

**The Impact of  
El Niño Southern Oscillation Events on Water  
Resource Availability in Central Sulawesi, Indonesia**

**A hydrological modelling approach**

Dissertation  
zur Erlangung des Doktorgrades  
der Mathematisch-Naturwissenschaftlichen Fakultäten  
der Georg-August-Universität zu Göttingen

vorgelegt von

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aus Düsseldorf

Göttingen 2005

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Tag der mündlichen Prüfung: 28.10.2005

**EcoRegio**

herausgegeben von  
Prof. Dr. Gerhard Gerold  
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Band 21

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D 7 (Diss. Universität Göttingen)

Shaker Verlag  
Aachen 2006

**Bibliographic information published by Die Deutsche Bibliothek**

Die Deutsche Bibliothek lists this publication in the Deutsche Nationalbibliografie; detailed bibliographic data is available in the internet at <http://dnb.ddb.de>.

Zugl.: Göttingen, Univ., Diss., 2005

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Printed in Germany.

ISBN-10: 3-8322-5361-0

ISBN-13: 978-3-8322-5361-5

ISSN 1612-5894

Shaker Verlag GmbH • P.O. BOX 101818 • D-52018 Aachen

Phone: 0049/2407/9596-0 • Telefax: 0049/2407/9596-9

Internet: [www.shaker.de](http://www.shaker.de) • e-mail: [info@shaker.de](mailto:info@shaker.de)

## VORWORT

In Bezug auf die globalen Umweltfragen (Strategic Plan for Climate Change Science Program – water cycle, 2003) besitzt das Verständnis und die Modellierung des Wasserhaushaltes höchste Priorität: „What are the mechanisms and process responsible for the maintenance and variability of the water cycle; are the characteristics of the cycle changing and, if so, to what extent are human activities responsible for those changes?“

Die vorliegende Dissertation entstand in Rahmen des vom Bundesministerium für Bildung und Forschung geförderten Deutschen Klimaforschungsprogramms DEKLIM und war im Bereich Klimawirkungsforschung in das interdisziplinäre Projekt IMPENSO „Der Einfluß von ENSO (El Niño - Southern Oscillation) auf die Wasserressourcen und die lokale Bevölkerung in einem Regenwaldrandgebiet Indonesiens“ eingebettet. Die drei Teilprojekte umfassen die Analyse der Klimavariabilität und ENSO-Prognose, die Auswirkungen von ENSO Ereignissen auf den Wasserhaushalt und die sozioökonomischen Auswirkungen und potentielle Vorsorgemaßnahmen für die lokale Bevölkerung. Für ein tropisches mesoskaliges Einzugsgebiet in Zentralsulawesi wird erstmalig der Wasserhaushalt analysiert und mit dem prozessbasierten hydrologischen Modell WASIM-ETH simuliert sowie plausible Szenarien zur Prognose der Auswirkungen von ENSO Ereignissen und Landnutzungsänderungen entwickelt. Dabei waren mit dem Neuaufbau von Pegel und Klimastationen vor Ort umfangreiche logistische Probleme zu lösen. Dank der im Rahmen des Projektes geschulten lokalen Mitarbeitern (Dept. of Forestry – Palu) konnte das Monitoring hydrologischer und meteorologischer Parameter kontinuierlich durchgeführt werden. Die ENSO-Szenarien zeigen eine deutliche Verringerung des Trockenwetterabflusses und Erhöhung der Abflussvariabilität, die mit fortschreitender Waldkonversion noch verstärkt wird. Auf die für die Bevölkerung essentielle Reisproduktion wirken sich ENSO-Jahre daher mit einer erheblichen Reduktion der Bewässerungsfläche aus. Für das Untersuchungsgebiet beläuft sich danach der agrarökonomische Verlust auf ca. 300.000 – 1.500.000 \$! Es bleibt zu hoffen, dass die Empfehlungen aus dem IMPENSO-Projekt zur besseren kleinbäuerlichen Vorwarnung und Vorsorge bei ENSO-Jahren von den regionalen Planungsbehörden umgesetzt werden. Die Arbeit hat dazu einen wichtigen wissenschaftlich-hydrologischen Grundbaustein gelegt.

Gerhard Gerold  
Göttingen, Juli 2006



## DANKSAGUNG

An erster Stelle gilt mein Dank Herrn Prof. Dr. Gerhard Gerold, der diese Arbeit von Anfang an begleitet und in jeglicher Hinsicht unterstützt hat. Außerdem möchte ich Herrn Prof. Dr. Bernd Diekkrüger für die Übernahme des Koreferates meiner Arbeit meinen Dank aussprechen. Den Mitgliedern der IMPENSO - Mannschaft Frau Dr. Regina Birner, Prof. Dr. Gode Gravenhorst, Prof. Dr. Manfred Zeller, Dodo Gunawan und Alwin Keil gilt mein besonderer Dank für die interessante und fruchtbare interdisziplinäre Projektzusammenarbeit. Besonders möchte ich auch Frau Sabine Hippe für Ihre tatkräftige Hilfe in allen administrativen Belangen danken.

