MENAdrought Synthesis of Drought Monitoring, Early Warning, and Seasonal Forecasting Tools and Capability Development

Final Report

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Drying Water pond (*photo*: Seersa Abaza / IWMI)

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Executive Summary

Purpose

This report (Pillar 1) synthesizes the development of drought monitoring, early warning and seasonal forecasting tools and capabilities in the MENAdrought project countries of Jordan, Lebanon and Morocco. It focuses on how the MENAdrought team and national partners collaboratively and iteratively developed, tested, refined, applied and enabled the use of the enhanced Composite Drought Indicator (eCDI) drought monitoring product and seasonal forecasting tools in each country, and how these technologies are being embedded within relevant institutions. However, our report presents only minimal technical details and methods because they will be published separately.

This report should be read in conjunction with the MENAdrought Synthesis of Drought Vulnerability Reports for each project country (Pillar 2 reports: Fragaszy et al. 2022a, 2022b) and the Synthesis of MENAdrought Development of Drought Mitigation, Preparedness and Response Management Plans report (Pillar 3 report: Jobbins et al. 2022). The Pillar 2 reports detail project findings on the underlying causes of vulnerability to drought impacts in each country and serve as a link between impact assessment and policy planning. They also include primary outputs produced using the eCDI, including drought history during the period 2000-2020 and drought hazard maps. The Pillar 3 report (Jobbins et al. 2022) describes the drought management planning undertaken through the project as well as the specific analyses done to support it.

Requirements for and Approach to eCDI Development

In each country, government agencies and other stakeholders spelled out the requirements for drought monitoring and management systems and tools including the eCDI specifically. This occurred through the needs assessment process reported by Fragaszy et al. (2020) and Jedd et al. (2020), as well as subsequent engagements during the MENAdrought program. These needs included:

- **Output temporal requirements:** Rapid and frequent production of the eCDI—at least monthly—and low latency, so that, for example, December conditions are reported in early January.

- **Output spatial requirements:** High enough spatial resolution to capture major agricultural and hydrological basins and shifts in agroecological zones.

- **Ease of production and use:** The indicator must be producible by national agencies while being compatible with their computing and modeling requirements, internet bandwidth, technical staff capacities and capabilities, and institutional setups.

- **Initial focus on monitoring agricultural drought, particularly in rainfed systems:** Primarily rainfed cereals and rangelands as well as olives and legumes, which are the basis of smallholder agricultural systems in the region.

- **Adequate accuracy and precision for drought management policy decision-making:** Stakeholders need confidence in the information produced to support decisions that have major political economic ramifications.

Accordingly, co-development of the eCDI occurred in three primary stages, during which the MENAdrought national partners—the Ministry of Water and Irrigation (MWI) and the Jordanian Meteorological Department (JMD) in Jordan, the Ministry of Energy and Water (MoEW) in Lebanon, and the Directorate of Strategy and Statistics (DSS) from the Ministry of Agriculture (MoA) in Morocco—were closely involved or led core workstreams:

- Stage 1 (2016-2017): Establishment of the modeling framework and production of the ‘default’ eCDI (Bijaber et al. 2018) for each project country.
- Stage 2 (2018-2019): Input validation and model output validation and calibration in each project country.
- Stage 3 (2019-present): Model refinement, process improvement and training and capacity-building to enable operational production and information use by national partners.

eCDI Composition and Production

We co-developed an eCDI that government agencies in Jordan and Morocco now produce independently—their own staff on their own servers—and we anticipate Lebanese agencies to be able to do so as well by the end of 2022 provided conditions in that country, primarily electricity and internet availability, permit the final installation of the system. The eCDI is a spatialized, weighted indicator produced using a combination of remote sensing and environmental modeling inputs. It is based on anomalies relative to average conditions since 2000 for a specific month and a specific 5 x 5 km grid location:

- 3-month Standardized Precipitation Index (SPI, 40% weighting)
- Normalized Difference Vegetation Index (NDVI, 20%);
- Root-zone soil moisture anomaly (SMA, 20%); and
- Day-night land surface temperature amplitude anomaly (LST, 20%).

Following integration, eCDI values for each pixel are categorized according to percentiles into one of the following classes: no drought, moderate drought, severe drought, or extreme drought.

eCDI Validation, Refinement, Production Process, Web Interface and Near-future Improvement Opportunities

The iterative eCDI development process incorporated quantitative and qualitative validation components to assess the accuracy of the modeled inputs and the eCDI as a whole and support subsequent refinements. These initial assessments included:

- Relationship with cereal production and yields;
- Comparison with available observation data;
- Assessment of performance as a function of land cover and use; and
- Qualitative assessment of eCDI performance with key stakeholders.

The eCDI showed a better relationship to cereal production and yield data than precipitation alone, which is a core aspect of its legitimacy to government officials and other stakeholders. The satellite-derived precipitation information used in the eCDI compared favorably with ground station precipitation monitoring data. Also, local experts largely considered the eCDI to be concordant with their observations where local validation was undertaken in Morocco and Jordan.

We improved the eCDI's performance primarily by validating and refining data inputs, adding and removing model components and inputs, undertaking additional data pre-processing, and modifying the eCDI calculation to reduce errors from cloud cover and provide additional (temporal and spatial) datapoints for eCDI calculations using a sliding window technique. Modeling improvements included the use of the dynamic phenology model within Noah-MP intended to improve soil moisture calculations. We also changed data sources for two of the input indices due to the planned cessation of a satellite mission.

We simplified the modeling system so that almost all processes are undertaken through a reproducible model workflow. This enables monthly drought maps to be produced within 10 days of the new month and ensures that agencies are able to continue production of the eCDI independently beyond the term of the funded MENAdrought project. Likewise, we developed a web user interface that enables various temporal and spatial aggregations of eCDI statistics to ease exploration of current conditions relative to past events and support decision-making.

Near-future eCDI improvement opportunities include building support networks and user/stakeholder engagement mechanisms. In both Jordan and Morocco, government agencies have supported the development of validator networks comprised of officials in local government agencies (and potentially also civil society) who will assess local drought conditions and comment on the perceived accuracy of eCDI outputs. This will support improvements to the drought early warning system and drought preparedness, mitigation and response management plans over time.

Development of Drought Triggers for Policy Decision Support

To develop trigger thresholds for drought management actions described in the Pillar 3 report, we assessed eCDI results statistically and in relation to annual rainfed staple crop production and yield. This resulted in the development of three types of triggers:

- Season-specific eCDI triggers for each country;
- For Morocco, a 'cumulative eCDI' based on eCDI values in December and March; and
- A Drought Severity and Coverage Index (DSCI) for Lebanon.[1]

The cumulative eCDI is based on temporal aggregation of monthly eCDI scores within a hydrological year to produce a single value for each province/governorate, which can then be spatially aggregated. The assessment used to produce this trigger showed that cumulative eCDI values are highly correlated with barley production, which we consider a relevant proxy for annual production of rangeland species, and more widely for rainfed cereals.

The DSCI aggregates spatial coverage of eCDI scores to enable spatially and temporally scalable assessments of drought intensity. It can be used from the province to the national level, and scores can be assessed month by month or continuously through a given year (or years).

The season-specific and cumulative eCDI triggers both reflect relationships between eCDI values in specific months and annual staple crop production and yields. The season-specific triggers do not incorporate any weighting for monthly eCDI values, whereas the Moroccan cumulative eCDI incorporates a statistically derived (stepwise regression) weighting system for the eCDI values of December and March of a given year. The DSCI triggers are derived statistically in relation to their highest values of the past 20-year period.

Seasonal Precipitation Forecasting

The MENAdrought team developed convolutional neural network (CNN) models, an artificial intelligence approach, to improve global precipitation forecasts in relation to the project countries. We trained the CNN models with observation data from the period 2000-2014 and applied regionalization techniques for the test period 2015-2022.

Despite using only one type of predictor (precipitation forecasts from four global modeling centers), our first attempt at a CNN model for Morocco accurately forecast precipitation with a lead time of 2-3 months. The CNN models' outputs showed major improvement over the global forecast in terms of the spatial location of precipitation as well as volume and anomalies.

Subsequently, we improved results in Morocco by adding sea-surface temperature predictors. In Jordan, we improved results by adding another global modeling center's precipitation forecast as a predictor and by training the CNN models in parallel according to climate region groups; in short, we trained the model using data from the more humid highlands climate region and, in parallel, using data from the Badia and arid climate regions. The CNN models are run first for the highlands and then for the other areas; and the results are then joined to form the final forecast.

The CNN models accurately forecast the location and timing of drought (using SPI) onset and recovery in Morocco in 2015-2016 and 2021-2022. Overall, the CNN-produced 2-months lead time forecast had a very high correlation with observed (CHIRPS) rainfall in the subhumid regions of Morocco, with an r value of 0.93, and a low correlation in the arid regions with an r value of 0.43.

In Lebanon, however, inclusion of additional predictors did not improve results substantially. Additional research is needed to identify useful predictors and undertake parallel model training.

Exploring eCDI and Streamflow Forecasting

Given the success with precipitation forecasting in Morocco, the MENAdrought team explored the possibility of forecasting the eCDI using the CNN outputs to force the Land Information System (LIS) model. This presented

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[1] Note that development of the DSCI trigger was experimental, and it is not included in the Lebanese Drought Action Plan described in the Pillar 3 report.

numerous technical challenges given that the LIS model requires subdaily inputs at fine spatial resolution. Whereas the timing of precipitation within the period is irrelevant for SPI, it is obviously critical for land surface/subsurface interactions. Given this issue, and the challenge in temperature and downward solar radiation forecasting with such temporal precision, outputs to date have been unsuccessful, particularly regarding the soil moisture input.

We suggest that future development efforts for agricultural and meteorological drought forecasting beyond SPI in the project countries should focus on precipitation and temperature-driven indices (such as the Standardized Precipitation and Evapotranspiration Index, SPEI) rather than use complex land surface models to produce indices such as the SMA.

In addition to drought forecasting, we conducted pilot research to use the CNN precipitation outputs to force streamflow models. The MENAdrought team parameterized the coupled LIS/Weather Research Forecast (WRF)-Hydro model for the Oum Rabia basin in Morocco and simulated streamflow over the 2000-2015 period. The model simulations reflected the trend in observed streamflow during normal and drought years in this period, albeit with timing and magnitude discrepancies, particularly during high flow events.

Pilot Development of Operational Crop-type Mapping Software

We also developed an operational software for crop-type mapping that is intended to be easily usable by the Moroccan Ministry of Agriculture staff in several applications to:

- increase the accuracy of annual crop yield statistics;
- support decision-making about drought management response measures in major rainfed and irrigated cropping systems;
- direct ground-truthing teams to survey drought impacts on cereal damage together with the insurance firm Mutuelle Agricole Marocaine D'Assurance (MAMDA) and the agricultural bank Crédit Agricole du Maroc (CAM); and
- to enable future developments associated with the drought monitoring and early warning system including thematic drought-risk mapping and staple crop yield forecasting.

The advanced machine learning software developed for Morocco and tested in the ‘intermediate’ bioclimate zone around Rabat uses open-source Sentinel satellite imagery to identify over 80 crop classes. To date, the greatest success has been with annual field crops, and future work would aim to improve results for orchards. Going forward, this approach could be used in the other countries and beyond if established training data approaches are adhered to.

Validation of the eCDI for Use in Monitoring Pastoral Areas in Morocco

From November 2020 to March 2021, Moroccan local government officials assessed the accuracy of the monthly eCDI maps in relation to drought severity and geographical extent in the pastoral areas they monitored. They also provided information on the most affected localities, as well as the status of annual and perennial biomass (including evidence of degradation or regeneration), livestock loading, heat stress, snow cover and unusual transhumant movements. This validation covered the primary rangeland areas—over 1,900,000 ha in the arid, semiarid and subhumid bioclimate zones—and provided an important means of connecting data generation to field conditions and those who oversee them.

Overall, the validators judged the eCDI to be 73% accurate (averaging reported accuracy for drought geography and drought intensity), with a range from 57% to 83% depending on the specific pastoral area and month. The lowest accuracies were found for forest areas in the Beni Mellal-Khénifra and Fez-Meknès regions and areas affected by snow cover. The values reported for the months of December and March were 97% correlated with all the months of the season, which shows strong alignment with the cumulative eCDI trigger.

These results, and the evaluation of the cumulative eCDI in relation to barley production, suggest that the eCDI is broadly useful to support monitoring of conditions in rangelands in the most important arid and semiarid areas. They also show a few simple changes to its calculation (for example, masking forests and snowy areas) could make incremental improvements in the accuracy of eCDI outputs for pastoral areas.

Development and Institutionalization of Drought Monitoring Capability

A core focus of the system design and associated engagements was for the outputs to function and support agency decision-making after the MENAdrought project is finished. This is achieved through the choices of data inputs, and by building capabilities, technology transfer and institutionalization of developed tools and skillsets. For example, input data were chosen based on various criteria such as the data being cost-free, length of the available data record, radiometric sensing channels that can detect key drought indicators, space and time resolution, and the commitment of data providers to maintain their provisioning systems. The eCDI developments were themselves underpinned by explicit and iterative assessment of the partner countries' needs and collaborative processes. This social and technical effort supported the project's development of drought early warning systems and their operationalization, including through drought management planning described in the associated Pillar 3 report.

These efforts included targeting validation studies with local partners, technical tool co-development and associated research efforts toward specific policy implementation goals in the project countries. For example, in Jordan, we focused heavily on ensuring the early warning system could support implementation of the Water Sector Policy for Drought Management and building a common understanding of the eCDI tool across relevant agencies and teams that have technical, coordination and decision-framing roles. Likewise, in Morocco, collaborative development efforts focused on supporting implementation of new legal regimes (namely, Water Law 36-15 and Rangelands Law 113-13, both from 2016), including through supporting increased central and local government interaction, collaboration, and information-sharing.

We supported various capacity-building approaches through training, technology transfer and iterative modeling refinements. These covered all technical aspects required to produce the eCDI operationally and use it effectively:

- Model installation, parameterization and calibration;
- Input data preparation, pre-processing and model execution;
- Output interpretation and validation; and
- Information-sharing.

We focused in particular on simplifying and expediting model execution processes, primarily by streamlining input data preparation, pre-processing and coding frameworks to operate the model. In many cases, this required novel methods and coding frameworks to address the issues identified through ongoing operation of the eCDI over time. It also included training officials with technical and policy roles in the usage of this information for drought impact and vulnerability assessment, as well as in drought management planning and related applications.

In addition to development of human and technical capacities, we sought to ensure project sustainability through the institutionalization of demand for early warning tools. This has been achieved primarily through the drought management policy planning described in the Pillar 3 report.

The needs assessment process identified barriers to information-sharing as a key problem for the existing drought monitoring and management arrangements. We sought to address this through careful prioritization of the drought monitoring information required through drought management planning, creation of a web interface, supporting the integration of eCDI outputs into other tools, or simply open publication of the results, which Moroccan agencies now do regularly[2]. More broadly, though, the eCDI validation efforts, and especially the creation of a network of regional validators, supports the objective of institutionalizing drought monitoring and early warning within the 3 Pillars framework.

Future Research-for-Development Opportunities

We suggest several potential research-for-development opportunities that would build on MENAdrought's technical achievements, as well as the opportunity to replicate drought early warning systems in other countries in the MENA region and beyond. These research opportunities focus on sector-specific drought mapping and forecasting tools. The latter tools in particular relate to crop production and rainfall runoff (streamflow) modeling linked to crop-type

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[2] See Indice Composite de la Sècheresse.

mapping, seasonal forecasting and the development of associated information-sharing platforms. They would enable the expansion of drought early warning systems to cover related food and water security elements, and potentially, associated economic and financial risk components as well.

However, with changing climate conditions leading to increased frequency and intensity of droughts in the MENA region, adaptation activities need to be embedded and operationalized within government decision-making frameworks so that timely actions are taken to reduce impacts across communities. This requires activities beyond research; it requires policy development and technical assistance programming that is tried, tested and trusted, and, critically, is part of drought action planning by government agencies.

Producing data through early warning systems is just the first step. The systems must be used in a coordinated way across multiple ministries, despite the attendant challenges, to meet the objectives of the Nationally Determined Contributions to the United Nations Framework Convention on Climate Change. This requires a long-term commitment to support key government agencies and emerging drought management institutions that oversee drought preparedness, mitigation and response actions.

ملخص تنفيذي

الهدف

ويجمع هذا التقرير (الركيزة ١) بين تطوير أدوات وقدرات رصد الجفاف والإنذار المبكر والتنبؤ الموسمي في بلدان مشروع منطقة الشرق الأوسط وشمال إفريقيا للجفاف في كل من الأردن ولبنان والمغرب. وهو يركز على كيفية قيام فريق منطقة الشرق الأوسط وشمال أفريقيا للجفاف والشركاء الوطنيين بشكل تعاوني بتطوير واختبار وصقل وتطبيق وتمكين استخدام منتجات رصد الجفاف وأدوات التنبؤ الموسمية لمؤشر الجفاف المركب المحدث في كل دولة، وكيفية إدماج هذه التكنولوجيات في المؤسسات ذات الصلة. ومع ذلك، يقدم تقريرنا الحد الأدنى من التفاصيل والأساليب الفنية فقط لأنه سيتم نشرها بشكل منفصل:

وينبغي قراءة هذا التقرير مقترنا مع توليف تقارير منطقة الشرق الأوسط وشمال إفريقيا للجفاف حول التعرض للجفاف لكل دولة من بلدان المشروع (تقارير الركيزة ٢: Fragaszy et al. ٢٠٢٢a, ٢٠٢٢b) وتوليف تقرير منطقة الشرق الأوسط وشمال إفريقيا للجفاف حول وضع (استحداث) خطط إدارة التخفيف من حدة الجفاف والتأهب له وإدارة (اليّات) الاستجابة له (تقرير الركيزة ٣: Jobbins et al. ٢٠٢٢). وتقدم تقارير الركيزة ٢ تفاصيل عن نتائج المشاريع المتعلقة بالأسباب الكامنة وراء قابلية التأثر بآثار الجفاف في كل دولة، وتشكل بمثابة حلقة وصل بين تقييم الأثر وعملية تخطيط السياسات. وهي تشمل أيضا المخرجات الأولية التي تم إنتاجها باستخدام مؤشر الجفاف المركب المحدث، بما في ذلك تاريخ الجفاف خلال الفترة الممتدة من عام ٢٠٠٠ الى عام ٢٠٢٠ وخرائط مخاطر الجفاف. و يصف تقرير الركيزة ٣ (Jobbins et al. ٢٠٢٢) التخطيط لإدارة الجفاف الذي تم إجراؤه من خلال المشروع بالإضافة إلى التحليلات المحددة التي أجريت لدعمه.

متطلبات ونهج تطوير مؤشر الجفاف المركب المحدث

حددت الوكالات الحكومية وأصحاب المصلحة الآخرون في كل دولة متطلبات نظم وأدوات رصد الجفاف وإدارته، بما في ذلك على وجه التحديد مؤشر الجفاف المركب المحدث وذلك من خلال عملية تقييم الاحتياجات التي أفاد بها Fragaszy et al. (٢٠٢٠) و Jedd et al. (٢٠٢٠)، فضلا عن التعهدات اللاحقة التي قدمت خلال برنامج منطقة الشرق الأوسط وشمال إفريقيا للجفاف. وتشمل هذه الاحتياجات ما يلي:

- المتطلبات الزمنية للإنتاج: الإنتاج السريع والمتكرر لمؤشر الجفاف المركب المحدث eCDI - شهريًا على الأقل - و "الكُمُون " المنخفض ، بحيث يتم ، على سبيل المثال ، الإبلاغ عن ظروف ديسمبر في أوائل يناير.

- متطلبات المخرجات المكانية: استبانة مكانية عالية الدقة بما يكفي لالتقاط الأحواض الزراعية والهيدرولوجية الرئيسية والتحولات في المناطق الإيكولوجية الزراعية.

- سهولة الإنتاج والاستخدام: يجب أن يكون المؤشر قابلاً للتطبيق من قبل الوكالات الوطنية مع مراعاة متطلبات الحوسبة والنمذجة ، وعرض النطاق الترددي للإنترنت ، وقدرات ومؤهلات الموظفين الفنيين ، والهياكل المؤسسية.

- التركيز الأوّلي على رصد الجفاف الزراعي، ولا سيما في النظم البعلية: في المقام الأول الحبوب البعلية والمراعي وكذلك الزيتون والبقوليات، التي تشكل أساس النظم الزراعية لصغار الحائزين في المنطقة.

- الدقة والصحة الكافيتين في اتخاذ القرارات المتعلقة بسياسات إدارة الجفاف: يحتاج أصحاب المصلحة إلى الثقة في المعلومات المقدمة لدعم القرارات التي لها تداعيات اقتصادية سياسية كبيرة.

وبناءً على ذلك ، تم التطوير المشترك لمؤشر الجفاف المركب المحدث (eCDI) في ثلاث مراحل أولية ، قام خلالها الشركاء الوطنيون لمنطقة الشرق الأوسط وشمال إفريقيا للجفاف (MENAdrought) - وزارة المياه والري (MWI) و دائرة الأرصاد الجوية الأردنية (JMD) في الأردن ، ووزارة الطاقة والمياه (MoEW) في لبنان ، ومديرية الإستراتيجية والإحصاء (DSS) في وزارة الزراعة (MoA) في المغرب - بالمشاركة عن كثب أو بقيادة مسارات العمل الأساسية:

- المرحلة الأولى (٢٠١٦-٢٠١٧): إنشاء إطار النمذجة والإنتاج"الافتراضي" لمؤشر الجفاف المركب المحدث (eCDI) (Bijaber et al، ٢٠١٨) لكل دولة من دول المشروع.

- المرحلة الثانية (٢٠١٨-٢٠١٩): اعتماد المدخلات واعتماد مخرجات النماذج ومعايرتها في كل دولة من دول المشروع.

- المرحلة الثالثة (٢٠١٩ إلى الوقت الحاضر): تحسين النموذج وتحسين العمليات والتدريب وبناء القدرات لتمكين الشركاء الوطنيين من الإنتاج التشغيلي واستخدام المعلومات.

تركيب وإنتاج مؤشر الجفاف المركب المحدث (eCDI)

لقد شاركنا في تطوير مؤشر الجفاف المركب المحدث (eCDI) و الذي تقوم الوكالات الحكومية في كل من الأردن والمغرب بإنتاجه الآن بشكل مستقل - موظفوها على خوادمهم الخاصة - ونتوقع أن تكون الوكالات اللبنانية قادرة على القيام بذلك أيضًا بحلول نهاية عام ٢٠٢٢ بشرط أن تكون الظروف في ذلك

البلد، في المقام الأول الكهرباء وتوافر الإنترنت، يسمح بالتركيب النهائي للنظام. و مؤشر الجفاف المركب المحدث (eCDI) هو مؤشر مكاني مرجح ينتج باستخدام مزيج من مدخلات الاستشعار عن بعد والنمذجة البيئية. ويستند إلى حالات شاذة مقارنة بمتوسط الظروف منذ عام ٢٠٠٠ لشهر محدد وموقع شبكة محدد بطول ٥ × ٥ كيلومترات:

- المؤشرالموحد لهطول الأمطار لمدة ٣ أشهر (SPI، ترجيح ٤٠٪)
- مؤشر الاختلاف النباتي القياسي (NDVI، ٢٠٪) ؛
- شذوذ رطوبة التربة في منطقة الجذر (SMA، ٢٠٪) ؛ '
- شذوذ في سعة درجة حرارة سطح الأرض ليلاً ونهارًا (LST، ٢٠٪).

عقب الدمج ، يتم تصنيف قيم مؤشر الجفاف المركب المحدث (eCDI) لكل بكسل (pixel) وفقًا للنسب المئوية على أنها واحدة مما يلي: لا جفاف، أو جفاف معتدل، أو جفاف شديد، أو جفاف متطرف.

التحقق من صحة مؤشر الجفاف المركب المحدث (eCDI) وصقله وعملية الإنتاج وواجهة الويب وفرص التحسين في المستقبل القريب

وتضمنت عملية تطوير مؤشر الجفاف المركب المحدث (eCDI) مكونات للتحقق الكمي والنوعي لتقييم دقة المدخلات المنمذجة ومؤشر الجفاف المركب المحدث (eCDI) ككل ودعم التحسينات اللاحقة. وشملت هذه التقييمات الأولية ما يلي:

- العلاقة مع إنتاج الحبوب والمحاصيل.
- مقارنة مع بيانات المراقبة المتاحة.
- تقييم الأداء كدالة للغطاء الأرضي وللاستخدام.
- التقييم النوعي لأداء مؤشر الجفاف المركب المحدث (eCDI) مع أصحاب المصلحة الرئيسيين.

أظهر مؤشر الجفاف المركب المحدث (eCDI) علاقة أفضل بإنتاج الحبوب وبيانات المحاصيل من بيانات هطول الأمطار وحده، ويمثل هذا جانبا أساسيًا من شرعيته بالنسبة للمسؤولين الحكوميين وأصحاب المصلحة الآخرين. وتقارن المعلومات هطول الأمطار المستمدة من السواتل (الأقمار الصناعية) والمستخدمة في مؤشر الجفاف المركب المحدث (eCDI) بصورة إيجابية مع بيانات رصد هطول الأمطار في المحطات الأرضية. كما اعتبر الخبراء المحليون إلى حد كبير أن مؤشر الجفاف المركب المحدث (eCDI) يتفق مع ملاحظاتهم في الحالات التي تم فيها التحقق محليا في المغرب والأردن.

قمنا بتحسين أداء مؤشر الجفاف المركب المحدث (eCDI) بشكل أساسي من خلال التحقق من صحة مدخلات البيانات وتنقيحها، وإضافة وإزالة مكونات النموذج والمدخلات، وإجراء معالجة مسبقة للبيانات الإضافية، وتعديل حساب مؤشر الجفاف المركب المحدث (eCDI) لتقليل الأخطاء من الغطاء السحابي وتوفير نقاط بيانات إضافية (زمنية ومكانية) لحسابات مؤشر الجفاف المركب المحدث (eCDI) باستخدام تقنية النافذة المنزلقة. تضمنت تحسينات النمذجة استخدام نموذج الفينولوجيا الديناميكي داخل Noah-MP (نوع لسطح الأرض ذو الخيارات متعددة المعايير) بهدف تحسين حسابات رطوبة التربة. قمنا أيضًا بتغيير مصادر البيانات لاثنين من مؤشرات المدخلات بسبب التوقف المخطط لمهمة الأقمار الصناعية.

قمنا بتبسيط نظام النمذجة بحيث يتم تنفيذ جميع العمليات تقريبًا من خلال سير عمل نموذج قابل للتكرار، مما يتيح إنتاج خرائط شهرية للجفاف في غضون ١٠ أيام من الشهر الجديد ويكفل قدرة الوكالات على مواصلة إنتاج هذه الخرائط بشكل مستقل إلى ما بعد فترة مشروع الجفاف الممول لمنطقة الشرق الأوسط وشمال إفريقيا للجفاف. وبالمثل، قمنا بتطوير واجهة لمستخدمي الويب تمكن مختلف التجميعات الزمنية والمكانية لإحصاءات مؤشر الجفاف المركب المحدث (eCDI) من تسهيل استكشاف الظروف الحالية مقارنة بالأحداث السابقة ودعم صنع القرار.

وتشمل فرص تحسين مؤشر الجفاف المركب المحدث (eCDI) في المستقبل القريب بناء شبكات دعم وآليات إشراك المستخدمين/أصحاب المصلحة. وفي كل من الأردن والمغرب، دعمت الوكالات الحكومية تطوير شبكات التحقق التي تتألف من مسؤولين في الوكالات الحكومية المحلية (وربما المجتمع المدني) الذين سيقومون بتقييم ظروف الجفاف المحلية وبتقديم تعليقات على الدقة المتصورة لنواتج مؤشر الجفاف المركب المحدث (eCDI). وسيدعم ذلك إدخال تحسينات على نظام الإنذار المبكر بالجفاف وخطط التأهب للجفاف والتخفيف من آثاره وإدارة الاستجابة له بمرور الوقت.

