تفسیر کمی داده‌های گرانی با استفاده از گرادیان‌های گرانی

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چکیده

تفسیر کمی در سال‌های اخیر کاملاً مورد توجه قرار گرفته است. دو روش به نام‌های سیگنال تحلیلی و واهمامیخت ایلر (EULDPH) در این مقاله مورد بحث قرار گرفته‌اند. بعد از مروری کوتاه روی پایه‌های ریاضی این دو روش، دو مثال صحرایی به منظور امتحان کارایی و محدودیت‌های این روش‌ها در مورد ساختمان‌های زمین‌شناسی پیچیده استفاده شده است. این روش‌ها تاکنون در مورد داده‌های مصنوعی و یا داده‌های با دقت بالا مانند داده‌های گرادیومتریک یا خردگرانیسنجی به‌کار گرفته شده است. در این‌جا از داده‌های با دقت کم به منظور محاسبهٔ بی‌هنجاری‌های باقی‌مانده استفاده شده‌اند. گرادیان‌های گرانی از مقادیر بی‌هنجاری‌های باقی‌مانده محاسبه شده‌اند. سپس با استفاده از گرانی در روش‌های سیگنال تحلیلی و EULDPH ، مختصات آنومالی تعیین شده است. دو مثال صحرایی، یکی در غرب تهران (مردآباد) و دیگری در جنوب‌غربی ایران در نظر گرفته شده‌اند. در مثال اول هدف ما تعیین محل آنومالی هیدروکربور و در مثال دوم هدف تعیین ناهنجاری کرومیت است.

کلیدواژه: آنومالی باقی‌مانده، گرادیان گرانی، سیگنال تحلیلی، واهمامیخت ایلر

چالش‌های موجود در تشابه‌سازی فرایند ذوب برف ـ رواناب

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چکیده

تشابه‌سازی فرایند ذوب برف ـ رواناب از تحلیل‌های لازم برای بهره‌برداری بهینه از منابع آب است که جزء زیربرنامه‌های اصلی و مهم در مدل‌های هیدرولوژی (آبشناسی) است. این فرایند و مدل‌سازی آن از دیرباز از دیدگاه‌های مختلف مورد توجه قرار گرفته است و یکی از آنها، مشکلات و چالش‌های رودرروی آن است. در مقاله حاضر توفیقات در تشابه‌سازی ذوب برف ـ رواناب در دهه اخیر همراه با مشکلاتی که هنوز رودرروی آن است، بررسی و ارزیابی شده است. بررسی‌ها نشان می‌دهد که توفیقات اصلی در این دهه، روی‌کرد به تولید و استفاده از مدل‌های توزیعی و استفاده از فناوری‌های جدید به خصوص سیستم اطلاعات جغرافیایی (GIS) و ادغام آن با اطلاعات سنجش از راه دور بوده است، اما مشکل اصلی که همواره محققان گذشته از دیرباز نیز بر آن اذعان داشته‌اند و همچنان باقی است، مشکل داده، آمار و اطلاعات است. مطالعه گسترده و عمیق مراجع مختلف طی دهه اخیر نشان می‌دهد که زیر برنامه برف مدل‌های هیدرولوژی و آنچه به‌عنوان فرایند ذوب و تجمع برف محاسبه می‌نمایند، بسیار نادر به طور مستقل مورد ارزیابی قرار گرفت است و دلیل آن نیز نبود داده، بوده است. در نهایت با توجه به مشکلات فوق پیشنهاد شده تا طی یک تلاش همگانی زیر نظر موسسه‌ای بین‌المللی مانند اتحادیه بین‌المللی علوم هیدرولوژی (IAHS) داده‌های تحقیقات انجام شده که در مراکز مختلف به انجام رسیده است، گردآوری شود و آنها را برای استفاده عموم محققان در دسترس قرار دهند.

کلیدواژه: تشابه‌سازی فرایند ذوب برف ـ رواناب، مدل‌های هیدرولوژی برف، داده‌های هیدرولوژی برف، سیستم اطلاعات جغرافیایی

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Application of shaping filters to adjust wavelets of vibroseis and impulsive sources □

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Abstract

Vibroseis is the cheapest and the most convenient source of energy for seismic data acquisition. Unfortunately, in certain areas continuous seismic date acquisition with Vibroseis is not possible (due to the varying terrain conditions, jungles woods and swamp or others environmental problems). Impulsive sources, alternatively, can be used to maintain continuous subsurface coverage and to keep the fold at the desired level.

Different seismic sources usually generate different seismic wavelets. Vibroseis source produces a two-sided signal after correlation, whereas an impulsive source results in a one-sided (causal) signal. During interpretation, if the above mentioned differences, the would mat be taken into account resulting seismic sections could possibly reveal false facies changes.

In this study we showed that how one could solve this problem by applying two-sided recursive (TSR) shaping filters. We employed a deterministic, non-trace adaptive procedure considering the known parts of the seismic signal.

The proposed strategy contains a minimum-phase conversion of both the Vibroseis and impulsive seismic data. It followed by a deconvolution and subsequent bandwidth limitation in the frequency range of data using a zero-phase band pass filter.

Keywords: digital filtering, impulsive seismic source, seismic data processing, TSR-shaping filter, Vibroseis, wavelet adjustment

□ Full paper in Farsi section

A Laboratory study of warm-cloud seeding □

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Abstract

In this study, cloud formation and its seeding efficiency at room temperature have been envestigated by different particles such as ambient aerosols, salt, and smoke induced by burning match. In the first step, the effect of ambient aerosol concentration on the time of clearing cloud was considered. Since the aerosols concentration is almost constant during the day, therefor it is accepted as base point for comparison of not-seeded and seeded condition for cloud formation and precipitation. The effect of aerosols concentration variation in different days also were considered. In the second step, the effect of salt and smoke injected as seeding nuclei to the chamber on the cloud clearing time was studied. The salt solution density were used with 20, 30 and 40 g/lit.

The time of cloud clearing by the salt nuclei is less than ambient aerosols. The results showed, the more salt solution density, the less cloud clearing time. In most experiments with increasing smoke concentration the precipitation increased too and extraordinary amounts of smoke concentration rarely caused cloud to be overseed. The experimental results on nucleation efficiency showed that hygroscopic and giant salt particles are more efficient than smaller smoke particles but with respect to higher concentrations of smoke it is observed that the cloud has precipitated in shorter time by smoke nuclei. In fact, if it would be possible to make the experiments under the quantity control coditions, the cloud could be cleaned with salt nuclei in the shorter time.

Keywords: Cloud Condensation Nuclei, Cloud Droplets, Heterogeneous Nucleation, cloud Seeding Efficiency, Over seed, Smaze

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Estimate of porosity from compressional wave velocity in Shurijeh sandstone formation with considering the effect of clay content □

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Abstract

In this research the porosity of Shurijeh formation in northeast of Iran is measured from neutron and density logs in the well GL2. Then we measured compressional wave velocity from acoustic log, and the clay content from geology log. With the data of clay content, porosity and compressional wave velocity we found a linear relationship between these parameters as follows:

$$V_p = 5.55 - 9.62\phi - 1.37C \qquad R^2 = 0.86$$

where V_p, ϕ and C are respectively the velocity of saturated sandstone (in km/s), porosity and clay content (both in fractional volume).

Based on the above relationship, if V_p calculated from sonic log and with the knowledge of the clay content, them the porosity of the formation could be estimated.

Keywords: porosity, clay content, compressional velocity

□ Full paper in Farsi section

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The study of solar eclipse of 11th Aug. 1999 on ionosphere and calculation of recombination factor□

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Abstract

The study of variations of different ionospheric layers at the day of solar eclipse and the calculation of the recombination factor of electrons (α), were our aim. In this regard, the measurements were made with an ionospheric vertical sounding instrument at the interval 15 to 1 minutes at the control day and the day of solar eclipse. The ionospheric data extracted from the ionospheric records (ionograms) and electron density variations with height of the different layers were obtained based on the relation between electron density and frequency of the layers. Finally the recombination factor for F_1 layer was calculated. The behaviors of the electron density variations indicate a rapid decrease of ionization of different ionospheric layers.

Keywords: ionosphere, ionogram, recombination factor, electron density

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Amplification of Seismic Waves in Alluvium Deposits□

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Abstract

In the present study seismic data was carried out at Bibi –Shahr Banoo mountainous area located in Shar-e-Ray south-east of Tehran to estimate amplification of seismic waves. For this purpose microtremors and explosion generated waves were acquired. The layout of three recording stations was arranged along a profile. Microtremors were recorded after midnight with time interval of 30 minutes; record length for each interval was 2 minutes. Explosion charges were about 120 kg of dynamite, and 850 kg of amfo. Three Protable Data Acquisition System (PDAS 100) recording stations along a profile with interval of 50 to 150 meters were deployed to record the seismic waves. Data was processed using Digital Signal Processing (DSP) software. Then the classical Spectrum ratio and Nakamura's ratio methods have been evaluated. It should be noted that, all obtained results are reliable in frequency range of 0 to 10 Hertz. The obtained results were classified in four stages as follows:

Microtremors: obtained amplification factor, in average, from two recording stations using Nakamura's ratio method shows greater values than that of obtained from classic reference station method. The obtained results for the used methods is summerised as the following;

Explosion: The above result was obtained the same, while explosion was used as a source.

