**Appendix 3.** The P-GBSD model

The present study demonstrates the use of a coupled Physical-Group-Built System Dynamics Model (P-GBSDM) for shock scenario simulation and data extraction. This model was selected for the present study due to 1) its capacity to accurately represent complex socio-environmental systems as a result of its dynamically coupled structure and built-in feedback networks and 2) the participatory nature of model development, including variables and system level flow networks defined by local stakeholders. The P-GBSDM, built by Inam, Adamowski, and Malard of the present paper, was created by integrating the physical Spatial Agro Hydro Salinity Model (SAHYSMOD) with a participatory, group-built system dynamics model (GBSDM) consisting of social, environmental, and economic variables. The GBSDM is a participatory model and all of its assumptions (e.g. farmer perceptions, government loan pay-back ratio, sedimentation rate, farm water storage potential, surface water /groundwater use ratio, crop rotation etc.) were refined through interviews with local stakeholders. Moreover, constants/parameters were defined through discussions with scientists with the necessary and relevant expertise (e.g., irrigation engineers, land reclamation experts, research officers, modelers etc.).The overall participatory (GBSD) model and its structure, equations, development methodology, and component details are presented in Inam et al. (2017). Socioeconomic interdependencies and feedbacks were determined through the participatory model-building process (conducted by Inam, Adamowski and Malard of the present paper) with local stakeholders in the Rechna Doab basin of northeastern Pakistan (Inam et al., 2015). The participatory model-building approach used in the initial stages of P-GBSDM development involved the application of stakeholder-built causal loop diagrams (CLD). The particular CLDs used for the GBSDM initialization were constructed by local Rechna Doab stakeholders in response to neutral situational prompts posed by researchers relating to local agricultural and community livelihood dynamics. Individual stakeholders created their own diagrams and the individual thought maps were eventually integrated to form one large, cohesive, group diagram. After the group CLD construction, the final CLD was digitized using Vensim Software (Ventana Systems, 2015). The necessary variables and their links and feedbacks were integrated in Vensim as an organized, digital version of the stakeholder-designed, group-CLD. Sub-modules of the GBSDM describing agricultural, economic, water, and farm management factors were linked together with these feedbacks and finally integrated with the physically based SAHYSMOD. The model was coupled, in part, through the application of Tinamit (developed by Malard, Inam, and Adamowski of the present paper), a novel tool used to couple SD and physically-based models, which allows the integrated models to exchange data at runtime (Malard et al., 2017). Tinamit, which itself consists of three Python classes that code for model wrappers: one for physically-based models, one for system dynamics models, and one for coupled models, greatly facilitates the process of coupling SD and physically-based models. Figure A3.1 illustrates the basic concept behind the model coupling process using Tinamit as a wrapper program. This special form of model coupling allows for the exploration of the complex relationships among various system elements, as well as the resulting behavioral dynamics of the system, while retaining stakeholder values and inputs. Following the development of the integrated model, a validation approach was used to substantiate and test the structure and behavior of the coupled model. The model's performance has been investigated for optimum calibration and validation using a behavior pattern-based sensitivity analysis (Peng et al., 2020). Model robustness under different operating conditions was also assessed (Inam et al., 2017). Detailed information related to data input requirements for each model as well as data sourcing techniques and processes is outlined in Inam et al. (2015, 2017, 2017a), while the resilience code and associated Vensim structure have been published using the figshare platform (Carper and Alizadeh, 2021). Full model documentation can be found at: https://tinamit.readthedocs.io/es/latest/.

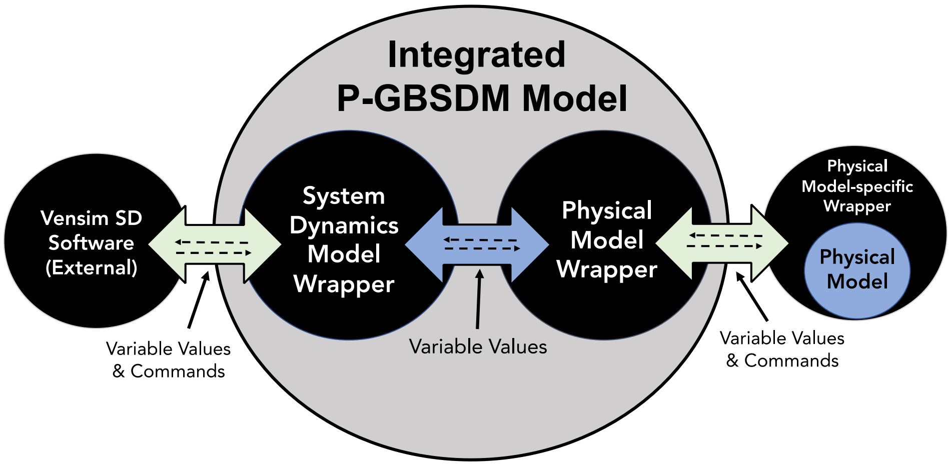


**Fig. A3.1.** Diagram of P-GBSDM coupling using Tinamit as a wrapper (*adapted from Malard et al., 2017*)

The model was tested and validated many times using different techniques. In the first technique, model components (i.e. SDM and Physical model (SAHYSMOD)) were tested individually. Conventional model testing techniques based on statistical methods (e.g. RMSE, NSE, R2, ME, etc.) (Moriasi et al., 2012) are difficult to apply for an SDM component of a coupled model, Barlas (1989) comprehensively describes the reasons for that, hence, a model testing framework based on procedures (reality check, unit consistency, extreme value test, behavior test etc. (see section 6.0 of Inam et al., 2017)) described in the system dynamics model literature (Barlas, 1989; Sterman, 2000; Qudrat- Ullah and Seong, 2010) were used to validate the SDM. For testing the physical side of the coupled model, conventional model calibration and validation techniques based on statistical indicators (e.g. RMSE, NSE, R2, ME, etc.) (Moriasi et al., 2012) were used (see Inam et al., 2017). Later, a behavior-based sensitivity analysis of the coupled model was carried out to determine the influence of input parameters on the general behavior trends (rather than numerical point values) of the coupled model outputs (see Peng, et al. (2020) for details).

The fully integrated model consists of several stocks (i.e. system reservoirs or known quantities), including irrigation efficiency, lined canal length, constructed capacity, silted capacity, water requirements, farmer income, and tube well numbers. The model also uses flows (usage/exchange rates, such as seepage, runoff, income, expenditure, decay, construction, and water consumption) and table functions (lining, water harvesting and irrigation efficiency policies, inflation factors, perception states, and canal water distribution) that comprehensively define the system. The coupled model is deterministic and uses a simulated time-step of six months (one season) (Inam et al., 2017a); for this study, a time series of 30 years (i.e. 60 seasons) was established for the periods between 1989 and 2019. The GBSDM transfers values of seepage, irrigation use, groundwater extraction, and water application efficiency *to* SAHYSMOD and takes values of cropped area, water table depth, groundwater quality, drainage volume, and root zone salinity *from* SAHYSMOD. The stock and flow structure of the model allows the user to test different socio-environmental scenarios with special regard for aquifer sustainability, controlled tube well growth, and the design of cropping patterns for maximum yield. Simulations using the coupled P-GBSDM allow the user to identify and test economically feasible, stakeholder-developed and accepted strategies, as well as potential solutions and policy changes.