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# Sustainability indicators and indices for the water-energy-food nexus for performance assessment: WEF nexus in practice – South Africa case study

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**Abstract:** The missing link between cross-sectoral resource utilisation and management, and full-scale adoption of the water-energy-food (WEF) nexus has been lack of analytical tools to support policy and decision-making. This paper defined WEF nexus sustainability indicators and developed a methodology to calculate composite indices to facilitate WEF nexus performance, monitoring and evaluation. WEF nexus indicators were integrated through the Analytic Hierarchy Process (AHP) in a multi-criteria decision-making (MCDM). Data were normalised to determine composite indices. The method established quantitative relationships among WEF nexus sectors to indicate resource utilisation and performance over time, using South Africa as a case study. A spider graph of normalised indices was used to illustrate WEF nexus indicator performance and inter-relationships, providing a synopsis of the level of interactions and inter-connectedness of WEF nexus sectors. The shape of the spider graph is determined by the level of the interdependencies and interactions among the WEF nexus sectors, whose management is viewed either as sustainable or unsustainable depending on the classification of the developed integrated index. The spider graph produced for South Africa shows an over emphasis on food self-sufficiency and water productivity at the expense of other sectors, which results from the sectoral approach in resource management. Although the calculated integrated index of 0.203 for South Africa is classified as lowly sustainable, the emphasis is on the quantitative relationships among the indicators and on how to improve them to achieve sustainability. The developed method provides evidence to decision makers, indicating priority areas for intervention. The analytical model is another niche area for the WEF nexus, as it is now capable to evaluate synergies and trade-offs in a holistic way to improve efficiency and productivity in resource use and management for sustainable development.

**Keywords:** Adaptation; climate change; composite indices; resilience; livelihoods; adaptation

## 1. Introduction

Global challenges such as climate change, land degradation, migration, increasing population growth and urbanisation require an integrated systems approach to sustainably manage resources to ensure availability at all times [1,2]. Such integrated solutions require a paradigm shift from the current 'silo' approaches to cross-cutting ones that recognise and facilitate cross-sectoral convergence and coherence in resource management [3,4]. One such approach is the water-energy-food (WEF) nexus, which came into prominence after the Bonn conference in 2011 [5,6], and has since grown into an

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internationally accepted framework for integrated and sustainable resource planning and management, particularly in this era of resource scarcity [7]. It has evolved into an approach that provides opportunities for cross-sectoral collaboration and harmonisation of policies to address complex problems in a sustainable manner [8]. The WEF nexus distinguishes itself from previous cross-sectoral approaches such as the Integrated Water Resources Management (IWRM), which is water-centric, by being polycentric and considering all sectors in equal terms [3,9].

The essence of the WEF nexus is three dimensional as it can be used as either an analytical tool, a conceptual framework, or a discourse [10]. As an analytical tool, the nexus systematically applies quantitative and qualitative methods to understand the interactions among WEF resources; as a conceptual framework, it simplifies an understanding of WEF linkages to promote coherence in policy-making and enhances sustainable development; and as a discourse, it is a tool for problem framing and promoting cross-sectoral collaboration [11]. Thus, the WEF nexus approach is a pathway for understanding complex and dynamic interlinkages between issues related to water, energy and food security. In this regard, it can also be used to monitor the performance of the WEF nexus indicators that are related to the 2030 Global Agenda of the Sustainable Development Goals (SDGs), particularly SDGs 2 (zero hunger), 6 (clean water and sanitation) and 7 (affordable and clean energy) [12]. The WEF nexus is an innovative integrated approach through which cross-sectoral sustainability indicators can be derived. Sectoral approaches to resources management risk major and unintended consequences as they always fail to manage cross-sectoral synergies and trade-offs [3,13].

Although the WEF nexus is envisaged to address the three interlinked global security concerns of access to water, sustainable energy and food security, there are gaps that remain to turn the nexus into a fully-fledged operational framework [11]. For this reason, the concept has been criticised for lack of clarity and practical applicability [14] and some have even branded it as repackaging of the IWRM [15]. The criticisms have been aided by the substantial amount of literature that has been published recently highlighting the importance of the WEF nexus as a conceptual framework and as a discourse, but evidently lacking on analytical tools that can be used to provide real world solutions [9,16-18]. Therefore, what remains with the WEF nexus are methods to evaluate synergies and trade-offs in an integrated way and decision support tools that can be used to prevent conflicts, reduce investment risks and maximise on economic returns [17,19]. As observed by Albrecht et al. [11], existing tools lack these main attributes and most of them either remain theoretical or maintain a sectoral approach to resource management. Previously developed WEF nexus analytical tools have not been well-adopted as they are generally complex or difficult to replicate in other areas and sector integration to establish the linkages among the sectors is not clear or is not established at all [11,20]. For the WEF nexus to be a true nexus, it needs a decision support tool that assesses the three sectors as a whole, eliminating a "silo" approach in resource development, utilisation and management. There is need for an integrated WEF nexus tool capable of assessing resources development and utilisation in a holistic way [20,21].