Nakamura's method: In comparison between microtremors and explosion generated waves, the Nakamura's method, in average resulted greater amplification factor while explosion was used as a source.

Classic reference station method: In comparison between microtremors and explosion, classic reference station method, in average resulted greater amplification factor while explosion was used as a source.

Keywords: amplification factor, alluvium deposits, Nakamura's method, reference station method

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□ Full paper in Farsi section

rainfall and snow water equivalent in a mountainous catchment:, *in* Proc. Int. Symp. On Forest Hydrol., Tokyo, Japan, 31-37.

Tani, M., 1996, An approach to annual water balance for small mountainous catchments with wide spatial distributions of rainfall and snow water equivalent: Jour. of Hydrology, **183**, 205-225

Todini, E., 1996, The ARNO rainfall-runoff model: Jour. of Hydrology, **175**, 339-382.

Tokar, A.S., and Johnson, P.A., 1999, Rainfall-Runoff Using Artificial Neural Networks, ASCE: Jour. of Hydrologic Engineering, 232-239.

USACE, 1991, User Manual: SSARR Model Streamflow Synthesis and Reservoir Regulation, North Pacific Division, Portland, Oregon.

USACE, 1998, Engineering and Design-Runoff from Snowmelt, Engineering Manual 1110-2-1406.

Williams, J.R., Jones, C.A., and Dyke, P.T., 1984, A modeling approach to determining the relation between erosion and soil productivity: Trans. ASAE, **27**, 129-144.

W.M.O., 1986, Intercomparison of Models of Snowmelt Runoff: Operational Hydrology Report **38**, World Meteorological Organization, Geneva.

Zuzel, J.F., and Cox, L.M., 1975, Relative Importance of Meteorological Variables in Snowmelt: Water Resources Research, **11**, 174-176.

(SEUS): in Proceedings 62nd Western Snow Conference, Santa Fe, NM, York, N.Y. 155-168.

Jordan, R., 1990, User's guide for CRREL, One Dimensional Snow Temperature Model: USA Cold regional Research and Engineering Laboratories, Hanover, New Hampshire.

Jordan, R., 1991, A one-dimensional temperature model for a snow cover, Technical documentation for SNTHERM89: USA Cold Regional Research and Engineering Laboratory, Special Report 91-16.

Leavesley, G.H., Lichty, R.W., Troutman, B.M., and Saindon, L.G., 1983, Precipitation-runoff modeling system, User's manual: USGS Water Resources Investigation, Report 83-4238.

Leavesley, G.H., 1989, Problem of snow runoff modeling for a variety of physiographic and climatic condition: Hydrological Science, **34**, 617-634.

Linsley, R.K., Jr., 1943, A simple Procedure for the Daily Forecasting of Runoff from Snowmelt: Transaction of the American Geophysical Union, Part III, 62-67.

Maidment, D.R., 1992, Handbook of Hydrology: McGraw-Hill Publication, New York.

Maidment, D.R., 1993, Development a spatially distributed unit hydrograph by using GIS, Hydrogis: Application of GIS in hydrology and water resources management: Proceeding of Vienna Conference April 1993, IAHS Publ. **211**, 181-182.

Martinec, J., Rango, A., and Major, E., 1998, Snowmelt Runoff Model (SRM): User's Manual, version 4.0.

Meijerink, A.M.J, De Brouwer, H.A.M., Mannaerts, Ch.M., and Valenzuels, 1994, Introuduction to the use of geographic information systems for practical hydrology: UNESCO, Publication, **23**.

Melloh, Rae A., 1999, A Synopsis and Comparison of Selected Snow Algorithm: U.S. Army Corps of Engineers, CRREL.

Micovic, Z., and Quick, M.C., 1999, A rainfall and snowmelt runoff modeling approach to flow estimation at ungauged sites in British Columbia: Jour. of Hydrology **226**, 101-120.

Morid, S., 2000, Snowmelt-runoff simulation for snowbound ungauged catchments, Ph.D. thesis, Indian Institute of Technology, Delhi.

Morid, S., Gosain, A.K., and Keshari, A.K., 2000, An algorithm for monitoring snow water equivalent in un-gauged catchments using GIS: Proceeding of Conference on Integrated Water Resources Management for Sustainable Development, 2, New Delhi, India, 1181-1190.

Nagler, T., and Rott, H., 1997, Application of ERS-1 SAR for snowmelt runoff modeling: Remote Sensing and Geographic Information Systems for Design and Operation of Water Resources Systems: IAHS Publication, **242**, 119-126.

Pasricha, A., and Gosain, A.K., 2000, Watershed Modeling Using Geographical Information System, submitted for International Conference on Remote Sensing and GIS, India.

Peck, E.L., 1976, Catchment modeling and initial parameter estimation for the National Weather Service River Forecast System: NOAA Technical Memorandum NWS Hydro-31, U.S. National Weather Service, June.

Richardson, C.W., 1981, Stochastic Simulation of Daily Precipitation, Temperature, and Solar Radiation: Water Resources Research, **17**, 182-190.

Sajikumar, K., and Thandaveswara, B.S., 1999, A non-linear rainfall-runoff model using an artificial neural network: Jour. of Hydrology, **216**, 32-55.

Singh, V.P., 1995, Computer Models of Watershed Hydrology, Water Resources Publications.

Stein, J., 1985, An elaboration of two methods to investigate unfrozen water movement in a snow-soil environment, Ph.D. thesis, Univ. of Alaska, Fairbanks.

Sugawara, M., and Watanbe, I., 1985, Tank Model: Proceeding of International Workshop on operational applications of Mathematical Models (Surface Water) in Developing Countries, 13-52.

Swany, A.N., and Brivio, P.A., 1996, Hydrological modelling of snowmelt in the Italian visible and infrared remote sensing: International Journal of Remote Sensing, **16**, 3169-3188.

Swift, L.W., Jr., 1976, Algorithm for solar radiation on mountain slope: Water Resource Research, **12**, 108-102.

Tani, M., 1994, Estimating spatial distribution of

Allen, R.G., 1997, Self-Calibration method for estimating solar radiation from air temperature: Jour. of Hydrology, **2**, 56-67.

Akhan, Osman A., 1984, Simulation of runoff from snow-covered hillslopes: Water Resources Research, **20**, 707-713.

Alekhin, Y. M., 1964, Short-range forecasting of lowland-river runoff (translated from Russian): IPST, Jerusalem, 149-169.

Anderson, E.A., 1973, National Weather Service Forecast System, Snow accumulation and ablation mode: NOAA Tech. Memorandum NWS Hydro-17, U.S. Dept. of Commerce, Silver Spring, Maryland.

Andrson, E. A., 1976, A Point Energy and Mass Balance Model of a Snow Cover: NOAA, Tech. Report NWS NO. 19, U.S. Dept. of Commerce, Silver Spring, Maryland.

Arnold, J.G., Williams, J.R., Srinivasan, R., and King, K.W., 1996, SWAT-Soil and Water Assessment Tool - Documentation and User's Manual: USDA-ARS, Temple, Texas.

Arnold, J.G., Muttiah, R.S., Srivansan, R., and Allen, P.M., 2000, Regional estimation of base flow and groundwater recharge in the Upper Mississippi river basin: Jour. of Hydrology, **227**, 21-40.

Artan, G.A., Neale, C.M.U., and Tarboton, D.G., 2000, Characteristic length scale of input data in distributed models: implications for modeling grid size: Jour. of Hydrology, **227**, 128-139.

AV-SWAT, 1999, ArcView Interface for SWAT 99.2, User's Guide: Blackland research Center, Temple, Texas.

ASCE-II, Task Committee on application of ANNs in hydrology, 2000, Artificial Neural Networks in Hydrology, II: Hydrology Application, ASCE: Jour. of Hydrologic Engineering, **5**, 124-137.

Bales, R.C., and Harrington, R.F., 1995, Recent Progress in Snow Hydrology: Prepared for the AGU quadrennial report to the IUGG.

Barry, R.G., 1981, Mountainous Weather and Climate: Methuen & Co., New York, USA.

Barry, R., Prevost, M., Stein, J., and Plamondon, A.P., 1990, Application of a snow cover energy and mass balance model in a Balsam, Fir Forest: Water Resource Research, **26**, 1079-1092.

Bathurst, J.C. and Cooley, K.R., 1996, Use of the SHE hydrological modeling system to investigate basin response to snowmelt at Reynolds Creek, Idaho: Jour. of Hydrology, **175**, 181-211.

Brubaker, K., Rango, A., and Kustas, W., 1996, Incorporating radiation inputs into the snowmelt runoff model: Hydrological Processes, **10**,1329-1343

Cazorzi, F., and Dalla Fontana, G., 1996, Snowmelt modeling by combining air temperature and a distributed radiation index: Jour. of Hydrology, **181**, 169-187.