Ohne die Hilfe von Frau Oki Hadiyati für die Feldarbeit in Palu, Indonesien wäre diese Arbeit nicht möglich gewesen. Mein tiefster Dank gilt auch Dudi, Kemyll, Kiki, Dudin, Rina, Hendra, Dr. Heiner Kreilein und Robert Karsten. Die außerordentlich herzliche Aufnahme bei der Familie von Pak Sudarmi in Tomado hat meinen Aufenthalt in Zentral-Sulawesi zusätzlich bereichert. Für das Korrekturlesen dieser Arbeit, zahlreiche hilfreichen Kommentare und die moralische Unterstützung während der gesamten Promotionszeit möchte ich mich herzlich bei Ulrike Falk, Alexander Kleinhans, Georg Dechert und Kerstin de Vries bedanken. Mein Dank gilt ebenso allen anderen Mitarbeiterinnen und Mitarbeitern des Geographischen Institutes. Insbesondere danke ich auch meinen Eltern für ihre uneingeschränkte Unterstützung, die ich auf meinem bisherigen Lebensweg erfahren habe.

Constanze Leemhuis





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## LIST OF ABBREVIATIONS

CO <sub>2</sub>	Carbon dioxide
d	Index of agreement
DEKLIM	German Climate Research Program
DTM	Digital terrain model
EI (mm · time <sup>-1</sup> )	Interception
ENSO	El Niño Southern Oscillation
ET (mm · time step <sup>-1</sup> )	Evapotranspiration
ETP (mm · time step <sup>-1</sup> )	Potential Evapotranspiration
ETR (mm · time step <sup>-1</sup> )	Real Evapotranspiration
FAO	Food and agricultural organization of the United Nations
IBK	Institute of Bioclimatology
IDW	Inverse distance weighting
IMPENSO	The Impact of ENSO) on water resource management and the Local Communities in Central Sulawesi / Indonesia
IWRM	Integrated water resource management
MAE	Mean absolute error
MHQ <sub>month</sub>	average monthly high water discharge
MM5	Pennsylvania State University/National Center for Atmospheric Research mesoscale model
MNQ <sub>month</sub>	average monthly low water discharge
MQ	average discharge
LAI (m <sup>2</sup> · m <sup>-2</sup> )	Leaf area index
LLNP	Lore Lindu National Park
PEST	Parameter estimation program
PHA	Potential homogeneous area
PTF	Pedotransfer functions
R <sup>2</sup>	Coefficient of efficiency after Nash & Sutcliffe

RMSE	Mean square error
SAGA	System for automatic Geoecological analysis
SEWAB	Surface Energy and Water Balance model
SFB-552	Collaborative Research Centre (Stability of rainforest margins, Central-Sulawesi, Indonesia).
SOI	Southern Oscillation index
SST (°C)	Sea surface temperature
SST3 (°C)	Sea surface temperature, ENSO region 3
TANALYS	Topography analysis program
WASIM-ETH	Water balance Simulation Model



## SUMMARY

The El Niño/ Southern Oscillation (ENSO) phenomenon is the strongest known natural interannual climate fluctuation. The most recent two extreme ENSO events of 1982/83 and 1997/98 severely hit the socio-economy of main parts of Indonesia. As the climate variability is not homogeneous over the whole Archipelago of Indonesia, ENSO events cause negative precipitation anomalies of diverse magnitude and duration in different regions. Understanding the hydrology of humid tropical catchments is an essential prerequisite to investigate the impact of climate variability on the catchment hydrology. Together with the quantitative assessment of future water resource changes they are essential tools to develop mitigation strategies on a catchment scale. These results can be integrated into long term Integrated Water Resource Management (IWRM) strategies.

The general objective of this study is to investigate and quantify the impact of ENSO caused climate variability on the water balance and the implications for water resources of a mesoscale tropical catchment.

The mesoscale Palu River catchment (1°20'S, 21°01'E) is located in Central Sulawesi, Indonesia and covers an area of 2694 km<sup>2</sup>. The topography of the catchment varies from 0-2500 m.a.s.l. Due to the monsoonal setting of Central Sulawesi ENSO years are described by decreased precipitation from July till October, which corresponds with the dry period. Up to 40 % of the basin is covered by mountainous rainforest (Lore Lindu Nationalpark). Illegal logging activities within the Lore Lindu Nationalpark constantly endanger the mountainous tropical rainforest ecosystems.