One of the ways to measure WEF nexus performance is through a set of sustainability indicators that are expressed through composite indices [22,23]. Sustainability indicators and indices usually convey information on the performance and current status of resources at any scale [24-26], and for quantifying the state or trend of resource utilisation [27]. Sustainability indicators can be used individually or can be combined, where all individual indicator scores are integrated into one composite index [28,29]. WEF nexus sustainability indicators and indices provide decision-making with an important analytical framework that indicates the state of water, energy and food resources, both in short-term and long-term perspectives. As important components of the WEF nexus, sustainability indicators and indices provide the needed parameters to balance resource planning, governance and technology development to enhance human wellbeing, now and in the future [30]. They are measurable parameters that indicate the performance of ecological, social, or economic systems [31]. They connect statements of intent (objectives) and measurable aspects of natural and human systems [32].

Sustainability refers to long-term stability of the economy and environment, achievable through integrating and acknowledging of economic, environmental and social concerns throughout the decision-making process [33,34]. The essence of sustainable development is to balance different and

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competing necessities against an awareness of the environment, social and economic limitations faced by humankind [35]. Sustainability is, therefore, a complex and multidimensional concept, which includes efficiency, equity and intergenerational equity based on socio-economic and environmental aspects [36]. A sustainable system is one providing for the economy, the ecosystem, and social well-being and equity at all times [31,37]. Thus, sustainability indicators are simplified decision support tools that aim to minimise the amount of complex interrelationships among resources, converting those relationships into simple formulations that make assessments easier [38]. Thus, sustainability indicators are essential tools in modelling the WEF nexus as it intends to balance cross-sectoral resource planning, utilisation and management [9,18]. This study, therefore defined WEF nexus indicators and applies the Analytic Hierarchy Process (AHP) to develop composite indices to mathematically establish numerical relationships, interlinkages and interdependences among water, energy and agriculture (agriculture being a proxy for food) resources, using South Africa as a case study.

## 2. Materials and Methods

### *2.1. Criteria for selecting WEF nexus sustainability indicators*

The core of the WEF nexus is its integrated systems approach and cross-sectoral management of resources, that any planned developments in any one sector should only be implemented after considering the impacts on other sectors [9,18]. As already alluded to, WEF nexus sustainability indicators are measurable parameters that are directly linked to the WEF nexus, and measure the performance of the utilisation and management of water, energy and food resources. Selected measurable sustainability indicators for WEF nexus performance are those that are related to resource availability, accessibility, self-sufficiency and how these influence respective production (productivity) (Table 1). Resource availability, accessibility, self-sufficiency and productivity are the major drivers of the securities of water, energy and food from where indicators are defined [30,39-41]. Any other indicators that do not relate to these drivers are excluded from the list of WEF nexus indicators. As the same drivers are also key in the securities of water, energy and food, the defined WEF nexus sustainability indicators should also evolve around resource availability, accessibility, self-sufficiency and productivity, key drivers in resource management [42,43]. The same drivers are also crucial in sustainability dimensions that include economic (increasing resource efficiency), social (accelerating access for all), and environmental (investing to sustain ecosystem services) [44]. Thus, the main criteria used to define and select WEF nexus indicators were (i) any indicators available in literature that referred to water, energy and food resources, but (ii) were not directly linked to the nexus and its drivers, or (iii) were not key to WEF securities, were excluded from the list of WEF nexus indicators. However, the selection of indicators is dependent on the characteristics of each particular place and can always be adjusted.

Within each WEF nexus sustainability indicator are pillars that sustain the indicators. These pillars also play an important role when establishing numerical relationships among indicators, but fall short of being WEF nexus indicators according to the set criteria. Each WEF nexus sector has its set of indicators and pillars that are used to establish quantitative relationships within the WEF nexus. For example, a country may have abundant water resources per capita (availability), but may not be affordable for the majority of the population or accessible to many as supplies from the sources may not be stable due to systems failures (stability) [45,46]. Furthermore, a country may have sufficient energy supplies, but they are not reliable or the energy type is condemned. All these factors were considered when establishing indicator relationships.

The selected WEF nexus indicators and pillars (Table 1) can be adopted anywhere, as they are the same indicators used for the SDGs (https://unstats.un.org/sdgs/metadata/). Country baseline data for the indicators is collected from World Bank indicators or from national statistical offices.