تطوير محفّزات الجفاف لدعم القرار السياسي

لوضع عتبات "المحفّزات" لإجراءات إدارة الجفاف الموضحة في تقرير الركيزة ٣ ، قمنا بتقييم نتائج مؤشر الجفاف المركب المحدث (eCDI) باستخدام الإحصائيّات ومقارنا بالإنتاج السنوي للمحاصيل الأساسية البعلية و عائداتها. أدى ذلك إلى تطوير ثلاثة أنواع من المحفزات:

- محفّزات مؤشر الجفاف المركب المحدث (eCDI) الخاصة بالموسم لكل دولة ؛

- وبالنسبة للمغرب، تم في كانون الأول/ديسمبر وآذار/مارس إنشاء " مؤشر الجفاف المركب المحدث التراكمي" يستند إلى قيم مؤشر الجفاف المركب المحدث (eCDI) لشهري ديسمبر ومارس الخاص بالمغرب.
- استخدام مؤشر شدة الجفاف وتغطيته (DSCI) بالنسبة للبنان[٣].

ويستند مؤشر الجفاف المركب المحدث التراكمي إلى التجميع الزمني للدرجات الشهرية التي يحققها هذا المركز في غضون سنة هيدرولوجية لإنتاج قيمة واحدة لكل مقاطعة/محافظة، التي يمكن عندئذ تجميعها مكانيا. أظهر التقييم المستخدم لإنتاج هذا المحفّز أن قيم مؤشر الجفاف المركب المحدث (eCDI) التراكمي مرتبطة ارتباطًا وثيقًا بإنتاج الشعير، والذي نعتبره بديلا مناسبًا للإنتاج السنوي لأنواع المراعي، وعلى نطاق أوسع للحبوب البعلية.

يجمع مؤشر شدة الجفاف وتغطيته (DSCI) التغطية المكانية لدرجات مؤشر الجفاف المركب المحدث (eCDI) للتمكين من تقييمات مكانية وزمنية لشدة الجفاف قابلة للتطوير. يمكن استخدامه من مستوى المقاطعة إلى المستوى الوطني، ويمكن تقييم الدرجات شهريًا أو بشكل مستمر خلال سنة (أو سنوات) معينة.

تعكس كلا من محفزات مؤشر الجفاف المركب المحدث (eCDI) الخاصة بالموسم و مؤشر الجفاف المركب المحدث (eCDI) التراكمي العلاقات بين قيم مؤشر الجفاف المركب المحدث (eCDI) في أشهر محددة والإنتاج السنوي للمحاصيل الأساسية وعائداتها. ولا تتضمن المحفزات الخاصة بالموسم أي ترجيح للقيم الشهرية لمؤشر الجفاف المركب المحدث (eCDI)، بينما يشتمل مؤشر الجفاف المركب المحدث التراكمي للمغرب على نظام ترجيح مشتق إحصائيًا (الانحدار التدريجي) لقيم مؤشر الجفاف المركب المحدث (eCDI) لشهري ديسمبر ومارس في عام معين. و يتم اشتقاق محفزات مؤشر شدة الجفاف و نطاقه (DSCI) إحصائيًا مقارنة بأعلى قيمها في فترة العشرين عامًا الماضية.

التنبؤ الموسمي بهطول الأمطار

قام فريق منطقة الشرق الأوسط وشمال إفريقيا للجفاف بتطويرنماذج للشبكة العصبية الملتفّة (CNN) وهو نهج ذكاء اصطناعي، لتحسين التنبؤات العالمية لهطول الأمطار فيما يتعلق ببلدان المشروع. قمنا بتدريب نماذج الشبكة العصبية الملتفّة (CNN) باستخدام بيانات المراقبة للفترة الممتدة من عام ٢٠٠٠ الى عام ٢٠١٤ و بتطبيق تقنيات الهيكلة الإقليمية لفترة اختبار من عام ٢٠١٥ الى عام ٢٠١٩.

و على الرغم من استخدام نوع واحد فقط من أدوات التنبّؤ (توقعات هطول الأمطار من أربعة مراكز نمذجة عالمية)، فإن محاولتنا الأولى لنموذج الشبكة العصبية الملتفّة (CNN) للمغرب تنبأت بدقة بهطول الأمطار بفترة زمنية تتراوح من شهرين إلى ٣ أشهر. و أظهرت مخرجات نماذج الشبكة العصبية الملتفّة (CNN) تحسنًا كبيرًا عن التوقعات العالمية من حيث الموقع المكاني لهطول الأمطار فضلا عن الأحجام والشذوذ.

بعد ذلك، قمنا بتحسين النتائج في المغرب بإضافة متنبئات لدرجة حرارة سطح البحر. في الأردن، قمنا بتحسين النتائج من خلال إضافة توقعات هطول الأمطار لمركز نمذجة عالمي آخر كمؤشر وتدريب نماذج الشبكة العصبية الملتفّة (CNN) بالتوازي وفقًا لمجموعات منطقة المناخ ؛ باختصار، قمنا بتدريب النموذج باستخدام بيانات من منطقة المناخ الأكثر رطوبة في المرتفعات، وبالتوازي مع ذلك، باستخدام بيانات من منطقتي البادية والمناخ القاحل. يتم تشغيل نماذج الشبكة العصبية الملتفّة (CNN) أولاً للمرتفعات ثم للمناطق الأخرى ؛ ثم يتم ضم النتائج لتشكيل التوقعات النهائية.

تتنبأ نماذج الشبكة العصبية الملتفّة (CNN) بدقة بموقع وتوقيت (باستخدام مؤشر هطول الأمطار القياسي SPI) بداية الجفاف و التعافي من الجفاف في المغرب في ٢٠١٥-٢٠١٦ و ٢٠٢١-٢٠٢٢. بشكل عام، كان لتوقعات المهلة الزمنية لشهرين التي أصدرتها الشبكة العصبية الملتفّة (CNN) ارتباطًا كبيرًا للغاية بهطول الأمطار (CHIRPS) الملحوظ في المناطق شبه الرطبة من المغرب ، بقيمة (ر) r تبلغ ٠,٩٣ ، وارتباط منخفض في المناطق القاحلة بقيمة (ر) r تبلغ ٠,٤٣.

بيد أن إدراج مؤشرات إضافية للتنبؤ في لبنان لم يحسن النتائج بشكل كبير. هناك حاجة إلى مزيد من البحث لتحديد المتنبئات المفيدة والاضطلاع بتدريب نموذجي مواز.

استكشاف مؤشر الجفاف المركب المحدث (eCDI) والتنبؤات بتدفق المجاري المائية

نظرا للنجاح في التنبؤ بهطول الأمطار في المغرب ، يستكشف فريق منطقة الشرق الأوسط وشمال إفريقيا للجفاف (MENAdrought) إمكانية التنبؤ بمؤشر الجفاف المركب المحدث (eCDI) باستخدام مخرجات الشبكة العصبية الملتفّة (CNN) لفرض نموذج نظام معلومات الأراضي (LIS). وقد طرح ذلك العديد من التحديات التقنية نظرًا لأن نموذج نظام معلومات الأراضي (LIS) يتطلب تقديم مدخلات فرعية بدقة مكانية كبيرة. و في حين أن توقيت هطول الأمطار خلال الفترة ليست له صلة بمؤشر هطول الأمطار القياسي SPI ، فمن الواضح أنه أمر بالغ الأهمية بالنسبة للتفاعلات سطح الأرض (السطحية) / تحت سطح الأرض (الجوفية). و مع هذه المسالة ، والتحدي في التنبؤ بدرجات الحرارة بهذه الدقة الزمنية ، كانت المخرجات حتى الآن غير ناجحة ، لا سيما فيما يتعلق بمدخلات رطوبة التربة. سوف نستكشف السبل لمعالجة هذه المسائل في بقية المشروع.

بالنظر إلى هذه المشكلة، والتحدي في درجات الحرارة والتنبؤ بالإشعاع الشمسي الهبوطي بمثل هذه الدقة الزمنية، لم تنجح المخرجات حتى الآن، لا سيما فيما يتعلق بمدخلات رطوبة التربة.

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[٣] لاحظ أن تطوير محفز مؤشر شدة الجفاف وتغطيته (DSCI) كان تجريبيًا، ولم يتم إدراجه في خطة العمل اللبنانية لمكافحة الجفاف الموصوفة في تقرير الركيزة ٣.

نقترح أن تركز جهود التطوير المستقبلية للتنبؤ بالجفاف الزراعي والأرصاد الجوية بما يتجاوزمؤشر هطول الأمطار القياسي (SPI) في بلدان المشروع على مؤشرات هطول الأمطار ودرجة الحرارة (مثل المؤشر القياسي للامطار و التبخر، SPEI) بدلاً من استخدام نماذج سطح الأرض المعقدة لإنتاج مؤشرات مثل SMA.

و بالإضافة إلى التنبؤ بالجفاف ، أجرينا بحثًا تجريبيًا لاستخدام مخرجات هطول الأمطار للشبكة العصبية الملتفّة CNN لفرض نماذج تدفق المجاري. قام فريق منطقة الشرق الأوسط وشمال إفريقيا للجفاف (MENAdrought) بتحديد معايير النموذج المزدوج LIS/Weather Research Forecast (WRF)-Hydro (نظام معلومات الأراضي/ البحث والتنبؤ بالطقس – هايدرو) لحوض أم ربيعة في المغرب ومحاكاة تدفق المجاري خلال الفترة الممتدة من عام ٢٠٠٠ الى عام ٢٠١٥. وعكست نماذج المحاكاة الاتجاه في التدفق الملحوظ خلال السنوات العادية وسنوات الجفاف في هذه الفترة ، وإن كان ذلك مع تباين في التوقيت والحجم ، لا سيما أثناء أحداث التدفق المرتفع.

التصميم التجريبي لبرنامج رسم الخرائط العملية لأنواع المحاصيل

كما قمنا بتطوير برمجيات تشغيلية لرسم خرائط أنواع المحاصيل والذي من المفترض أن يكون قابلاً للاستخدام بسهولة من قبل موظفي وزارة الزراعة المغربية في عدة تطبيقات من أجل:

- زيادة دقة إحصاءات غلة المحاصيل السنوية؛
- دعم اتخاذ القرار بشأن تدابير الاستجابة لإدارة الجفاف في أنظمة الزراعة البعلية والمروية الرئيسية؛
- فرو تمكين الميداني (المعاينة الميدانية) المباشرة لمسح آثار الجفاف على أضرار الحبوب)أضرار آثار الجفاف على الحبوب(جنبًا إلى جنب مع التعاضدية الفلاحية المغربية للتأمينات (ماماMAMDA) و المصرف الفلاحي القرض الفلاحي المغربي (الكامCAM)؛
- و تمكين التطورات المستقبلية المرتبطة برصد الجفاف ونظام الإنذار المبكر بما في ذلك رسم خرائط مواضيعية لمخاطر الجفاف والتنبؤ بعائدات المحاصيل الزراعية الأساسية.

يقوم برنامج التعلم الآلي المتقدم الذي تم تطويره للمغرب وتم اختباره في المنطقة البيولوجية المناخية « الوسيطة » حول الرباط باستخدام صور الأقمار الصناعية مفتوحة المصدر "سنتينيل" (Sentinel) لتحديد أكثر من ٨٠ فئة من المحاصيل. و حتى الآن، كان النجاح الأكبر في المحاصيل الحقلية السنوية ، وسيهدف العمل المستقبلي إلى تحسين نتائج البساتين. ومن أجل المضي قدما، يمكن استخدام هذا النهج في البلدان الأخرى وخارجها إذا تم التقيد بنهج بيانات التدريب المعمول بها.

المصادقة على مؤشر الجفاف المركب المحدث (eCDI) لاستخدامه في مراقبة المناطق الرعوية في المغرب

من نوفمبر ٢٠٢٠ إلى مارس ٢٠٢١، قام مسؤولو الحكومة المحلية المغربية بتقييم دقة الخرائط الشهرية لمؤشر الجفاف المركبٍ المحدث (eCDI) فيما يتعلق بشدة الجفاف والنطاق الجغرافي في المناطق الرعوية التي رصدوها. كما قدموا معلومات عن أكثرالمواقع تضرراً ، فضلاً عن حالة الكتلة الحيوية السنوية والدائمة (بما في ذلك أدلة التدهور أو التجدد) ، وتحميل الماشية ، والإجهاد الحراري ، والغطاء الثلجي ، وحركات رعاة الانتجاع غير العادية. و لقد غطى هذا التحقق مناطق المراعي الرئيسية- أكثر من ١٩٠٠٠٠٠ هكتار في المناطق البيولوجية المناخية القاحلة وشبه القاحلة وشبه الرطبة- ووفر وسيلة مهمة لربط توليد البيانات بالظروف الميدانية وأولئك الذين يشرفون عليها.

بشكل عام ، اعتبر المدققون أن مؤشر الجفاف المركب المحدث (eCDI) دقيق بنسبة ٧٣ ٪ (متوسط الدقة المسجلة لجغرافيا الجفاف وشدة الجفاف) ، بنسب تتراوح من ٥٧ ٪ إلى ٨٣ ٪ اعتمادًا على المنطقة الرعوية المحددة والشهر. وسجلت أدنى درجات الدقة في مناطق الغابات في بني ملال خنيفرة وفاس مكناس والمناطق المتضررة من الغطاء الثلجي. وبلغت القيم المسجلة لشهري ديسمبر ومارس نسبة ٩٧٪ مرتبطة بجميع أشهر الموسم ، مما يظهر توافقًا قويًا مع محفّز مؤشر الجفاف المركب المحدث (eCDI) التراكمي.

تشير هذه النتائج، وتقييم مؤشر الجفاف المركب المحدث (eCDI) التراكمي فيما يتعلق بإنتاج الشعير، إلى أن مؤشر الجفاف المركب المحدث (eCDI) مفيد بشكل عام لدعم رصد حالة المراعي في أهم المناطق القاحلة وشبه القاحلة، كما أنها تُظهر بعض التغييرات البسيطة في حساباتها (على سبيل المثال ، إخفاء الغابات والمناطق الثلجية) التي يمكن أن تؤدي إلى زيادة تحسينات في دقة مخرجات مؤشر الجفاف المركب المحدث (eCDI) للمناطق الرعوية.

تطوير وإضفاء الطابع المؤسسي على القدرة على رصد الجفاف

وكان أحد مجالات التركيز الأساسية لتصميم النظام وما يتصل به من ارتباطات هو أن تؤدي النواتج وظيفتها وتدعم عملية صنع القرار لدى الوكالات بعد الانتهاء من مشروع منطقة الشرق الأوسط وشمال إفريقيا للجفاف (MENAdrought). و يتم تحقيق ذلك من خلال خيارات مدخلات البيانات، ومن خلال بناء القدرات ونقل التكنولوجيا وإضفاء الطابع المؤسسي على الأدوات والمهارات المستحدثة. فعلى سبيل المثال، اختيرت بيانات المدخلات استنادا إلى معايير مختلفة مثل كون البيانات مجانية، وطول سجل البيانات المتاحة، وقنوات الاستشعار الإشعاعي التي يمكن أن تكشف مؤشرات الجفاف الرئيسية، وتحديد المكان والزمان، والتزام مقدمي البيانات بالمحافظة على نظم التزويد الخاصة بهم. واستندت التطورات التي شهدتها المبادرة في حد ذاتها إلى تقييم صريح

ومتكرر لاحتياجات البلدان الشريكة وعملياتها التعاونية. وقد دعم هذا الجهد الاجتماعي والتقني تطوير المشروع لنظم الإنذار المبكر بالجفاف وتفعيلها، بما في ذلك من خلال التخطيط لإدارة الجفاف الوارد وصفه في تقرير الركيزة ٣ ذات الصلة.

وشملت هذه الجهود استهداف دراسات التحقق مع الشركاء المحليين، والمشاركة في تطوير الأدوات التقنية ، وجهود البحث المرتبطة بها من أجل تحقيق أهداف محددة لتنفيذ السياسات في بلدان المشروع. فعلى سبيل المثال ، ركزنا بشدة ، في الأردن، على ضمان أن نظام الإنذار المبكر يمكن أن يدعم تنفيذ سياسة قطاع المياه لإدارة الجفاف وبناء فهم مشترك لأداة مؤشر الجفاف المركب المحدث (eCDI) عبر الوكالات والفرق ذات الصلة التي لها أدوار فنية وتنسيقية وصياغة القرار. وعلى غرار ذلك، في المغرب، ركزت جهود التنمية التعاونية على دعم تنفيذ الأنظمة القانونية الجديدة (أي قانون المياه ٣٦-١٥ وقانون المراعي ١١٣-١٣ ، وكلاهما من سنة ٢٠١٦)، بما في ذلك من خلال دعم زيادة التفاعل والتعاون وتبادل المعلومات بين الحكومات المركزية والمحلية.

ودعمنا مختلف نُهج بناء القدرات من خلال التدريب ونقل التكنولوجيا وتحسين النمذجة المتكررة. وشملت هذه الأنشطة جميع الجوانب التقنية اللازمة لإنتاج مؤشر الجفاف المركب المحدث (eCDI) من الناحية التشغيلية واستخدامها بفعالية:

- تركيب النموذج ، وتحديد المعايير ، والمعايرة ؛
- إعداد البيانات المدخلة والمعالجة المسبقة وتنفيذ النموذج ؛
- تفسير المخرجات والتحقق من صحتها؛
- تبادل المعلومات.

ولقد ركزنا بشكل خاص على تبسيط وتسريع عمليات تنفيذ النموذج ، في المقام الأول من خلال تبسيط إعداد بيانات المدخلات وأطر المعالجة المسبقة و الترميز لتشغيل النموذج. في كثير من الحالات ، تطلب ذلك أساليب وأطر ترميز جديدة لمعالجة القضايا التي تم تحديدها من خلال التشغيل المستمر لمؤشر الجفاف المركب المحدث (eCDI) بمرور الوقت. كما تضمنت تدريب المسؤولين الذين يضطلعون بأدوار تقنية وسياساتية في استخدام هذه المعلومات لتقييم آثار الجفاف وقابلية التأثر به؛ فضلا عن عمليات تخطيط إدارة الجفاف والتطبيقات ذات الصلة.

و بالإضافة إلى تنمية القدرات البشرية والتقنية ، سعينا إلى ضمان استدامة المشروع من خلال إضفاء الطابع المؤسسي على الطلب على أدوات الإنذار المبكر. و لقد تحقق ذلك في المقام الأول من خلال تخطيط سياسة إدارة الجفاف الذي ورد وصفه في تقرير الركيزة ٣.

و حددت عملية تقييم الاحتياجات الحواجز التي تحول دون تبادل المعلومات باعتبارها مشكلة رئيسية في الترتيبات القائمة لرصد الجفاف وإدارته. و لقد سعينا إلى معالجة ذلك من خلال تحديد الأولويات بعناية لمعلومات مراقبة الجفاف المطلوبة من خلال تخطيط إدارة الجفاف، وإنشاء واجهة على الإنترنت، ودعم دمج مؤشر الجفاف المركب المحدث (eCDI) في أدوات أخرى ، أو ببساطة النشر المفتوح للنتائج ، وهو ما تفعله الوكالات المغربية الآن بانتظام. و لكن على نطاق أوسع، فإن جهود التحقق من صحة مؤشر الجفاف المركب المحدث (eCDI)، ولا سيما إنشاء شبكة من المدققين الإقليميين ، تدعم هدف إضفاء الطابع المؤسسي على رصد الجفاف والإنذار المبكر ضمن إطار الركائز الثلاث.

فرص الأبحاث من أجل التنمية المستقبلية

نقترح العديد من الفرص المحتملة للأبحاث من أجل التنمية التي تعتمد على الإنجازات التقنية لمنطقة الشرق الأوسط وشمال إفريقيا للجفاف (MENAdrought)، فضلاً عن فرصة تكرار أنظمة الإنذار المبكر بالجفاف في بلدان أخرى في منطقة الشرق الأوسط وشمال إفريقيا وخارجها. و تركز فرص الأبحاث هذه على رسم خرائط للجفاف وأدوات التنبؤ الخاصة بقطاعات محددة. و تتعلق الأدوات الأخيرة بشكل خاص بإنتاج المحاصيل و بإنتاج المحاصيل وجريان هطول الأمطار (تدفق المجاري) المرتبطة برسم خرائط أنواع المحاصيل ، والتنبؤ الموسمي ، وتطوير منصات تبادل المعلومات ذات الصلة. وستمكّن من توسيع أنظمة الإنذار المبكر بالجفاف لتشمل عناصر الأمن الغذائي والمائي ذات الصلة ، وربما عناصر المخاطر الاقتصادية والمالية المرتبطة بها أيضا.

ومع ذلك، ومع تغير الظروف المناخية التي تؤدي إلى زيادة تواتر وشدة حالات الجفاف في منطقة الشرق الأوسط وشمال أفريقيا، وجب دمج أنشطة التكيف وتفعيلها في أطر صنع القرار الحكومية حتى يتسنى اتخاذ إجراءات في الوقت المناسب للحد من آثارها عبر المجتمعات المحلية. و يتطلب هذا أنشطة تتجاوز نطاق البحث؛ حيث يتطلب وضع سياسات وبرمجة للمساعدة التقنية يتم تجربتها واختبارها وتكون موثوقا بها، وهو، بشكل حاسم، جزء من تخطيط العمل المتعلق بالجفاف من قبل الوكالات الحكومية.

إن إنتاج البيانات من خلال أنظمة الإنذار المبكر لايمثل سوى الخطوة الأولى. حيث يجب استخدام النظم بطريقة منسقة عبر وزارات متعددة، على الرغم من التحديات المصاحبة، لتحقيق أهداف المساهمات المحددة وطنيا في اتفاقية الأمم المتحدة الإطارية بشأن تغير المناخ. وهذا يتطلب التزاما طويل الأجل بدعم الوكالات الحكومية الرئيسية والمؤسسات الناشئة لإدارة الجفاف التي تشرف على إجراءات التأهب للجفاف والتخفيف من حدته والتصدي له.

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[٤] انظرمؤشر الجفاف المركب Indice Composite de la Sècheresse

Résumé analytique

Objectif

Le présent rapport (Pilier 1) fait la synthèse du développement d'outils et de capacités de surveillance de la sécheresse, d'alerte précoce et de prévision saisonnière dans les pays participant au projet de la région du Moyen-Orient et de l'Afrique du Nord sur la Sécheresse (MENADrought), à savoir la Jordanie, le Liban et le Maroc. Il met l'accent sur la façon dont l'équipe de MENAdrought et les partenaires nationaux ont, de manière collaborative et itérative, élaboré, mis à l'essai, perfectionné, appliqué et permis l'utilisation du produit de surveillance de la sécheresse, l'Indice Composite de Sécheresse Amélioré (eCDI), et les outils de prévision saisonnière dans chaque pays, ainsi que la manière dont ces technologies sont intégrées dans les institutions concernées. Toutefois, notre rapport ne présente que peu de détails techniques et de méthodes, car ils seront publiés séparément.

Ce rapport doit être lu conjointement avec le Rapport de Synthèse des Rapports de la Région du Moyen-Orient et de l'Afrique du Nord sur la Sécheresse (MENAdrought) concernant la vulnérabilité à la sécheresse pour chaque pays du projet (Rapports du Pilier 2 : Fragaszy et al. 2022a, 2022b) et la Synthèse du Rapport de la Région du Moyen-Orient et de l'Afrique du Nord sur la Sécheresse (MENADrought) sur le Développement de Plans d'Atténuation, de Préparation et de Gestion de la Réponse à la Sécheresse (Rapport du Pilier 3 : Jobbins et al. 2022). Les rapports du Pilier 2 détaillent les résultats du projet relativement aux causes sous-jacentes de la vulnérabilité aux impacts de la sécheresse dans chaque pays et servent de lien entre l'évaluation d'impact et la planification politique. Ils comprennent également les principaux résultats produits (les produits primaires produits) à l'aide de l'Indice Composite de Sécheresse Amélioré (eCDI), notamment l'historique des sécheresses qui ont sévi pendant la période 2000-2020 et les cartes des risques de sécheresse. Le rapport du Pilier 3 (Jobbins et al. 2022) décrit la planification de la gestion de la sécheresse entreprise dans le cadre du projet ainsi que les analyses spécifiques effectuées pour l'appuyer.

Exigences et approche du développement de l'Indice Composite de Sécheresse Amélioré (eCDI)

Dans chaque pays, les agences gouvernementales et les autres parties prenantes ont énoncé les exigences relatives aux systèmes et outils de surveillance et de gestion de la sécheresse, y compris l'eCDI en particulier. Cela s'est produit dans le cadre du processus d'évaluation des besoins communiqué par Fragaszy et al. (2020) et Jedd et al. (2020), ainsi que des engagements subséquents pendant le programme MENAdrought (la Région du Moyen-Orient et de l'Afrique du Nord sur la Sécheresse). Ces besoins comprenaient:

- **Les exigences temporelles de sortie:** Production rapide et fréquente de l'eCDI - au moins une fois par mois - et faible latence, de sorte que, par exemple, les conditions de décembre soient signalées début janvier.
- **Les exigences spatiales de sortie:** Résolution spatiale suffisamment élevée pour saisir les principaux bassins agricoles et hydrologiques et les changements dans les zones agroécologiques.
- **Facilité de production et d'utilisation:** L'indicateur doit pouvoir être produit par les agences nationales tout en étant compatible avec leurs exigences en matière de calcul et de modélisation, de largeur de bande Internet, de capacités et de compétences du personnel technique et de configurations institutionnelles.
- **L'accent est d'abord mis sur la surveillance de la sécheresse agricole, en particulier dans les systèmes pluviaux:** Principalement les céréales pluviales et les terres de parcours, ainsi que les olives et les légumineuses, qui constituent la base des systèmes agricoles des petits exploitants de la région.
- **Exactitude et précision adéquates pour la prise de décision en matière de politique de gestion de la sécheresse:** Les parties prenantes doivent avoir confiance dans les informations produites pour soutenir les décisions qui ont des ramifications politico-économiques majeures.

En conséquence, le codéveloppement de l'eCDI s'est déroulé en trois étapes principales, au cours desquelles les partenaires nationaux de MENAdrought - le Ministère de l'Eau et de l'Irrigation (MWI) et le Département météorologique jordanien (JMD) en Jordanie, le Ministère de l'Energie et de l'Eau (MoEW) au Liban, et la Direction de la

Stratégie et des Statistiques (DSS) du Ministère de l'Agriculture (MoA) au Maroc - ont été étroitement impliqués ou ont mené des groupes de travail centraux:

- Étape 1 (2016-2017): Mise en place du cadre de modélisation et production de l'eCDI "par défaut" (Bijaber et al. 2018) pour chaque pays du projet.
- Étape 2 (2018-2019): Validation des données d'entrée et validation et calibrage des données de sortie du modèle dans chaque pays du projet.
- Étape 3 (2019-aujourd'hui): Raffinement du modèle, amélioration des processus, formation et renforcement des capacités pour permettre la production opérationnelle et l'utilisation des informations par les partenaires nationaux.

Composition et production de l’eCDI

Nous avons co-développé un eCDI que les agences gouvernementales en Jordanie et au Maroc produisent maintenant indépendamment - leur propre personnel sur leurs propres serveurs - et nous prévoyons que les agences libanaises seront également en mesure de le faire d'ici la fin de 2022, à condition que les conditions dans ce pays, principalement la disponibilité de l'électricité et de l'Internet, permettent l'installation finale du système. L'eCDI est un indicateur spatialisé et pondéré produit à partir d'une combinaison de données de télédétection et de modélisation environnementale. Il est basé sur les anomalies par rapport aux conditions moyennes depuis 2000 pour un mois spécifique et une grille spécifique de 5 x 5 km:

- Indice standardisé des précipitations sur 3 mois (SPI, pondération de 40 %)
- Indice de végétation par différence normalisée (NDVI, 20 %) ;
- Anomalie de l'humidité du sol dans la zone racinaire (SMA, 20 %) ; et
- Anomalie d'amplitude de la température de surface jour-nuit (LST, 20 %).