Chen, Ch., Nijssen, B., Wang, Y., Tsang, L., Hwang, J., and Lettenmaier, D.P., 1998, Mapping the spatial distribution and time evaluation of snow water equivalent using neural network iterative approach and a snow hydrology model: Proceeding of the 1998 IEEE International Geoscience and Remote Sensing Symposium, IGARSS, **3**, 1258-1260.

Clair, Th.A., and Ehrman, J.M., 1998, Using neural network to assess the influence of changing seasonal climates in modifying discharge, dissolved organic carbon, and nitrogen export in eastern Canadian rivers: Water Resources Research, **34**, 447-455.

Cline, D., Elder, K., and Bales, R., 1997, Scale effects in a distribution SWE and Snowmelt Model for Mountain Basins: Proc. Western Snow Conference 65th Annual Meeting, 1997, Banff, Canada.

Crawford, N.H., and Linsley, R.K., 1964, Digital Simulation in Hydrological Modeling: Stanford University, Stanford, California.

Dawson, C.W., And Wilby, R., 1998, An artificial neural network approach to rainfall runoff modeling: Hydrologic Science Journal, **43**, 47-66.

Hall, D.K., and Martinec, J., 1985, Remote Sensing of Ice and Snow, Chapman and Hall, New York.

Hanson, C.L., Cumming, K.A., Woolhiser, D.A., and Richardson, C.W., 1994, Microcomputer Program for Daily Weather Simulation in the Contiguous United States: Agriculture Research Service, U.S. Department of Agriculture.

Hargreaves, G.H., and Samani, Z.A., 1982, Estimating potential evapotranspiration, Jour. of Irrigation and Drainage Engineering, ASCE, **108**, 25-230.

Hills, R., McManamon, A., and Hartman, R.K., 1994, Snow Estimation and Updating System

4-2. Remote Sensing (RS)

Remote sensing is being increasingly used in snowmelt-runoff simulation. Grain size and shape, impurity content, near surface liquid water content, depth and surface roughness as well as solar radiation, are the main parameters, which affect spectral reflectivity of snow. Different attempts in this field have been used to acquire snow properties using different electromagnetic spectrums or to prepare required data and input files. The most common properties and features that are purposed to extract through remote sensing are snow albedo, grain size, SWE, density and snow cover mapping (Nagler and Rott, 1997; Swany and Brivio, 1996).

The possibility for detecting snowpack properties is largely determined by the wavelength being used to the remote sensing instrument. Visible and near infrared wavelengths cannot penetrate far into the snowpack, therefore they are mainly used for extracting surface information of the snowpack, these waves cannot produce an image through clouds. Bales and Harrington (1995) reported recent attempts to validate reflectances derived from Thematic Mapper (TM) imagery using ground-acquired spectrometry, highlighting the importance of the solar zenith angle in determining reflectances.

Microwave wavelength can penetrate into the snowpack and it can also acquire data in cloudy conditions or night time. But the interpretation of their images is more difficult compared with visible and near infrared wavelengths. Some of literature exists on the use of microwave wane lengths in capturing various information from the snowy terrain (Hall and Martince, 1985; Bales and Harrington, 1995). Since the microwave signal from the snowpack is a volume-integrated response to wetness, density, surface and substrate roughness, and stratigraphy, it is difficult to invert the signals to recover the various physical properties of interest. (Hall and Martince, 1985; Bales and Harrington,1995). Among the operational hydrological models the SRM Model (Martinec et al, 1998) relies more on remote sensing information. In this model snow cover area (SCA) is an input and RS which are among the best sources for computing SCA. Discussion about the relative advantages and disadvantages of using remote sensing data from various satellites for snowmelt runoff forecast, and many interesting findings on snow cover mapping are available in Swany and Brivio (1996) and Nagler and Rott (1997).

5. Conclusion

During the last decade, a lot of effort has been successfully made to sort out problems of distributed snowmelt-runoff modeling that can be attributed to the improvement of the computer software and hardware. It seems the data problems as described by Leveasly (1989) still exist. Data is a serious problem, especially in developing countries. Developing and applying improved weather generator modules is the strategy of some of the operational models to overcome data problems. Application of remote sensing and especially GIS has been one of the most advances in snow hydrology. Subsequently many previous models upgraded and modified themselves for distributed analysis and new models with this concept were developed. But, fewer attempts have been made to evaluate snowmelt components of the hydrological models individually. It is suggested that an association like IAHS (International Association of Hydrological Science) announces for an international effort to collect proper available data set regarding snow hydrology research and put them on web site to be used by other researchers. Making public domain of these data sets can provide valuable information for hydrology researchers, model developers and those involved with simulating snowmelt-runoff with synthesized data. ANN as a new model structure is a new scope for investigation of snowmelt-runoff modeling and more attempts are needed in this regard. Water is going to be the main confection for future societies. Potential water in permanent snow capped area may provide future water resources, and the hydrologist will have the main role of applying these resources efficiently and economically.

Reference

Aizen, V.B., Aizen, E.M., and Melack, J.M., 1996, Precipitation, melt and runoff in the Northern Tien Shan: Jour. of Hydrology, **186**, 229-251.

Albert, M.R., and Krajeski, G.N., 1998, A fast, physical-based point snowmelt point snowmelt model for distributed application: Hydrological Processes, **12**, 1809-1824.

surface temperature is 2.5°C less than the air temperature when the air temperature is subzero, whereas it is zero when air temperature is zero or more. This suggestion has been also used for some other research works (Brubaker et al, 1996).

3-3. Solar Radiation

Solar radiation is one of the most important sources of energy for creating snowmelt. Also when spatial analysis of snowmelt is to be considered, this variable gains in significance for its effect on the above process. Surprisingly, this meteorological parameter is not a readily available data in many catchments. Model developers have used different strategies to handle this meteorological parameter. In the ARNO model, it has been calculated according to the evaporation from the reference evapotranspiration (Todini, 1996). The SWAT (Arnold et al., 1996) and EPIC (Williams et al., 1984) model uses the stochastic approach to generate daily solar radiation introduced by Richerdson (1981). This method has been also used by some of the weather data generator software (e.g. USCLIMATE (Hanson et al., 1994) and CilGen (Nelson, 1999)). Of course, there are some models like SHE model (Bathurst and Cooley, 1996) that assume radiation data can be supplied from the observatory stations.

In another study carried out by Hargreaves and Samani (1982), they correlated solar radiation to temperature and extraterrestrial radiation. This approach has been used more frequently by other studies to estimate incident solar radiation. Recently, Morid (2000) have applied ANNs to estimate daily solar radiation and compared the results with those of Richardson (1981) and Hargreaves and the Samani (1982) method, modified by Allen (1997). They concluded that although ANN performs better than other methods, but for use in the operational hydrological models, the method of Hargreaves and Samani (1982) is more appropriate and applicable for the estimation of radiation.

4. Application of New Technology in Snowmelt Simulation

Geographical Information System, Remote Sensing, Information Technology are the new technologies which are currently increasingly used in snow hydrology. The main objectives of these applications are data acquisition, data elaboration and pre-processing.

4-1. Geographical Information System (GIS)

One of the main states of progress throughout the last decade is the implementation of GIS in hydrological models. GIS is not a directly suitable technique for hydrological modelling in the true sense, the main reason being that GIS does not explicitly represent the time varying of the data structure (Maidment 1993). But the coupling of GIS as a pre- processor and hydrologic models seems to be a logical direction (Meijerink et al., 1994). This is the procedure that now many hydrological models like SWAT (AV-SWAT, 1999) and MIKE BASIN (Danish Hydraulic Institute, 2000) have implemented to enhance their model capability by developing proper GIS interface. The integration of GIS and remote sensing is another combination in enhancing hydrological model powerfulness. For spatial analysis, digital elevation model (DEM) is the basic element, which is used by GIS. A DEM is an ordered array of numbers that represents the spatial distribution of elevations above some arbitrary datum in the landscape. In principal, a DEM describes the elevation of any point in a given area in digital format. Slope and aspect maps, hill shading watershed delineation and channel network are the main information that can be obtained by using DEM. Scaling is an important issue while using DEM for spatial analysis. The effect of using DEM with different sizes can be found in Cline et al. (1997) and Artan et al. (2000). Another important issue in this regard is using DEM in the parameterization of watershed with various approaches like D∞ (infinite number of possible directions), D8 (eight single directions), etc. Pasricha and Gosain (2000) explored and evaluated the automatic techniques for parameterization of the watershed using D8 and D∞ approaches. It was found that D8 does well under situations where large-scale (≈ 5m contour interval) is available. At the same time, the D∞ approach also gives results on such a large scale, which are equally good or rather better than those given by D8 approach. But on a small scale, D8 uses its entities and shows its robustness applied. Using R^2 (correlation coefficient), the performance of the model simulation changed from 0.6 to 0.9 at monthly simulation and at daily time scale from 0.41 to 0.71 (Morid, 2000). These differences show the importance and significant role of snow module in runoff simulation in snowy terrain. This problem is pronounced for operational models while applying them for large basins.