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**Table 1.** Sustainability indicators and pillars for WEF nexus sectors

| Component | Indicator | Units | Pillars |
|---|---|---|---|
| 1. Water | Proportion of available freshwater resources per capita (availability) | $m^3$/capita | Affordability Stability Safety |
| | Proportion of crops produced per unit of water used (productivity) | US$/$m^3$ | |
| 2. Energy | Proportion of the population with access to electricity (accessibility) | % | Reliability Sufficient Energy type |
| | Energy intensity measured in terms of primary energy and GDP (productivity) | MJ/GDP | |
| 3. Food | Prevalence of moderate or severe food insecurity in the population (self-sufficiency) | % | Accessibility Availability Affordability Stability |
| | Proportion of sustainable agricultural production per unit area (cereal productivity) | kg/ha | |

*2.2. Definitions for the selected WEF nexus sustainability indicators*

Based on the major drivers of WEF securities, which include availability, accessibility, self-sufficiency and productivity, WEF nexus sustainability indicators were defined and selected. The selected WEF nexus sustainability indicators were defined as:

i. Proportion of available freshwater resources per capita ($m^3$/capita). This indicator refers to the estimate of the total available freshwater water resources per person in a country, thus termed **water availability** [47].
ii. Proportion of crops produced per unit of water used ($/$m^3$). This indicator refers to a measure of output from an agricultural system in relation to the water it consumes, and thus called **water productivity** [48]. In this study we used the economic water productivity which is expressed in US$ per unit of water consumed [49].
iii. Proportion of the population with access to electricity, is expressed as percentage (%) of the total population with electricity access and is referred to as **energy accessibility** [50].
iv. Energy intensity measured in terms of primary energy and GDP (MJ/GDP). Energy intensity is defined as the energy supplied to the economy per unit value of economic output, and is termed as **energy productivity** [51].
v. Prevalence of moderate or severe food insecurity in the population. This is the percentage (%) of individuals in the population who have experienced food insecurity at moderate or severe levels during the reference year and is termed as **food self-sufficiency** [52].
vi. Proportion of sustainable agricultural production per unit area (kg/ha). This is the ratio between the area under productive and sustainable agriculture and the agricultural land area [53]. Only cereals where considered in this study and refers the indicator as **cereal productivity.** Sustainable agriculture refers to an agricultural production system that produce food in a way that protects and improves natural environments, and the social and economic conditions of farmers and workers, while at the same time safeguarding the local communities, the health and welfare of all species within the farming system [54].

*2.3. Method to calculate and integrate indicator indices and develop the WEF nexus analytical model*

The main approach used to develop the WEF nexus analytical model is the multi-criteria-decision making (MCDM), a tool for structuring and solving complex decisions and planning problems that involve multiple criteria [55]. The MCDM is a cross-sectoral planning tool to overcome the increasing demand of essential resources with a vision of sustainable development [56]. With the increasing complexity and multiplicity of managing resources, the sectoral analysis is no longer relevant. The MCDM was preferred as it solves socio-economic, environmental, technical and institutional barriers in resources management in a holistic way [57].

In this study, the MCDM was used to integrate and establish WEF nexus indicators and calculate indices through the AHP, which is an MCDM method [58,59]. The AHP, introduced by Saaty [60], is a theory of measurement to derive ratio scales from both discrete and continuous paired comparisons to help decision makers to set priorities and make the best decisions. The AHP comparison matrix is determined by comparing two indicators at a time using Saaty's scale, which ranges between 1/9 and 9 (Table 1) [59]. A range between 1 and 9 represents an important relationship, and a range between 1/3 and 1/9 represents an insignificant relationship. A rating of 9 indicates that in relation to the column factor, the row factor is 9 times more important. Conversely, a rating of 1/9 indicates that relative to the column indicator, the row indicator is 1/9 less important. In cases where the column and row indicators are equally important, they have a rating of 1. The scale has been successfully applied in research in recent years [61-63]. In the case of the WEF nexus, the index of an indicator in relation to others is determined by the impact of that particular indicator on its overall rating. For example, if the total renewable water resources per capita is 855 $m^3$/year, how the other water indicators like water scarcity and agriculture production influence this value?

Table 2 provides the interpretation of the numerical relationships among indicators. For example, the degree of influence of the effect of energy accessibility relative to water availability or any other indicator is determined based on baseline information obtainable from national statistics, World Bank indicators, Aquastat or any other recognised database, or from an expert in the field or from literature [43]. The available statistical information on indicators provides the baseline to establish the numerical relationship among indicators.

**Table 2.** Fundamental scale for pairwise comparisons in an AHP

| Intensity of Importance | Definition | Explanation |
|---|---|---|
| 1 | Equal importance | Element a and ***b*** contribute equally to the objective |
| 3 | Moderate/weak importance of one over another | Experience and judgment slightly favour element ***a*** over ***b*** |
| 5 | Essential or strong importance | Experience and judgment strongly favour element ***a*** over ***b*** |
| 7 | Demonstrated importance | Element ***a*** is favoured very strongly over ***b***; its dominance is demonstrated in practice |
| 9 | Absolute importance | The evidence favouring element over ***a*** over ***b*** is of the highest possible order of affirmation |
| 2, 4, 6, 8, 1/2, 1/4, 1/6, 1/8 | Intermediate values between the two adjacent judgments | When compromise is needed. For example, 4 can be used for the intermediate value between 3 and 5 |
| 1/3 | Moderately less important | |
| 1/5 | Strongly less important | |
| 1/7 | Very strongly less important | |
| 1/9 | Extremely less important | |
| Reciprocals of above nonzero | If ***a*** has one of the above numbers assigned to it when compared with ***b***. Then ***b*** has the reciprocal value when compared with ***a***. | |