Suite à l'intégration, les valeurs eCDI pour chaque pixel sont répertoriées selon les percentiles dans l'une des classes suivantes: pas de sécheresse, sécheresse modérée, sécheresse sévère ou sécheresse extrême.

Validation et perfectionnement de l'eCDI, processus de production, interface Web et possibilités d'amélioration à court terme

Le processus itératif de développement de l'eCDI a incorporé des composants de validation quantitatifs et qualitatifs pour l'exactitude des données modélisées et de l'eCDI dans son ensemble, et pour soutenir les améliorations ultérieures. Ces évaluations initiales comprenaient:

- La relation avec la production et les rendements céréaliers;
- La comparaison avec les données d'observation disponibles;
- L'évaluation de la performance en fonction de la couverture et de l'utilisation des terres; et
- L'évaluation qualitative de la performance de l'eCDI avec les principales parties prenantes.

L'eCDI a montré une meilleure relation avec les données de production et de rendement des céréales que les seules précipitations, ce qui constitue un aspect essentiel de sa légitimité auprès des responsables gouvernementaux et les autres parties prenantes. Les informations sur les précipitations dérivées des satellites utilisées dans l'eCDI ont été comparées favorablement aux données de surveillance des précipitations des stations terrestres. En outre, les experts locaux ont largement considéré l'eCDI comme concordant avec leurs observations lorsque la validation locale a été entreprise au Maroc et en Jordanie.

Nous avons amélioré les performances de l'eCDI principalement en validant et en affinant les entrées de données, en ajoutant et en supprimant des composants et des entrées de modèle, en entreprenant un prétraitement supplémentaire des données et en modifiant le calcul de l'eCDI pour réduire les erreurs dues à la couverture nuageuse et fournir des points de données supplémentaires (temporels et spatiaux) pour les calculs de l'eCDI à l'aide d'une technique de fenêtre coulissante. Les améliorations de la modélisation comprenaient l'utilisation du modèle de phénologie dynamique dans Noah-MP afin d'améliorer les calculs de l'humidité du sol. Nous avons également modifié les sources de données pour deux des indices d'entrée en raison de l'arrêt prévu d'une mission satellite.

Nous avons simplifié le système de modélisation de sorte que presque tous les processus sont entrepris via un flux de travail reproductible. Cela permet de produire des cartes mensuelles de la sécheresse dans les 10 jours suivant le début du mois et de s'assurer que les agences sont en mesure de poursuivre la production de l'eCDI de manière indépendante au-delà de la durée du projet MENAdrought financé par l'UE. De même, nous avons développé une interface utilisateur web qui permet diverses agrégations temporelles et spatiales des statistiques de l'eCDI afin de faciliter l'exploration des conditions actuelles par rapport aux événements passés et de soutenir la prise de décision.

Les possibilités d'amélioration de l'eCDI à court terme comprennent la mise en place de réseaux de soutien et de mécanismes d'engagement des utilisateurs/parties prenantes. En Jordanie et au Maroc, les agences gouvernementales ont soutenu le développement de réseaux de validation composés de fonctionnaires des agences gouvernementales locales (et éventuellement de la société civile) qui évalueront les conditions de sécheresse locales et commenteront l'exactitude perçue des résultats de l'eCDI. Cela permettra d'améliorer le système d'alerte précoce à la sécheresse et les plans de gestion de la préparation, de l'atténuation et de la réponse à la sécheresse au fil du temps.

Élaboration de déclencheurs de sécheresse en soutien aux décisions politiques

Afin de développer des seuils de déclenchement pour les actions de gestion de la sécheresse décrites dans le rapport du Pilier 3, nous avons évalué les résultats de l'eCDI d'un point de vue statistique et par rapport à la production et au rendement des cultures pluviales annuelles de base. Cela a permis de développer trois types de déclencheurs:

- Des déclencheurs eCDI spécifiques à la saison pour chaque pays;
- Pour le Maroc, un "eCDI cumulatif" basé sur les valeurs de l'eCDI en décembre et en mars; et
- Un Indice de Sévérité et de Couverture de la Sécheresse (DSCI) pour le Liban.[5]

L'eCDI cumulé est basé sur l'agrégation temporelle des scores eCDI mensuels au cours d'une année hydrologique afin de produire une valeur unique pour chaque province/gouvernorat, qui peut ensuite être agrégée spatialement. L'évaluation utilisée pour produire ce déclencheur a montré que les valeurs eCDI cumulées sont fortement corrélées avec la production d'orge, que nous considérons comme un indicateur pertinent de la production annuelle des espèces de parcours, et plus largement des céréales pluviales.

Le DSCI regroupe la couverture spatiale des scores eCDI pour permettre des évaluations de l'intensité de la sécheresse qui soient modulables dans l'espace et dans le temps. Elle peut être utilisée à l'échelle provinciale ou nationale, et les scores peuvent être évalués mois par mois ou de manière continue sur une année (ou plusieurs années) donnée(s).

Les déclencheurs eCDI spécifiques à la saison et cumulatifs reflètent tous deux les relations entre les valeurs eCDI au cours de mois spécifiques et la production et les rendements annuels des cultures de base. Les déclencheurs saisonniers n'intègrent aucune pondération pour les valeurs mensuelles de l'eCDI, tandis que l'eCDI cumulatif marocain intègre un système de pondération statistique (régression progressive) pour les valeurs de l'eCDI de décembre et mars d'une année donnée. Les seuils de déclenchement de l'indice DSCI sont calculés statistiquement par rapport aux valeurs les plus élevées des 20 dernières années.

Prévision des précipitations saisonnières

L'équipe MENAdrought a développé des modèles de réseaux neuronaux convolutifs (CNN), une approche d'intelligence artificielle, afin d'améliorer les prévisions de précipitations globales en relation avec les pays du projet. Nous avons entraîné les modèles CNN avec des données d'observation de la période 2000-2014 et appliqué des techniques de régionalisation pour la période de test 2015-2022.

Malgré l'utilisation d'un seul type de prédicteur (prévisions de précipitations provenant de quatre centres de modélisation mondiaux), notre première tentative de modèle CNN pour le Maroc a permis de prévoir avec précision les précipitations avec un délai de 2 à 3 mois. Les sorties des modèles CNN ont montré une amélioration majeure par rapport aux prévisions globales en termes de localisation spatiale des précipitations ainsi que de volume et d'anomalies.

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[5] Il convient de noter que le développement du déclencheur DSCI était expérimental et qu'il n'est pas inclus dans le plan d'action libanais contre la sécheresse décrit dans le rapport du Pilier 3.

Par la suite, nous avons amélioré les résultats au Maroc en ajoutant des variables prédictives de la température de surface de la mer. En Jordanie, nous avons amélioré les résultats en ajoutant les prévisions de précipitations d'un autre centre de modélisation mondial en tant que prédicteur et en entraînant les modèles CNN en parallèle en fonction des groupes de régions climatiques; en bref, nous avons entraîné le modèle en utilisant les données de la région climatique plus humide des hauts plateaux et, en parallèle, en utilisant les données des régions climatiques arides et de Badia. Les modèles CNN sont exécutés d'abord pour les hautes terres, puis pour les autres régions, et les résultats sont ensuite combinés pour former la prévision finale.

Les modèles CNN ont prévu avec précision l'emplacement et le moment de l'apparition et de la reprise de la sécheresse (en utilisant l'indice SPI) au Maroc en 2015-2016 et 2021-2022. Dans l'ensemble, les prévisions à deux mois produites par les CNN présentaient une très forte corrélation avec les précipitations observées (CHIRPS) dans les régions subhumides du Maroc, avec une valeur r de 0,93, et une faible corrélation dans les régions arides, avec une valeur r de 0,43.

Au Liban, cependant, l'inclusion de variables prédictives supplémentaires n'a pas amélioré les résultats de manière substantielle. Des recherches supplémentaires sont nécessaires pour identifier les variables prédictives utiles et entreprendre la formation de modèles parallèles.

Exploration de l'eCDI et de la prévision des débits d'eau

Compte tenu du succès des prévisions de précipitations au Maroc, l'équipe MENAdrought a exploré la possibilité de prévoir l'eCDI en utilisant les sorties CNN pour forcer le modèle des Systèmes d'information sur les sols (LIS). Cela a présenté de nombreux défis techniques étant donné que le modèle LIS nécessite des entrées infra-quotidiennes à une résolution spatiale fine. Alors que le moment des précipitations au cours de la période n'est pas pertinent pour le SPI, il est évidemment essentiel pour les interactions entre la surface terrestre et la subsurface. Compte tenu de ce problème et de la difficulté de prévoir la température et le rayonnement solaire descendant avec une telle précision temporelle, les résultats obtenus jusqu'à présent ont été infructueux, en particulier en ce qui concerne l'humidité du sol.

Nous suggérons que les futurs efforts de développement pour la prévision des sécheresses agricoles et météorologiques au-delà de l'indice SPI dans les pays du projet se concentrent sur les indices basés sur les précipitations et la température (tels que l'indice standardisé de précipitation et d'évapotranspiration, SPEI) plutôt que d'utiliser des modèles complexes de surface terrestre pour produire des indices tels que l'indice SMA.

Outre la prévision des sécheresses, nous avons mené des recherches pilotes pour utiliser les sorties de précipitations du CNN afin de forcer les modèles de débit d'eau. L'équipe MENAdrought a paramétré le modèle couplé LIS/ WRF-Hydro Weather Research Forecast (WRF) pour le bassin d'Oum Errabiâ au Maroc et a simulé le débit des cours d'eau sur la période 2000-2015. Les simulations du modèle reflètent la tendance des débits observés pendant les années normales et les années de sécheresse au cours de cette période, bien qu'il y ait des différences dans le temps et dans l'ampleur, en particulier pendant les épisodes de débit élevé.

Développement pilote d'un logiciel opérationnel de cartographie des types de cultures

Nous avons également développé un logiciel opérationnel pour la cartographie des types de cultures qui est destiné à être facilement utilisable par le personnel du ministère marocain de l'agriculture dans plusieurs applications pour:

- accroître la précision des statistiques annuelles relatives au rendement agricole,
- soutenir la prise de décision concernant les mesures de réponse à la gestion de la sécheresse dans les principaux systèmes de cultures pluviale et irriguée,
- diriger des équipes de vérification sur le terrain pour étudier les impacts de la sécheresse sur les dommages aux céréales avec la Mutuelle Agricole Marocaine d'Assurance (MAMDA) et la banque agricole Crédit Agricole du Maroc (CAM), et
- permettre les développements futurs associés au système de surveillance et d'alerte précoce de la sécheresse, y compris la cartographie thématique des risques de sécheresse et la prévision des rendements des cultures de base.

Le logiciel avancé d'apprentissage automatique développé pour le Maroc et testé dans la zone bioclimatique "intermédiaire" autour de Rabat utilise l'imagerie satellite Sentinel à source ouverte pour identifier plus de 80 classes de cultures. À ce jour, ce sont les grandes cultures annuelles qui ont connu le plus de succès, et les travaux futurs viseront à améliorer les résultats pour les vergers. À l'avenir, cette approche pourrait être utilisée dans les autres pays et au-delà si les approches établies en matière de données de formation sont respectées.

Validation de l'eCDI pour la surveillance des zones pastorales au Maroc

De novembre 2020 à mars 2021, les fonctionnaires locaux marocains ont évalué la précision des cartes eCDI mensuelles par rapport à la gravité de la sécheresse et à l'étendue géographique dans les zones pastorales qu'ils surveillaient. Ils ont également fourni des informations sur les localités les plus touchées, ainsi que sur l'état de la biomasse annuelle et pérenne (y compris les preuves de dégradation ou de régénération), le chargement en bétail, le stress thermique, la couverture neigeuse et les mouvements transhumants inhabituels. Cette validation a couvert les principales zones de parcours - plus de 1 900 000 ha dans les zones bioclimatiques arides, semi-arides et subhumides - et a fourni un moyen important de relier la production de données aux conditions sur le terrain et à ceux qui les supervisent.

Dans l'ensemble, les validateurs ont jugé que l'eCDI était précis à 73 % (en faisant la moyenne de la précision rapportée pour la géographie de la sécheresse et l'intensité de la sécheresse), avec une fourchette allant de 57 % à 83 % en fonction de la zone pastorale spécifique et du mois. Les précisions les plus faibles ont été trouvées pour les zones forestières dans les régions de Beni Mellal-Khénifra et Fès-Meknès et les zones affectées par la couverture neigeuse. Les valeurs rapportées pour les mois de décembre et mars étaient corrélées à 97% avec tous les mois de la saison, ce qui montre un fort alignement avec le déclenchement cumulatif de l'eCDI.

Ces résultats, ainsi que l'évaluation de l'eCDI cumulé en relation avec la production d'orge, suggèrent que l'eCDI est largement utile pour soutenir le suivi (la surveillance) des conditions des pâturages dans les zones arides et semi-arides les plus importantes. Ils montrent également que quelques modifications simples de son calcul (par exemple, masquer les forêts et les zones enneigées) pourraient améliorer progressivement la précision des résultats de l'eCDI pour les zones pastorales.

Développement et institutionnalisation de la Capacité de Surveillance de la Sécheresse

L'un des objectifs principaux de la conception du système et des engagements associés était que les résultats fonctionnent et soutiennent la prise de décision des agences après la fin du projet MENAdrought. Cet objectif est atteint grâce au choix des données d'entrée et au renforcement des capacités, au transfert de technologie et à l'institutionnalisation des outils et des compétences développés. Par exemple, les données d'entrée ont été choisies sur la base de divers critères tels que la gratuité des données, la longueur de l'enregistrement des données disponibles, les canaux de détection radiométrique qui peuvent détecter les indicateurs clés de la sécheresse, la résolution spatiale et temporelle, et l'engagement des fournisseurs de données à maintenir leurs systèmes d'approvisionnement. Les développements de l'eCDI ont eux-mêmes été étayés par une évaluation explicite et itérative des besoins des pays partenaires et des processus de collaboration. Cet effort social et technique a soutenu le développement de systèmes d'alerte précoce à la sécheresse et leur opérationnalisation, notamment par le biais de la planification de la gestion de la sécheresse décrite dans le rapport associé du Pilier 3.

Ces efforts ont consisté à cibler les études de validation avec les partenaires locaux, le codéveloppement d'outils techniques et les efforts de recherche associés sur des objectifs spécifiques de mise en œuvre des politiques dans les pays concernés par le projet. Par exemple, en Jordanie, nous avons veillé à ce que le système d'alerte précoce puisse soutenir la mise en œuvre de la politique de gestion de la sécheresse dans le secteur de l'eau et à ce que l'outil eCDI soit compris par toutes les agences et équipes concernées qui jouent un rôle technique, de coordination et d'encadrement des décisions. De même, au Maroc, les efforts de développement collaboratif se sont concentrés sur le soutien à la mise en œuvre de nouveaux régimes juridiques (à savoir la Loi sur l'Eau 36-15 et la Loi sur les Pâturages 113-13, toutes deux datant de 2016), notamment en soutenant une interaction, une collaboration et un partage d'informations accrus entre le gouvernement central et les autorités locales.

Nous avons soutenu diverses approches de renforcement des capacités par le biais de la formation, du transfert de technologie et de l'amélioration itérative de la modélisation. Celles-ci couvraient tous les aspects techniques nécessaires à la production opérationnelle et à l'utilisation efficace de l'eCDI:

- Installation, paramétrage et étalonnage du modèle ;
- Préparation des données d'entrée, prétraitement et exécution du modèle ;
- Interprétation et validation des résultats ; et
- Partage de l'information.

Nous nous sommes concentrés en particulier sur la simplification et l'accélération des processus d'exécution du modèle, principalement en rationalisant la préparation des données d'entrée, le prétraitement et les cadres de codage pour faire fonctionner le modèle. Dans de nombreux cas, cela a nécessité de nouvelles méthodes et de nouveaux cadres de codage pour résoudre les problèmes identifiés par l'exploitation continue de l'eCDI au fil du temps. Il s'agissait également de former les fonctionnaires jouant un rôle technique et politique dans l'utilisation de ces informations pour l'évaluation de l'impact de la sécheresse et de la vulnérabilité, ainsi que pour la planification de la gestion de la sécheresse et les applications connexes.

Outre le développement des capacités humaines et techniques, nous avons cherché à assurer la durabilité du projet par l'institutionnalisation de la demande d'outils d'alerte précoce. Cet objectif a été atteint principalement grâce à la planification de la politique de gestion de la sécheresse décrite dans le rapport Pilier 3.

Le processus d'évaluation des besoins a identifié les obstacles relativement au partage de l'information comme un problème clé pour les dispositifs existants de surveillance et de gestion de la sécheresse. Nous avons cherché à résoudre ce problème en hiérarchisant soigneusement les informations de surveillance de la sécheresse nécessaires à la planification de la gestion de la sécheresse, en créant une interface web, en soutenant l'intégration des résultats de l'eCDI dans d'autres outils, ou simplement en publiant ouvertement les résultats, ce que les agences marocaines font désormais régulièrement[6]. De manière plus générale, les efforts de validation de l'eCDI, et en particulier la création d'un réseau de validateurs régionaux, soutiennent l'objectif d'institutionnalisation de la surveillance de la sécheresse et de l'alerte précoce dans le cadre des 3 Piliers.

Recherche future pour les opportunités de développement

Nous suggérons plusieurs possibilités de recherche pour le développement qui s'appuieraient sur les réalisations techniques de MENAdrought, ainsi que sur la possibilité de reproduire les systèmes d'alerte précoce à la sécheresse dans d'autres pays de la région MENA et au-delà. Ces opportunités de recherche se concentrent sur les outils de cartographie et de prévision de la sécheresse spécifiques à un secteur. Ces derniers outils concernent en particulier la production agricole et la modélisation du ruissellement pluvial (débit) liée à la cartographie des types de cultures, aux prévisions saisonnières et au développement de plateformes de partage d'informations associées. Ils permettraient d'étendre les systèmes d'alerte précoce à la sécheresse pour couvrir les éléments liés à la sécurité alimentaire et à la sécurité de l'eau et, éventuellement, les éléments associés aux risques économiques et financiers.

Cependant, les changements climatiques entraînant une augmentation de la fréquence et de l'intensité des sécheresses dans la région MENA, les activités d'adaptation doivent être intégrées et mises en œuvre dans les cadres décisionnels des gouvernements afin que des mesures soient prises en temps voulu pour réduire les impacts sur les communautés. Cela nécessite des activités allant au-delà de la recherche ; il faut élaborer des politiques et des programmes d'assistance technique éprouvés, testés et fiables et, surtout, faire partie des plans d'action contre la sécheresse, élaborés par les agences gouvernementales.

La production de données par le biais de systèmes d'alerte précoce n'est qu'une première étape. Les systèmes doivent être utilisés de manière coordonnée par plusieurs ministères, malgré les difficultés qui en découlent, afin d'atteindre les objectifs des contributions déterminées au niveau national à la Convention-cadre des Nations unies sur les changements climatiques. Cela nécessite un engagement à long terme pour soutenir les agences gouvernementales clés et les institutions émergentes de gestion de la sécheresse qui supervisent les actions de préparation, d'atténuation et de réponse à la sécheresse.

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[6] voyez L'Indice Composite de la Secheresse

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List of Acronyms

ABH	Agence de Bassin Hydraulique (Morocco)
ASI	Agricultural Stress Index
CAM	Crédit Agricole du Maroc
CHIRPS	Climate Hazards Group InfraRed Precipitation with Station data
CNCT	Centre National de la Cartographie et la Télédétection (Tunisia)
CNN	Convolutional Neural Network
CNRS	National Council for Scientific Research (Lebanon)
CRTS	Centre Royal de Télédétection Spatiale (Morocco)
DAP	Drought Action Plan
DGCA	Directorate General of Civil Aviation (Lebanon)
DGE	Direction Générale de l'Eau (Morocco)
DGF	Direction Générale des Forêts (Tunisia)
DGRE	Direction Générale des Ressources en Eau (Tunisia)
DMN	Direction de la Météorologie Nationale (Morocco)
DSCI	Drought Severity and Coverage Index
DSS	Directorate of Strategy and Statistics (Morocco)
eCDI	enhanced Composite Drought Indicator
ECMWF	European Centre for Medium-Range Weather Forecasts
ENSO	El Niño/Southern Oscillation
eVIIRS	EROS Visible Infrared Imaging Radiometer Suite
FCDO	Foreign, Commonwealth & Development Office
IMERG	Integrated Multi-satellite Retrievals for GPM
INRA	Institut National de la Recherche Agronomique (Morocco)
INM	Institut National de la Météorologie (Tunisia)
IWMI	International Water Management Institute
JMD	Jordanian Meteorological Department
JVA	Jordan Valley Authority
LARI	Lebanese Agricultural Research Institute
LIS	Land Information System
LRA	Litani River Authority
LST	Land Surface Temperature
MAMDA	Mutuelle Agricole Marocaine D'Assurance
MENA	Middle East and North Africa
MO	Mediterranean Oscillation
MoA	Ministry of Agriculture (Morocco)
MoEW	Ministry of Energy and Water (Lebanon)
MWI	Ministry of Water and Irrigation (Jordan)
NAO	North Atlantic Oscillation
NCARE	National Center for Agriculture Research and Extension (Jordan)
NDVI	Normalized Difference Vegetation Index
NMME	North American Multi-Model Ensemble
SMA	Soil Moisture Anomaly
SPEI	Standardized Precipitation and Evapotranspiration Index
SPI	Standardized Precipitation Index
SSI	Standardized Streamflow Index
USAID	United States Agency for International Development
WMO	World Meteorological Organization

1. Introduction

The MENAdrought project works in Jordan, Lebanon and Morocco and uses the Three Pillars approach of the Integrated Drought Management Program (IDMP) to improve overall drought management (WMO and GWP 2014). The three pillars are:

1. Drought monitoring and early warning systems;
2. Impact and vulnerability assessments; and
3. Mitigation, preparedness and response planning.

This report focuses on the Pillar 1 components. However, it also describes linkages between the developed eCDI and drought impact and vulnerability assessments (Pillar 2 reports: Fragaszy et al. 2022a, 2022b; Belhaj Fraj et al. 2022a; and Pillar 3 report: Jobbins et al. 2022), as well as drought management planning. It also provides a technical overview of methods and results—the details of which are intended for publication elsewhere (Bergaoui et al. forthcoming). Likewise, it describes the capacity and capability development components related to the drought early warning system.[7]

This section describes the MENAdrought national stakeholders' drought monitoring needs and the resultant eCDI development work. The rest of the report is structured as follows:

- Section 2: Technical composition and production of the eCDI, its validation and usage;
- Section 3: Seasonal forecasting and future eCDI development;
- Section 4: Development and institutionalization of drought monitoring capabilities;
- Section 5: Future research-for-development opportunities; and
- Annexes providing additional background information, and detailed results and figures.

This report does not show eCDI-based drought history or impact information; that can be found in the relevant drought vulnerability synthesis reports (Fragaszy et al. 2022a; 2022b; Belhaj Fraj et al. 2022a; IWMI and DSS 2022). Annex A provides background information on drought, its relationship to related concepts such as aridity, water scarcity and desertification, as well as drought types. This information may be useful to readers less familiar with drought and water management literature.

1.1 MENAdrought Pillar 1: The Problem Context

The WMO recommends use of the Standardized Precipitation Index (SPI) for meteorological drought monitoring because of its efficacy, simplicity to calculate, multiple time scales and space-time comparability (Sheffield et al. 2014). Most governments in the MENA region monitor drought operationally using the SPI (Bazza et al. 2018) calculated from agrometeorological observation sites.

However, the distribution and density of stations is generally insufficient to allow reliable spatialization, and most governments face other significant challenges in SPI production including data inaccessibility, temporal data gaps, short periods of record, lack of observation-site calibration and other data quality issues (Fragaszy et al. 2020). Acknowledging these issues—and recognizing opportunities to expand beyond precipitation monitoring—MENA governments requested technical support for improving drought monitoring and management at the WMO-convened High-Level Meeting on National Drought Policy in 2013. Individual countries reiterated this need at a conference convened by the Food and Agriculture Organization of the United Nations (FAO) in Cairo in 2015.

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[7] The drought early warning system comprises the drought monitoring and seasonal forecasting tools described in this report, as well as impact monitoring, which is described in the Pillar 3 report.

The MENAdrought project is a result of this request for technical cooperation, and the eCDI approach to drought monitoring and management is based on a convergence-of-evidence approach (Svoboda et al. 2002; Hayes et al. 2005), which is becoming increasingly common in national drought monitoring systems around the world (Pulwarty and Sivakumar 2014).

1.2 Drought Monitoring Needs

In project engagements, stakeholders described a wide range of needs to improve drought monitoring and early warning systems (Fragaszy et al. 2020). In sum, these needs relate to what information is produced, shared and used for decision-making.

In all project countries, the themes of relevance included the following needs: Drought definitions, information sharing mechanisms, ground-truthing of remote sensing-derived information, observation data quality challenges, and intersectoral engagement and interaction (that is, between government, water managers, farmers and other water stakeholders and users). Table 1 shows each country's initial needs relating to these themes. We provide more detail in Annex B regarding the summary themes as well as the entire set of results from each country.

Table 1. *Drought monitoring needs expressed by stakeholders in three MENAdrought countries.*

	Morocco	Jordan	Lebanon
Drought definitions	• Indicators for tiered drought definitions and interventions	• Clear technical definitions for drought • Government-wide consensus on indicators	• Create definitions for triggers of drought management or declaration mechanisms
Institutional analysis	• Address drought data purchase and political sensitivity barriers • Improve data availability for technical analysts • Data-sharing platform	• Formally regularize data-sharing agreements • Data purchase barriers • Data-sharing platform	• Formalize information networks • Data-sharing platform
Technical capacity	• Uniform data standards, including periodicity	• Improve technical capacity to use existing models and data • Validate remote-sensing data	• Ground-truth remote sensing data • Increase capacity for extension services to use information • Data quality improvements
Knowledge gaps	• Integrate drought monitoring with seasonal forecasting, rainfall runoff and groundwater recharge models	• Links with groundwater recharge and discharge • Link to crop planting and irrigation advice • Link to climate change adaptation and finance sector • Link to water pricing regimes	• Understand drought-crop connection • Improve understanding of connections between snowpack and drought
eCDI development	• Validate eCDI beyond rainfed crops and in more geographic areas	• Host in agency with remote sensing and Geographical Information System (GIS) capacity • Link with end-users • Open-source data • Appropriate time scales • Train other agencies and decision-makers to interpret eCDI • Make eCDI and input layers freely available	• Host should easily share information and act as data clearinghouse • Host should have strong GIS and remote sensing skills
Intersectoral engagement	• Develop network of eCDI evaluators	• Intragovernmental cooperative environment and coordination • Provide channels for two-way communication with farming organizations	• Create political demand and policy role for drought monitoring data • Find avenues to reach farmers and affected populations • Boost public awareness of drought

Source: Fragaszy et al. 2020.

1.3 National Partners' Requirements for the eCDI

Building on this information, government agencies and other stakeholders spelled out the requirements for drought monitoring and management systems and tools including the eCDI specifically. This occurred through the needs assessment process reported by Fragaszy et al. (2020) and Jedd et al. (2020), as well as subsequent engagements during the MENAdrought program. These needs included:

- **Output temporal requirements:** Rapid and frequent production of the eCDI—at least monthly —and low latency so that, for example, December conditions are reported in early January.

- **Output spatial requirements:** High enough spatial resolution to capture major agricultural and hydrological basins and shifts in agroecological zones.

- **Ease of production and use:** The indicator must be producible by national agencies while being compatible with their computing and modeling requirements, internet bandwidth, technical staff capacities and capabilities, and institutional setups.