3. Data Related Problems

Although data handling is going to be less difficult compared with the last decades, still many of the major problems in simulating snowmelt-runoff are related to data availability, data quality, and the ability to extrapolate accurately point measurements to areal values. Precipitation, air temperature and radiation are the main data for snowmelt-runoff simulation (Zuzel and Cox, 1975), and problems associated with spatial and temporal distribution of them are significant for many approaches in snowmelt simulation.

3-1. Precipitation

Precipitation distribution and its form (snow or rain) are the most important factors in producing accurate estimates of snow accumulation, snowmelt and consequent runoff. The spatial distribution of precipitation in a basin is affected by a number of factors that include storm type, wind velocity and direction, topography and elevation. In mountainous regions the mechanism of the constitution of rainfall is very complicated. Like many factors such as lee side or weather side, relief and wind effect on precipitation and snowfall and its accumulation. This orographic enhancement of precipitation is modeled by the precipitation gradients. Although the gradient is usually positive but it increases generally up to some extent with an increase in elevation. Because of scarce rain gauge network in high lands, this threshold is often not known. More about this context can be found in Leveasely (1989); Micovic and Quick, (1999).

Recent researches are more concerned about using satellite and radar information for this evaluation. James (1999) figures out the rain cell speed and direction, and then marches each rain cell across the subareas by using an interpolating function between adjacent hyetographs. For the interpolation, he fits a lagging function to the cell. Application of GIS and radar images or satellite data, and overlapping of DEM cells and radar images can improve the estimate of spatial distributions of rainfall defined by point rain gauges. The key point is to establish the relationship between the radar image and the actual rainfall for the study area (Chen, 1998). Although using precipitation laps rate is not an accurate enough procedure, especially for daily or shorter time scales, but still for operational studies it is the best applicable model and some models use it for this purpose (e.g. $\text{SWAT}_{99.2}$., SRM model)

3-2. Temperature

Air temperature is one of the major components in the determination of snowmelt rates and the form of precipitation. Elevation is the main components that affect the spatial distribution of air temperature, though not in the same manner as that for precipitation. Air temperature usually decreases with increasing elevation at an average lapse rate of about 6°C/km. However, the variation about this average can be quite large. Barry (1981) presented excellent discussions pertaining to temperature lapse rate.

Distributed parameter models usually use temperature lapse rates to extrapolate measured air temperature for all subbasins or elevation zones or cells in 3D scheme. Hydrological models usually use a constant lapse rate for the entire year (SWAT (Arnold et al., 1996)), whereas in some cases they have applied seasonal or monthly lapse rate and even daily lapse rates in (SRM Model (Martinec, et al. 1998)). The use of seasonal or monthly constant rate does not reflect the variability observed in the daily lapse rates and can be a source of simulation error. To minimize these errors, the constant lapse rates are usually optimized (Leavesley, 1989).

In addition to air temperature, snow surface temperature is essential for solving energy balance equations and calculating net radiation transfer. There are rare measurements available for this parameter and usually estimated by daily temperature measurements. Kuzmin (Alekhin, 1964) postulated that snow surface temperature is the same as air temperature when air temperature is subzero, whereas snow surface temperature is zero when it is zero or more. Anderson (1976) experimental observations suggested that snow wind, elevation, etc.) For instance, Konovalov (Aizen et al., 1996) with 380 day of observations on the Tuyksu glacier defined 10-day snowmelt equation:

$$W_{de} = 62 * T_{de} + 54 \qquad r= 0.70, SE=8.3 \qquad (4)$$

Aizen (1996) based on 32 years of observations on the Gloubina glacier presented the following equations to predict snow and ice melt for northern Tien Shan:

$$W_d = 6.4 * T_d + 8.7 \qquad r = 0.71, SE=1.9 \qquad (5)$$

$$W = 0.32(T_s + 9.5)^{3.46} \qquad r = 0.79, SE=78 \qquad (6)$$

where T_d, T_{de} and T_s (°C) are daily, 10-day and summer average air temperature, W_d, W_{de} and W(mm) are daily, 10-day and annual melt of ice, snow and firn receptively. SE (mm) are standard error of W_d, W_{de} and W and r is regression coefficient.

2-6. Data Requirements of the Methods

Among the above-mentioned approaches from data requirment point of view, energy budget and flow transmission based models require more data and deal with more complicated equations. The Anderson model (1976) is one of the most complete energy budget based models that many further researches have been carried out to use and calibrate it for different areas (Stein, 1985; Barry et al., 1990). The flow transmission based models have received comparatively less attention because of complicated parameter requirements, although this approach provides a more accurate prediction of the magnitude and timing of snowmelt than current operational models (Melloh, 1999). The statistical approaches require observed snowmelt for a moderate period of time. For instance, in SWAT$_{ver99.2}$, the minimum and maximum rates of snowmelt during a year are required. Usually this approach is more relevant for the specific site in which the data have been collected. Specially, for the dams that are fed by snowmelt, future snowmelt is predicted by this method. Relatively, temperature based, and temperature-radiation based approaches need less and easily available data in comparison with other methods. Capabilities for running in big basins and incorporating spatial and temporal variation of snowmelt process are another advantages of temperature-radiation method. For example SRM has been applied for Yellow River basin in China, with area of 122000 km^2, (Martince et al., 1998).

2-7. Snow Water Equivalence (SWE) Distribution

SWE calculations and its spatial distribution have been the main concern in hydrological models and have been estimated in different ways. Tani (1994, 1996) developed a simple technique of spatial filtering of digital elevation data to correlate rainfall and SWE against elevation. Hills et al. (1994) developed a methodology to generate real-time gridded snow water equivalent, using ground-based and airborne snow data collected over the western U.S. All of these research works were based on some direct measurements that make them unsuitable for ungauged catchments. In an attempt authors specifically considered such catchments and developed an algorithm for SWE monitoring of ungauged catchments using the SWAT model (Arnold et al., 1996) and Swift (1976) algorithm for calculating spatial variation of incident solar radiation (Morid et al., 2000). The gridded SWE incorporates the spatial variability of the snowpack induced by the geographical information system (GIS) to store, analyze and display the spatial data necessary to perform the estimation.

2-8. Calibration and Validation

As already stated, snowmelt simulation is a common module in hydrological models, but the output of snow module has been rarely calibrated and validated independently by the modelers. Snowmelt models are traditionally calibrated by the predicted and observed discharges at the basin outlet and still in many of the recent research works, the model performance is evaluated in the same manner (Brubaker et al., 1996; Micovic and Quick, 1999; Arnold et al., 2000). Again this is because of a deficit of observed data. It sometimes happens that in spite of satisfactory water yield, the values of the components of flow are independently meaningless (Cazorzy and Dalla Fontana, 1996). This problem is pronounced for operational models while applying them for large basins. The authors applied the SWAT model to a 16.1 km^2 snow bound basin located in Iran. All the data sets and parameters were kept constant and only different snowmelt simulation algorithms including: temperature based, temperature-radiation based, and energy budget based, were as:

$$\Delta Q = Q_n + Q_e + Q_h + Q_g + Q_m \qquad (2)$$

where

ΔQ = change in the heat storage of the snow cover

Q_n = net radiation transfer

Q_e = latent heat transfer

Q_h = sensible heat transfer

Q_g = heat transfer across the snow-soil interface

Q_m = heat transfer by mass changes (advected heat)

The model includes important snowpack processes, such as snow ripening, pore water retention and flow of water through the pack. These models are preferable for continuous simulation with a short time interval (e.g. hourly or 6 hours). However, the main limitation of these kinds of models is data. Therefore, the use of these models for operational works or ungauged catchments, necessitates the development of appropriate methodology to deal with limited data.

2-3. Temperature - Radiation Based Method

In some of the recent researches, investigators have incorporated radiation as an index in the melt rate equation (Brubket, et al., 1996;Cazorzi & Fonatana, 1996). The Brubket method led to the development of a new version of Snow Runoff Model (SRM). In these studies temperature and radiation both have been used as input for the developed models. This method has advantages in terms of simplicity and practicability of temperature-based method and more precession of energy balance method, although it does not have all its components. Capabilities for running in big basins and incorporating spatial and temporal variation of snowmelt process are another advantages of this method.

2-4. Flow Transmission Based Method

This category of snowmelt approach also uses surface energy balance to estimate melt water input to snowpack, the major difference with energy budget based method is that in this method a mathematical solution to the flow of water through the snow has been included that makes it more physically based.

The research work of Akhan (1984) is one such attempt. He developed a physical-based mathematical model of runoff from snow-covered hill slopes that included realistic metamorphism components and improved models of water transmission. His work is one of the most complete models using theoretic equations.

Akan (1984) assumed snowpack as an ideal rigid porous medium which consists of two bodies; (1) the main body that is unsaturated with respect to liquid water, and (2) a thin saturated layer of basal flow. The settling of the melt layer was neglected and the flow of liquid water was considered to be one-dimensional.