*Source: Saaty, 1977* [59]

*2.4. An overview of the Analytical Hierarchy Process (AHP) in integrating different indicators*

Of the many MCDM methods available [Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), Simple Additive Weighting (SAW), Analytic Hierarchy Process (AHP), Multi Attribute Utility Theory (MAUT), Elimination and Choice Expressing the Reality (ELECTRE), Preference Ranking Organization Method for Enrichment Of Evaluations (PROMETHEE), etc.], the AHP remains the most used and widely accepted because of its robustness as demonstrated by comparative studies on MCDM methods [64-66]. Some of the methods like the TOPSIS actually apply the AHP in their applications [64]. The AHP is used in many fields and various specialities such as Environmental Sustainability, Economic Wellbeing, Sociology, Programming, Resource Allocation, Strategic Planning and Project/Risk Management to aggregate distinct indicators and monitor performance, for benchmarking, policy analysis and decision-making [22,67-69]. These fields, and more recently WEF nexus performance, cannot be measured using a single indicator but through a set of distinct indicators which need to be standardised and normalised.

The advantages of using the AHP over other MCDM methods are its usefulness in the hierarchical problem presentation, the appeal of pairwise comparisons in preference elicitation and its flexibility and ability to check inconsistencies [64,70-72]. Despite the subjective judgments in an AHP, results remain vital for policy evaluation and performance assessment as the method captures both subjective and objective evaluation measures [73]. This uncertainty is dealt with by engaging experts and the use of reliable baseline data in establishing relationships among indicators [74,75]. However, studies have shown that the AHP accuracy is compromised, if there are too many criteria or factors (more than 9) used during the pairwise comparison [64,76,77].

### *2.5. Calculation and normalisation of indices*

Indicators and pillars (Table 1) are important for establishing numerical relationships among indicators through a comparison matrix by indexing the indicators. Each indicator is compared and related to other indicators and is assigned a value (index) according to Saaty's AHP pairwise comparisons matrix (PCM) (Table 2) and then normalised to have the indicator [59,60].

Through the PCM, the AHP calculates the indices for each indicator by taking the eigenvector (a vector whose direction does not change even if a linear transformation is applied) corresponding to the largest eigenvalue (the size of the eigenvector) of the matrix, and then normalising the sum of the components [78]. The eigenvalue method synthesises a pairwise comparison matrix $A$, to obtain a priority weight vector for several decision criteria and alternatives. Here an eigenvector of matrix $A$ is used for the priority weight vector. In eigenvector method, the priority weight vector is set to the right principal eigenvector $w$ of the pairwise comparison matrix $A$. Therefore, the eigenvector method is to find the maximum value $\lambda$ and its corresponding vector $w$ such that [79]:

$$Aw = \lambda w \quad (1)$$

The overall importance of each indicator is then determined. The basic input is the pairwise matrix, $A$, of $n$ criteria, established based on Saaty's scaling ratios, which is of the order ($n \times n$) [80]. $A$ is a matrix with elements $a_{ij}$. The matrix generally has the property of reciprocity, expressed mathematically as:

$$a_{ij} = \frac{1}{a_{ij}} \quad (2)$$

After generating this matrix, it is then normalised as a matrix $B$, in which $B$ is the normalized matrix of $A$, with elements $b_{ij}$ and expressed as:

$$b_{ij} = \frac{a_{ij}}{\sum_{j=1} n \; a_{ij}} \quad (3)$$

Each weight value $w_i$ is computed as:

$$w_i = \frac{\sum_{j=1} n \; b_{ij}}{\sum_{i=1} n \sum_{j=1} n \; b_{ij}}, i, j = 1,2,3 \ldots, n \quad (4)$$

The integrated WEF nexus index is then calculated as a median of all the indices of indicators. The integrated composite index represents the overall performance of resource development, utilisation and management as seen together.

### *2.6. Determining the consistency of the pairwise comparison matrix*

In an AHP method, the indices derived from a PCM should always be consistent at an acceptable ratio. The consistency ratio ($CR$) indicates the likelihood that the matrix judgments were generated randomly and are consistent [81]. $CR$ indicates the amount of allowed inconsistency (0.10 or 10%). Higher $CR$ values indicate that the comparisons are less consistent, while smaller values indicate that

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comparisons are more consistent. When *CRs* are above 0.1, the pairwise comparison is not consistent and should be revaluated [59]. The *CR* is calculated as [82]:

$$CR = \frac{CI}{RI} \quad [5]$$

where: *CI* is consistency index, RI is the random index, the average of the resulting consistency index depending on the order of the matrix given by Saaty [59]. *CI* is calculated as:

$$CI = \gamma - \frac{n}{n-1} \quad [6]$$

where: $\lambda$ is the principal eigenvalue (shaded section of Table 4), and n is the numbers of criteria or sub-criteria in each pairwise comparison matrix.