The Water Flow and Balance Simulation Model (WaSiM-ETH) is a process-based fully distributed catchment model. The spatial resolution is determined by a grid and the time resolution can vary from minutes to days. The main processes of water

flux, -storage and phase transition are simulated by physically-based simplified process descriptions. WASIM-ETH has been successfully applied to the Gumbasa subcatchment (1275 km<sup>2</sup>) of the Palu River catchment. The calculated model efficiency of the calibration and validation period achieved satisfactory results, which verified the hydrological model as a suitable prediction tool. In addition a predictive sensitivity analysis was carried out. The simulation of the water balance with WASIM-ETH has applied to the period Sept. 2002- Sept. 2004. To obtain a feasible data source for the hydrological model an monitoring program of hydrological and meteorological data has been launched in September 2002 and is operating until present. The simulation results of WASIM-ETH are characterized by uncertainties due to the model structure, uncertainties of input data and parameters and to the overall low data availability. Of major importance are:

- (1) The uncertainty of areal precipitation regarding their spatial and temporal pattern has a strong effect on the overall modelling performance.
- (2) A two year time series is not sufficient to obtain stable and reliable modelling results.
- (3) The hydrological model is particular sensitive to the spatial pattern of soil physical properties.

The implications of possible future climate and land use conditions on the water balance of the Gumbasa River sample catchment were assessed by a scenario analysis, which simulates a sequence of possible future events. The scenarios quantify the changes of the water balance if the climate or the land use change for the base year 2003. For the generation of spatial and temporal variable caused rainfall anomaly scenarios as input data for a hydrological model of the Gumbasa River watershed a statistical scenario approach was applied. For the generation of land use scenarios an elevation dependent total change scenario was chosen. The conclusions of the scenario analysis with the hydrological model WASIM-ETH are:

- (1) The scenario analysis with the hydrological model WASIM-ETH proves and quantifies that ENSO caused precipitation anomalies lead to an increase of the discharge variability.

- (2) The modelling results demonstrate that beside local climate variability the catchment characteristics have an influence on the impact magnitude of ENSO related rainfall anomalies on the water balance of a catchment.
- (3) Due to the soil data availability of the sample catchment the degree of surface disturbance is not considered by the land-use scenario. Therefore the most important factor of land use scenario uncertainty is the “low-flow problem”, because the infiltration rate is not correctly simulated by the applied scenarios.

A case study, calculation of the potential irrigation area of the Gumbasa River Irrigation Scheme, shows how the results of the scenario analysis of the hydrological model could be implemented for further agricultural evaluation and management. The outline, methodology, results and implications of the presented research study on the impact of ENSO events on the water resource availability of a mesoscale tropical catchment in Central Sulawesi Indonesia represent a useful foundation for the implementation of an Integrated Water Resource Management.

## RINGKASAN

Kejadian ENSO (*El Nino Southern Oscillation*) adalah fenomena alami fluktuasi iklim antar tahunan terkuat yang diketahui. Dua peristiwa ENSO terakhir yaitu tahun 1982/1983 dan 1997/1998 sangat mempengaruhi kondisi sosial-ekonomi sebagian besar wilayah Indonesia. Mengingat variabilitas iklim tidak seragam diseluruh kepulauan Indonesia, peristiwa ENSO yang menyebabkan anomali negatif dari curah hujan berbeda besar dan lamanya dari satu tempat dengan tempat lainnya. Memahami hidrologi daerah tangkapan hujan di wilayah tropik basah adalah prasyarat yang mendasar dalam meneliti dampak variabilitas iklim di daerah aliran sungai. Bersama-sama dengan pendugaan kuantitatif perubahan sumber daya air dimasa mendatang, mereka adalah piranti utama dalam mengembangkan strategi penanganan dalam skala daerah tangkapan. Hasil-hasil ini untuk jangka panjang dapat diintegrasikan kedalam strategi manajemen sumber daya air terpadu (Integrated Water Resource Management, IWRM).

Tujuan umum dari studi ini adalah meneliti dan mengkuantifikasikan dampak ENSO yang menyebabkan variabilitas iklim terhadap neraca air dan implikasinya terhadap sumber daya air dari daerah tangkapan berskala menengah di daerah tropis.