Albert and Krajeski (1998) made another attempt for this category of snowmelt simulation. The surface energy balance is almost equivalent to that of Eq.(3). The water equivalent of melt, equal to the available energy from the surface energy balance, is added to rainfall and routed through the snowpack. The water volume flux equation is used in this model is expressed below:

$$\frac{\partial U}{\partial t} = -n\vartheta^{-1}\left(1 - S_{wi}\right)^{-1}\left[\frac{\rho_w kg}{\mu_w}\right]^{\frac{1}{n}} U^{-1-\frac{1}{n}}\frac{\partial U}{\partial x} \qquad (3)$$

where:

U = volume flux of water (cm s^{-1}),

t = time (s), n is dimensionless porosity of snow,

n = dimensionless effective saturation (S) exponent,

ϑ = dimensionless porosity of snow,

S_{wi} = irreducible water saturation of snow (% of total volume),

ρ_w = absolute permeability of snow (g cm^3),

k = absolute permeability of snow (cm^2),

g =s acceleration due to gravity (cm s^{-1}),

μ_w = viscosity of water (g cm^{-1} s^{-1})

x = vertical spatial coordinate (cm).

These series of models have received comparatively less attention as they involve many parameters, which are difficult to evaluate, although this approach provides more accurate prediction of the magnitude and timing of snowmelt than current operational models (Melloh, 1999).

2-5. Statistical Method

Several attempts have been also made to correlate snowmelt with other meteorological and physiographical variables (e.g. temperature,

Table 1. Snowmelt modeling approaches.

Method	Models / Methodology
Temperature based Method	Degree-Day (Linsley, 1943); EPIC (Williams et al., 1984); $SWAT_{ver96.2}$ (Arnold, et al. 1996), TANK (Sugawara and Watanbe, 1985)
Energy budget based Method	Kuzmin (Alekhin, 1964); SNOW17 (Anderson ,1973); ARNO (Todini 1996); SHE (Bathurst and Cooley, 1996); PRMS (Leavesly et al., 1983); US. Corp of Engineers (USACE, 1998), SSARR (USACE, 1991), NWSREFS (Peck, 1976), SNTHERN, (Jordan 1990,1991)
Temperature-radiation Method	Cazorzi and Fontana (1996);SRM (Martinec et al., 1998)
Flow transmission Method	Akhan (1984); SNAP (Albert and Krajeski 1998)
Statistical Method	Aizen et al. (1996), $SWAT_{ver99.2}$ (SWAT, 2000)

changing seasonal climates in modifying discharge and few chemical components using ANNs. For mapping the spatial distribution and time evolution of snow water equivalent Chen et al. (1998) used ANNs to develop a multi-parametric algorithm to invert measured parameters by remote sensing to snow parameters like SWE. Tokar and Johnson (1999) used ANNs for daily runoff simulation of Little Patuxent River in Maryland. However, in all the three studies, snow depth was measured and has been directly put as input. The reason for this consideration can be ANN's simplicity, ability to extract the relationship between the inputs and outputs of the process without considering physics explicitly. It is also capable of mapping one multivariate space to another, given a set of data representing that mapping. Even if the data is noisy, short length and involving errors, ANNs have been known to identify the underlying rule (Dawson and Wilby, 1998; Tokar and Johnson, 1999; Sajikumar and Thandaveswara 1999 and ASCE II, 2000).

Attempts have been made to review some of these snow models, which are more operational. World Meteorological Organization (WMO, 1986) carried out an extensive comparison of snowmelt runoff models in which hundreds of model runs were performed in six selected test basins. However, they only compared the results regardless of the algorithm. The U.S. Army Corps of Engineers (USACE, 1998), Singh (1995) compared the structure and approach of snowmelt models. In another work by the U.S. Army Corps of Engineers, Cold Regions Research & Engineering Laboratory (CRREL) the focus was given on the snowmelt algorithm, their developmental setting, equations, strength, and limitations (Melloh, 1999), however their study was confined to operational models being developed in the USA. In another attempt, Morid (2000) assessed response of a numbers of snow models to synthesized data. He showed that using synthesized data could give better results in comparison to using simple temperature based equation for lower time scales.

2-1. Temperature Based Method

Temperature based method is the first attempt in snowmelt modeling and has been used in many different ways for calculating snowmelt. Some of the equations used are based on minimum temperature (T_{min}), some are based on maximum temperature (T_{max}), some other are based on mean temperature (T_m) and some are based on a combination of them (Maidment, 1992). The general from of the method is as follow:

$$M=C_d\,(T_a-T_b) \qquad (1)$$

where M is melt (mm.day^{-1}), C_d is degree-day melt coefficient (mm °C^{-1}day^{-1}), T_a is air temperature (°C) and T_b is base temperature at which melt will occur, normally 0 °C.

2-2. Energy Budget Based Method

Many studies have been directed toward an understanding of the energetic of snowmelt. One of the first and complete attempts was made by Anderson (1976) in the Hydrologic Laboratory of the Office of Hydrology, U.S. Army Corps of Engineers. The model was developed based on the works carried out by Crawford and Linsley (1964) and Anderson (1973). The Anderson model is based on two equations: (1) the energy exchanges at the snow-air and snow-soil interfaces and (2) the heat and mass transfers within the snow cover. The model takes into account the physical processes associated with the accumulation, melt and energy transfer of the snow cover. The energy balance approach for calculating snowmelt applies the law of conservation of energy to a control volume. The snow-ground interface acts as the lower boundary of the control volume, whereas the snow-air interface acts as its upper boundary. The use of a volume allows the energy fluxes into the snow to be expressed as internal energy changes. The energy balance of snow cover can be expressed

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Challenges in Snowmelt-Runoff Simulation

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Research note

Abstract
Snowmelt-runoff simulation is a significant and common module in hydrological models. During the last decade, a number of hydrological distributed models, have been developed, using different snowmelt algorithms and many of the previous models have been updated with more improved snowmelt approaches. Also, an especial consideration has been developed to distributed modeling. In the present paper, snowmelt modules of hydrological models have been reviewed. Data problems to some extent have been resolved compared with the previous decade, but it is still the main obstacle. Application of Geographical Information System (GIS) has been one of the great successes and some of the models have been facilitated by GIS interface. In spite of these improvements, because of the rareness of snowmelt measurements in a few studies snowmelt components of hydrological models have been independently evaluated. It has been suggested that under the coordination of International Association of Hydrological Science (IAHS), in an international attempt, snowmelt data set of different research works that have been done so far to be collected and made available to snow hydrologist and modelers.

Key words: snow hydrology, snow simulation problems, ungauged catchments

1. Introduction

Snow accumulation and ablation are the prime phenomena which are of concern to the hydrologist and water resources managers dealing with snowy catchments and snow fed rivers. Exhaustive studies have been carried out on this phenomenon in the last decades, but still there are many bottlenecks in the way of snow-runoff simulation. An excellent review on problems associated with snowmelt runoff modeling for a variety of physiographic and climate conditions was presented by Leavesley (1989). He discussed a number of problems associated with snowmelt-runoff simulation, reasons why they occurred, and solution being used or proposed to solve them. He summarized common problems as follows:

- Definition of the spatial and temporal distribution of input model.
- Measurement or estimation of snow accumulation, snowmelt, and runoff process parameters for a range of application and scales.
- Development of accurate short term and long term snowmelt runoff forecasts.

In this paper, we have looked into those problems again after a decade and at the beginning of the new millennium, to see where we – snow hydrologists- were, and where we are now? The issues discussed in this paper are related to modelling approaches, data availability, and specific model applications. We have also explored the application of new technology and new scopes in snow hydrology

2. Modeling Approaches

Snowmelt simulation is usually a module in rainfall-runoff simulation models. Some of these models have used sophisticated methods for their snow module and some of them have sufficed only to a simple equation. Briefly, they can be categorized into five classes, namely: temperature-based, energy budget, temperature-radiation, flow transmission and statistical methods. Table 1 refers to some of the hydrological model categories with respect to the above defined classification, along with some of the cited research works and a brief discussion about them will be given in the next sections.

In addition to the said method, recently a number of emerging techniques such as Artificial Neural Networks (ANNs) are being considered for use in snowmelt-runoff simulation and prediction. Clair and Ehrman (1998) used total snow depth as input nodes for assessment of influence of

Reference

Abramowitz, M., and Stegun, I.A., 1970, Hanbook of mathematical functions: Dover Publ., New York.

Agarwal, B.N.P., and Lal, T., 1972, Calculation of the vertical gradient of the gravity field using the Fourier transform: Geophysical prospecting **20**, 448-458.

Blakely, J., and Simpson, R.W., 1986, Approximating edges of source bodies from magnetic or gravity anomalies: Geophysics, **51**, 1494-1498.

Cordell, L., and Grauch, V.J.S., 1985, Mapping basement magnetization zone from aeromagnetic data in the San Juan basin, New Mexico: *in* Hinze, W. J., Ed., The utility of regional gravity and magnetic anomaly maps: Soc. Expl. Geophys., 181-197

Dean, W.C., 1958, Frequency analysis for gravity and magnetic interpretation: Geophysics **13**, 97-127.

