Figure 5 were proposed for the MDIH scheme, and irrigation water requirement (IWR) was calculated as an optimized combination of these three patterns during the feasibility studies (AECOM, 2022a). For the Phamong area, about 70ha of crops in total are expected to be irrigated by the reservoir, with different number of hectares targeted each month based on the seasonality of crops as captured by the cropping patterns. 10% of available land has been dedicated to apples and other specialty crops in the Phamong area to encourage partnership with commercial farmers. The remote location of the Phamong scheme limited the fraction allocated to commercial farming and specialty crops in the area (10%) relative to the other 3 schemes in the more accessible Leribe area (up to 50% in Likhakeng and 60% in Manka and Tsoili Tsoili).

A chart with different colored rectangular shapes

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**Supplementary Figure 3**: Cropping Pattern 1

A screenshot of a computer

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**Supplementary Figure 4**: Cropping Pattern 2

A diagram of a schedule

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**Supplementary Figure 5**: Cropping Pattern 3

## Groundwater Valuation

Groundwater makes up a relatively small proportion (11.4%) of total water use in Lesotho, but it is a principal source of potable water for the majority of the rural population (Leketa et al., 2018). Estimated groundwater abstractions for domestic use are 22,552,662 m³/year, far exceeding those for industrial use which total around 473,040 m³/year (Leketa et al., 2018). Use of developed and undeveloped springs as well as handpumps, high-capacity production boreholes and river abstraction (Senqu / Orange) systems are all somewhat contingent upon groundwater supplies. However, with the rapid growth within the Senqu (Orange) River Basin, dependence on groundwater resources has expanded greatly (WRP et al., 2007). Groundwater systems in the country often respond to short-term and long-term changes in climate variables, withdrawal, and land use. As the need for reliable year-round sources for towns becomes an increasing priority, several towns have augmented river abstraction systems with the conjunctive use of groundwater from boreholes and wellfields.

### Groundwater Availability for the MDIH project

The water resources assessment for the MDIH project (AECOM, 2022a) notes that the limited groundwater resources in the region are already heavily committed to rural domestic water supply and would be insufficient for the purposes of large-scale commercial irrigated horticultural irrigation. Groundwater, in combination with rainwater harvesting from the facility roofs may, however, play a role in supplying potable water for the proposed training and / or service centers, as the costs of treating surface water intended for the irrigation schemes for this purpose would be prohibitive and potentially create competition for the water from the irrigation scheme supply infrastructure.

While no estimates of the volume of water needed to supply the training centers are provided from the feasibility studies, the Agronomic Assessment Report (AECOM, 2022b) estimates a water requirement of 200m3 per year for the service center housing the post-harvest handling (PHH) and integrated cold chain (ICC) facility at Phamong. It is not clear how much of this requirement could be met through rainwater harvesting, which would be less costly than groundwater abstraction, but from our analysis the implementation of ICM in the basin contributes an annual average range of 8,924 m3 to 126,483m3 to deep aquiferrecharge across the climate scenarios examined. This suggests that the potable water demand for the service and training center at Phamong could be met by the groundwater recharge resulting from ICM measures and encouraged the inclusion of groundwater benefits in the assessment of the ICM scenario.

### Groundwater Value

In purely financial terms, the value of groundwater can be derived from its uses, and from its local availability and quality compared with alternate sources of water (Foster and Chilton, 2022; Bann and Wood, 2012; Fenichel et al., 2016). Proper functioning of many lowland ecosystems also depends on groundwater discharge, including products they provide such as fish, fuel, and wood (Emerton and Bos 2004; Hérivaux and Grémont 2019). The economic value of groundwater can be divided into three main components (Deloitte, 2013; Qureshi et al., 2012):

1. **Extractive value** which measures the value associated with the actual, intended, or potential use of the extracted groundwater by the various sectors of the economy.
2. **Non-extractive value** such as the role that groundwater discharge plays in supporting ecosystems and wetlands, providing ‘base flow’ into surface water resources and supporting recreational activities.
3. **Option values** relate to the value individuals derive from maintaining or preserving the groundwater for their own future benefit, or for future generations.

In addition, groundwater value is driven by a number of factors including its supply and demand and institutional and policy factors (Qureshi et al., 2012; Deloitte, 2013), including:

1. The attributes of the groundwater resource (such as scarcity, quality, and reliability).
2. The availability and cost of alternative water sources which in turn depend principally on location of use; and
3. The type of use (such as irrigation, mining, manufacturing, domestic etc.).

The value of groundwater also has the potential to grow over time in response to increasing future water demands (population and economic growth) and / or growing scarcity or unreliability of surface water supplies as a result of low or less predictable rainfall.

### Estimates of the Economic Value of Groundwater from Literature

There are relatively few published estimates of the economic value of groundwater. Where these do exist, they tend to be old (few published studies after 2016), focus on changes in the quality of groundwater (e.g. Rinaudo et al., 2005; Bergstrom et al., 2004; Brox et al., 2003; Hasler et al., 2005), examine the factors that affect groundwater value (Qureshi et al., 2012), or present frameworks for assessing the full range of groundwater benefits (or total economic value) (Department of Environment, 2014; Bann and Wood, 2012, Fenichel et al., 2016; Foster and Chilton, 2022). In cases where changes in groundwater supply are investigated, these are typically for a reduction in supply or to understand people’s preferences for impacts to wetlands and rivers caused by increased groundwater abstraction (e.g. Garrod, Powe and Willis, 2000).