*2.7. Application of the model: South Africa Case Study*

South Africa is used as a case study to apply the developed WEF nexus analytical model. The data used is specifically for South Africa and the results thereof. However, the methodology can be replicated anywhere and at any scale.

2.7.1. Pairwise comparison matrix for WEF nexus indicators for South Africa

The PCM to determine the relationship among WEF nexus components for South Africa is given in Table 4. The diagonal elements are the values of unity (i.e., when an indicator is compared with itself the relationship is 1). Since the matrix is also symmetrical, only the lower half of the triangle is filled in and the remaining cells are reciprocals of the lower triangle. The relationships are established using the scale given in Table 2 and the overview of the country indicator status according to a particular year, in this case for 2017 as shown in Table 3 in relation with the classification categories given in Table 6, respectively. Thus, the indicator values given in Table 3 provide the basis to classify the indicator according to Table 2. There is a close relationship between Tables 2, 3 and 6 when determining the coefficients given in 4.

**Table 3.** Overview of the WEF nexus indicators for South Africa

| WEF nexus | Indicator | Status 2017 |
|---|---|---|
| **1. Water** | Proportion of available freshwater resources per capita (availability) | 821.42 m³/cap |
| | Proportion of crops produced per unit of water used (water productivity) | US$26.2/m³ |
| **2. Energy** | Proportion of population with access to electricity (accessibility) | 84.2% |
| | Energy intensity measured in terms of primary energy and GDP (productivity) | 8.7 (MJ/GDP) |
| **3. Food** | Prevalence of moderate or severe food insecurity in the population (self-sufficiency) | 6.1% |
| | Proportion of sustainable agricultural production per unit area (cereal productivity) | 3.8 kg/ha |

*Source: World Bank Indicators*

**Table 4.** Pairwise comparison matrix for WEF nexus indicators

| Indicator | Pairwise comparison matrix | | | | | |
|---|---|---|---|---|---|---|
| | Water availability | Water productivity | Energy accessibility | Energy productivity | Food self-sufficiency | Cereal productivity |
| Water availability | 1 | 1 | 1 | 1/3 | 1/3 | 1 |
| Water productivity | 1 | 1 | 3 | 3 | 1 | 1 |
| Energy accessibility | 1 | 1/3 | 1 | 1 | 1/5 | 1/3 |
| Energy productivity | 3 | 1/3 | 1 | 1 | 1 | 5 |
| Food self-sufficiency | 3 | 1 | 5 | 1 | 1 | 7 |
| Cereal productivity | 1 | 1 | 3 | 1/5 | 1/7 | 1 |

2.7.2. Normalised pairwise comparison matrix for WEF nexus indicators

The normalisation of the PCM for the indicators (Table 4) is shown in Table 5 where each index is calculated using Equations 3 and 4, respectively. The sum of indices should always be 1 (as shown in Table 5). The summing of the indices to 1 shows that the indicators are now numerically linked or related and can now be analysed together as a whole for sustainable development. The CR for the normalised pairwise matrix is 0.01, which is within the acceptable range. The weighted average of the calculated indices is the WEF nexus integrated index, which is classified according to the categories given using Table 6. The indices are ranked according to their weight, the highest being ranked 6 and the lowest ranked 1 in order to calculate the weighted average. The integrated WEF nexus composite index for South Africa was calculated at 0.203, classifying the country into a lowly sustainable category (Table 6).

**Table 5.** Normalised pairwise comparison matrix and composite indices

| Indicator | Normalised pairwise comparison matrix | | | | | | Indices |
|---|---|---|---|---|---|---|---|
| | Water availability | Water productivity | Energy accessibility | Energy productivity | Food self-sufficiency | Crop productivity | |
| Water availability | 0.100 | 0.214 | 0.071 | 0.051 | 0.091 | 0.065 | 0.099 |
| Water productivity | 0.100 | 0.214 | 0.214 | 0.459 | 0.272 | 0.065 | 0.221 |
| Energy accessibility | 0.100 | 0.071 | 0.071 | 0.153 | 0.054 | 0.022 | 0.079 |
| Energy productivity | 0.300 | 0.071 | 0.071 | 0.153 | 0.272 | 0.326 | 0.199 |
| Food self-sufficiency | 0.300 | 0.214 | 0.357 | 0.153 | 0.272 | 0.457 | 0.292 |
| Crop productivity | 0.100 | 0.214 | 0.214 | 0.031 | 0.039 | 0.065 | 0.111 |
| **CR = 0.01** | | | | | | | **∑ = 1** |
| **Composite WEF nexus index (weighted average)** | | | | | | | **0.203** |

The indices for the indicators vary between 0 and 1, where 0 represents an unsustainable resource management and 1, highly sustainable resource management (Table 6). Some countries could be falling in the highly sustainable category, but 1 is almost impossible to achieve.

*2.8. Classification categories for indicators and the WEF nexus integrated index*

Table 6 shows the classification categories for the indicators as well as the WEF nexus integrated index for ranking resource use and performance. Categorising indicators forms the basis to establish the numerical relationship between the indicators by first classifying an indicator according to a given classification criteria or standard. The classification is useful especially when scaling the indicators using Table 2. It helps in determining the intensity of importance of an indicator.