Klingele, E.E., and Marson, I., 1991, Automatic interpretation of gravity gradient data in two dimension, Vertical gradient: Geophysical prospecting, **39**, 407-439.

Marson I., and Klingele, E.E., 1993, Advantages of using the vertical gradient of gravity for 3-D interpretation: Geophysics, **58**, 1588-1595.

Nabighian, M.N., 1984, Toward a three dimensional automatic interpretation of potential field via jeneralised Hilbert transform-fundamental relations: Geophysics, **49**, 780-786.

Reid, A.B., Allsop, J.M., Granser, H., Millet, A.J., and Somerton, I.W., 1990, Magnetic interpretation in three dimensions using Euler deconvolution: Geophysics, **37**, 1043-1045.

Sarma, D.D., and Selvaraj, J.B., 1990, Two-dimensional orthonormal trend surface for prospecting: Computer Geosience, **16**, 897-909.

Thompson, D.T., 1982, EULDPH, A new technique for making computer assisted depth estimates from magnetic data: Geophysics, **47**, 31-37.

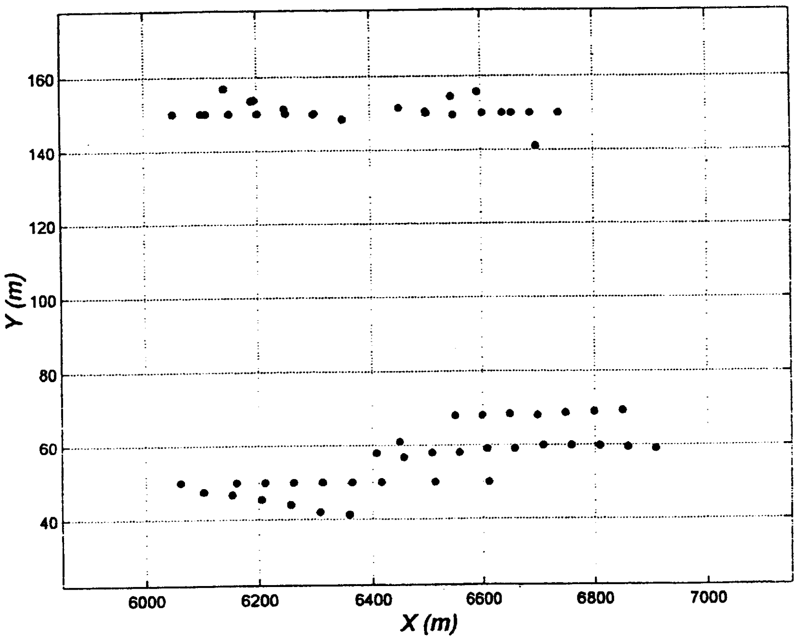

Figure 11. The maxima of the analytic signals in Mard Abad.

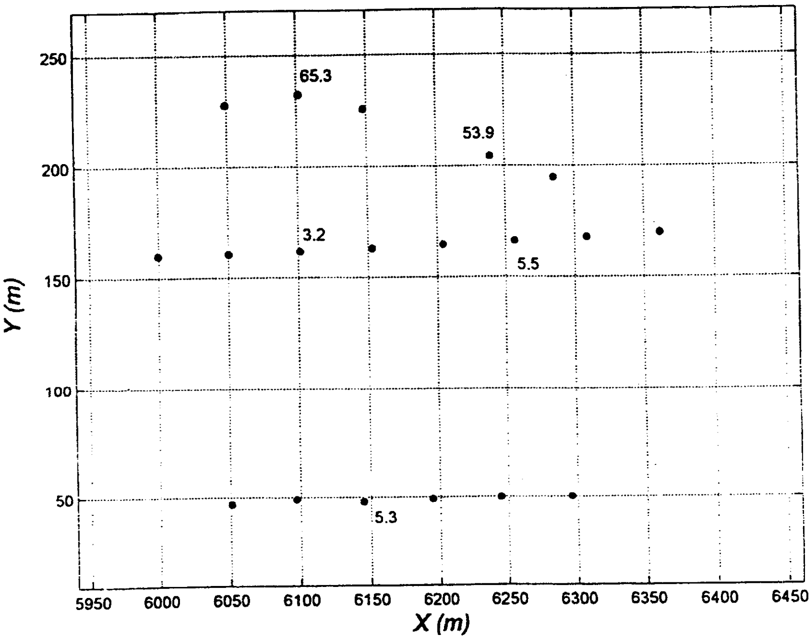

Figure 12. The coordinates of the source bodies via EULDPH in Mard Abad.

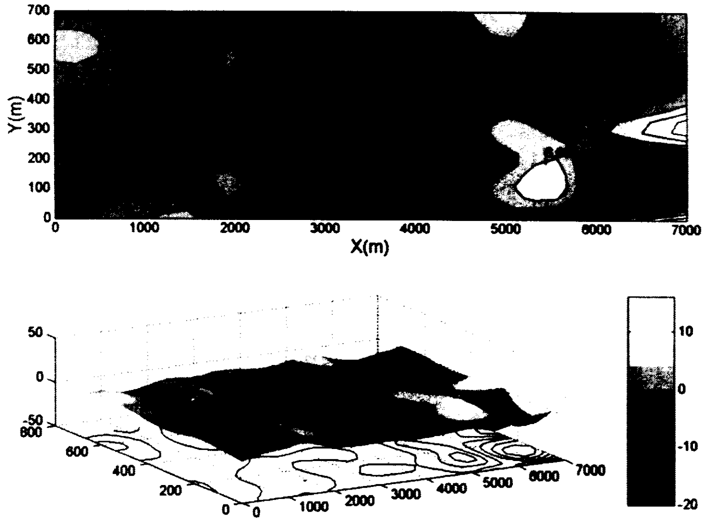

Figure 9. First vertical derivative map of Mard Abad (mGal/m).

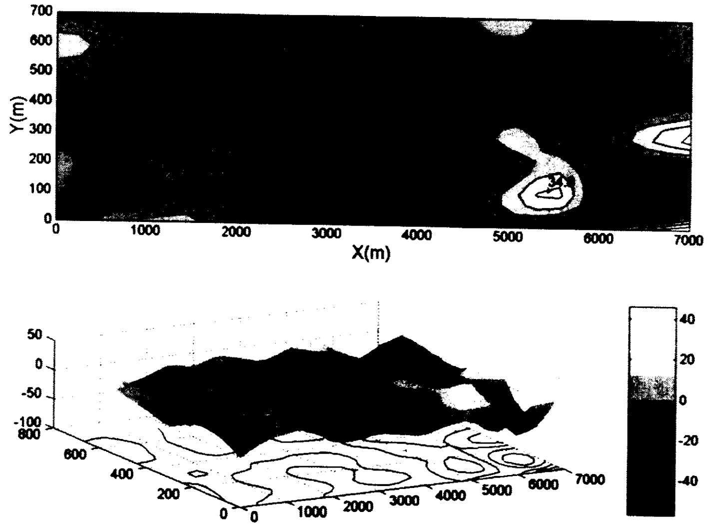

Figure 10. Second vertival derivative map of Mard Abad (mGal/m^2).

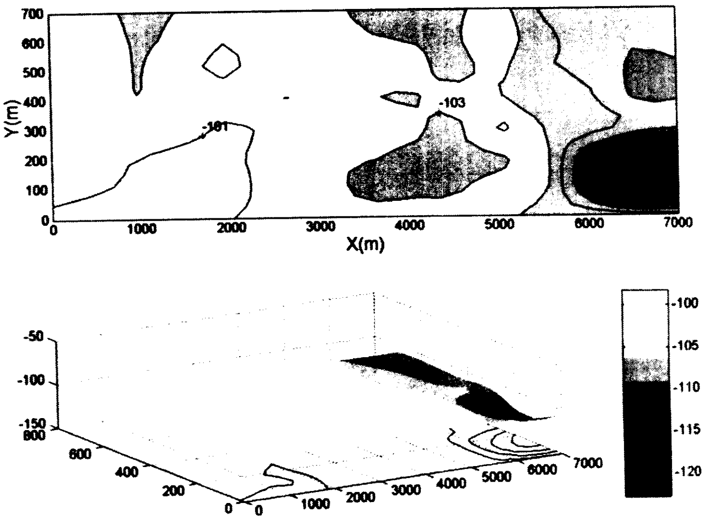

Figure 7. Bouger anomaly map of Mard Abad (mGal).