- **Initial focus on monitoring agricultural drought, particularly in rainfed systems:** Primarily rainfed cereals and rangelands as well as olives and legumes, which are the basis of smallholder agricultural systems in the region.

- **Adequate accuracy and precision for drought management policy decision-making:** Stakeholders need confidence in the information produced to support decisions that have major political economic ramifications.

Accordingly, co-development of the eCDI occurred in three primary stages (Figure 1), during which the MENAdrought national partners—the Ministry of Water and Irrigation (MWI) and the Jordanian Meteorological Department (JMD) in Jordan, the Ministry of Energy and Water (MoEW) in Lebanon, and the Directorate of Strategy and Statistics (DSS) from the Ministry of Agriculture (MoA) in Morocco—were closely involved or led core workstreams:

- Stage 1 (2016-2017): Establishment of the modeling framework and production of the 'default' eCDI (Bijaber et al. 2018) for each project country.

- Stage 2 (2018-2019): Input validation and model output validation and calibration in each project country.

- Stage 3 (2019-present): Model refinement, process improvement and training and capacity-building to enable operational production and information use by national partners.

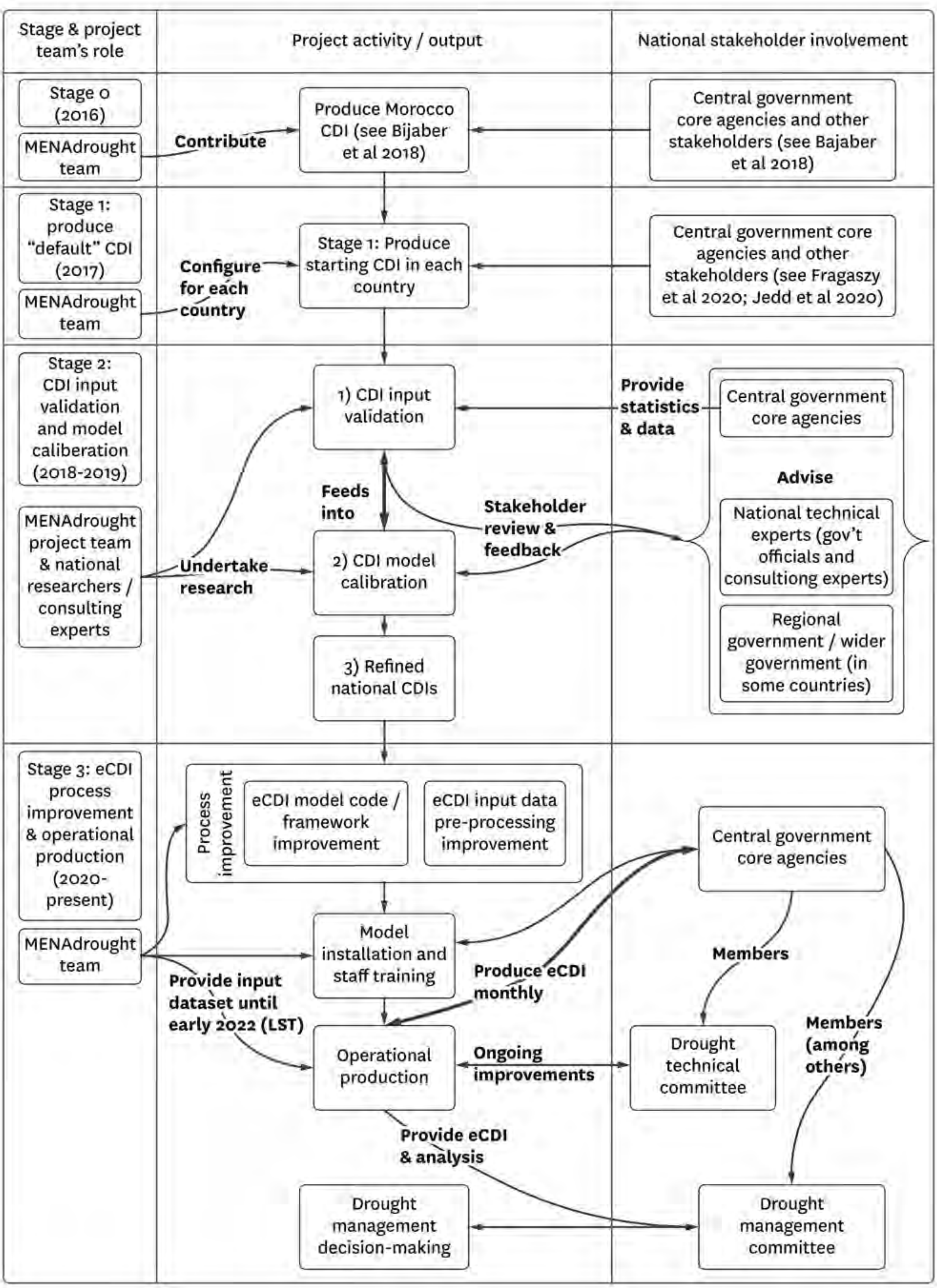

Figure 1. *Stages in the development of the operational eCDI.*

2. Technical Composition and Production of the eCDI, Its Validation and Usage

This section first describes the operational eCDI (Stage 3) currently in production by national agencies in Jordan and Morocco, and anticipated for Lebanon by the end of 2022 if local conditions permit. It then describes the early validation work and subsequent refinements that helped us reach the current eCDI product. Then we describe the monthly eCDI production process and the web interface for its use. Bergaoui et al. (forthcoming) present greater depth of description including more technical detail and theoretical discussion in relation to these three subsections. Lastly, we describe the development of 'drought triggers' for use in drought response management planning (Jobbins et al. 2022).

2.1 eCDI Composition and Integration

The operational eCDI requirements constrained our possible choices for eCDI development. These requirements meant that data inputs for the eCDI must have complete national coverage, both spatially and temporally, for the period of record, as well as frequent production and/or collation. Following reviews of data availability and accessibility in each country[8], we opted to rely entirely on satellite remote sensing and modeled data for operational eCDI production.

eCDI Inputs and Pre-processing. The operational eCDI in each country includes the following input indices:

- Three-month Standardized Precipitation Index (SPI);
- Normalized Difference Vegetation Index (NDVI);
- Root-zone soil moisture anomaly (SMA); and
- Day-night land surface temperature amplitude anomaly (hereafter, diurnal LST), which is a proxy for the evapotranspiration anomaly.

Annex C, Table C1 (Bergaoui et al. Forthcoming) summarizes the data used to produce each input index, additional data filtering or processing, data latency, temporal and spatial scale of data, and index calculation method.

eCDI Calculation and Ranking. Input index integration is a critical component of developing an eCDI. We used a linear model because it is effective, easy to understand and simple to calculate. We set the weights based on the following three components: experience (Bijaber et al. 2018), test results of the model as discussed with stakeholders, and validation work (see Section 2.2). Following these processes and analyses, we settled on the following:

$$\text{eCDI} = a_{1\,(40\%)}\ \text{SPI} + a_{2\,(20\%)}\ \text{NDVI} + a_{3\,(20\%)}\ \text{SMA} + a_{4\,(20\%)}\ \text{diurnal LST}$$

We used a sliding window technique to produce 6 values per index per month for a total of 122 values per input index per month for the period of interest (February 2000 to March 2020[9] and February 2000 to present). We then normalized the four components through percentile ranking. The eCDI calculation is undertaken on the four ranked components such that we also obtain 122 monthly eCDI values (for the 2000-2020 period of interest) and rank them into percentiles.

The final resulting eCDI is divided into four categories as shown in Table 2 below.

Table 2. *eCDI categorization.*

Drought class	Class name	eCDI percentile	Significance
	Normal	>20	No drought
D1	Moderate drought	10-20	Once per 5-10 years
D2	Severe drought	2-10	Once per 10-50 years
D3	Exceptional drought	0-2	Once per 50 years and more

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[8] This has been partially reported in Fragaszy et al. (2020) and elaborated upon in each country's baseline assessment produced at the beginning of Stage 2 in 2019 (McKee et al. 2019a, 2019b, 2019c).

[9] We used this period for drought typology and hazard mapping, as described in the Pillar 2 reports, and triggers determination, as described in Section 2.4 of this report. We note that for each monthly eCDI run, the ranking is re-produced for all past data, which results in changes to the drought series history as new datapoints are added.

2.2 eCDI Validation and Refinement

In this subsection we describe the summary eCDI validation results from Stage 2 (see Figure 1), subsequent modifications to the eCDI in Stage 3, and ongoing developments. Note that these studies reflect the Stage 2 eCDI, and we subsequently made substantive changes to it as a result of the findings. Additional and subsequent aspects of validation are described in Sections 2.4 and 3.4.

2.2.1 Overview of Validation Undertaken and Stakeholder Feedback

We evaluated the input indices and the Stage 2 eCDI in multiple ways, including:

- Comparison with available observation data;
- Assessment of performance as a function of land cover and use;
- Relationship with cereal production and yields; and
- Qualitative assessment of eCDI performance with key stakeholders (during Stages 1, 2 and 3 per Figure 1).

In relation to precipitation, the number of observation stations with available data, their spatial representativeness, and their period of record varied a lot between countries. Observation data were unavailable for day-night LST and, except for a limited amount in Jordan, for SMA too. Crop production and yield data were highly limited in Lebanon, which precluded robust analysis of their relationship with the eCDI.

Annex C, Table C2 (Bergaoui et al. Forthcoming) summarizes the validation analyses from Stage 2 and the results for each input index and/or the whole eCDI in each MENAdrought partner country, as well as any eCDI modification undertaken in response to those results. In Annex D, we also show an example validation questionnaire (in French) used in Morocco as part of the rangelands monitoring assessment described in Section 3.4. Note that in some cases, questionnaires like this were used to prompt conversations in workshops rather than handed out to numerous individuals to produce semi-quantitative data.

Overall, the national-level quantitative evaluations increased stakeholders' confidence in the findings, but stakeholder assessments and feedback on the Stage 2 eCDI indicated some concerns with spatial and temporal inconsistency at the basin and regional levels. Officials and experts described the eCDI results as 'noisy' because eCDI classes could vary significantly within relatively homogeneous subbasins (i.e., 'extreme drought' pixels adjacent to 'moderately wet' pixels) or shift between classes frequently across monthly time-steps.

From a drought management perspective, this raised concerns about the accuracy of the tool at the subbasin and regional level, as well as its usefulness and veracity for decision-making in relation to drought management. This 'noise' does not align with empirical knowledge of the relevant socioeconomic systems the eCDI monitors at the intended spatial (subbasin) and temporal (monthly) scales. Likewise, significant spatial and temporal inconsistency in relatively small areas would make its application for drought management purposes at the intended scales problematic.

2.2.2 Refinements to Produce the Stage 3 eCDI

eCDI refinements for Stage 3 primarily attempted to address this issue of noise while training its secondary focus on input index improvement (especially LST and SMA) and eCDI production timing so that it could be ready significantly earlier each month. Also, the refinements reflected the need to change satellite data inputs due to the cessation of the eMODIS mission in October 2022.

To address eCDI noise and enable earlier monthly production, we shifted from CHIRPS (Climate Hazards Group InfraRed Precipitation with Station data) to the IMERG (Integrated Multi-satellite Retrievals for GPM) precipitation dataset as IMERG produces daily precipitation values. Then, following additional comparison of CHIRPS and IMERG to observation datasets available in the MENAdrought countries, which showed that CHIRPS is generally more accurate, we reverted to the use of CHIRPS in Morocco and Lebanon, with additional data pre-processing applied for Morocco[10]. We continue to use IMERG in Jordan because it is more accurate than CHIRPS in the arid areas of southern Jordan.

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[10] In sum, we developed CNN models to estimate the CHIRPS final product (which is available 2-3 weeks after the end of the month) using the CHIRPS preliminary product (which is available one to two days after the end of the month) as input and historical CHIRPS final product data for the training dataset.

Likewise, we applied various data pre-processing refinements (described in summary in Annex C, Table C1) to produce complete and daily values for NDVI and diurnal LST. This ensured full spatial coverage (no missing pixels) with daily data, which enabled the application of sliding windows for calculation of input indices and the eCDI itself to allow empirical percentile ranking.

Modeling improvements primarily included the use of the dynamic phenology model within Noah-MP to incorporate assimilated observation data and account for plant processes that respond to cold, heat and drought stresses (Nie et al. 2021). This incorporates observation data that relates to biophysical feedbacks that increase surface temperature and further reduce soil moisture, and as such it is particularly intended to improve soil moisture calculations.

These refinements reduced model output noise in a manner consistent with expectations. For example, as shown in Figure 2, in January of 2016, the Stage 1 eCDI showed severe drought categories (dark red) interspersed with relatively humid categories (light blue). In contrast, the Stage 3 eCDI was more consistent regionally, and the localized variation was less extreme.

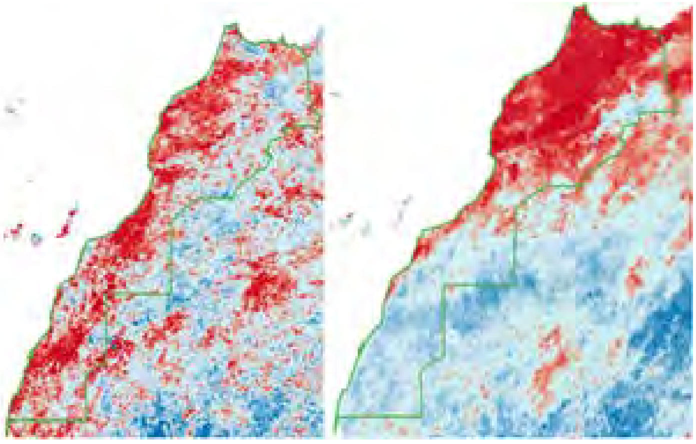

Figure 2. *Comparison of Stage 1 eCDI (left) and Stage 3 eCDI (right) from Morocco for the month of January 2016. Darker red indicates deeper drought and darker blue indicates wetter conditions.*

2.2.3 Refinements Made Due to Cessation of the MODIS Mission

Overview. The MODIS satellite mission was expected to have reduced capabilities starting from October 2022[11], which necessitated a change in satellite datasets for our NDVI and LST inputs. So, we amended the eCDI framework to use either eMODIS data or eVIIRS data.

Data Continuity between eMODIS and eVIIRS. VIIRS was launched in 2011, whereas MODIS data is available from 2000. While VIIRS provides operational continuity for MODIS and produced data are comparable, they have differences. For the eCDI index to be calculated from input indices datasets as ‘seamlessly’ as possible, we had to ‘create’ VIIRS data from MODIS data for the 2000-2012 period using bias-correction algorithms.

In this way, once the switch to VIIRS occurs, the eCDI input datasets will be based on eMODIS data that has been ‘converted’ to VIIRS for the years 2000-2012 and thenceforth from VIIRS data. We used geometric mean regression (Benedict et al. 2021) for each pixel to determine regression coefficients at the pixel level.

2.2.4 Opportunities for Building Support Networks and User/Stakeholder Engagement Mechanisms

Near-future eCDI improvement opportunities primarily relate to building support networks and user/stakeholder engagement mechanisms.

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[11] At the time of writing, NASA announced that MODIS data would be collected through the end of 2022. https://nsidc.org/data/modis

Agencies are building support networks including officials in the regions to provide ongoing quantitative and qualitative feedback on the eCDI. This data gathering will enable them to undertake more robust eCDI validation studies (and drought impact and vulnerability studies) in the future. For example, in Morocco, 70 government officials covering key cereal-producing and rangeland regions provided feedback on the eCDI during the 2020-2021 agricultural/hydrological year (see Section 3.4 for more detail).

These ongoing participatory validation efforts are critical to improve the accuracy and build local ownership of the outputs, and additional quantitative assessments, such as that described in Section 3.4, may support wider eCDI model refinement in the future. But for now, national agencies are focused on getting a broad understanding of the eCDI within the initial socioenvironmental parameters of its establishment.

2.3 Production of the eCDI and Web Interface

2.3.1 Production

As an operational information tool produced by national agencies monthly, ensuring the simplicity and speed of eCDI production is paramount. Accordingly, the MENAdrought team worked to streamline the computational framework as much as possible, and the Stage 3 eCDI has been produced almost entirely through a single program coded in Python.

Once the Land Information System (LIS) Noah-MP model has been installed and parameterized (as it has been in Jordan and Morocco, and is anticipated to be in Lebanon prior to the end of 2022), agencies undertake the following process to produce the past month's eCDI map within 7 days of the end of the month (Bergaoui et al. Forthcoming):

Firstly, remote sensing data are downloaded, pre-processed and used as inputs for the LIS model (for LST and SMA) and the calculations for NDVI and SPI. The model outputs are then aggregated to daily data. Next, the sliding window is used to produce input index values and the weighted eCDI for the month, which are percentile-ranked in relation to the entire 20+ year period and reported according to the drought classes shown in Table 2.

The monthly eCDI information and associated bulletins are provided to interagency committees with a drought monitoring remit and form a core source of information for ongoing drought management. In Jordan and Morocco, some of this information sharing occurs through the web interface described below. Then, how they are used specifically varies between countries, as discussed in the Pillar 3 report on drought mitigation, preparedness and response management (Jobbins et al. 2022).

In addition, the outputs are the basis for a range of research and policy planning activities, including analysis of drought history, hazard mapping and impacts evaluation. The Pillar 2 reports document these applications of the eCDI in the project countries.

2.3.2 Web Interface

We also developed a web interface to support the monitoring and management committees in analyzing drought monitoring data and associated decision-making. The web interface enables various temporal and spatial aggregations of eCDI data, which eases comparison of drought events across the country, through time, or in relation to past events.

For example, we coded the web interface so that it can calculate the DSCI at the national or district level, and at various temporal aggregations. Figure 3 shows subdistrict-level drought statistics in Jordan, and Figure 4 shows Morocco's national-level DSCI produced by using both CHIRPS and IMERG data[12]. The web interface is a key enabler of information sharing and decision support.

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[12] Note that these results were one source of the rationale to shift back to CHIRPS from IMERG. The DSCI that is produced using SPI derived from CHIRPS data shows the recent five-year dry period in Morocco and the intense 2022 drought more effectively than the DSCI produced using SPI derived from IMERG.

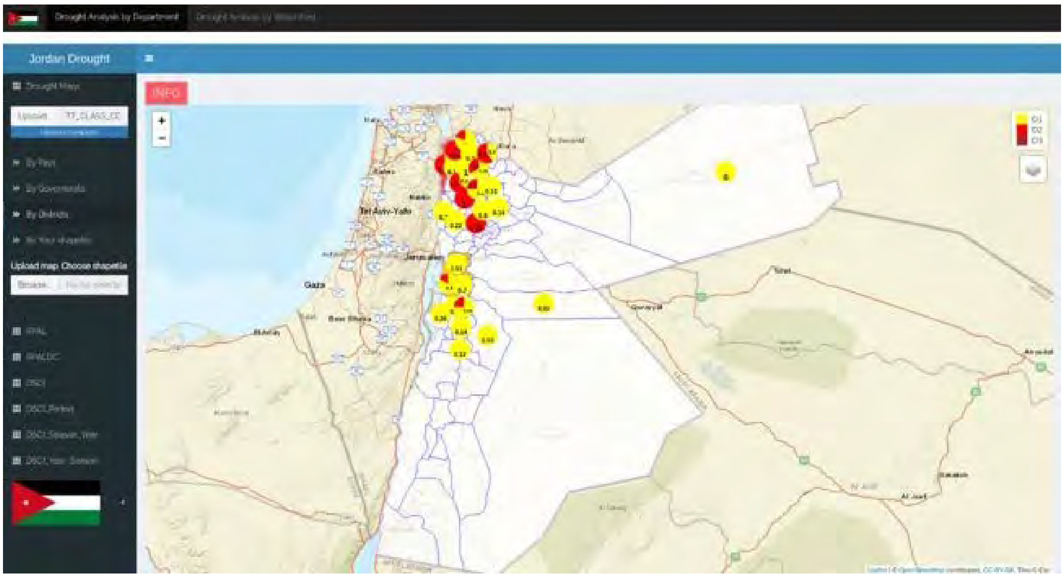

Figure 3. *The web interface showing subdistrict-level drought statistics in Jordan.*

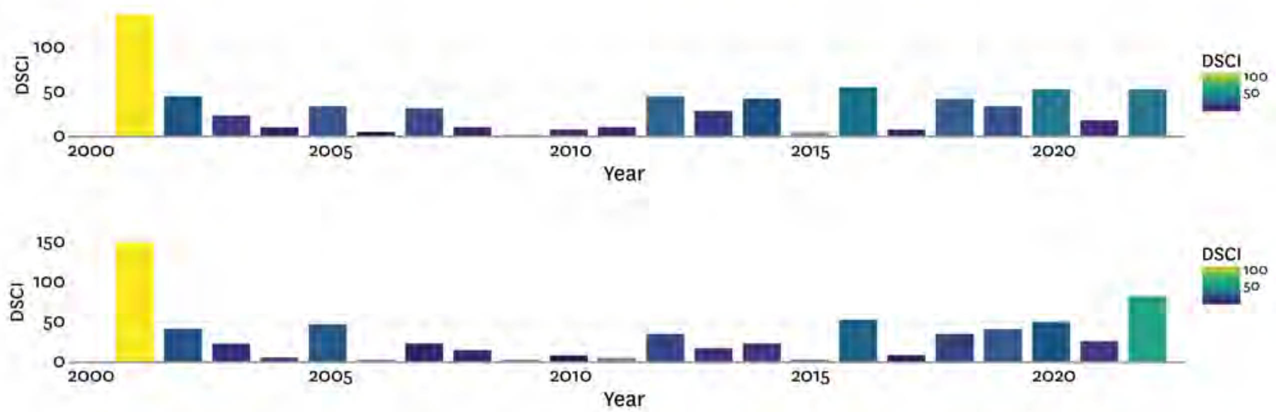

Figure 4. *The web interface in Morocco showing the 2000-2022 annual DSCI calculated using IMERG precipitation inputs (top) and CHIRPS inputs (bottom).*

2.4 Development of Drought Triggers for Policy Decision Support

2.4.1 Overview

We used eCDI outputs to develop drought trigger thresholds for inclusion in each country's Drought Action Plan (DAP; see Pillar 3 report). These triggers represent the scientific evidence base to support decision-making on drought management response actions. They are the fundamental link between the drought monitoring system and drought management response planning.

The triggers stem from an assessment of past drought typology, frequency, duration, timing, spatial extent, severity and impact. Thus, the DAPs include triggers for action corresponding to drought characteristics that are expected to lead to specific impacts. These characteristics are a mix of:

- Drought intensity (drought class);
- Drought coverage (spatial extent); and
- Drought duration (temporal extent).

Given priority impacts in the DAPs, data availability and the associated focus of the drought early warning systems derived through the MENAdrought project, these triggers are primarily focused on the relationship between drought characteristics and rainfed staple crop production over the past 20 years.

This is the first attempt to develop quantitative triggers to respond to priority impacts. Future interdisciplinary investigations, and inputs from regional feedback networks (Drought Reporter Networks) described in Section 2.1 could enable the creation of additional triggers focused on specific economic sectors, agroecological zones, or other themes.

Triggers are designed for effective and timely decision-making, and they all derive from monthly eCDI values that are combined and aggregated in slightly different ways. We developed multiple types of triggers due to differences in data availability, strength of correlation and intended use for drought management policy. This resulted in the development of three types of triggers that we describe further in the rest of this subsection[13]:

- Season-specific eCDI triggers for each country;
- A 'cumulative eCDI' for Morocco, based on eCDI values in December and March, the critical part of the growing season; and
- Use of the eCDI to calculate the DSCI (Akyuz 2017) for Lebanon.

Each of these types of triggers has specific thresholds for the definition of watch, alert, emergency and/or crisis levels of drought. Table 3 shows the triggers included in the Jordanian, Lebanese and Souss-Massa (Morocco) DAPs[14] including in relation to the eCDI classes described in Table 2 (or minor modifications of them) with drought levels.

2.4.2. Description of Season-specific Triggers and their Derivation

The season-specific eCDI trigger for each country is conceptually simple. In short, the trigger is based on:

- The presence of pixels with certain eCDI values in an area of interest;
- Proportional coverage of pixels with certain eCDI values in the area of interest; and
- Length of time (consecutive or not, depending) with proportional coverage of pixels with certain eCDI values in an area of interest.

For Jordan and Morocco, we developed the season-specific triggers shown in Table 3 through statistical analysis of crop production statistics in relation to eCDI values. In Jordan, we used the anomaly of the aggregated production of all rainfed staples (cereals, olives and legumes) from the northern highlands as a proxy for the degree of drought impacts. For Lebanon, where crop production data are not reliable (being discontinuous and not quality-controlled), we used the same season-specific values as Jordan given that the northern highlands agroecological zones are comparable to primary agricultural areas in Lebanon. In Morocco, we used the deviation from historical maximum barley crop production as a proxy to assess drought impacts on cereals and rangelands.

2.4.3 Season-specific Triggers in Jordan and Lebanon

Staple crops in Jordan include cereals (wheat and barley), olives and legumes (lentils and chickpea). They are rainfed in the northern highlands, and irrigated in the groundwater-based systems of the Azraq and Amman-Zarqa basins. Drought impacts on production correspond to initial stress in January-March or to terminal stress in March-May.

In the 2000-2020 period, the years 2001 and 2008 were the driest years and had the strongest drought according to the eCDI (see Pillar 2 reports) with a corresponding drop in rainfed staple crop production in the northern highlands, as shown in Figure 5. In contrast, the wet years 2002, 2010, 2012 and 2015 show positive crop production anomalies in northwestern Jordan.

Our analysis showed that 2 dry months out of 3 in each season correspond systematically (100% of cases, and statistically significant results) to a negative production anomaly. In winter, this consists of one 'moderate' and one 'severe' dry month during the period Dec-Feb. In spring this consists of at least two 'severe' months during the period March–May. Therefore, we developed the season-specific triggers shown in Table 3.

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[13] Here we provide an overview, and we intend to publish more detailed methods and results in a forthcoming article.

[14] As described further in the Pillar 3 report, at the time of writing, none of the DAPs had been approved formally by any agency's executive leadership or political body. Therefore, they should be considered as draft policy or guidance for relevant agencies.

Figure 5. *The anomaly of rainfed staple crop production (y-axis, in standard deviations) per year (x-axis), compared to the long-run average in Irbid, Ajloun, Jerash, Balqa and Madaba in Jordan. The red arrows and associated maps show select years' eCDI values from December (far left) through June.*

2.4.4 Season-specific Triggers in Souss-Massa, Morocco

Moroccan officials are interested in using the eCDI for monitoring rangelands to support the implementation of the Rangelands Law 113-13 (see Section 3.4 for more detail on this). Given the absence of rangelands biomass data—and barley being a nationally critical and predominantly rainfed cereal crop, as well as a suitable proxy for annual rangeland species—we estimated drought impacts on rangelands and cereal production via the relationship between eCDI values and the annual deviation from maximum barley grain production.

Barley grain production is mainly affected by water deficit, with little effect from subsidy rates or biotic stresses such as pests and diseases. Grain yield is affected by drought conditions at key growth stages, from early vigor (December) to the phase of assimilate remobilization from the plant's vegetative to reproductive parts (March).

The deviation from maximum barley grain production was estimated as the ratio of a given season's production to maximum grain production over the period 2001-2020. This calculation was performed for quality-controlled data in 30 provinces (9 regions) out of 39. Deviations to maximum production were calculated per bioclimate: subhumid, semiarid superior, semiarid intermediate, semiarid inferior and arid zones (see the Pillar 2 report on Morocco for more detail on these zones).