Daerah tangkapan berskala menengah Sungai Palu ( $1^{\circ}20' \text{ LS}$ ,  $121^{\circ}01' \text{ BT}$ ) berlokasi di Sulawesi Tengah, Indonesia dan mencakup areal seluas  $2694 \text{ km}^2$ . Topografi daerah tangkapan bervariasi dari 0-2500 m d.p.l. Dengan adanya seting monsoon di Sulawesi Tengah, tahun-tahun ENSO dijelaskan dengan menurunnya jumlah curah hujan dari Juli sampai Oktober, yang berhubungan dengan periode musim kemarau. Kurang lebih 40% dari lembah sungai ditutupi oleh hutan hujan tropis (Taman Nasional Lore Lindu). Namun kegiatan penebangan hutan ilegal di dalam taman nasional secara konstan mengancam ekosistem hutan hujan tropis.



Model simulasi neraca dan aliran air (WaSiM-ETH) adalah model hidrologi berbasis proses yang terdistribusi penuh untuk suatu wilayah tangkapan. Resolusi ruang ditentukan oleh sebuah grid dan resolusi waktu dapat bervariasi dari menit sampai hari. Proses utama dari limpahan air, penyimpanan dan fase transisi disimulasi oleh uraian proses berbasis fisik yang disederhanakan. WASIM-ETH telah berhasil diterapkan di daerah tangkapan Gumbasa ( $1275 \text{ km}^2$ ) dari daerah aliran Sungai Palu. Perhitungan efisiensi model dari periode kalibrasi dan validasi memperoleh hasil yang memuaskan, yang telah memperlihatkan model hidrologi sebagai alat prediksi yang sesuai. Simulasi neraca air dengan model WASIM-ETH telah diterapkan untuk periode September 2002 – September 2004. Untuk mendapatkan sumber data yang layak bagi model hidrologi, program monitoring data hidrologi dan meteorologi telah dilakukan sejak September 2002 dan beroperasi sampai sekarang. Hasil simulasi WASIM-ETH dicirikan oleh ketidak pastian akibat struktur model, input data dan parameter serta kurangnya ketersediaan data. Hal-hal pokok yang penting adalah :

- 1) Ketidak pastian mengenai wilayah curah hujan berdasarkan pola ruang dan waktu yang sangat mempengaruhi keseluruhan penampilan model.
- 2) Data series selama dua tahun tidak mencukupi untuk memperoleh hasil yang dapat diandalkan.
- 3) Model hidrologi sangat sensitive terhadap pola ruang dari sifat fisik tanah.

Implikasi untuk kemungkinan iklim dan kondisi penggunaan lahan dimasa mendatang terhadap neraca air dari contoh Sungai Gumbasa telah diduga dengan analisis skenario, dengan mensimulasi sebuah bagian dari kemungkinan peristiwa mendatang. Skenario tersebut mengkuantifikasi perubahan neraca air bila iklim atau tata guna lahan berubah dari basis tahun 2003. Untuk membuat variabel ruang dan waktu yang disebabkan skenario anomali curah hujan sebagai data input model hidrologi untuk daerah tangkapan Sungai Gumbasa, pendekatan skenario secara statistik telah diterapkan. Untuk membuat skenario tata guna lahan dipilih skenario perubahan total yang tergantung pada elevasi. Kesimpulan dari analisa skenario dengan model hidrologi WASIM-ETH adalah :

- 1) Analisa skenario dengan model hidrologi WASIM-ETH membuktikan dan menguatifikasikan bahwa ENSO sebagai penyebab anomali curah hujan mengakibatkan meningkatnya variabilitas pengisian.
- 2) Hasil modeling menunjukkan bahwa disamping variabilitas iklim lokal, karakteristik daerah tangkapan mempunyai pengaruh terhadap besarnya pengaruh anomali curah hujan terkait dengan ENSO terhadap neraca air daerah tangkapan.
- 3) Mengingat ketersediaan data tanah dari contoh daerah tangkapan, tingkat gangguan permukaan tidak dipertimbangkan dalam skenario tata guna lahan. Oleh karena itu faktor yang sangat penting dari ketidak pastian skenario tata guna lahan adalah “problem aliran rendah”, karena laju infiltrasi tidak disimulasi secara tepat oleh skenario yang diterapkan.

Sebuah studi kasus, yaitu perhitungan areal irigasi potensial dari jaringan Irigasi Sungai Gumbasa menunjukkan bagaimana hasil analisis skenario model hidrologi dapat diimplementasikan lebih lanjut untuk manajemen dan evaluasi pertanian. Kerangka, metodologi, hasil dan implikasi dari riset studi pengaruh peristiwa ENSO terhadap ketersediaan sumber daya air dari daerah tangkapan sungai skala menenga daerah tropis di Sulawesi Tengah Indonesia yang telah dipaparkan ini menunjukkan dasar yang berguna untuk implementasi Manajemen Sumber Daya Air Terpadu.