Supplementary Table 6 summarizes the published values from the literature review conducted on economic value of groundwater. Studies undertaken before 2000 were not included in this review as these were considered less reliable given the advances in the application of environmental valuation techniques that have taken place over the past 20 years, and the biophysical, economic, and social changes that have taken place since then and which are likely to shape people’s preferences (demand) for water supply and quality attributes. Groundwater value is highly dependent and sensitive to location and end use which limits the choice of estimates suitable for use in benefits transfer. This is thus an added limitation to our study.

**Supplementary Table 6**: Summary of Literature Review on Groundwater Valuation (Published Values)

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  | **Published value** | **Currency** | **Unit** | **Price Year** | **Source** |
| WTP to maintain groundwater benefits | 60-160 | USD | per HH | 2018 | Charalambous (2019); global median value based on a review of 50 studies |
| Shadow price of water for crop irrigation | 0.01-0.25 | USD | per m3 | 2018 | Bierkens et al (2019); based on marginal value of water for irrigation of four staple crops and 1 cash crop in the 11 most groundwater-depleted countries in the world |
| Value of the contribution that groundwater makes to the average acre of Kansas land with access to the aquifer | 17 | USD | per acre foot | 2016 | Fenichel et al (2016); represents value added to land prices for agricultural land overlying / with access to an aquifer |
| Value of flow regulation services attributable to native vegetation | 2.37 | ZAR | per m3 | 2017 | Turpie et al (2017); estimated in terms of the cost of providing equivalent artificial surface storage capacity required to maintain current water yields |
| Use value of groundwater | 2000 | AUS$ | per ML | 2013 | Deloitte (2013) |
| Value added by groundwater for agriculture and associated rural domestic supply | 1.21-2.69 | NAD | per m3 | 1999 (high) 2000 (low) | Bann and Wood (2012) |
| Value of groundwater recharge | 0.046 | Naira | per liter | 2002 | Acharya and Barbier (2002); groundwater recharge function performed by the Hadejia–Jama’are ﬂoodplain in northern Nigeria which is threatened by planned upstream water utilization schemes. |

The values in Supplementary Table 6 were adjusted to the 2021 price year (based on available data) using GDP deflator data from the World Bank (World Bank, 2022) to obtain more current groundwater values for our analysis. Eq. 10 was used to calculate the adjusted groundwater values (Supplementary Table 7) used in our study from the values obtained in the literature.

Eq. (12)

where,

*Plater* – Groundwater value in current analysis year (2021 in our case)

*Pearlier* – Groundwater value in earlier year (extracted from literature)

*RPIlater* – Retail price index in current analysis year (2021 in our case)

*RPIearlier* – Retail price index in earlier year (based on values extracted from literature)

**Supplementary Table 7**: Summary of Literature Review on Groundwater Valuation (Adjusted Values for Analysis)

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  | **Base (USD/m3)** | **Low (USD/m3)** | **High (USD/m3)** | **Unit** | **Notes** |
|  | 0.20 | 0.01 | 0.67 | m3 |  |
|  | **Adjusted value** | **Currency** | **Unit** | **Price Year** | **Source** |
| WTP to maintain groundwater benefits | 64.65 | USD | per HH | 2021 | Charalambous (2019) - low |
| WTP to maintain groundwater benefits | 172.41 | USD | per HH | 2021 | Charalambous (2019) - high |
| Shadow price of water for crop irrigation | 0.01 | USD | m3 | 2021 | Bierkens et al (2019) - low |
| Shadow price of water for crop irrigation | 0.27 | USD | m3 | 2021 | Bierkens et al (2019) - high |
| Value of the contribution that groundwater makes to the average acre of Kansas land with access to the aquifer | 0.02 | USD | m3 | 2021 | Fenichel et al (2016) |
| Value of flow regulation services attributable to native vegetation | 0.20 | USD | m3 | 2021 | Turpie et al (2017) |
| Use value of groundwater | 2.25 | USD | m3 | 2021 | Deloitte (2013) |
| Value added by groundwater for agriculture and associated rural domestic supply | 0.27 | USD | m3 | 2021 | Bann and Wood (2012) - low |
| Value added by groundwater for agriculture and associated rural domestic supply | 0.67 | USD | m3 | 2021 | Bann and Wood (2012) - high |
| Value of groundwater recharge | 0.01 | USD | m3 | 2021 | Acharya and Barbier (2002) |

## GCM Skill Assessment

To evaluate the fit of the GCMs, we compared seasonality (long-term average per month) and average annual depth of precipitation in the study area with historical GCM runs and observed data (from the Princeton dataset) between 1950-2011. From this simple assessment, we calculated,

1. Correlations between monthly observed and GCM simulated precipitations
2. Bias in precipitation depth of GCM simulated versus observed data.
3. Predicted shift in long-term precipitation for each GCM relative to its historical baseline.

While there is no strict threshold recommendation for evaluating GCM fits, our analysis uses correlation threshold of 0.7 to select the final suite of GCMs to include in the analysis shown in Table 4 of the main manuscript. Supplementary Figure 6 visualizes the skill assessment for precipitation data from one of the GCM models. For the ACCESS-CM2 model, correlation was > 0.7 to the Princeton historical data and so it was included while calculating the climate-informed robustness index (CRI) using the bivariate normal distribution.

A graph of different colored bars

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**Supplementary Figure 6**: Seasonality and fit of historical ACCESS-CM2 model simulations to Princeton Precipitation data (1950 – 2011)

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