Through this assessment, and consideration of the Souss-Massa DAP's priority impact of groundwater degradation (and, therefore, also drought impacts on the wider hydrological cycle and irrigated agricultural systems), we developed the season-specific triggers for Souss-Massa shown in Table 3. We assume that the drought trigger derived from rainfed agricultural output statistics is usable for identification of moderate hydrological droughts in a given season. We did not explore potential triggers for severe hydrological droughts occurring over prolonged periods. With the existing modeling system that produces the eCDI, this would require assessing correlations between eCDI, SPI and/or DSCI values and hydrological data such as streamflow statistics.

2.4.5 Development of a Cumulative eCDI and Associated Triggers in Morocco

The cumulative eCDI is a metric of drought severity based on temporal aggregation of eCDI scores within a growing season to produce a single value per province, which can then be spatially aggregated by bioclimate. We applied a two-way stepwise regression on all months. We obtained a significant regression between the values of all months and the yearly deviation from maximum barley production (as the predictor) to deduce a single eCDI value for each year that is significantly related to the December and March eCDI values. This was estimated as $0.1205 + (0.2309 \times eCDI_{December}) + (0.4237 \times eCDI_{March})$ for most of the provinces and bioclimates.

The correlation was significant in all bioclimates except for the subhumid zone where forests are predominant. Therefore, we recommend for future operational use masking of pixels in forests and highlands with significant snow cover. The results of the regression relationship are shown in Figure 6. The correlations are indicative of a good fit between the cumulative eCDI and barley production. Therefore, our use of barley as a proxy for rangelands productivity is appropriate.

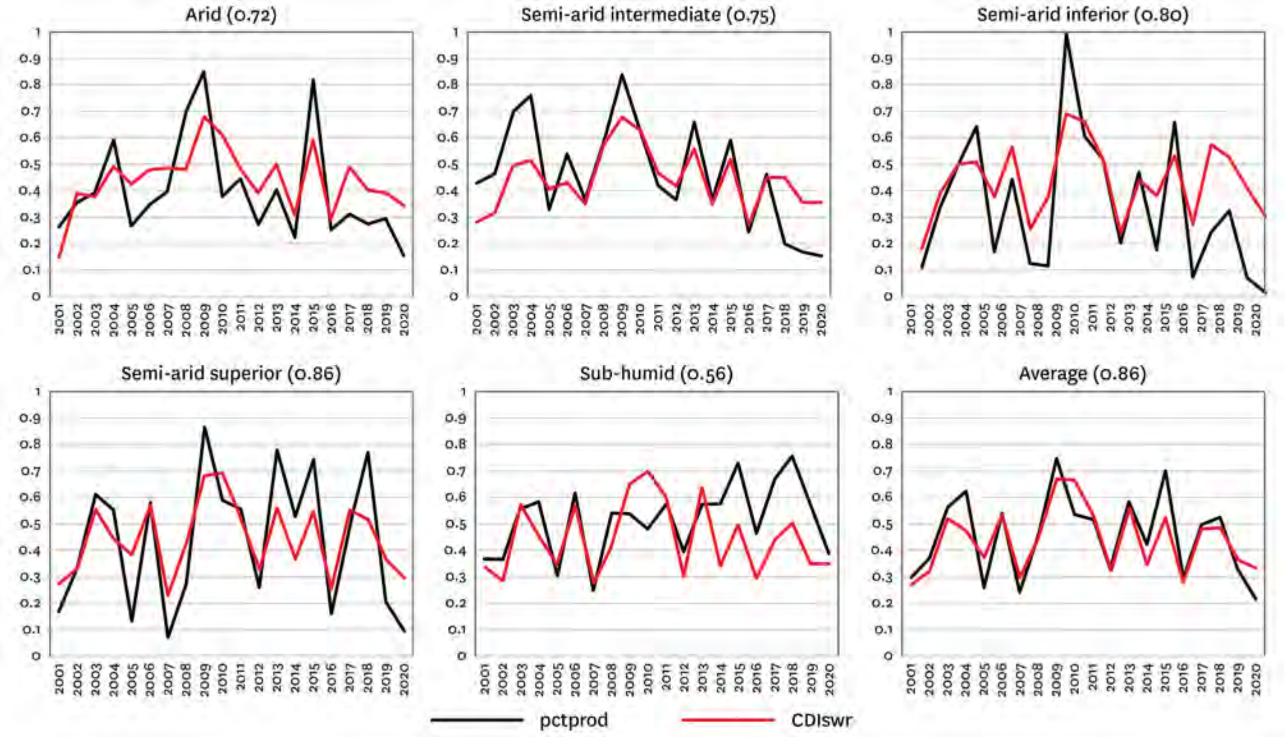

Figure 6. *Time-series of cumulative eCDI (red line) and deviation from maximum barley production (black line) by bioclimate zone. Average values across Morocco are shown in the bottom right plot.*

The same approach was used to assess the regression relationship between the cumulative eCDI and barley production for the Souss-Massa region, as shown in Figure 7. With these results, we developed the Souss-Massa DAP cumulative eCDI trigger threshold based on barley production falling below 40% of the historical maximum. The statistics indicate

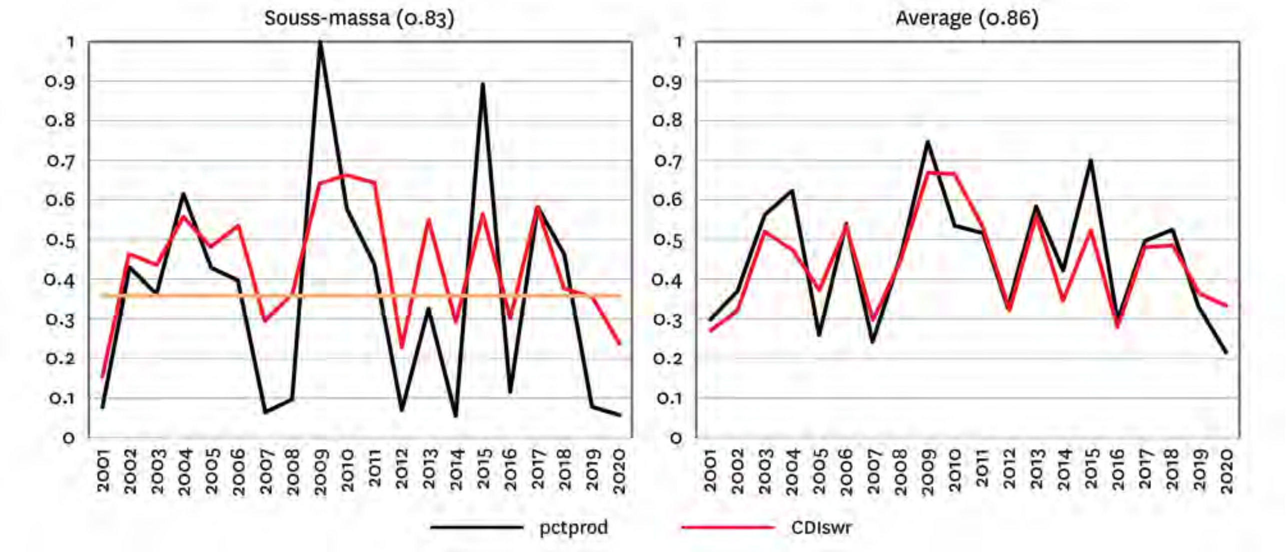

Figure 7. *Time-series of cumulative eCDI (red line) and deviation from maximum barley grain production (black line) for the Souss-Massa region (left) and the average for all agroecological zones in Morocco (right). The orange line corresponds to the trigger value (cumulative eCDI value of 0.36) that is associated with production falling below 40% of the historical maximum.*

that this trigger threshold would be more widely applicable across Moroccan regions and bioclimate zones where serious dry conditions correspond to significant reductions in barley grain production and therefore severe food imbalances. The use of March values (alongside December ones) allows early warning of three months before the primary anticipated impacts on rainfed agriculture—cereal-based systems and rangelands—and therefore in relation to food security and livestock as well as rural livelihoods of vulnerable populations.

2.4.6 Development of the DSCI and Associated Experimental Triggers in Lebanon

The DSCI aggregates spatial coverage of eCDI scores including all drought classes from moderate to exceptional. This enables spatially (and temporally) scalable assessments of drought intensity; the DSCI can be used from the province to national level, and scores can be assessed month by month or continuously through a given agricultural/hydrological season or years (Akyuz 2017). It is derived statistically from the eCDI results, and we did not assess it in relationship to agricultural production given that secondary statistics do not allow assessing retrospectively drought impacts on agricultural and water resources (Fragaszy et al. 2022b; Fayad 2017).

We focus the DSCI on the rainy season only (Sep-May) because this period's values are highly correlated to values from the full year ($0.86<r^2<0.92$, Figure 8). Based on these results, impact reports and expert knowledge, we consider that a DSCI score of 30% of the maximum recorded cumulative DSCI during the whole period (which occurred in 2002) could be an appropriate trigger. This value of 533 would be appropriate whether it occurs during the autumn, winter or spring seasons as it corresponds to a dry year in all cases. This potential trigger does not correspond to a specific drought class within the DAP (or as shown in Table 3), and instead would be a 'generic' trigger indicating cumulative dry conditions across the country.

Additionally, the DSCI of the period September to February is significantly correlated to the whole season DSCI ($0.77<r^2<0.87$). Using data from this period allows early drought classification in March (when eCDI results through February are produced) to confirm drought in the major agroecological zones of Lebanon (data not shown).

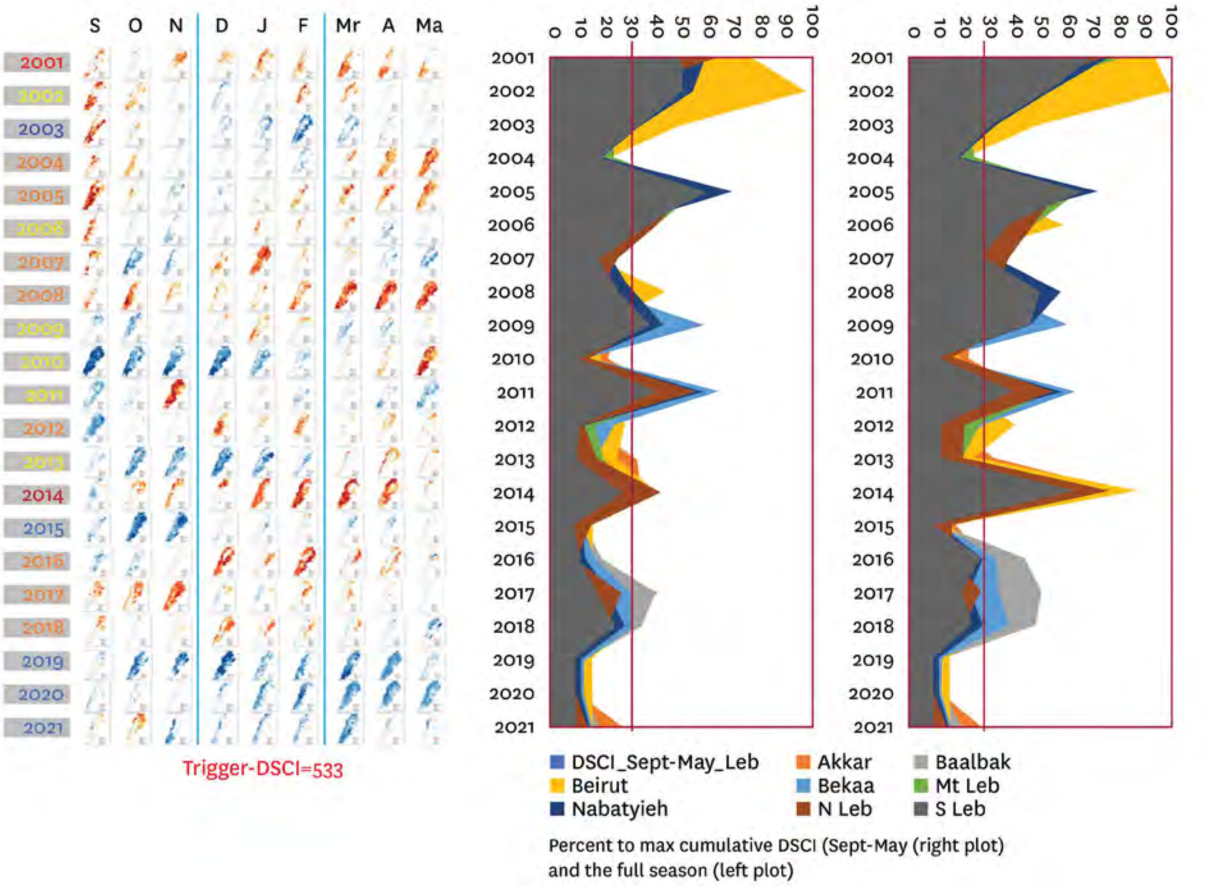

Figure 8. *Monthly eCDI values from September (S) to May (Ma) for the period 2001-2021 (left plot); full year (center plot; Sep-Aug) and rainy season only (right plot; Sep-May) percent to maximum cumulative DSCI for key agroecological zones. Note: N, S and Mt correspond to North, South and Mount Lebanon, respectively.*

Table 3. *Triggers in Drought Action Plans (DAPs).*

Drought level (eCDI)	Trigger (derived from eCDI)
Watch – All countries: Absence of drought	N/A
Alert	Lebanon and Jordan, winter and spring: Detection of one 'moderate' drought class. Souss-Massa, Morocco: Any month with more than 30% of the basin showing 'severe' or 'exceptional' drought class per the eCDI.
Emergency	Lebanon and Jordan, winter: At least 1 month of 'moderate' drought and 1 month of 'severe' drought during this period. Lebanon and Jordan, spring: At least 2 months of 'severe' drought during this period. Souss-Massa: Two consecutive months with more than 30% of the basin showing 'severe' or 'exceptional' drought according to the eCDI.
Crisis	Lebanon and Jordan, winter: At least 1 month of 'exceptional' drought consecutive with 1 month of 'severe' drought during this period. Souss-Massa: Either (a) three or more consecutive months with more than 30% of the basin showing 'severe' or 'exceptional' drought per the eCDI; or (b) a cumulative eCDI value greater than 0.36.

2.5 Section Summary

eCDI Composition and Production. We co-developed an eCDI that government agencies in Jordan and Morocco now produce independently—their own staff on their own servers—and we anticipate Lebanese agencies to be able to do so as well by the end of 2022 provided conditions in that country, primarily electricity and internet availability, permit the final installation of the system. The eCDI is a spatialized, weighted indicator produced using a combination of remote sensing and environmental modeling inputs. It is based on anomalies relative to average conditions since 2000 for a specific month and a specific 5 x 5 km grid location:

- 3-month Standardized Precipitation Index (SPI, 40% weighting)
- Normalized Difference Vegetation Index (NDVI [20%]);
- Root-zone soil moisture anomaly (SMA, 20%); and
- Day-night land surface temperature amplitude anomaly (LST, 20%).

Following integration, eCDI values for each pixel are categorized according to percentiles into one of the following classes: no drought, moderate drought, severe drought, or extreme drought.

eCDI Validation, Refinement, Production Process, Web Interface and Near-future Improvement Opportunities. The iterative eCDI development process incorporated quantitative and qualitative validation components to assess the accuracy of the modeled inputs and the eCDI as a whole and support subsequent refinements. These initial assessments included:

- Relationship with cereal production and yields;
- Comparison with available observation data;
- Assessment of performance as a function of land cover and use; and
- Qualitative assessment of eCDI performance with key stakeholders.

The eCDI showed a better relationship to cereal production and yield data than precipitation alone, which is a core aspect of its legitimacy to government officials and other stakeholders. The satellite-derived precipitation information used in the eCDI compared favorably with ground station precipitation monitoring data. Also, local experts largely considered the eCDI to be concordant with their observations where local validation was undertaken in Morocco and Jordan.

We improved the eCDI's performance primarily by validating and refining data inputs, adding and removing model components and inputs, undertaking additional data pre-processing, and modifying the eCDI calculation to reduce errors from cloud cover and provide additional (temporal and spatial) datapoints for eCDI calculations using a sliding window technique. Modeling improvements included the use of the dynamic phenology model within Noah-MP intended to improve soil moisture calculations. We also changed data sources for two of the input indices due to the planned cessation of a satellite mission.

We simplified the modeling system so that almost all processes are undertaken through a reproducible model workflow. This enables monthly drought maps to be produced within 10 days of the new month and ensures that agencies are able to continue production of the eCDI independently beyond the term of the funded MENAdrought project. Likewise, we developed a web user interface that enables various temporal and spatial aggregations of eCDI statistics to ease exploration of current conditions relative to past events and support decision-making.

Near-future eCDI improvement opportunities include building support networks and user/stakeholder engagement mechanisms. In both Jordan and Morocco, government agencies have supported the development of validator networks comprised of officials in local government agencies (and potentially also civil society) who will assess local drought conditions and comment on the perceived accuracy of eCDI outputs. This will support improvements to the drought early warning system and drought preparedness, mitigation and response management plans over time.

Development of Drought Triggers for Policy Decision Support. To develop trigger thresholds for drought management actions described in the Pillar 3 report, we assessed eCDI results statistically and in relation to annual rainfed staple crop production and yield. This resulted in the development of three types of triggers:

- Season-specific eCDI triggers for each country;
- For Morocco, a 'cumulative eCDI' based on eCDI values in December and March; and
- A Drought Severity and Coverage Index for Lebanon[15].

The cumulative eCDI is based on temporal aggregation of monthly eCDI scores within a hydrological year to produce a single value for each province/governorate, which can then be spatially aggregated. The assessment used to produce this trigger showed that cumulative eCDI values are highly correlated with barley production, which we consider a relevant proxy for annual production of rangeland species, and more widely for rainfed cereals.

The DSCI aggregates spatial coverage of eCDI scores to enable spatially and temporally scalable assessments of drought intensity. It can be used from the province to the national level, and scores can be assessed month by month or continuously through a given year (or years).

The season-specific and cumulative eCDI triggers both reflect relationships between eCDI values in specific months and annual staple crop production and yields. The season-specific triggers do not incorporate any weighting for monthly eCDI values, whereas the Moroccan cumulative eCDI incorporates a statistically derived (stepwise regression) weighting system for the eCDI values of December and March of a given year. The DSCI triggers are derived statistically in relation to their highest values of the past 20-year period.

3. Seasonal Forecasting and Related Modeling

In this section, we describe MENAdrought's work on seasonal precipitation forecasting and its connections to wider drought forecasting[16]. The project team transferred this technology and trained national partners in Jordan and Morocco to run the relevant models, but not in Lebanon given the inability to produce reliable forecasting results with the predictors tested to date. We also describe MENAdrought's pilot research on streamflow forecasting, crop-type mapping, and validation of eCDI usage for rangeland conditions monitoring.

3.1 Establishing Base CNN Models for Precipitation Forecasting

3.1.1 Overview of Method and Initial Tests

Seasonal forecasts are based on several model simulations: computer programs that are fed climate indices,

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[15] Note that development of the DSCI trigger was experimental, and it is not included in the Lebanese Drought Action Plan described in the Pillar 3 report.

[16] Note that more technical details will be published in the future.

observations on sea-surface temperature, and El Niño/Southern Oscillation (ENSO), North Atlantic Oscillation (NAO), Mediterranean Oscillation (MO) and other data.

One globally prominent seasonal forecast system is called the North American Multi-Model Ensemble (NMME). It consists of coupled models from several North American modeling centers. However, all NMME models are poor at predicting rainfall in the MENA region even one month in advance (Roy et al. 2020).

We used CNN models to improve the outputs of four dynamic models within NMME (CFS, CanCM4, GEOS-5 and GFDL-NEMO) for rainfall prediction with a lead time of two months. A CNN is an artificial neural network used in image recognition and processing, and is useful for processing pixel data. CNN models consist of several layers that assist the computer in identifying the relevant features for a given task. They rely on the non-random nature of images, including the tendency for pixel position and 'neighborhood' to be meaningful, and the fact that elements of interest can appear anywhere in an image[17]. In short, we used CNN models to predict precipitation values based on past relationships between NMME data and the observed CHIRPS values.

We developed 12 month-specific CNN models as well as 36 models for lead-time forecast: one model each for (a) same-month forecast; (b) 1-month forecast; (c) 2-month forecast; and (d) 3-month forecast. These CNN models take the 100 km^2 NMME model output, and other predictors as described below, and both refine them and downscale them spatially to a 5 km^2 output so that they match observed CHIRPS data.

The loss function of the CNN model, rewritten by the IWMI team, uses a 'regionalization' technique which consists in identifying coherent regions based on their specific rainfall regime (Badr et al. 2015). This maximizes clustering and minimizes differences within regions by instructing the model to focus improvement of the loss function on those areas of interest. Morocco thus had 7 climate regions, Jordan 5 and Lebanon 4.

The team used the 1982-2014 period for training data and then tested the CNN model outputs over the 2015-2022 period. For the initial test, the sole predictors were the global rainfall values from the four NMME models.

These first attempts focused on absolute precipitation values per month and were very promising. The example shown in Figure 9 illustrates that CNN results improved greatly on the NMME models and closely mirror observed precipitation. The CNN model captured the general distribution and intensity of higher rainfall events observed in the CHIRPS precipitation data and reflected the regional dry areas well for the period shown.

January 2019 (Forecast ready since the first week of November 2018)

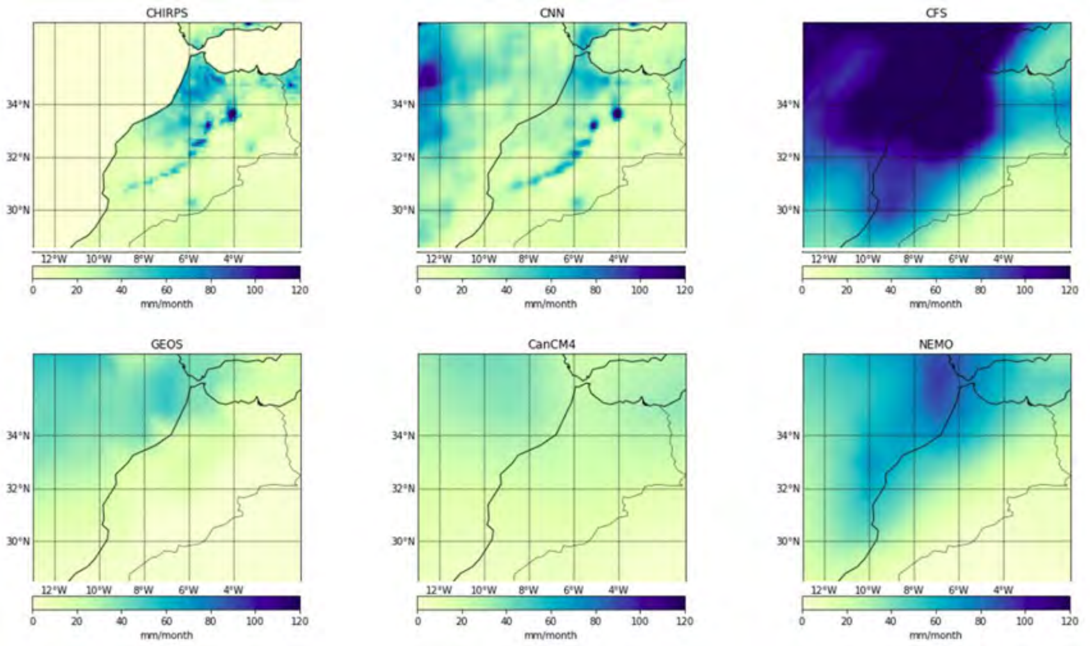

Figure 9. *Precipitation forecasting with 2-month lead time: at top left is observed January precipitation; top middle is the CNN model predicting January precipitation (2-month lead time from November); and the other panels (top right and bottom row) show 4 NMME model outputs for the same 2-month lead time prediction.*

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[17] See this explainer for more information on CNNs: https://poloclub.github.io/cnn-explainer/

3.2 Seasonal Forecasting Model Refinements and SPI Forecasting Results

Seasonal Forecasting Model Refinements and Final Characteristics. Following this successful first attempt, we tested the addition of numerous additional predictors for Morocco, Jordan and Lebanon including geopotential height, the European Centre for Medium-range Weather Forecasts (ECMWF) dynamical model output, temperature at different heights and sea-surface temperature of the Mediterranean Sea (all countries), the Atlantic Ocean (Morocco) and the Indian Ocean (Lebanon and Jordan). These led to moderate improvements in Morocco and Jordan but not Lebanon.

While testing these additional predictors, we noticed that data outputs in Jordan tended to correlate according to climate regions. Therefore, we trained the CNN models according to climate regions that appeared to shift coherently in the datasets: (1) the highlands region; and (2) the other 4 climate regions of Jordan encompassing primarily the *Badia* and arid areas. This method of focusing model development, training and optimization significantly improved the results for Jordan; it would be a likely avenue to pursue in Lebanon given more time.

The final seasonal forecasting models transferred to Moroccan and Jordanian agencies therefore include the following characteristics:

Morocco: Seven climate regions; predictors including NMME models and sea-surface temperature of the Mediterranean and Atlantic Ocean; and a system that produces forecasts of rainfall volume and anomalies, as well as a three-month SPI.

Jordan: Five climate regions; predictors including NMME models and ECMWF; model training and outputs according to climate region groupings (one for the highlands, the other for *Badia* and desert areas); and a system that produces forecasts of rainfall volume and anomalies.

Example Results from Morocco. Analysis of the predictions carried out for the testing period (2015-2019) showed that the CNN-produced 2-month lead time forecast had a very high correlation with observed (CHIRPS) rainfall in subhumid areas, with an *r* value of 0.93, and low correlation in arid areas, with an *r* value of 0.43 (Figure 10).

Weaker correlation in the arid regions was partially driven by rare extreme precipitation events. This finding is highly relevant given that climate change scenario analyses (CMI and IWMI 2021) anticipate an overall decrease in precipitation in the arid regions of Morocco but an increase in extreme precipitation events.