**Table 6.** WEF nexus indicators performance classification categories

| Indicator | Unsustainable | Lowly sustainable | Moderately sustainable | Highly sustainable |
|---|---|---|---|---|
| Water availability ($m^3$/per capita) | < 1 700 | 1 700 – 6 000 | 6 001 -15 000 | > 15 000 |
| Water productivity (US$/$m^3$) | < 10 | 10 - 20 | 21 - 100 | > 100 |
| Food self-sufficiency (% of pop) | > 30 | 15 - 29 | 5 - 14 | < 5 |
| Cereal productivity (kg/ha) | < 500 | 501 – 2 000 | 2 001 – 4 000 | > 4 000 |
| Energy accessibility (% of pop) | < 20 | 21 - 50 | 51 - 89 | 90 - 100 |
| Energy productivity (MJ/GDP) | > 9 | 6 - 9 | 3 - 5 | < 3 |
| WEF nexus composite index | 0 - 09 | 0.1 - 0.2 | 0.3 - 0.6 | 0.7 - 1 |

*2.9. Conceptual framework for developing WEF nexus analytical model*

Figure 1 is a graphical representation of the conceptual outline used to develop the WEF nexus analytical model. The initial step was to define the sustainability indicators for each WEF nexus sector (water, energy and food). The indicators were framed in a way that reflects the securities of water, energy and food from a nexus perspective [31,83-88]. However, the indicators can be adapted to a

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particular situation, as they do not always apply in every situation. For example, the indicator on 'proportion of sustainable agricultural production per unit area' does not always apply in all situations as countries like Japan and Italy import between 50% and 70% of their food requirements because of limited land, but have enough food [89,90].

Within each indicator, there are defined pillars that determine the performance of an indicator. Indicators and pillars are necessary for establishing numerical relationships among sectors by means of indices. The second step involved determining composite indices for the indicators, establishing quantitative relationships among the indicators, using the AHP as a MCDM. The AHP was used to normalise, standardise and integrate distinct data from the indicators, and to form a single index or a set of indices through the (PCM).

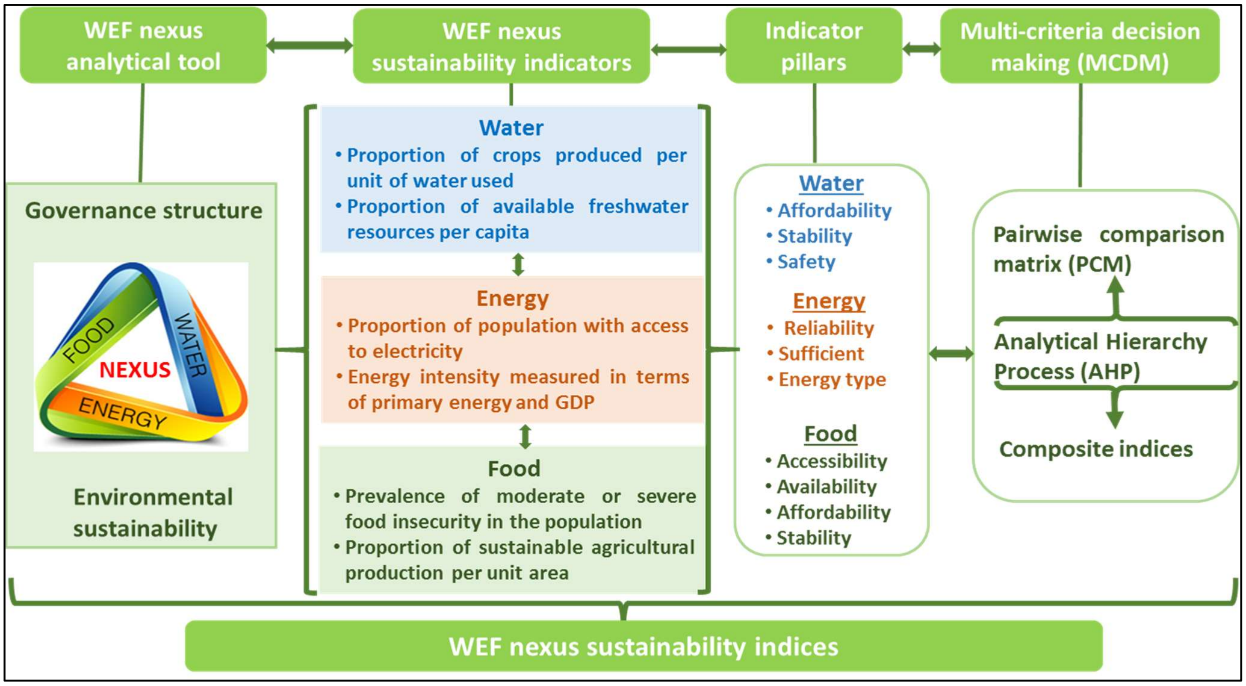


**Figure 1.** Conceptual framework to develop WEF nexus indicators and indices.

## 3. Results

### *3.2. Performance of WEF nexus indicators in South Africa*

The calculated indices (shown in the last column of Table 5) are used to construct the spider graph, to give a clear overview of the interactions, interconnectedness and interdependences among sectors as seen together. Figure 2 provides a synopsis of the current outlook and general performance of the WEF nexus sectors in South Africa, showing an imbalance in resource planning, allocation, utilisation and management. The further the distance of the indicator from the centre of the axis, the greater the level of sustainable development or the closer it is to the axis the greater the level of unsustainability.