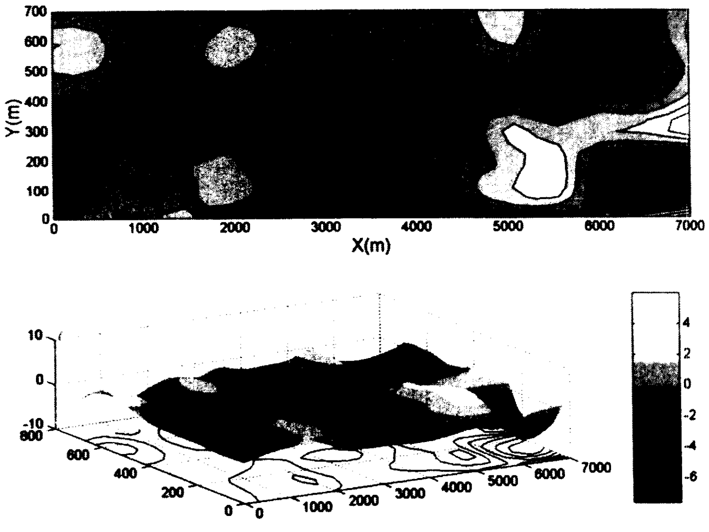

Figure 8. Residual anomaly map of Mard Abad (mGal).

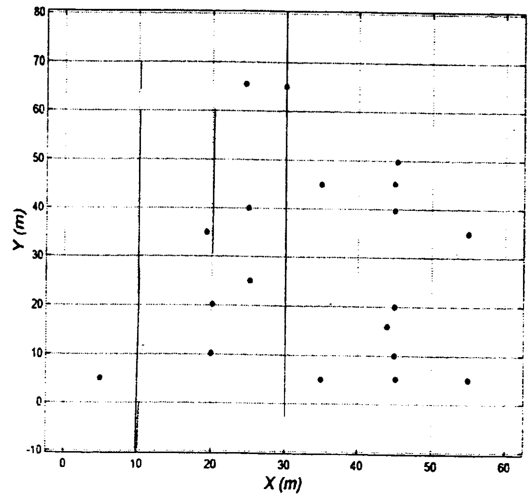

Figure 5. The maxima of the analytic signals in Nosrat Abad.

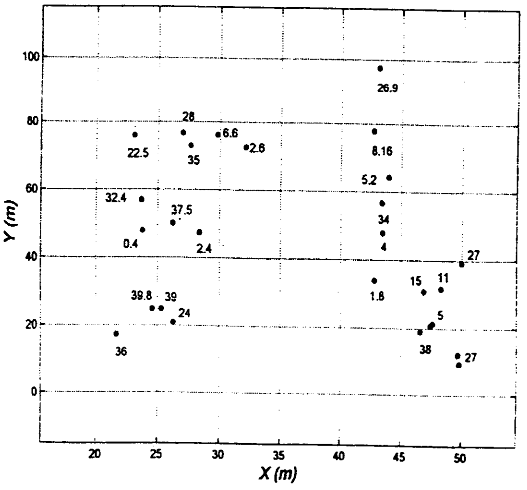

Figure 6. The coordinates of the source bodies via EULDPH in Nosrat Abad.

was very close to the real depth.

Another survey is in the area where we are looking for the hydrocarbon. The Bougour anomaly map is presented in Fig. (7) in which the location of source is quite obvious (the black area) with magnitude less than -120 mGal. The residual anomalies are mapped in Fig. (8) in which the main perturbing body is located with the magnitude of less than -6 mGal in the black area. After computing the first vertical derivatives in figure (9) the position of source has been limited to the smaller area with the center about x= 6600 and y= 100The second vertical derivatives map, Fig. (10) confirms the same area as in Fig. (9) for existing Hydrocarbon. To consider the first and the second vertical derivative maps the most probable area for existing hydrocarbon is between x= 6000 to 7000 and y= 0 to 200. The maxima of the amplitudes of the analytic signals is shown in Fig. (11) where a nice clustering of the results happens. The results from the EULDPH method are demonstrated in Fig. (12). The average depth of the points shown in this figure are in close agreement with geology surveys. The EULDPH has been used in windows including 4 and 4 points in x and y directions and the selected structural index is 2. The criterion for rejecting was selected to be 15 percent of the standard deviations of the three unknowns. There is a good correlation between the results from EULDPH and the analytic signal methods which is promising for the quantitative interpretation of noisy gravity data.

6. Conclusion

One can see from the numerical results that the methods work nicely. In the case of a relatively low-depth Choromite, the clustering of the points computed by the analytic signal method is not so good. To consider the areas of existing maxima of the analytic signal for solving Euler's equation, we obtained an accurate solution which is partly verified by drilling the area. However in a petroleum exploration, the maxima of the analytic signal shows a very nice clustering and orientation. The EULDPH method generates acceptable results, especially in depth determination which is in close agreement with the geological surveys. However for a final confirmation of results they are to be checked with other methods. Applicating the EULDPH to deep anomalies with complex geology structures is questionable.

Acknowledgements

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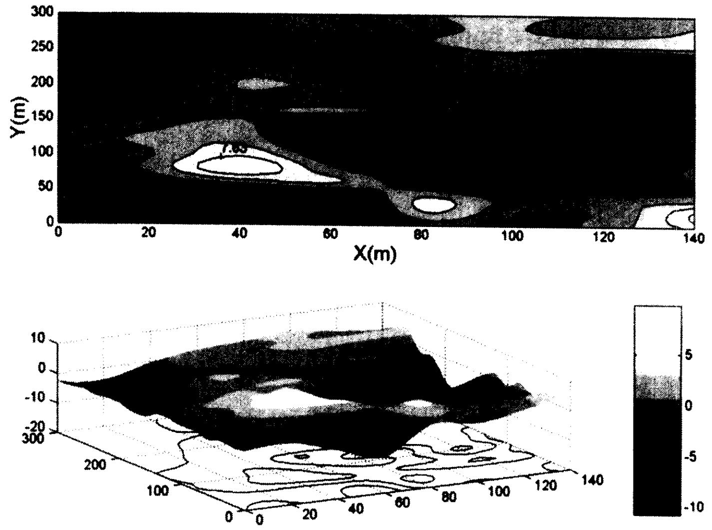

Figure 3. First vertical derivative map of Nosrat Abad (mGal/m).

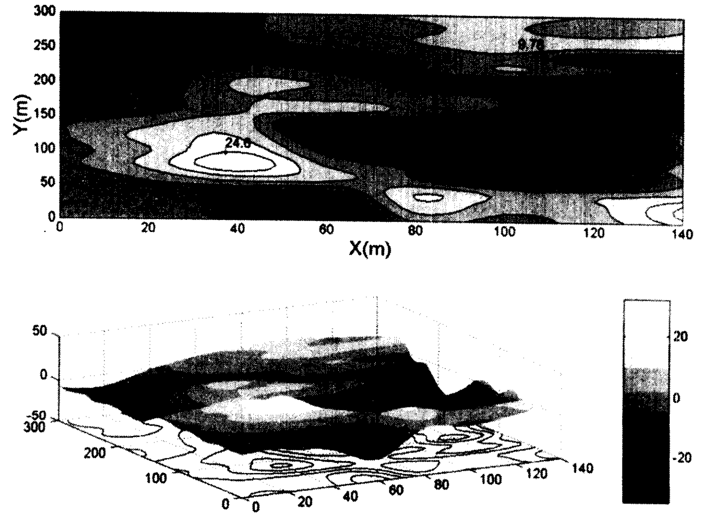

Figure 4. Second vertical derivative map of Nosrat Abad (mGal/m^2).

maxima of the analytic signals were located through the automatic method expressed by Blakely and Simpson (1986). The results are shown in Fig. (5). As indicated by this figure the area of interest was selected, where the EULDPH method was used. The Fig. (6) shows the point sources and the depths i.e., the values close to the points. The depth solution for a single point was rejected based on the criterion if the standard deviations of the three unknowns had been bigger than 15 percent. The suitable structural index was found to be N=2. Most of the points which were detected for the existence of Choromit then were approved correct by drilling. The estimated depth

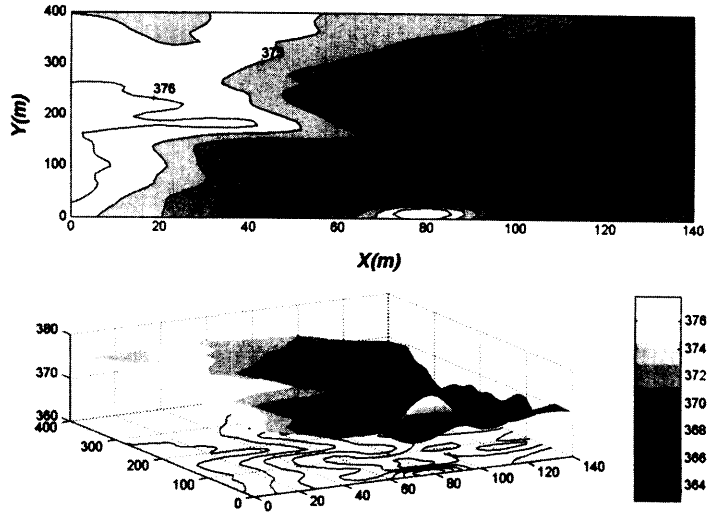

Figure 1. Bougour anomaly map of Nosrat Abad (mGal).