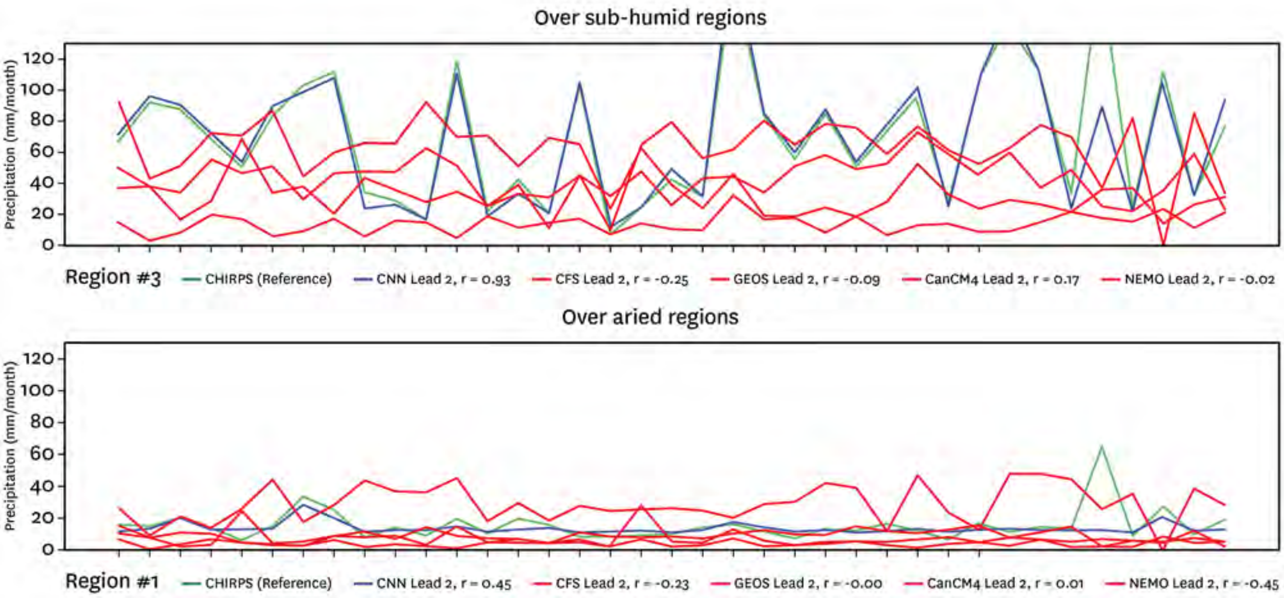
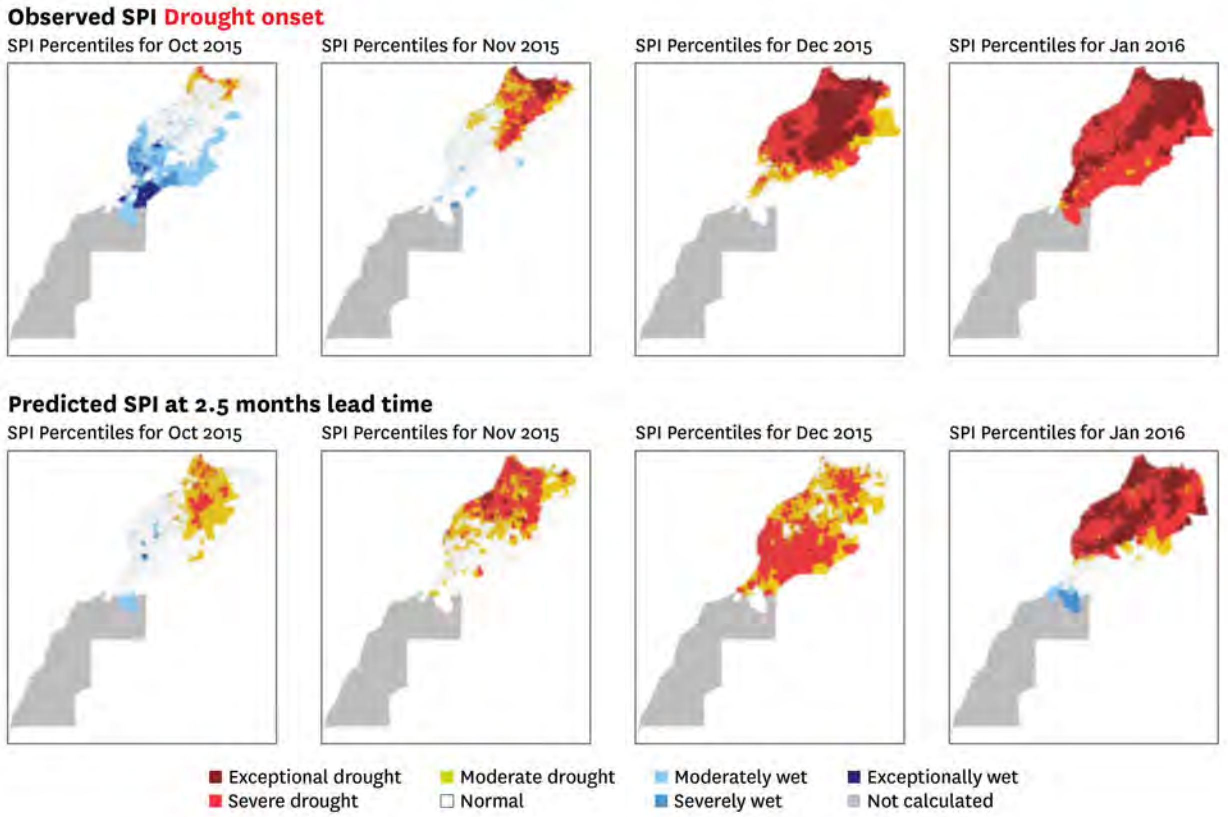


Figure 10. *Comparison of observed (CHIRPS) precipitation to 2-month lead time forecast from MENAdrought CNN model and 4 select models from the NMME over 2000-2019. The training period was 2000-2015 and the testing period 2015-2019. Note: the correlation between the green line (CHIRPS) and the blue line (CNN 2-month lead time) and the confirmation that during the training and validation period we were able to simulate the dry and wet events.*

The examples presented in Figures 11 and 12 show that the predicted SPI at 2.5-month lead time for the 2015-2016 drought year in Morocco captured the general progression of the drought through the winter period as well as recovery in the late spring.



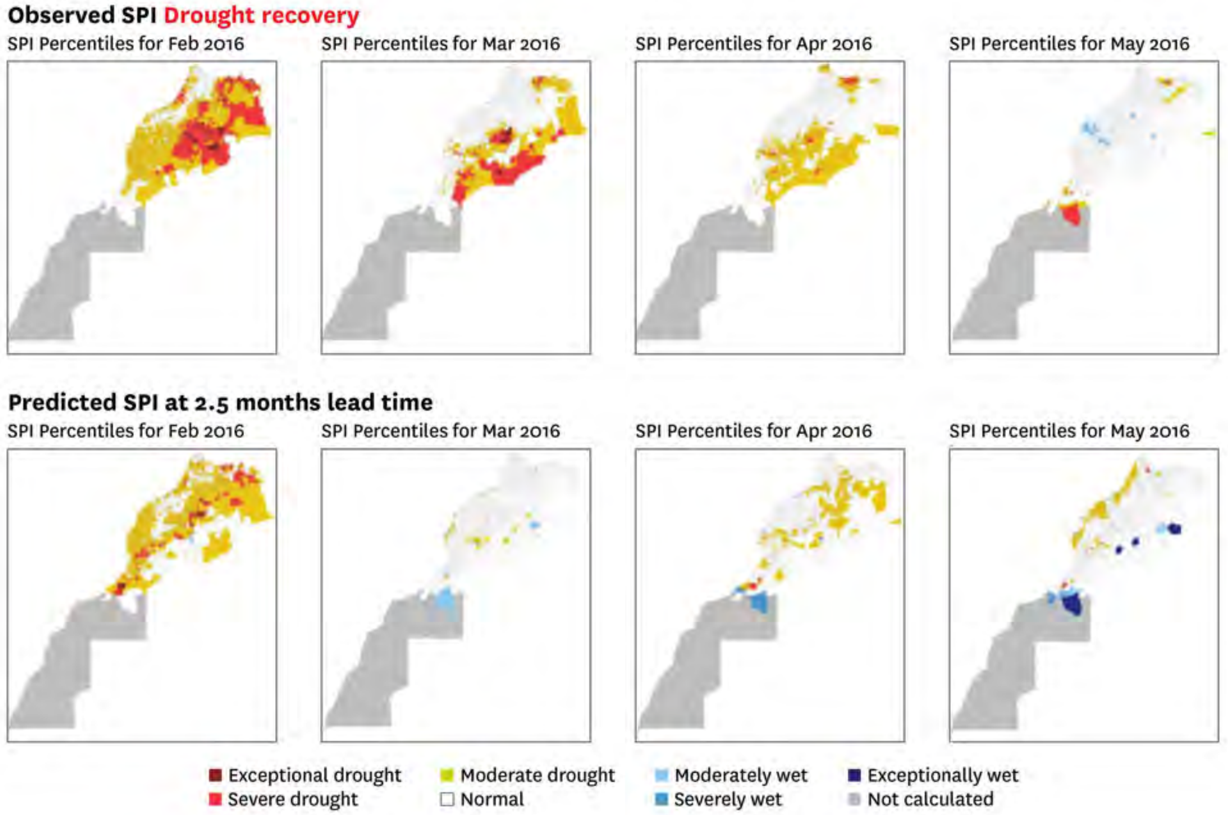
Observed SPI Drought onset

SPI Percentiles for Oct 2015 | SPI Percentiles for Nov 2015 | SPI Percentiles for Dec 2015 | SPI Percentiles for Jan 2016

Predicted SPI at 2.5 months lead time

SPI Percentiles for Oct 2015 | SPI Percentiles for Nov 2015 | SPI Percentiles for Dec 2015 | SPI Percentiles for Jan 2016

Figure 11. *Comparison of observed (CHIRPS) SPI and predicted SPI at 2.5-month lead time in Morocco from October 2015 to January 2016.*



Observed SPI Drought recovery

SPI Percentiles for Feb 2016 | SPI Percentiles for Mar 2016 | SPI Percentiles for Apr 2016 | SPI Percentiles for May 2016

Predicted SPI at 2.5 months lead time

SPI Percentiles for Feb 2016 | SPI Percentiles for Mar 2016 | SPI Percentiles for Apr 2016 | SPI Percentiles for May 2016

Figure 12. *Comparison of observed (CHIRPS) SPI and predicted SPI at 2.5-month lead time in Morocco from February to May 2016.*

3.3 Exploring Drought Forecasting Using the eCDI

We tested the CNN models for wider forecasting purposes with the objective of running the LIS model for eCDI forecasting, but the results using LIS were poor. We suggest that future development for agricultural and meteorological drought forecasting beyond SPI in the project countries should focus on precipitation and temperature-driven indices (such as the SPEI) rather than using complex land surface models to produce indices such as the SMA. This is because temperature forecasting is typically more successful than precipitation forecasting, and so results could be more reliable than SPI as well as providing additional value in relation to agricultural drought forecasting.

The LIS model requires precipitation, temperature, relative humidity, wind-speed and solar radiation data in 6-hour time-steps. Therefore, we took the raw forecast of these indicators from the GEOS-5 model (one of the models within the NMME platform) and did bias-corrected statistical temporal (from monthly to 6-hourly) and spatial (from 100 km^2 to 5 km^2) downscaling. With these data, we ran the LIS model to produce the root-zone soil moisture component, diurnal LST and NDVI components of the eCDI.

Results for the root-zone soil moisture forecast were not very good, likely due to model assumptions around evapotranspiration. Temporal smoothing for precipitation downscaling also introduces challenges: whereas for SPI the distribution of rainfall within the period is not relevant, in the case of LIS, forcing, precipitation, temperature and surface radiation in each time-step are highly relevant for modeling various processes.

3.4 Pilot Research That Builds on the eCDI System

3.4.1 Forecasting Streamflow

In addition to drought forecasting, we undertook a preliminary pilot project to assess the potential for streamflow forecasting using the CNN model outputs to force the coupled LIS-Noah-MP and Weather Research and Forecasting-Hydro (LIS/WRF-Hydro) models (Wegiel et al. 2021). The objective of this pilot research was to forecast streamflow volumes and produce the Standardized Streamflow Index (SSI) for relevant basins (Shukla and Wood 2008; Sutanto and Van Lanen 2021). The SSI is comparable to the SPI in terms of development and use; it reports streamflow anomalies in relation to historical periods.

LIS/WRF-Hydro uses the LIS framework and the Noah-MP model described in Section 2 (and in Bergaoui et al. Forthcoming) and incorporates the WRF-Hydro dynamic streamflow routing and discharge model (Gochis et al. 2018). Our efforts focused on the Oum Rabia basin in Morocco as basin-specific calibration is important to improve model skill and the usefulness of the outputs. As a new coupled modeling framework (LIS/WRF-Hydro is still under initial development), this research provided a test case for the model application writ large, as well as for national agencies to evaluate its applicability.

In short, the long-term opportunity is to provide national agencies with a modeling tool that, once validated, would be able to produce operational monitoring and forecasting through a potentially relatively straightforward programming framework. At present, the national agencies do not have effective operational hydrological modeling capacity for forecasting purposes and therefore rely on universities or consultants for specific analyses. This presents a significant barrier to their use of relevant modeling, and leads to an absence of that type of information in their planning efforts. For example, operational streamflow forecasting could support dam management and optimization of water supply between urban water supply, hydropower production, irrigation and environmental flows.

During the MENAdrought project, the LIS/WRF-Hydro model was compiled and executed successfully, and we tested several model configuration options over the 2000-2015 period. The model simulations reflected the trend in observed streamflow during normal and drought years in this period, albeit with timing and magnitude discrepancies, particularly during high flow events. However, the model is very computationally demanding, and it requires several types and relatively long time-series of in situ data for calibration in each hydrological basin.

3.4.2 Crop-type Mapping

We developed a crop-type mapping software using an advanced machine learning Python code and available observation data (with 80 crop classes, determined by a field survey, for the year 2016). The software code includes routines to:

1. create a shapefile with field measurements;
2. download Sentinel satellite images;
3. filter the Sentinel imagery to have only cloud-free images;
4. apply the SNIC algorithm (Achanta and Süsstrunk 2017) and create a segmentation map (clustered pixels) for crop parcel delineation;
5. find the optical reflectance signatures of different crop types based on observation data and other information such as the cropping calendar;
6. calculate the average signature for each crop type;
7. find for every pixel the difference between the average crop signatures;
8. define the crop type for every pixel by minimizing the differences; and
9. use the segmented map (from step 4) to cluster the single pixels.

The software generates maps (Figure 13) that are used as an input in drought vulnerability assessment, including in relation to risk exposure (such as the area of particular crops exposed to drought hazard) and the differential impacts on exposed crops as a function of specific climatological thresholds and whether irrigated or rainfed. This supports the directing of field staff for more thorough drought impact recording where the insurance firm MAMDA and the agricultural development bank CAM may undertake financial remediation interventions.

Staff from the DSS will be trained to use this software to generate maps yearly using updated ground-truthing inputs. They will also be trained to generate crop failure maps and improved yield statistics over the Moroccan regions, provinces and bioclimate zones. In our experience with this software, the results were good for identification of annual field crops but less successful with perennial tree crops—which would be a likely target of additional research and development in the future.

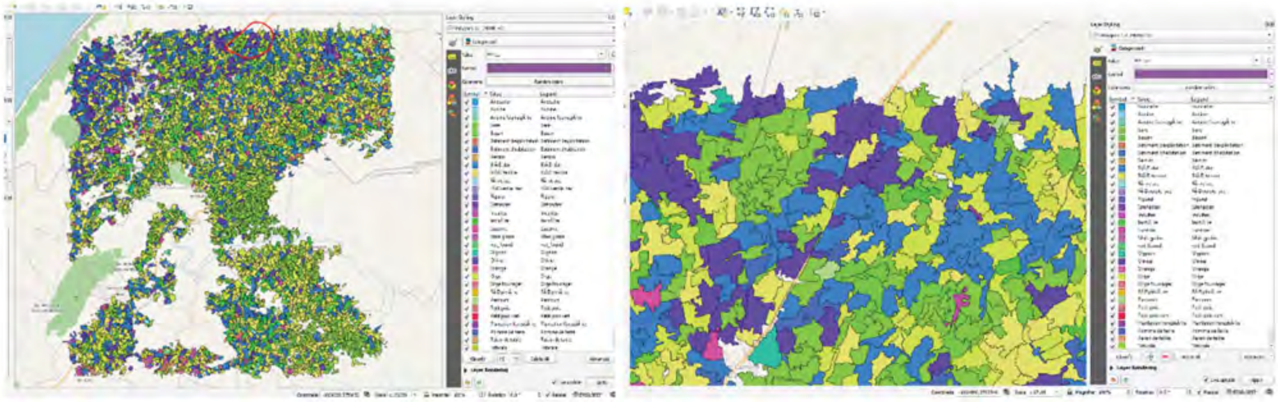


Figure 13. *Crop-type mapping example output from Morocco.*

3.4.3 Validation of the eCDI for Use in Monitoring Pastoral Areas in Morocco

As described above, Moroccan stakeholders wish to use the eCDI to support their work in monitoring rangelands and pastoral areas. We undertook qualitative evaluation of the eCDI for this purpose, beginning in 2020-2021.

The MoA convened a network of field experts from the Regional Department of Agriculture (DRA) in (a) the dryland regions of Laayoune-Sakia Hamra, Draa-Tafilalt, Marrakech-Safi and Souss-Massa; (b) the semiarid areas of Oriental, Beni Mellal-Khénifra and Rabat-Salé-Kenitra; and (c) the subhumid areas of Fez-Meknès. In total, these field experts have the remit to monitor drought conditions over 2,063,496 ha of rangeland.

The IWMI team ran a series of workshops to train these regional validators. Then, from November 2020 to March 2021, these experts undertook validation assessments in the pastoral areas in their remit.

The regional validators reported their perceptions on drought class and the accuracy of the monthly eCDI maps in terms of the spatial coverage of drought and its severity. They also provided feedback on the most affected localities or subareas. Lastly, they described the tools, data, or information they used to make their judgement, and they provided supplementary notes on the status of annual and perennial biomass (including evidence of degradation or regeneration), livestock loading, heat stress, snow cover and unusual transhumant movements.

We report below the results from regional validators who provided information monthly[18] and from rangelands that were not affected by severe degradation (especially in the Draa-Tafilalt region) or snow cover (in the Atlas mountains). In total, the validation results shown cover 27 rangeland areas covering 1,915,941 ha (93% of the total area), distributed regionally as shown in Figure 14.

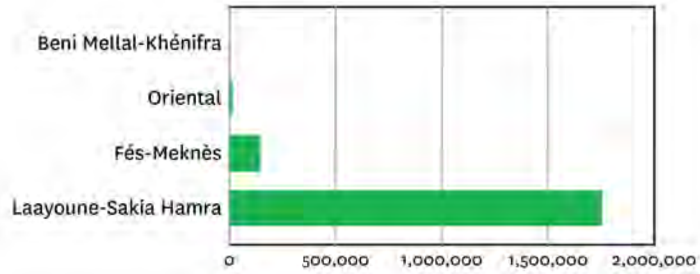


Figure 14. *Total area (ha) of observed rangeland by region.*

Overall, the validators judged the accuracy of the eCDI maps (the spatial extent of drought and its severity) over the 5 months to be 73%. This ranged from 57% to 83% depending on the specific pastoral area and month, as shown in Figure 15.

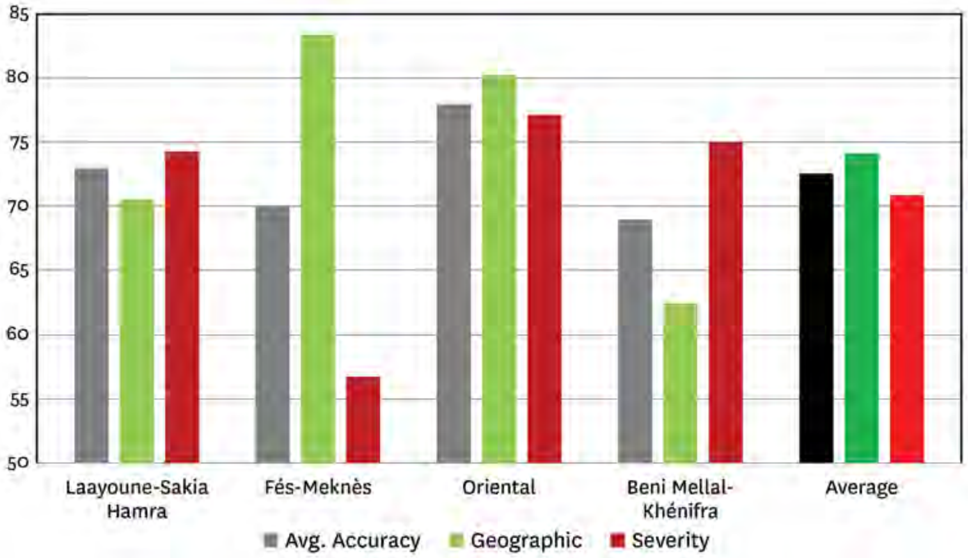


Figure 15. *Regional validators' assessment of eCDI accuracy in the major pastoral areas of Morocco.*

Notably, the lowest accuracies were found to be for forest areas in the Beni Mellal-Khénifra and Fez-Meknès regions. Furthermore, the values reported for the months of December and March were 97% correlated with all the months of the season.

These results suggest several conclusions:

1. The eCDI is broadly useful to support monitoring of rangelands in the most important arid and semiarid areas.

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[18] This covered 35 counties in 17 provinces and a total area of 2,001,035 ha. Validators from the Rabat-Salé-Kénitra, Marrakech-Safi and Souss-Massa regions did not monitor drought conditions each month, and so we have not included results from those areas in this description.

2. Masking of land with forest and snow cover, or the use of pre-existing DRA shapefiles delineating rangelands, would enable the generation of more accurate drought maps in pastoral areas.
3. It could be valid to use December and March eCDI results for winter and spring early warnings to support decision-making on the opening and closure of rangelands during the rainy season.

3.5 Section Summary

Seasonal Precipitation Forecasting. The MENAdrought team developed CNN models, an artificial intelligence approach, to improve global precipitation forecasts in relation to the project countries. We trained the CNN models with observation data from the period 2000-2014 and applied regionalization techniques for the test period 2015-2022.

Despite using only one type of predictor (precipitation forecasts from four global modeling centers), our first attempt at a CNN model for Morocco accurately forecast precipitation with a lead time of 2-3 months. The CNN models' outputs showed major improvement over the global forecast in terms of the spatial location of precipitation as well as volume and anomalies.

Subsequently, we improved results in Morocco by adding sea-surface temperature predictors. In Jordan, we improved results by adding another global modeling center's precipitation forecast as a predictor and by training the CNN models in parallel according to climate region groups; in short, we trained the model using data from the more humid highlands climate region and, in parallel, using data from the *Badia* and arid climate regions. The CNN models are run first for the highlands and then for the other areas; and the results are then joined to form the final forecast.

The CNN models accurately forecast the location and timing of drought (using SPI) onset and recovery in Morocco in 2015-2016 and 2021-2022. Overall, the CNN-produced 2-month lead time forecast had a very high correlation with observed (CHIRPS) rainfall in the subhumid regions of Morocco, with an r value of 0.93, and a low correlation in the arid regions with an r value of 0.43.

In Lebanon, however, inclusion of additional predictors did not improve results substantially. Additional research is needed to identify useful predictors and undertake parallel model training.

Exploring eCDI and Streamflow Forecasting. Given the success with precipitation forecasting in Morocco, the MENAdrought team explored the possibility of forecasting the eCDI using the CNN outputs to force the LIS model. This presented numerous technical challenges given that the LIS model requires subdaily inputs at fine spatial resolution. Whereas the timing of precipitation within the period is irrelevant for SPI, it is obviously critical for land surface/ subsurface interactions. Given this issue, and the challenge in temperature and downward solar radiation forecasting with such temporal precision, outputs to date have been unsuccessful, particularly regarding the soil moisture input.

We suggest that future development efforts for agricultural and meteorological drought forecasting beyond SPI in the project countries should focus on precipitation and temperature-driven indices (such as SPEI) rather than use complex land surface models to produce indices such as the SMA.

In addition to drought forecasting, we conducted pilot research to use the CNN precipitation outputs to force streamflow models. The MENAdrought team parameterized the coupled LIS/Weather Research Forecast (WRF)-Hydro model for the Oum Rabia basin in Morocco and simulated streamflow over the 2000-2015 period. The model simulations reflected the trend in observed streamflow during normal and drought years in this period, albeit with timing and magnitude discrepancies, particularly during high flow events.

Pilot Development of Operational Crop-type Mapping Software. We also developed an operational software for crop-type mapping that is intended to be easily usable by the Moroccan Ministry of Agriculture staff in several applications to:

- increase the accuracy of annual crop yield statistics;
- support decision-making about drought management response measures in major rainfed and irrigated cropping systems;
- direct ground-truthing teams to survey drought impacts on cereal damage together with the insurance firm MAMDA and the agricultural bank CAM; and
- to enable future developments associated with the drought monitoring and early warning system including thematic drought-risk mapping and staple crop yield forecasting.

The advanced machine learning software developed for Morocco and tested in the 'intermediate' bioclimate zone around Rabat uses open-source Sentinel satellite imagery to identify over 80 crop classes. To date, the greatest success has been with annual field crops, and future work would aim to improve results for orchards. Going forward, this approach could be used in the other countries and beyond if established training data approaches are adhered to.

Validation of the eCDI for Use in Monitoring Pastoral Areas in Morocco. From November 2020 to March 2021, Moroccan local government officials assessed the accuracy of the monthly eCDI maps in relation to drought severity and geographical extent in the pastoral areas they monitored. They also provided information on the most affected localities, as well as the status of annual and perennial biomass (including evidence of degradation or regeneration), livestock loading, heat stress, snow cover and unusual transhumant movements. This validation covered the primary rangeland areas—over 1,900,000 ha in the arid, semiarid and subhumid bioclimate zones—and provided an important means of connecting data generation to field conditions and those who oversee them.

Overall, the validators judged the eCDI to be 73% accurate (averaging reported accuracy for drought geography and drought intensity), with a range from 57% to 83% depending on the specific pastoral area and month. The lowest accuracies were found for forest areas in the Beni Mellal-Khénifra and Fez-Meknès regions and areas affected by snow cover. The values reported for the months of December and March were 97% correlated with all the months of the season, which shows strong alignment with the cumulative eCDI trigger.

These results, and the evaluation of the cumulative eCDI in relation to barley production, suggest that the eCDI is broadly useful to support monitoring of conditions in rangelands in the most important arid and semiarid areas. They also show a few simple changes to its calculation (for example, masking forests and snowy areas) could make incremental improvements in the accuracy of eCDI outputs for pastoral areas.

4. Development and Institutionalization of Drought Monitoring Capability

4.1 Collaborative Development Processes

4.1.1 Overview

From the beginning of the needs assessment, and at every check-in point throughout the project, national partners have been consistent in their desire for the project to be 'sustainable'. By this they mean that whatever monitoring system is built together, it is imperative that they can understand it, produce it regularly, maintain its production and enhance it over time. This underlying need guided the project activities and focus areas described in this section as well as in Section 2.

Stakeholder involvement in the development of drought monitoring regimes contributes to more effective monitoring, planning and management (Wilhite et al. 2014; Fragaszy et al. 2020). Figure 1 highlights the iterative process the IWMI team and project partners undertook to refine the eCDI as guided by the national partners' own evaluations, views and needs.

In the project countries, a wide range of stakeholders from government, academia, civil society and the private sector fed into the articulation of needs during Stage 1 (Fragaszy et al. 2020; Annex B). Subsequently, in Stage 2, representatives from a range of government agencies and experts they trusted, who were drawn from national academic and research institutes, evaluated the eCDI inputs and outputs, as described in Section 2.2.

This occurred through the production of technical analyses, engagements to test outputs according to expert knowledge, and multiple workshops in which technical and policy experts interacted to guide future steps. The national partners were also able to learn from the experiences of agencies in other countries through these forums and cross-project workshops which included representatives from all project countries.

Then in Stage 3, the project team solicited feedback from national partners on refinements made to the eCDI and its effects on model outputs. With the project team's support, national partners in Morocco and Jordan have continued and expanded wider expert validation processes with local government officials.

This collaborative process has been time-consuming but vital for national partners to contribute to the monitoring system and ensure that it reflects their needs and knowledge. This is a critical component for their acceptance of its use in policy decision support.

4.1.2 Collaborative Development in Morocco

Our efforts in Morocco focused on expanding access to and use of the eCDI within government (DSS) and beyond, as well as supporting local and central government agencies in the implementation of new legal regimes, particularly Water Law 36-15 and Rangelands Law 113-13. Therefore, officials from a range of central and local government agencies have been involved, particularly from the case study region of Souss-Massa (officials from the river basin agency ABH Souss-Massa) where the DAP work has focused. Also, given the relatively advanced state of the eCDI in Morocco early in the MENAdrought project, we have piloted and refined seasonal forecasting and related tools (see Section 3.4) in Morocco with feedback from governmental stakeholders.

The Moroccan Ministry of Agriculture shares eCDI outputs with MAMDA (an insurance company) which uses them, in addition to field surveys and precipitation station data from the national meteorological office (Direction de la Météorologie Nationale, DMN), to decide on insurance pay-outs to farmers, especially cereal growers, in affected areas. In addition, drought maps are shared with the Ministry of Interior, and drought status (Watch, Alert, Emergency, Crisis) is communicated to regional governors who work with local agencies on drought management[19].