In the case of South Africa, there is an evident over emphasis on food security (food self-sufficiency) and water productivity at the expense of other sectors. While energy productivity is fairly well managed, energy accessibility is the worst performing indicator. Although a lot has been done in accessing energy to 84.2% of the population, pillars like reliability and source or type of energy used also come into play. In this example, it is considered that 86% of South Africa's energy comes from coal [91], which is considered as environmentally unsustainable, and uses a lot of water. Coal releases a considerable amount of greenhouse gas (GHG) emissions (methane) into the atmosphere, which causes global warming [92]. Another area that needs to be improved is water management to ensure water

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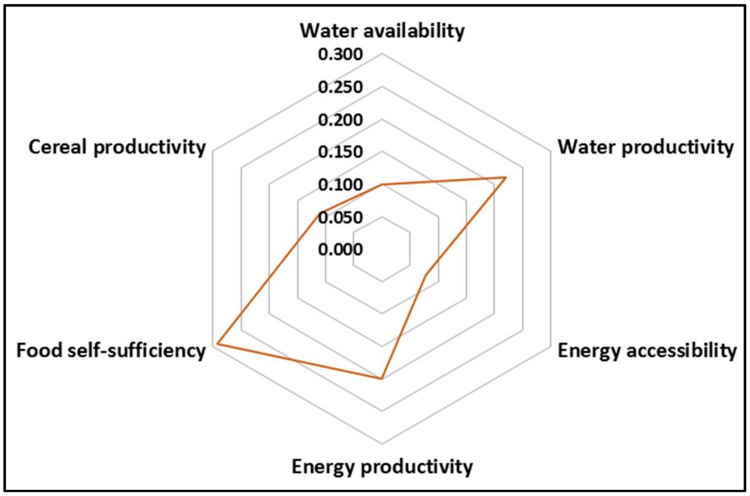
security in a country where annual water availability per capita is only 821.42 m$^3$, which is already unsustainable according to the classification given in Table 6. Improving water management, especially agricultural water management would free more water for other uses as agriculture currently consumes about 60% of available water resources [93]. The unsustainable water availability indicates the degree of water scarcity in South Africa. The country is classified as water scarce and it is among the thirty driest countries in the world [94,95]. Thus, the country's low performance in water availability indicator is greatly influenced by pillars such as stability and safety that are factored in during the pairwise comparison. Water infrastructure could be there to reach many households with tapped water, but supply is not guaranteed due to the water scarcity challenges. Water scarcity challenges have




promoted the country to use water resources optimally as water productivity is the second best performing indicator and is classified as moderately sustainable producing US$26.2/m$^3$ (Tables 3 & 4).

**Figure 2.** Performance of WEF nexus indicators in South Africa

However, for a balanced and sustainable resource development, utilisation and management, the country should target to make all sectors reach the highest index achieved in food self-sufficiency of 0.28 and attain a circular shape of the amoeba in the spider graph; otherwise, the current sectoral approach will continue creating an imbalance in the economy and retard development. Achieving a circular shape of the amoeba at an index of 0.28 would only indicate a balanced resource management, but it will still be regarded as lowly unsustainable. A balanced resource management shows that resources are being developed and utilised holistically to achieve sustainability. A deformed shape of the amoeba normally results from a sectoral approach in resources utilisation, development and management, which is the current situation for South Africa and elsewhere [9,96]. The developed WEF nexus analytical framework provides evidence to decision-makers on how to integrate strategies aimed at adapting to cross-sectoral approaches and translate to savings from costs associated with duplication of developmental projects, increased efficiencies due to streamlining of activities, and higher likelihood of success due to consideration of WEF nexus trade-offs and synergies [18].

## 4. Discussion

### *4.1. Applications of the WEF nexus analytical model*

A synopsis of a country's performance in resource utilisation and development, as well as the dynamics and changes over time, can be shown by means of a spider diagram as in Figure 2. The amoeba (the centrepiece) highlights a country's strengths, as well as priority areas needing intervention. The WEF nexus analytical model is, therefore, a decision support tool for tracking resource utilisation and performance, vividly capturing the interactions among sectors. The model differs from previously developed methods in that it portrays the polycentric nature of the WEF nexus, analysing sectors in a holistic way, viewing them in equal terms, as a whole and in an integrated manner, providing decision support to policy and resource managers. The approach links resource management and governance outcomes for sustainable development, which underlines the value of the of the nexus approach. These niches of the WEF nexus analytical model make it applicable in many fields of study, including assessing SDGs performance. Results from the analytical model can be used to set targets to meet a desired balance in resource development in line with relevant SDGs and country programmes over a certain period.