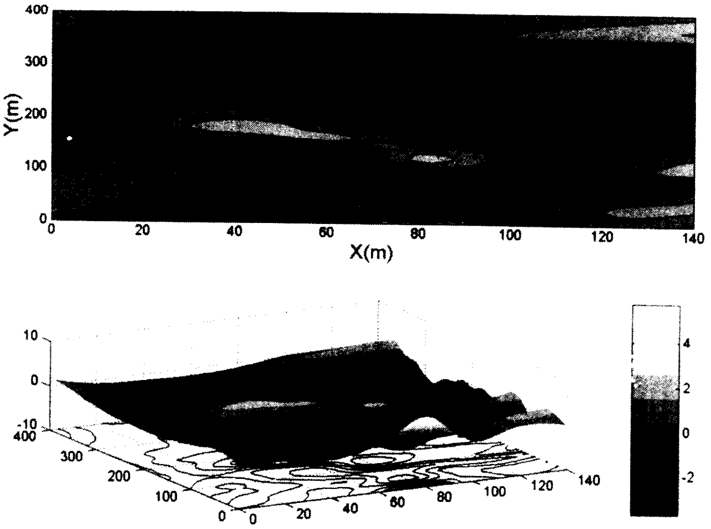

Figure 2. Residual anomaly map of Nosrat Abad (mGal).

selvaraj 1990). The results are shown in Fig. (2). In this figure the anomaly goes up to the magnitude of more than *2.6mGal* and in an area with x= 36 meter to 60 meter and y= 160 meter to 200 meter. The first vertical derivatives were computed as shown in Fig. (3). The white area centered at about x= 40 meter and y= 70 meter with the anomaly 7.63 mGal/m indicates the place of the main source. The second vertical derivative map in Fig. (4) shows the same area as of Fig. (3) with an amplitude of equal to 24.6 $mGal/m^2$. As implied by the first and second vertical derivative maps the center of the area of choromit is x= 40 meter and y= 75 meter. The of Blakely and Simson (1986). According to Marson and Klingele (1993) the horizontal position of the corners impose the position of the maxima of the signal amplitude.

3. Euler's equation

Thompson (1982) showed that for f (x, y, z) to be a homogenous function of degree N, the Euler's homogeneity equation holds,

$$(x-x_0).\frac{\partial f}{\partial x}+(y-y_0).\frac{\partial f}{\partial y}+(z-z_0).\frac{\partial f}{\partial z}=Nf \qquad (3)$$

Where x_0, y_0 and z_0 are the coordinates of source. Klingele et al. (1991) proved that the vertical gradient of gravity field of a point mass is a homogenous function of degree -3. Hence in equation (3) the function f can be replaced by the vertical gradient of gravity with N=3. For a source body to be represented by an appropriate distribution of point sources on the body's upper surface, N would be the structural index (Thompson, 1982). The value of this index has to be determined in practice together with the unknowns x_0, y_0 and z_0.

4. Computation method

Applying Euler's equation (3) for the interpretation of gravity data is quite straightforward. A suitable square window (3*3 or greater) of girded data is required. A 3*3 window produces a system 9 linear equations with three unknowns. This is an over determined system of linear equations solvable by least squares procedure. The areas of interest are windowed using different N. A rejection criterion (Thompson, 1982) based on the uncertaintity of solution, was established and the accepted solutions were plotted on the (x, y) plane. The solutions were rejected if the standard deviation of the unknowns, evaluates from the covariance matrix of the linear system happened to be bigger than say, 5 to 15 percent of the calculated depth (Marson and Klingele, 1993). Optimal choice of structural index caused the clustering of results in the x, y plane. The standard deviation of unknowns and clustering of solutions speed up the interpretation process and in the mean time saved the interpreter's judgment The input for equation (3) is the vertical and horizontal derivatives. To compute the horizontal derivatives we used a five point Lagrangian differentiation operator as in Abramowitz and Stegun, (1970).

$$\left.\frac{d^k f(x)}{dx^k}\right|_{x=x_j}=\frac{k!}{m!h^k}\sum_{i=0}^{m}A_i f(x_i) \qquad (4)$$

For the first order derivative k equals to 1, and for the five points operator, m equals to 5. The coefficients A_i are presented by Abramowitz et al. (1970) in the related tables.

For computing the first and second vertical derivatives, considering the responce filter functions suggested by Dean (1958), we used the following equations described by Agarwal and Lal (1972) as follows,

$$\frac{\partial g}{\partial z}=\frac{1}{4\pi^2}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}F_0(p,q)\sqrt{p^2+q^2}\,\exp[i(px+qy)]dpdq \qquad (5)$$

$$\frac{\partial^2 g}{\partial z^2}=\frac{1}{4\pi^2}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}F_0(p,q)(p^2+q^2)\,\exp[i(px+qy)]dpdq \qquad (6)$$

Where F_0 (p, q) is the Fourier transform of the data g_0 (x, y), which is the Bouguer or residual gravity anomaly, p and q are the discrete frequencies.

5. Numerical Results

To determine the coordinates of the perturbing body with the FULDPH method, we edited two computer codes in Fortran 77. The inputs to the these programs are residual anomalies. Then the first and second vertical derivatives were computed through implementation equations (5) and (6) respectively. Horizontal derivatives of the first vertical derivative are estimated by using equation (4). The analytic signal and EULDPH are then used to locate the point sources and their depths.

The first data used is a low-quality gravity data from Nosrat Abad, the region we are looking for the Choromit. The primary geological survey shows that the dip of the alternate lens is between 60 to 80 degree, and the direction of the dip is toward north and northwest of the survey area. Figure (1) shows the Bouguer gravity anomaly map of the area. The Choromit is most probably located in the west of the area as is shown in Fig. (1) in white. The residual gravity anomalies were computed by the orthonormal method (Sarma and

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Quantitative interpretation of gravity data through gravity gradients

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Abstract

A great deal of attention has been paid to quantitative interpretation in recent years Two methods, namely the analytic signal and the Euler deconvolution (EULDPH) were discussed in this paper. After a short review on the mathematical bases of the methods, two field examples were used to examine the efficiency and limits of the methods when they are applied on a complex geology structure. These methods have already been applied to synthetic models and high -resolution data such as gradiometeric or microgravity data. Noisy gravity data especially in areas of complex geology has rarely been used by these methods and the field examples are exceptions. The low- resolution gravity data was used to provide with residual anomalies. Gravity gradients were generated from the residual anomaly values. Then applying the gravity gradients to the analytic signal and EULDPH methods, we determine the coordinates of a perturbing body in the field of data. Two field examples, one in the west of Tehran (Mardabad) and another in the southwest of Iran are considered. In the first field we were to determine the location of a hydrocarbon density anomaly. In the second field, we were to determine a Choromit anomaly.

Key words: Residual anomaly, gravity gradient, analytic signal, EULDPH

1. Introduction

The determination of the depth and location of the corners of a perturbing body are two important prerequisites in the quantitative gravity interpretation. The basic concepts of 2-D analytic signal for magnetic data were discussed by Nabighian (1972, 1974). Cordell and Grauch (1985) presented a method for the location of abrupt changes in the density of subsurface rocks by locating the position of the maxima of horizontal gradient or gravity anomalies. Their method was automated by Blakely and Simpson (1986). This method can also be used for determining the location of an maxima of the analytic signal. EULDPH method is based on Euler's homogeneity principle. Reid et al. (1990) used it on magnetic data and briefly discussed the application of this technique to gravity survey. The counterpart of this method to the gravity gradiometric and microgravity has been introduced by Klingele et al. (1991). EULDPH is an efficient method for locating density contrasts, particularly in the case of interfering anomalies (Marson and Klingele, 1993). EULDPH needs no postulation on the geometry of the source body. This is a great advantage, since the vertical gravity gradient is more sensitive to geology structures than gravity itself and its interpretation is less influenced by the neighboring disturbing bodies. The vertical gradient if not measured directly, can be numerically estimated from the gravity anomalies. The vertical gradient can also be derived from Bouguer or residual anomalies. To locate the maxima of the analytic signal, the corners of the source body are determined. Then solving Euler's homogeneity equations for the areas including the maxima of analytic signal, results in the coordinates of the source body.

2. Analytic signal

According to Nabighian (1982)· the analytic signal of a vertical gradient of gravity produced by a 3-D source can be defined,

$$A(x,y)=\frac{\partial^2 g}{\partial x\partial z}+\frac{\partial^2 g}{\partial y\partial z}-i\frac{\partial^2 g}{\partial z^2} \qquad (1)$$

The corresponding amplitude is,

$$|A(x,y)|=\sqrt{\left(\frac{\partial^2 g}{\partial x\partial z}\right)^2+\left(\frac{\partial^2 g}{\partial y\partial z}\right)^2+\left(\frac{\partial^2 g}{\partial z^2}\right)^2} \qquad (2)$$

Green (1976) discussed the properties of analytical signal useful for 2 -D gravity data analysis. Hansen et al. (1987) demonstrated also the usefulness of this technique to the gravity field. The location of the maxima amplitude of the analytic signal is determinable by the method