4.1.3 Collaborative Development in Jordan

In Jordan, collaborative development efforts have focused on ensuring the eCDI is fit for use in the DAP, which is linked to the Water Sector Policy for Drought Management (MWI 2018). As such, there has been a particularly strong element of ensuring common understanding of the eCDI tool across the government agencies that make up the Drought Technical Committee and the National Drought Management Committee chaired by the MWI (see the Pillar 3 report). Likewise, the collaborative DAP process has ensured focus of the eCDI application while highlighting future priorities for development.

4.1.4 Collaborative Development in Lebanon

In Lebanon, collaborative development efforts have focused sharply on evaluating the eCDI in the light of expert knowledge and in relation to comparable modeling exercises performed at the MoEW. Paucity of observational data resulted in more emphasis being placed on expert knowledge evaluations, which has the silver lining of ensuring that a wider range of experts have been involved in testing the eCDI outputs and feeding into refinements. Feedback has focused development of the DAP and longer-term themes of interest, as well as led to development and consideration of the DSCI trigger.

4.2 Capability-building—Technology Transfer and Training

4.2.1 Technology Transfer

At the time of writing, engineers in Jordan and Morocco are running the entire system operationally and independently, and as noted, we anticipate that Lebanese agencies will have this capacity as well, provided that conditions allow it.

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[19] The *Wali* (governor) of each region, an administrative division including several provinces, consults with watershed agencies (ABH), regional directorates of the Ministry of Agriculture (DRA and ORMVA, which oversee, respectively, rainfed growing areas, pastures, rangelands and silvopastoral and forestry areas, and irrigated systems productivity), municipalities and water utilities.

This achievement is the result of years of work to develop local capabilities and capacities and to ensure that the monitoring system is fit for its purpose and suited to local capabilities, including through:

1. training local engineers in the installation, use and ongoing development of advanced modeling tools on local systems (elaborated further below);
2. drafting training and user manuals for operational use of models, quantitative and qualitative validation procedures, and output interpretation;
3. providing needed hardware systems, such as external drivers/servers and integrating relevant software to run the eCDI drought monitoring system;
4. establishing, parameterizing and calibrating modeling frameworks in each country using local data as available;
5. developing new data pre-processing and modeling processes such as the harmonic analyses described in Section 2.2;
6. adapting modeling frameworks to the operational capabilities and capacities of national partners; for example, enabling them to run on open-source operating systems;
7. writing programs to integrate operations from multiple models and simplify model interoperability;
8. writing numerous scripts to streamline eCDI production and semi-automate numerous core steps shown in Section 2.3, such as remote sensing data downloads and pre-processing, and eCDI integration; and
9. developing web interfaces for eCDI outputs (as shown in Section 2.4) to ease information-sharing and support the eCDI's use in operational decision-making and ongoing validation efforts.

Each of these individual components followed an iterative process. For example, when we improved the eCDI in Stages 2 and 3 to use new modeling processes (item 4 in the list above), we also had to revise related programs and scripts (items 6-7). Likewise, when we first installed LIS on local servers (items 1-2), we ran into numerous technical challenges that had to be addressed one by one. These challenges were exacerbated due to the need for remote system access because of Covid-19-related travel restrictions. Also, we found that remote training sessions were significantly less effective than in-person training.

4.2.2 Training

This is a critical component for sustainability of the project and ongoing production of the eCDI. We developed training modules and ran numerous technical trainings for staff of national partner agencies. These related to drought monitoring tools, eCDI validation and drought management planning.

Training for local engineers focused on the following elements related to the installation, use and ongoing development of advanced modeling tools on local systems:

- Installation and parameterization of the LIS model across national domains;
- Initiating climate forcing model components;
- Running scripts for data download and other pre-processing related to model runs;
- Production of eCDI inputs and undertaking LIS model runs, particularly in relation to the use of a dynamic vegetation scheme and the automation of the LIS run;
- Use of the web interface;
- Data quality checks and interpretation of the eCDI outputs; and
- Revising calibration of LIS model components, eCDI input weights and other modifiable components.

In addition, we trained (including through application) a wide variety of stakeholders on the following themes to support their use of the eCDI in decision-making and planning:

- Composition and interpretation of the eCDI;
- Validation of the eCDI through spatial and quantitative as well as qualitative and semi-quantitative methods;
- Drought-risk management via the IDMP's 3 Pillars approach; and
- Testing the potential of thematic monitoring by validating the drought monitor in rangelands (Morocco).

4.3 Institutionalization of Drought Monitoring via Interagency Collaboration

We summarize here the theme of institutionalization of drought monitoring; the Pillar 3 report expands on this significantly.

Through the needs assessment process, stakeholders in all the project countries emphasized the importance of improving interagency collaboration to improve drought monitoring and management (Fragaszy et al. 2020; Jedd et al. 2020). They especially linked this issue to the theme of data- and information-sharing (which was identified as one of the most important needs in all countries), ground-truthing of information, as well as policy coordination.

4.3.1 Information-sharing

The needs assessment found that in all MENAdrought project countries, information-sharing within and between government agencies, and between central and local governments, was a stumbling block for effective drought monitoring. The reasons for this barrier are varied and include the need to purchase data, the need for formal institutional data requests, the culture of data ownership by producing agencies that leads to their unwillingness to share information, and the political and financial challenges associated with drought management intervention decision-making. In all project countries, during the needs assessment, stakeholders promoted the idea of creating a data-sharing platform to solve this challenge by requiring agencies to submit specific data and provide all participating agencies with open access to compiled datasets and information.

We have worked to address this problem primarily through drought management planning efforts in each country as well as simplifying the visualization and integration of eCDI outputs. In short, the DAPs provide a clear and concise data-sharing framework whereby various agencies involved in the technical working group provide specific, high-priority impact monitoring on a regular basis, usually monthly, and all receive access to eCDI outputs. The provided information—the eCDI as well as environmental and socioeconomic information—feeds into decision-making processes and is visible across agencies. Agencies considered what data were currently collected and critical for priority impacts addressed by the DAP focus themes, as well as what monitoring should be improved over time.

In this way, environmental and socioeconomic monitoring data collection, collation and dissemination is novel in the project countries, purposeful and directed by end-needs. Likewise, some agencies have begun to publish eCDI outputs publicly, which is highly encouraging of agencies' confidence in the information (as shown in Figure 16).

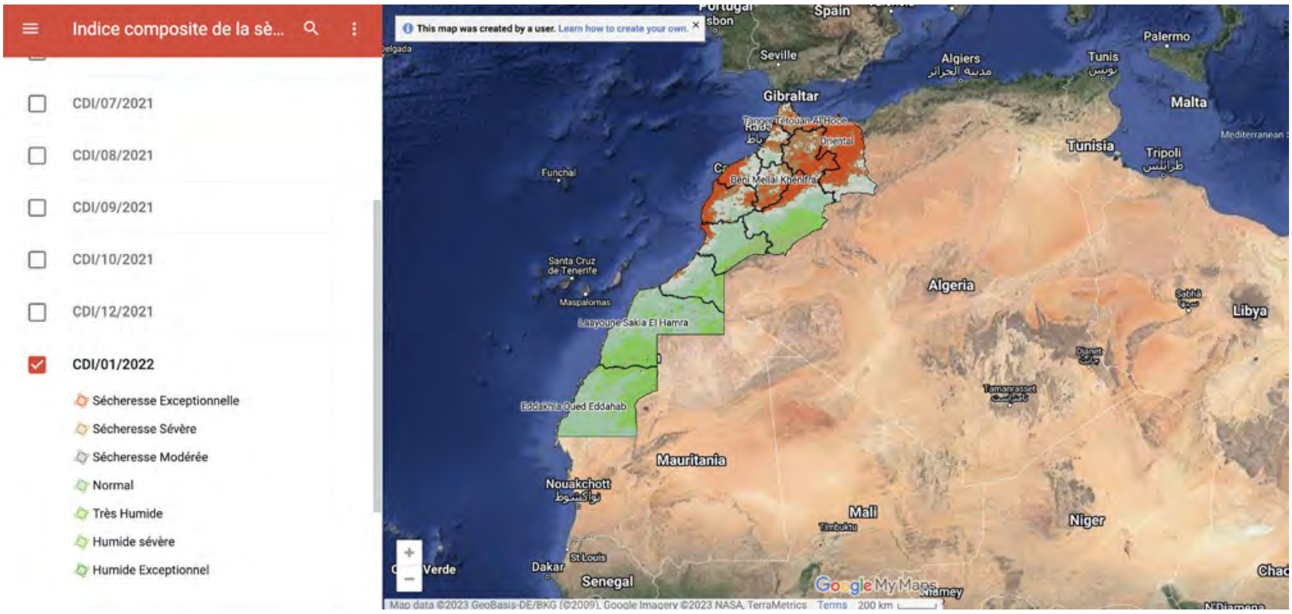

Figure 16. *Screenshot of Moroccan eCDI outputs for January 2022 published by the DSS*[20].

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[20] https://www.google.com/maps/d/viewer?mid=1z0hdz3xuU8e0ogvev3grFsC_jhwHc85L&ll=27.325081270681203%2C-6.840295897614376&z=5

4.3.2 Institutionalization via Validation Networks

During the needs assessment, interviewees expressed skepticism about the capacity of remote sensing and modeled data to provide relevant indicators at acceptable levels of accuracy, precision and geographic scale.

They often expressed this skepticism during discussion of highly localized climatic and hydrological patterns and in relation to the geographically small range between agroecological zones and transitional areas. As such, stakeholders stated that gaining widespread buy-in for drought monitoring tools like the eCDI would require adequate ground-truthing and validation to assess the relationship between reported eCDI values and drought effects. Stakeholders want to ensure monitoring tool outputs accurately reflect the drought impacts that they see on the ground, including at least the meteorological, agricultural and hydrological components.

We have described validation studies at length in Section 2.2 and briefly discuss here longer-term institutional collaboration through the establishment of validator networks. As described by Fragaszy et al. (2020), validation networks can be important drivers of drought monitoring institutionalization. In sum, they help to cement drought monitoring and management coalitions that create demand for information, and they support improvements over time, which increases the legitimacy of the information provided.

Morocco. As described in Section 3.4, during the 2020-2021 agricultural year, the DSS, the MENAdrought lead agency within the Moroccan Ministry of Agriculture, supported the establishment of a regional validation network. This included training sessions with local government officials from water and agricultural agencies (ABHs and DRAs, respectively) in every region to learn about the composition of the eCDI and how to interpret it. Subsequently, they reviewed the eCDI output monthly and provided feedback on it, as well as information on drought impacts (if any) in their region.

Jordan. In Jordan, we assessed the impacts of the 2021 drought in the Tafilah Governorate, which included, among several components, evaluation of the accuracy of the eCDI maps (Belhaj Fraj et al. 2022b). This type of effort will support long-term improvement of the drought early warning system overall and link it more effectively with drought management as undertaken through the DAP.

4.3.3 Institutionalization via Policy Linkages

During the needs assessment, government officials and others across the project countries stated the need to develop technical definitions of drought beyond precipitation deficit and seasonal SPI. These definitions would ease public declaration and/or intragovernmental drought confirmation processes, support tiered management intervention processes, and increase demand from policymakers for rigorous monitoring data.

The MENAdrought project has addressed this need most immediately using eCDI thresholds within DAPs, as described in depth in the Pillar 3 report. While decision-making on management actions is ultimately based on a range of information available about drought, as well as other political considerations, DAPs include guidance for tiered drought management responses based on eCDI values. In this way, the project has supported institutionalization of monitoring by promoting a management framework that has consistent monitoring information products at its core.

4.4 Section Summary

Development and Institutionalization of Drought Monitoring Capability. A core focus of the system design and associated engagements was for the outputs to function and support agency decision-making after the MENAdrought project is finished. This is achieved through the choices of data inputs, and by building capabilities, technology transfer and institutionalization of developed tools and skillsets. For example, input data were chosen based on various criteria such as the data being cost-free, length of the available data record, radiometric sensing channels that can detect key drought indicators, space and time resolution, and the commitment of data providers to maintain their provisioning systems. The eCDI developments were themselves underpinned by explicit and iterative assessment of the partner countries' needs and collaborative processes. This social and technical effort supported the project's development of drought early warning systems and their operationalization, including through drought management planning described in the associated Pillar 3 report.

These efforts included targeting validation studies with local partners, technical tool co-development, and associated research efforts toward specific policy implementation goals in the project countries. For example, in Jordan, we focused heavily on ensuring the early warning system could support implementation of the Water Sector Policy for Drought Management and building a common understanding of the eCDI tool across relevant agencies and teams that have technical, coordination, and decision-framing roles. Likewise, in Morocco, collaborative development efforts focused on supporting implementation of new legal regimes (namely Water Law 36-15 and Rangelands Law 113-13, both from 2016), including through supporting increased central and local government interaction, collaboration and information-sharing.

We supported various capacity-building approaches through training, technology transfer and iterative modeling refinements. These covered all technical aspects required to produce the eCDI operationally and use it effectively:

- Model installation, parameterization and calibration;
- Input data preparation, pre-processing and model execution;
- Output interpretation and validation; and
- Information-sharing.

We focused in particular on simplifying and expediting model execution processes, primarily by streamlining input data preparation, pre-processing, and coding frameworks to operate the model. In many cases, this required novel methods and coding frameworks to address the issues identified through ongoing operation of the eCDI over time. It also included training officials with technical and policy roles in the usage of this information for drought impact and vulnerability assessment, as well as in drought management planning and related applications.

In addition to development of human and technical capacities, we sought to ensure project sustainability through the institutionalization of demand for early warning tools. This has been achieved primarily through the drought management policy planning described in the Pillar 3 report.

The needs assessment process identified barriers to information-sharing as a key problem for the existing drought monitoring and management arrangements. We sought to address this through careful prioritization of the drought monitoring information required through drought management planning, creation of a web interface, supporting the integration of eCDI outputs into other tools, or simply open publication of the results, which Moroccan agencies now do regularly. More broadly, though, the eCDI validation efforts, and especially the creation of a network of regional validators, support the objective of institutionalizing drought monitoring and early warning within the 3 Pillars framework.

5. Future Research-for-Development Opportunities

5.1 Potential to Replicate MENAdrought Early Warning System in Other Countries

Aside from the applied research opportunities described below, it would also be possible to outscale the efforts of the MENAdrought project. In other words, it would be possible to replicate the existing drought early warning system, with appropriate modifications for local data and context, in other countries in the MENA region (for example, Iraq, Sudan, or Mauritania) or beyond.

During the MENAdrought project, we saw that this would be possible through IWMI contributions to the Center for Mediterranean Integration project entitled ‘The Water Security Nexus in North Africa: Catalyzing Regional Coordination Around Climate Change, Resilience and Migration[21] (CMI and IWMI 2021).

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[21] https://www.cmimarseille.org/programs/water-security-nexus-north-africa-catalyzing-regional-coordination-around-climate-change

For this project funded by the Foreign, Commonwealth & Development Office (FCDO), IWMI made significant contributions in Tunisia, including the following:

- Local installation and preparation of the MENAdrought-developed drought early warning system inclusive of the eCDI and seasonal rainfall forecasting;
- Training of young engineers from the water resources directorate (Direction Générale des Ressources en Eau, DGRE) in Tunisia to operate the early warning system independently; and
- Assessment of drought typology using the eCDI and training on principles for triggers determination.

Expanding on Drought Early Warning and Related Systems Developed through MENAdrought. In the Pillar 2 reports, we provide a range of future research-for-development opportunities related to technical drought monitoring, seasonal precipitation forecasting, rainfall runoff modeling and crop production modeling. Here we expand on those identified research-for-development opportunities through:

- Development of sector-specific drought mapping and forecasting tools;
- Development of operational water and food security early warning systems; and
- Implementation of interactive decision-support systems and dashboards for financial actors.

5.2 Sector-specific Drought Mapping and Forecasting Tools

Based primarily on the LIS modeling, seasonal forecasting and crop-type mapping developed through MENAdrought, it would be possible to develop sector-specific drought monitoring and forecasting tools focused on irrigated and rainfed cropping systems for annual and perennial staple crops, as well as pastoral, silvopastoral and forestry systems in a unified monthly map. It would be possible to calibrate the different components of the eCDI based on spatio-temporal impacts of drought on dominant cropping systems in specific areas. Indeed, this would respond, somewhat, to early recommendations of national stakeholders reviewing eCDI outputs to configure multiple versions of the eCDI for specific agricultural systems or agroecological zones.

5.3 Development of Operational Water and Food Security Early warning Systems

Building off the MENAdrought early warning system, it would be possible to develop operational models to produce information about food and water security status and forecasts. We would use the United States National Water Model WRF-Hydro and machine learning techniques, and calibrate the model at the country level to simulate and predict surface water parameters at the basin level (inflow, outflow, volumes in the surface water reservoirs and, if possible, allocation available to different sectors).

Likewise, building off MENAdrought crop-type mapping, we propose to develop improved crop maps for the project countries. Then, the combination of crop-type maps, drought forecast maps and new crop models would enable us to estimate crop harvested area, yield and production for different regions of a country.

Both forecasting systems could be linked to web interfaces for report generation. Also, key outputs of the models could be fed into national food and water security decision-support systems inclusive of dashboards that illustrate national status and trends in water availability and staple crop production.

5.4. Implementation of Interactive Decision-support Systems and Dashboards for Financial Actors

We would be able to develop information platforms that integrate drought, crop and water model outputs, as well as risk mapping, to be used by private and public sector financial actors including insurance companies, national agricultural development banks, and disaster management and compensation agencies. Further, we consider that this information could support the development of financial remediation and/or risk management schemes aimed at the most vulnerable populations, particularly rainfed farmers of staple crops.

With changing climate conditions leading to increased frequency and intensity of droughts in the MENA region, adaptation activities need to be embedded and operationalized by governments within decision-making frameworks so that timely actions are taken to reduce impacts across communities. This requires activities beyond research; it requires policy development and technical assistance programming that is tried, tested and trusted, and critically is part of drought action planning by government agencies. Producing data through early warning systems is just the first step, and must be implemented despite the complex challenges of developing action plans across multiple ministries in order to accomplish the objectives of the Nationally Determined Contributions to the United Nations Framework Convention on Climate Change. This requires a long-term commitment to support key government agencies and emerging drought management institutions that oversee drought preparedness, mitigation and response actions.

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Annex A.
Conceptualizing Drought in the MENA Region[22]

A1. Conceptual Clarification: Aridity, Water Scarcity, Desertification and Drought

Defining drought in areas such as the southern and eastern Mediterranean basin, which has high intra- and interannual variability in precipitation, temperature and water availability, is a major challenge. Understandably, stakeholders, including those with drought monitoring responsibilities, frequently conflate long-term water availability, climatic norms and water supply challenges with drought.

Differentiating clearly between aridity, water scarcity, desertification and drought—as well as ensuring stakeholders understand and apply the distinctions—is a necessary precondition for drought monitoring within the political context (Table A1). Whilst drought contributes to water scarcity and desertification, it is a temporary feature that affects the hydro-social framework—the way water and society make and remake each other—and human-environment interactions (Budds et al. 2014).

Making connections but also distinctions between these four terms is a precondition for establishing effective drought monitoring and management programs, particularly in vulnerable semiarid to subhumid climate transition zones.

Generally, the term 'arid' refers to natural environments of which chronic water scarcity is a defining feature. Operationally, aridity is defined as precipitation under a set figure (typically below the 200 mm/year isohyet). A related concept is desertification, which is land and vegetation degradation in arid, semiarid and subhumid areas.

Aridity and the presence (or lack) of perennial surface water resources are taken as proxies for drought by many in charge of agricultural management in the focus countries. For example, stakeholders in Lebanon frequently said the mountainous regions and lower Litani Basin do not experience droughts because annual rains and spring outflows are predictable whereas the Akkar Plain, a semiarid to arid region in the north of the country, suffers chronic drought nearly annually. The same pattern held in Tunisia, with stakeholders describing the mountainous northern regions as immune from drought when compared to the semiarid central plains.

Desertification is triggered by anthropogenic causes such as deforestation and land clearance, overgrazing, poor tilling and irrigation practices, etc., as well as (or in combination with) extreme climatic events such as drought and floods in dryland areas (UNEMG 2011).

Water scarcity reflects an underlying mismatch between available water resources and the water needs of people, the environment and the economy. Analyses of water scarcity such as those using the Water Stress Index (Luo et al. 2015) typically incorporate data on water resource availability and quality features, supply infrastructure, social access to water and environmental characteristics.

Table A1. *Characteristics of aridity, water scarcity and desertification.*

	Aridity (Mishra and Singh 2010)	Water scarcity	Desertification (UNCCD 1994)
Description	Dryness is a permanent physical condition of the landscape.	Water supply does not meet demand.	Land degradation in arid, semiarid and dry subhumid areas, resulting from various factors including climatic variations and human activities.
Definition type	Physical	Relative to human needs	Ecological process
Causal factors	Climate	Climate/hydrology; environmental, social, economic factors, increase in demand and infrastructure	Climate/hydrology; land, water and agricultural management practices
Common definitions	Typically, precipitation <200 mm/year	Water supply to demand ratio, water availability < 500 m3/year/capita	Vegetation cover and type; soil characteristics

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[22] This material is largely based on, and modified from, McDonnell et al. 2019.

A2. Conceptually Defining Drought in the MENA Region

Drought is defined conceptually as a significant negative deviation from the normal hydrological conditions of an area (Mishra and Singh 2010). It is a stochastic natural hazard, the direct effects of which can reach continental scale, and the indirect effects of which can be global given modern food chains (Wilhite 2000; World Bank and FAO 2012; Fragaszy 2015).

Defining drought in universal terms is not possible given its typically slow onset, the local environmental context, and the range of socioeconomic and agricultural factors controlling drought impacts (Mishra and Singh 2010). Dracup et al. (1980) and Salas (1993) show that drought definitions must consider drought type, duration, intensity, magnitude, extent and frequency.

Drought type is the specific water deficit under consideration; duration is the length of the deficit episode; intensity is the comparative deficit to long-term norms; magnitude is the ratio of the drought intensity to its duration; extent is the area under specified drought conditions; and frequency is the average return period of a drought exhibiting a particular magnitude and extent.

Therefore, operational drought definitions must be developed for local conditions, purposes and situations. They must also be determined by the impact and timeframe one desires to assess. Drought research increasingly aims to disentangle the climatic and anthropogenic components of drought's spread through socioenvironmental systems to understand how anthropogenic activities affect drought events (Van Loon et al. 2016).

Wilhite and Glantz (1985) characterized four major drought types, and Mishra and Singh (2010) added to this canon the category of groundwater drought. In brief, the classifications are defined as follows:

- Meteorological drought—lack of precipitation over a period of time;
- Agricultural drought—reduced soil moisture and crop impacts;
- Hydrological drought—inadequate surface/groundwater for established water uses;
- Socioeconomic drought—failure of water systems to meet water demands; and
- Groundwater drought–reduction in groundwater recharge and groundwater table levels.

Meteorological drought assessments compare the volume of precipitation in a distinct time-period and location to the long-term norm for that same period and location. Therefore, precipitation is the primary indicator used to assess meteorological drought, at times in combination with temperature and evapotranspiration. Given the little data needed, and the ease and speed with which the onset of meteorological drought can be determined, it is often the starting point to assess drought in the MENA region, as discussed in Section 1. In our focus countries, prior to the MENAdrought project, only precipitation information was used in operational policy definitions of drought (see Jobbins et al. 2022).

Agricultural drought refers to a period of soil moisture deficit leading to negative impacts on crops and/or rangeland degradation due to reduction in biomass. It may be determined through the interaction of hydrological, climatic and biological indicators. According to the WMO consensus, agricultural drought indices can be divided into 7 types (Sivakumar et al. 2011:

1. Precipitation-based indices
2. Temperature-based indices
3. Precipitation- and temperature-based indices
4. Indices based on precipitation, temperature and soil moisture/soil characteristics
5. Indices based on precipitation, temperature, relative humidity, solar radiation, wind speed and soil moisture/soil characteristics
6. Indices based on remote sensing
7. Composite indices (multiple indicators/indices)

These indicators are often analyzed in conjunction with locally specific crop water requirements during various crop growth stages (Mishra and Singh 2010). Agricultural drought has been assessed widely within the MENA region's semiarid and humid littoral regions where it can have major negative impacts on crop production as well as on the semiarid and arid rangelands where it impacts forage availability and irrigation water requirements (e.g., De Pauw 2005; Shetty 2006; FAO and NDMC 2008; Faour et al. 2012).

The impacts of agricultural droughts are usually assessed in rainfed agricultural areas rather than irrigated areas since drought impacts on the latter may be better assessed through hydrological drought and/or groundwater drought indices.

Hydrological drought is a composite classification that deals with overall water availability within a given basin for municipal, agricultural and environmental uses. As such, a wide range of indicators can be used. These include precipitation and snowpack, streamflow, reservoir levels, spring discharge, evapotranspiration, soil moisture, groundwater levels and recharge rates, vegetation responses and other factors depending on local conditions. To a certain extent, hydrological drought assessments rely on water balance modeling and they attempt to sequence and quantify drought impacts through time for a wide range of often-competing water uses (Zargar et al. 2011). As such, data requirements for making comprehensive hydrological drought assessments are quite high.

Groundwater drought assessment is especially relevant in the target countries given that groundwater systems that receive modern recharge are already utilized close to or beyond their annual average recharge rates (Al-Zubari 2014; Shah 2014). Therefore, any decline in recharge and drop in groundwater tables due to drought conditions can have serious and permanent repercussions on the entire resource system due to current utilization patterns.

For example, sustained drought conditions in Lebanon in the late 1990s led to a large increase in groundwater pumping from coastal aquifers as surface water resources were inadequately managed to meet local municipal and agricultural needs. These aquifers were already experiencing seawater intrusion and both direct drought impacts (reduced recharge) and indirect drought impacts (increased aquifer pumping) accelerated the deterioration of groundwater resources (Saadeh 2008).

Table A2. *Characteristics of drought types.*

Drought type	Definition (Mishra and Singh 2010)	Time frame for assessment	Primary indicators (WMO and GWP 2016)	Commonly used indices (WMO and GWP 2016)
Meteorological	Lack of precipitation over a specific time period	Shortest time frame, typically 1-6 months	Primarily precipitation	SPI is the most widely used index (Hayes et al. 2011)
Agricultural	Reduced soil moisture and resultant crop impacts	Agricultural season (typically up to one year)	Precipitation, soil moisture, potential evapo-transpiration, temperature, wind, crop condition	Soil moisture anomaly (SMA), Soil Moisture Deficit Index (SMDI), NDVI, SPEI, Palmer Drought Severity Index (PDSI)
Hydrological	Inadequate surface and/or groundwater for established water uses	May be interannual depending on hydrological system	Streamflow, snowpack, precipitation, reservoir levels, groundwater levels	Surface Water Supply Index, Aggregate Dryness Index (ADI), Low Flow Index, Streamflow Drought Index, Groundwater Resource Index
Socio-economic	Failure of water systems	Socio-economic	Water demand, reservoir levels, groundwater abstraction, precipitation, and social, economic, and environmental feedback	Assessment frameworks rather than specific indices since they include socioeconomic and potentially land-use impacts, factors and responses (e.g., Van Loon et al. 2016; Mehran et al. 2015)

Annex B.
Additional Detail on Drought Monitoring Needs

B1. Cross-country Similarities

B1.1 Drought Definitions

In 2015-2016 in all MENAdrought project countries, our interviewees—government officials as well as others—stated the need to develop technical definitions of drought beyond precipitation deficit and seasonal SPI in order to ease declaration processes, allow tiered intervention processes and increase demand from policymakers for rigorous monitoring data. This was one of the primary connections between drought monitoring and management, as described in Section 5. Stakeholders particularly focused on the need to incorporate different types of drought impacts into these definitions, beyond meteorological and hydrological drought components. This theme was of high importance in Morocco, among the highest-ranked drought management needs identified in Tunisia (as reported by Fragaszy et al. 2020), fourth in Lebanon, and third in Jordan. It was also raised frequently and at length during interview discussions on drought management needs and workshops.