In the presented scenario for South Africa, interventions could be to improve the provision of safe and reliable water, clean and safe energy and improve crop productivity. Possible intervention scenarios are weighed to assess their impacts before implementation. For example, South Africa aims to increase the area under irrigation by 149 000 ha in order to ensure food security [97]. However, before implementing such initiatives, decision makers should consider the impacts on water and energy by analysing all possibilities through the WEF nexus analytical framework.

As the WEF nexus has evolved into a multi-purpose and polycentric framework for simplifying and framing complex interactions between socio-economic and environmental concerns, the analytical model has enabled (i) assessing the performance and progress of SDGs, (ii) policy framing, (iii) developing context based climate change adaptation strategies, (iv) climate change scenario planning, (v) livelihoods transformation, (vi) project appraisal and (vii) governance structures, among other applications.

### *4.2. Strengths and weaknesses of the WEF nexus analytical model*

The developed WEF nexus analytical model has managed to establish relationships among different, but linked WEF sectors, moving the WEF nexus approach from a theoretical framework to an analytical and practical one that provides real world solutions. The analytical model has enabled the evaluation and management of synergies and trade-offs in resource planning and utilisation, which previous tools had failed to achieve. Besides their failure to establish numerical relationships among the WEF sectors, the other reason why previous models had not been well adopted is that they either had remained theoretical or had maintained a sectoral approach to resource management, rendering them inappropriate to offer any nexus evidence for decision makers to adopt. The selected sustainability indicators and the calculated indices in this study have simplified the understanding of the complex interrelationships among resources, by converting those relationships into a simple formulation that makes assessments easier.

However, it should be noted that a major weakness of the model is embedded in the use of the AHP, particularly its subjective judgments during the pairwise comparison matrix. Nevertheless, the developed WEF nexus analytical model remains vital for policy evaluation and performance assessment as the method captures both subjective and objective evaluation measures by using reliable baseline data during the pairwise comparison matrix categorisations and by engaging field experts. In addition, the subjectivity of the AHP is neutralised by its ability to check inconsistencies in the judgements by calculating the consistency ratio for benchmarking. The hierarchical problem presentation of the AHP makes it very relevant in WEF nexus modelling as it ranks resources according to how they are planned and managed, linking them to each other.

### *4.3. Key considerations when using the model*

The WEF nexus is a broad concept framed to understand and simplify the complex interactions and relationships among water, energy and food resources. The developed WEF nexus analytical model is designed to simplify and interpret these complexities in an integrated way for sustainable development. The model converts the complexities in the relationships among the WEF resources into a simple formulation that can be understood by all stakeholders for easy application and assessment at any scales. However, there are some considerations to make before applying the model at different scales or different purposes, which include:

a. The indicators defined for this study are those that measure the security of water, energy and food at country level. Although these are valid for this study and at country level, they can be adjusted for other purposes, but using the same procedure. The focus on the security of the three WEF resources was based on southern Africa regional priorities, but priorities may differ across scale and context, thus the indicators may be adjusted to suit each context and region. For example, at household level different indicators can be used depending on the objectives.
b. Although the AHP remains as the most used MCDM, consistency is very difficult to achieve where there are more than 9 criteria/indicators under consideration [98,99]. Yet, its ability to measure consistency is one of the factors that gives the AHP an age over the other methods.
c. A WEF nexus integrated index of 1 is almost impossible to achieve, even for individual indicators. This could be true in that optimal sustainable development is difficult to achieve and no society can claim to be using its resources optimally.

## 5. Conclusions

This study developed a WEF nexus analytical model, firstly by defining WEF nexus indicators, and secondly calculating the indicator composite indices for South Africa. Although the procedure uses data for South Africa, it can be replicated anywhere and at any scale. Thus, the procedure presents an inclusive and multi-scale analytical framework that defines and quantifies the interconnectivity of water, energy and food. The composite indices assess the interactions between the natural environment and the biosphere in a given context and at any scale, and the methodology presents the WEF nexus as a unique tool that can be used to (a) quantitatively assess the cross-sectoral linkages among resources and indicate performance of resource utilisation and management, (b) leverage an understanding of WEF linkages to promote coherence in policy-making and enhance sustainable development, and (c) guide and promote cross-sectoral collaboration. The indices provide a clear overview of the level of interactions, inter-relationships and inter-connectedness among sectors. The relationships are demonstrated in the form of interdependencies, constraints, synergies and trade-offs that arise when changes in one area affects others, and they are viewed as either positive or negative. When shown through a spider graph, the indices indicate areas needing immediate attention to create a balance in resource utilisation, increase efficiency and productivity, improve livelihoods and build resilience. The WEF nexus analytical framework simplifies the understanding of the complex and dynamic interlinkages between the issues related to the securities of water, energy and food and it provides evidence for decision-making and policy formulation.

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