B1.2 Information Sharing

Participants universally expressed the need to formalize and automate information-sharing processes; and, in all countries, they mentioned the potential of a drought data platform to facilitate this objective. In all project countries, information-sharing within and between government agencies, and between central and local government, is a stumbling block in effective drought monitoring. The reasons for this barrier are varied and include the need to purchase data, the need for formal institutional data requests, and the culture of data ownership by producing agencies that leads to their unwillingness to share information.

In all project countries, our interviewees promoted the idea of creating a data-sharing platform to solve this challenge by legally requiring specific agencies to submit data and then providing all participating agencies with open access to compiled datasets and information. They believed this would facilitate information collation, and therefore be key to addressing the challenge inherent in attempts to monitor and assess a much wider range of potential drought impacts simultaneously. Addressing data sharing was the most important theme in Morocco, the second most important in Tunisia and Lebanon, and the third in Jordan.

B1.3 Ground-truthing Remote Sensing-derived Information

Across the project countries, and especially in Tunisia and Lebanon, interviewees expressed skepticism about the capacity of remote sensing and modeled data to provide the relevant indicators at acceptable levels of accuracy, precision and geographic scale. This is described in Section 4.3.2.

This theme was frequently discussed in Morocco, although some eCDI validation has already taken place in the Oum Rabia basin. It was highly relevant in Tunisia, the most important issue in Lebanon, and the second most important issue in Jordan. It was particularly salient in Lebanon because of the expressed need to create a political demand for drought monitoring data. Stakeholders there perceive that political decision-makers are not interested in drought monitoring because they do not perceive drought as a significant problem for the country. Stakeholders consider that assuring the validity of drought monitoring and impacts data would help address this challenge of perception.

B1.4 Data Quality Challenges

Interviewees, especially technical government officials, civil society organization (CSO) representatives and researchers, raised concerns about the data quality of monitoring networks (described in Table B1). The specific challenges differed between countries but revolved around a few specific and consistent themes (Tables B2-B3):

- Data reliability—for example, related to the placement and calibration (or lack thereof) of climate monitoring stations;
- Monitoring data source bias—monitoring networks unevenly distributed in countries;
- Data continuity and frequency of production;
- Indicator and reporting unit consistency across levels of government; and
- Lack of electronic data management, as many data are still collected on physical spreadsheets.

B1.5 Intersectoral Engagement

Despite significant differences in the agroeconomic systems of the project countries, participants uniformly expressed the need to improve engagement between farmers—and the institutions that represent and interact with them—and government agencies in regard to drought monitoring. This generally reflects farmers' desire to receive more useful and tailored drought-related information, and to provide relevant information and therefore influence the agencies in charge of drought assistance and relief. Likewise, it reflects government officials' realization that farmers and those closest to them hold critical drought monitoring information and understand drought impacts on the local scale, and that ultimately the private sector and civil society drive drought management activities in the broadest sense. This theme was the most important in Tunisia, fifth in Jordan, and third in Lebanon.

Table B1. *Climatic and hydrological monitoring network and vegetation state monitoring.*

	Climate monitoring	Hydrological monitoring	Vegetation condition monitoring
Morocco	DMN: 42 synoptic, 206 automatic climate stations (Badi and Kasmi 2016); Other institutions: ~370 climate stations (OECD 2017)	DGE/ABHs: 265 principal surface water measuring stations and ~700 gauge stations (OECD 2017); 128 groundwater wells with automated groundwater data recording (Moumen et al. 2014)	INRA/DMN/DSS: Crop Growth Monitoring System for seasonal prediction, monitoring and modeling grain yields (Balaghi et al. 2013); CRTS: Production of eCDI (Bijaber 2017)
Tunisia	DGRE: ~850 precipitation stations (Mansour 2016); INM: 26 synoptic, 31 agrometeorological, 29 climatic stations, ~200 precipitation stations (El Hedi Louati et al. 2005)	DGRE: 60 principal surface water stations and 74 gauge stations (Mansour 2016); ~3,700 groundwater monitoring wells (Horriche and Besbes 2007)	CNCT, DGPA, DGF: NDVI and related indices for land cover/state, ex-post cereals yield estimation (BenSalah 2016)
Lebanon (CNRS 2015; MoEW 2014)	DGCA: 36 weather stations (some synoptic); LARI: 55 agrometeorological stations (various types); CNRS: 17 weather stations (various types); LAEC: 16 weather stations	LRA: 51 gauge stations (of which 9 are spring discharge stations); MoEW: 13 groundwater monitoring wells; CNRS: 3 snow monitoring stations	No official ongoing monitoring of vegetative state
Jordan	JMD: 13 synoptic, 8 agrometeorological, 25 climate, ~50 precipitation stations (Semawi 2006)	MWI/JVA: 47 surface water monitoring stations; ~600 spring discharge gauge stations; 222 groundwater monitoring wells (Hajahjeh 2006; Hayajeneh 2012; Nait 2015)	MoA/NCARE: NDVI and related indices such as VCI (Saba 2016)

Source: Fragaszy et al. 2020.

B2. Additional Detail: Drought Monitoring Stated Needs in Lebanon

Table B2. *Drought monitoring stated needs in Lebanon*.

Need	Description	Frequency	Relative frequency (%)
Ground-truthing	Improve reliability of monitoring product through ground monitoring including inputs; gather data from meteorological stations and streamflow gauges, well meters, soil moisture and micro-monitoring; take the crucial step to link those data with remotely sensed products.	21	18.9
Formalized information sharing	Create stable information sharing networks with automated mechanisms and a central hub for technical information.	12	10.8
Extension and outreach	Information translation: Ensure linkages between drought monitoring and extension and outreach programs.	10	9.0
Create political demand	Ensure policy relevance and uptake by creating demand for monitoring; tailor the information in a way that is useful to decision-makers.	8	7.2
Drought-crop connection	Understand the drought-crop connection: Offer irrigation and planting guidance.	6	5.4
Issue overlap	Connect with other issues: For example, irrigation efficiency, saline intrusion, groundwater pumping/recharge and electricity costs.	6	5.4
Agency host	Find the appropriate agency host. House the monitoring program in an agency that can easily share information; or create a central clearinghouse that can share information.	6	5.4
Security	Address data access issues in non-secure/border areas.	5	4.5
Individualize inputs	Understand the eCDI inputs: Make the connection between pure and applied research.	5	4.5
Open-source	Make the monitoring data and script open-source with transparent collection and dissemination.	4	3.6
Appropriate applications	Find a way that is technologically appropriate to reach farmers and affected populations.	4	3.5
Data quality	Ensure up-to-date and accurate data.	4	3.6
Management triggers	Link monitoring efforts to specific water availability and planning recommendations and/or drought declaration.	4	3.6
Geospatial analysis	Host the monitoring program in an agency that can do remote sensing and GIS analytical work.	3	2.7
Technical training	Host training sessions for using new monitoring tools.	3	2.7
Boost public awareness	Generate basic public awareness about drought and drought monitoring.	2	1.8
Water markets	Link monitoring efforts to water valorization.	2	1.8
Staff training	Have the right staff trained who are in charge of the disaster risk management systems.	2	1.8
Link prior efforts	Link to previous monitoring efforts to ensure sustainability.	2	1.8
Agency buy-in	Get buy-in from the agencies involved; build cooperation and buy-in at a high-level in each institution.	1	0.9
Revise as needed	Ensure that monitoring programs and projects are open to feedback, and are revised based upon new information.	1	0.9

B3. Additional Detail: Drought Monitoring Stated Needs in Jordan

Table B3. *Drought monitoring stated needs in Jordan.*

Need	Description	Frequency	Relative frequency (%)
Spatial analysis	Host the program in an agency that has the skills to utilize remotely-sensed products and GIS.	13	11.3
Detailed technical training	Improved technical training for engineers and officers.	11	9.6
Data sharing	Formalize the data sharing exchange program; create a permanent network with regular meetings.	10	8.7
Drought declaration	Create clear mechanisms for defining a drought and/or making a declaration.	10	8.7
Interagency buy-in	Create a cooperative environment with open communication between agencies, and buy-in amongst them.	9	7.8
Civil society involvement	Involve farmers, non-governmental organizations and the public in monitoring; use their input, and make products accessible to them.	8	7.0
Scientific consensus	Use a single indicator, or agree on multiple inputs.	8	7.0
Reliability	Use of reliable data sources; engage field validation efforts.	8	7.0
Drought committee	Appoint a national committee to coordinate stakeholders with the authority to declare drought.	6	5.2
Include groundwater	Link drought with groundwater resources and water balance modeling.	6	5.2
Crop guidance	Develop the capacity to provide crop planting advice related to timing and irrigation.	4	3.5
Regional connection	Link up with regional monitoring initiatives.	4	3.5
Proper time scale	Produce monitoring products on a frequent and tailored (downscaled) basis; understand the time-scale involved in processes related to drought.	4	3.5
Local vulnerability	Work with local offices and vulnerable areas.	3	2.6
Open data	Use openly available data and make the outputs readily accessible.	3	2.6
Simple training	Simplified training for political users.	2	1.7
Data platform	Have a data repository for ease of use.	2	1.7
Connect other issues	Understand how drought fits in with other domains, such as climate and finance.	2	1.7
Ease of use	Create a simple, easy-to-use early warning system.	1	0.9
Water markets	Understand how to inform water pricing programs.	1	0.9

B4. Additional Detail: Drought Monitoring Stated Needs in Morocco

Officials in Morocco described a range of needs to improve drought monitoring, with information sharing and communication being the most frequently mentioned aspects. Every interviewee and small meeting participant mentioned information sharing issues of some sort—technical, institutional or political—as a core barrier to effective drought monitoring and management.

Overall, stakeholders emphasized that individual agencies execute their own monitoring effectively provided a budget is made available, which they reported is typically the case. However, integration and sharing of the produced information streams remains weak. Stakeholders described a range of reasons why this occurs:

1. **Drought data sensitivity:** Drought data are considered politically sensitive, which exacerbates the other barriers described below. This limits exposure of drought data and prohibits general reporting on and circulation of information on climatic and agrometeorological conditions. This includes the eCDI map produced by Centre Royal de Télédétection Spatiale (CRTS). Numerous interviewees in government agencies said they have seen the map at least once and were intrigued by it, but they were unable to use the information effectively because they could not access it regularly. Non-governmental agency representatives had not heard of the drought map at all.
2. **Formality and data purchase:** Government agencies typically share information only with designated partner

agencies through formal conventions. Without such conventions, data, if their provision is permitted, must be purchased at high cost.

3. **Lack of information percolation:** When interagency data sharing occurs, often information only reaches the top managers of the receiving agency but not technical staff. This prevents the incorporation of shared information into monitoring, management and modeling systems. Without the expectation of regular and timely receipt of information products—including the eCDI drought map—technical staff are unable to evaluate information products and examine how best to use them.

4. **Uniform standards:** A wide variety of information sources are pertinent to drought monitoring and management; stakeholders said that lack of uniform standards for data collection, reporting and frequency of updates are major obstacles to monitoring and planning. In some cases, paper records are still used, complicating information exchange.

5. **Information security requirements:** Interviewees noted that a central government directive recently required all public sector entities to review their IT security systems before re-opening data-sharing platforms that contain sensitive information. Although expected to be a short-lived problem, this has interrupted information sharing activities with interviewed stakeholders.

Stakeholders also described a range of technical drought monitoring needs that focused on integration of existing information products for improved understanding of the present situation and improved seasonal forecasts. In particular, water managers have a long-term goal of integrating seasonal forecasts with rainfall-runoff models and groundwater recharge models to predict water availability with better accuracy. Agricultural agency representatives hope to link seasonal forecasting with crop growth models in addition to cereals; this is especially relevant for rangeland productivity considering the livestock sector is considered the most vulnerable to drought after rainfed cereals.

Annex C.
Additional Material from Section 2

Table C1. *eCDI input indices.*

Index	Data inputs	Additional filtering or processing	Data latency	Temporal scale of data	Spatial scale of data	Index calculation for use in CDI
SPI (3 months; McKee et al. 1993)	Jordan: IMERG (Hou et al. 2014; Skofronick-Jackson et al. 2017), daily download[23]	None	1-2 days	Daily	10 km x 10 km; resampled to 5 km x 5 km using a simple bilinear interpolation method (Chang 2009)	**Step 1:** Produce daily values. **Step 2:** Sum daily values across each month as represented by 6 different values deduced from a sliding window of two days difference starting from the beginning of the month. **Step 3:** Calculate SPI. **Step 4:** Calculate SPI percentiles per month across whole period (2000-2020).
	Lebanon: CHIRPS final (Funk et al. 2015)[24]	None	2-3 weeks after the end of the month	Daily	5 km x 5 km	Same as above
	Morocco: CHIRPS preliminary	Production of estimated CHIRPS final product using CNN models (see Sections 2.2 and 6)	1-2 days after the end of the month	Daily	5 km x 5 km	Same as above following the addition of a new Step 1: Provide CHIRPS preliminary data to CNN model to produce estimated CHIRPS final data.
	Tunisia: CHIRPS final (Funk et al. 2015)	None	2-3 weeks after the end of the month	Daily	5 km x 5 km	Same as for Jordan
NDVI	Current system*: eMODIS, download every 5 days from Earth Explorer[25]	Use cloud mask and quality control filters; additional cloud masking and daily interpolation	5 days	Average of 10 days	250 m x 250 m; aggregated at 5 km x 5 km	**Step 1:** we apply a 93-days window and a polynomial degree p=1 on each 250-m pixel. **Step 2:** Interpolate daily NDVI data from Savitsky-Golay filter (Savitzky and Golay 1964). **Step 3:** Produce monthly average NDVI values, and percentiles of these, as per Steps 2 and 4 shown for SPI.
	Prepared system*: VIIRS download every 5 days[26]	As above	5 days	Average of 10 days	375 m x 375 m; aggregated at 5 km x 5 km	As above
Diurnal LST	Current system: MODIS/ Terra (MOD11A1 Collection 6) daily download[27]; LIS-Noah-MP V7.2 (Kumar et al. 2006; Niu et al. 2011)	Use of cloud mask and quality control filters; model estimation gap-filling	4 hours	2x/day	1 km x 1 km; aggregated to 5 km x 5 km	**Step 1:** Collect and produce modeled daily values of day-night temperature amplitude. **Step 2:** Produce monthly average day-night temperature amplitude, and percentiles of these, as per Steps 2 and 4 shown for SPI.
	Prepared system* VIIRS daily download*	As above	4 hours	2x/day	375 m × 375 m; aggregated at 5 km x 5 km	As above
SMA	LIS-Noah-MP V7.2 (Kumar et al. 2006; Niu et al. 2011), GDAS forcings download every 6 hours from NASA portal[28]	Dynamic phenology module (Nie et al. 2021)	Model output	15-minute time-steps	1 km x 1 km; aggregated to 5 km x 5 km	Absolute values of root-zone soil moisture (from 4 layers) are a model output. **Step 1:** Produce daily soil moisture data by averaging soil moisture across all layers. **Step 2:** Produce monthly average soil moisture values, and percentiles of these, as per Steps 2 and 4 shown for SPI

Source: Bergaoui et al. Forthcoming.
Note: Asterisks (*) denote the system as it is prepared for implementation following operational monthly availability of the relevant VIIRS data.

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[23] See NASA GES DISC.
[24] CHIRPS preliminary and final product.
[25] https://earthexplorer.usgs.gov/ EROS Moderate Resolution Imaging Spectroradiometer (eMODIS) doi number: https://doi.org/10.5066/F7H41PNT
[26] https://www.earthdata.nasa.gov/learn/find-data/near-real-time/viirs
[27] https://e4ftl01.cr.usgs.gov/MOLT/MOD11C1.006/
[28] https://portal.nccs.nasa.gov/lisdata_pub/data/MET_FORCING/GDAS/

Table C2. *Stage 2 eCDI validation summary.*

Country	Indicator	Validation analyses	Results	Refinements made following Stage 2 validation
Jordan	SPI	1. Compared CHIRPS to long-term (1980-2017) station data (site-specific and spatial interpolation from 155 stations). 2. Compared CHIRPS to IMERG data.	Generally good but variable R^2. Best performance was during rainy season in the wetter regions (e.g., Irbid R^2=0.69); worst performance was in the desert regions.	Shift to IMERG and proposed to investigate shift to 2-month SPI. Not implemented.
	SMA	Compared model output to 11 ground stations in and near Irbid Governorate (northern highlands) with datasets from 2015-2016.	Low R^2 (0.37) except for one site with clay soils, which had higher soil water holding capacity (closer to parameter value in the LIS model). However, major difference in scale (1 km x 1 km model output vs individual soil sensor) introduces challenges.	The Noah-MP model is being refined (in the future) to run using its dynamic phenology scheme.
	eCDI	1. Evaluated relationship of each indicator and overall eCDI (and for multiple time-steps of each) to cereal (wheat and barley) yields and production per governorate. 2. Compared to an observation-based eCDI (Al-Bakri et al. 2019; Al-Adaileh et al. 2019). 3. Qualitative evaluation of eCDI's performance in reflecting past droughts in focus groups with key stakeholders.	1. Correlation between eCDI and cereal production was higher than for any single indicator ($p<0.05$) and varied highly across regions. 2. Both products generally agreed and successfully identified trend (both drought and wet periods), drought intensity and location. 3. Same as for point 2, and stakeholders provided recommendations for further improvement.	1. Proposed to investigate shift in indicator time-steps and weightings to fit eCDI to cereal production. Not implemented yet. 2. and 3: N/A
Lebanon	SPI	Compared CHIRPS to station data (2000-2016) from 3 sites in coastal, inland and semiarid areas.	Very high R^2 in coastal (0.86) and inland (0.90) areas; very low in semiarid (0.26) areas.	Shift to IMERG.
	NDVI	Comparison of NDVI in agricultural, high-elevation bare land (snow-affected) and mixed-evergreen forest at mid-altitude.	NDVI signal highly influenced by snow and cloud cover during the winter season, especially January to March.	Improved cloud masking procedures and use of daily interpolation.
	SMA	Comparison of CHIRPS data and soil moisture (SM) model output in semiarid areas.	1. SM output spatially displaced against other indicators (shifted eastward); 2. SM over-estimated for inland areas, at times exceeding precipitation, but overall correlation suggests SM data was capturing the signal in dry/wet months.	Introduce irrigation scheme in Noah-MP model and building in dynamic phenology scheme.
	eCDI	1. Attempted to assess relationship between eCDI and available national statistics on hydrology, water use, agriculture and ecology. 2. Evaluated correlation and temporal relationship between each input for 50 pixels covering major land cover/use types. 3. Compared eCDI with FAO-produced agricultural stress index and precipitation percentiles.	1. The sparse temporally and spatially discontinuous available statistics precluded statistical analyses of correlation between eCDI and the indicators. 2. High variability in inputs' correlation and temporal relationship dependent on land cover. 3. For most years except the years 2000 and 2001, the eCDI was in agreement with the national climatological drought and the FAO's Agricultural Stress Index (ASI).	1. N/A 2. Proposed to investigate separate input weights for eCDI based on land cover. Not implemented yet.
Morocco	SPI	Compared CHIRPS to observation station data.	As described by Bijaber et al. (2018) and Météo Maroc and ICBA (2019).	Shift to IMERG.
	eCDI	1. Assessed relationship between eCDI (and its component inputs) and cereal production and yield anomaly for three agricultural years, each of which had a different drought typology. 2. Survey of regional technical experts to assess eCDI performance and indicator relevance per region via analytic hierarchy process (AHP) method (Saaty 1987).	1. Results showed clear concordance for most agroecological zones but not all, and/or for specific periods of the drought year but not all. 2. Survey results aligned with statistical analyses of concordance between eCDI and agriculture statistics; indicator relevance informs re-weighting.	1 and 2: Proposed to investigate separate input weights for eCDI per agroecological zone. Not implemented yet.

Annex D.
Evaluation de la sècheresse de la saison agricole 2020-2021

Partie A. Evaluation de la sècheresse observee

1. Selon vos observations de terrain dans votre région, quel est le degré de sévérité (ou intensité) de la sécheresse du mois (Cochez une case)

Sècheresse Exceptionnelle	**Sècheresse Sévère**	**Sècheresse Modérée**	**Conditions normales**	**Modérément humide**	**Très Humide**	**Exceptionnellement humide**

2. Selon vos observations de terrain dans votre région, quelles sont les trois communes/localités les plus impactées par la sécheresse, et quelle est la proportion du territoire impactés ?

	Commune/localité	**% superficies impactés**
1.		
2.		
3.		

3. Quels types d'informations avez-vous utilisé pour évaluer les conditions de sécheresse sur le terrain et commentaires (exemples : observation visuelle de la végétation des parcours/zones sylvopastorales et arganier, charge cheptel et transhumance illégale et/ou conflictuelle, difficulté d'accès aux ressources en eaux et/ou conflits de partage, inflation des prix des aliments pour bétail et des denrées alimentaires de base, émergence de maladies et invasions d'insectes et de bio-agresseurs, vaccination du cheptel, données économiques, subventions, rapports internes d'évolution de saison agricole, évolution des travaux de conservation des eaux et sol/travaux agricoles, enquêtes des fermiers sédentaires et des transhumants, observation des niveaux piézométriques des nappes et des niveaux des ouvrages hydrauliques, tarissement de sources naturelles, l'humidité des sols dans la zone racinaire, etc.).

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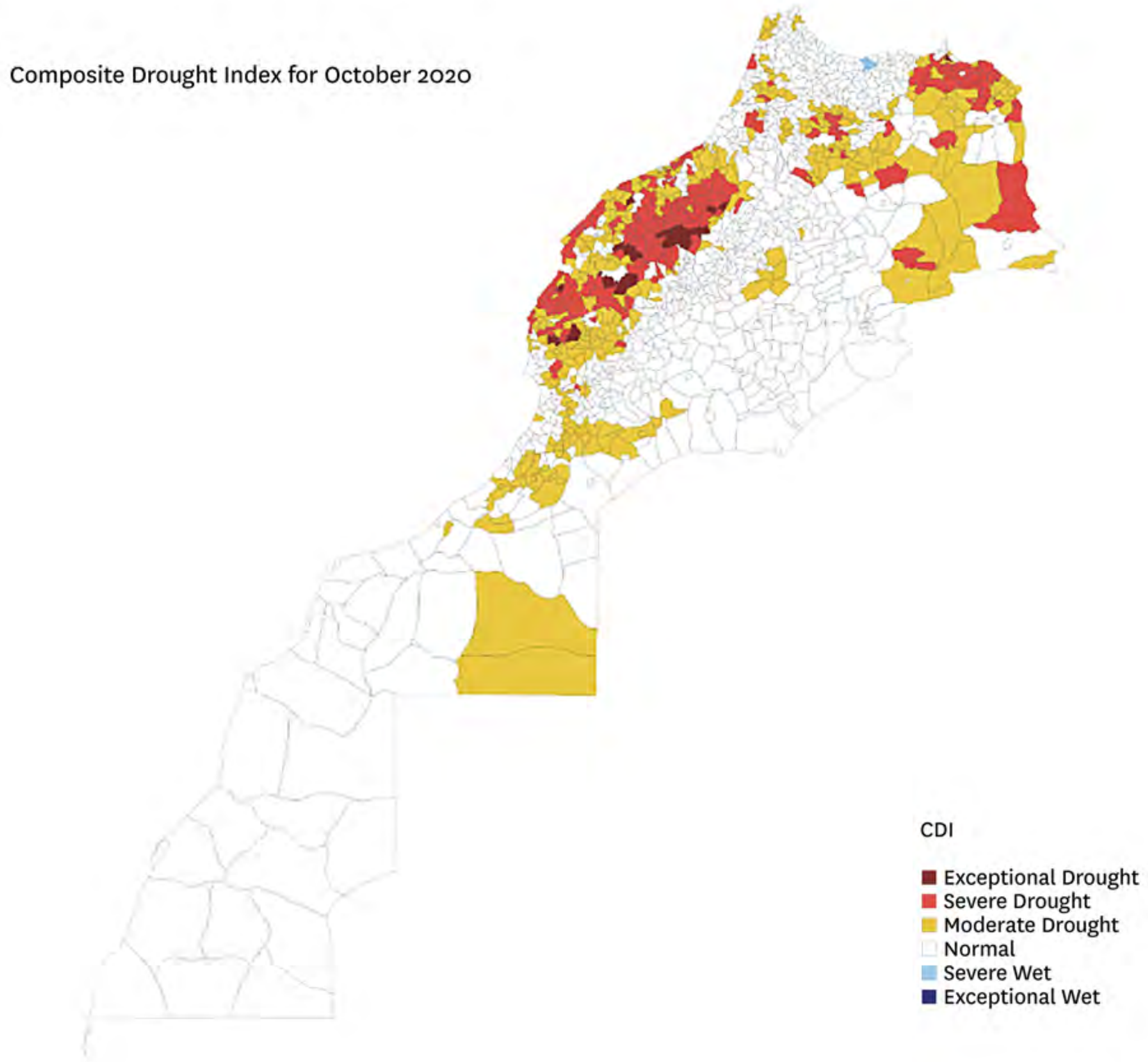
Partie B. Evaluation des cartes ecdi

4. Dans votre région (à délimiter manuellement sur la carte ci-dessous), quel est le degré de précision de l'étendue géographique et du niveau de sévérité de la sécheresse (0 : pas du tout précise, à 100 % : très précise). Le Composite Drought Index (indice composite de la sècheresse) englobe les conditions de végétation, réserve en eau du sol, stress d'évapotranspiration et pluviométrie (anomalies par rapport aux 20 dernières années).



Degré de précision de la répartition géographique de la sécheresse dans votre région			
0-25%	26-49%	50-75%	76-100%
Pourquoi?			
Degré de précision du niveau de sévérité (classes) de la sécheresse dans votre région			
0-25%	26-49%	50-75%	76-100%
Pourquoi?			

5. Commentaires sur les problèmes principaux provoqués par la sécheresse (sanitaire, eau potable, salinité…), les moyens déployés actuellement pour remédier a cette situation, et vos suggestions sur les meilleures actions de réponse à entreprendre à court, moyen et long terme?

6. Est-ce que cette carte est utile pour vos travaux quotidiens ? ☐ OUI ☐ NON

   Si oui, veuillez préciser la nature de cette utilité

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7. Contact

   Nom et Fonction : ………………………………………………………

   Adresse/Zone d'intervention (région) : …………………………………………………………

   ………………………………………………………………………………………………………

   Téléphone : ………………………………………………

   Email : …………………………………………………

Partners

Primary partners: International Water Management Institute (IWMI); National Drought Mitigation Center, University of Nebraska-Lincoln; Daugherty Water for Food Global Institute, University of Nebraska; Goddard Space Flight Center, National Aeronautics and Space Administration (NASA); and Johns Hopkins University.

National leaders:
Jordan: Ministry of Water and Irrigation
Lebanon: Ministry of Energy and Water
Morocco: Directorate of Strategy and Statistics (Ministry of Agriculture, Fisheries, Rural Development, Water and Forests, MAFRWF); ABH Souss-Massa (Ministry of Equipment, Transport, Logistics and Water)

National partners:
Jordan: Department of Statistics; Jordan Meteorological Department; Ministry of Agriculture; Ministry of Health; Ministry of Environment; National Agricultural Research Center; National Center for Security and Crisis Management; and the University of Jordan
Lebanon: American University of Beirut; Beirut and Mount Lebanon Water Establishment; Lebanese Agricultural Research Institute (LARI); Lebanese Meteorological Department-Directorate General of Civil Aviation; Litani River Authority; Ministry of Agriculture; Ministry of Environment; South Lebanon Water Establishment; National Center for Remote Sensing.
Non-governmental organizations: Agency for Technical Cooperation and Development (ACTED) and STAMMOSE
Morocco: Hassan II Institute of Agronomy and Veterinary Medicine; Ministry of Equipment, Transport, Logistics and Water; National Department of Meteorology (DMN); various regional directorates of agriculture (DRA); various river basin agencies (ABH); and various regional offices for agricultural development (OMRVA)

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